# Stationary Source Control Techniques Document for Fine Particulate Matter

EPA CONTRACT NO. 68-D-98-026
WORK ASSIGNMENT NO. 0-08

Prepared for:

Mr. Kenneth Woodard
Integrated Policy and Strategies Group (MD-15)
Air Quality Strategies and Standards Division
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

October 1998

Submitted by:

EC/R Incorporated
Timberlyne Center
1129 Weaver Dairy Road
Chapel Hill, North Carolina 27514

## Disclaimer

This report has been reviewed by the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, and has been approved for publication. Mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use.

## Copies

Copies of this document are available through the Library Services Office (MD-35), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711; or from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161 (for a fee). This document can also be found on the Internet at the U.S. Environmental Protection Agency website (http:\\www.epa.gov/ttn/oarpg).

## CONTENTS

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

TABLES (continued)

TABLES

TABLES (continued)

FIGURES

FIGURES (continued)

FIGURES (continued)

FIGURES (continued)

# TECHNICAL REPORT ABSTRACT

REPORT TITLE: Stationary Source Control Techniques Document for Fine Particulate Matter

REPORT DATE: September 30, 1997

CONTRACT NO.: EPA Contract No. 68-D3-0034

PRIME CONTRACTOR: EC/R Incorporated, Chapel Hill, North Carolina

WORK ASSIGNMENT NO.: III-34

PROJECT OFFICER: Ms. Mary Wilkins

ADDRESS: Information Transfer and Program Integration Division (MD-12)
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

PHONE: (919) 541-5229

PROJECT OFFICE: Office of Air Quality Planning and Standards

NUMBER OF PAGES: 242

SECURITY CLASSIFICATION: Unclassified (No Confidential Business Information)

REPORT ABSTRACT:

Stationary Source Control Techniques Document for Fine Particulate Matter presents recent developments in the control of particulate matter which have become available since preparation of an earlier document entitled Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (1982).

This document focuses on fine particulate matter ($PM_{10}$ and $PM_{2.5}$ - particles with an aerodynamic diameter less than or equal to an nominal 10 microns and 2.5 microns, respectively). Information presented in this document includes background on particulate matter emissions; measurement methods for particulate matter; types of particulate control devices, their operating principles, design, operation, and control efficiencies; costs and environmental effects of particulate matter control systems; and emerging technologies for particulate matter control.

KEY WORDS/DESCRIPTORS: Air Pollution, Air Pollution Control, Control Devices, Fine Particulate Matter, Costs, Control Efficiency

# 1. INTRODUCTION

The U.S. Environmental Protection Agency (EPA) has recently analyzed information on the health effects of elevated concentrations of respirable particulate matter (PM) in ambient air. This analysis lead to revisions of the national ambient air quality standards (NAAQS) for PM. The EPA has also added a new "indicator" to measure respirable PM concentrations. The previous indicator was $PM_{10}$, which is defined as particle matter having a nominal aerodynamic diameter of 10 micrometer ($\mu$m) or less. The additional indicator is based on smaller particles, $PM_{2.5}$, defined as PM less than or equal to 2.5 micrometer in aerodynamic diameter.[1]

## 1.1 PURPOSE OF THIS DOCUMENT

The purpose of this document is to support the development of implementation strategies for attaining revised ambient standards for PM, based on $PM_{2.5}$ and $PM_{10}$. This document is a revision of the EPA's 1982 guidance on *Control Techniques for Particulate Emissions from Stationary Sources*.[2] The focus of this document is on the control of $PM_{10}$ and $PM_{2.5}$ emissions from industrial sources. This document does not address nonindustrial sources, such as residential wood combustion and windblown dust, which are covered by separate guidance documents.

Although they account for a smaller fraction of national $PM_{10}$ emissions than nonindustrial sources (see Section 2), industrial sources can have significant ambient impacts. These can be especially important in urbanized areas which are typically centers of both population and industrial activity. In addition, PM emissions from industrial sources tend to be concentrated in the smaller size ranges, increasing their importance in the implementation of a potential standard for $PM_{2.5}$.

## 1.2 OTHER RESOURCES

The EPA has recently developed control techniques documents for a number of nonindustrial sources of PM emissions. In addition, reports have been prepared assessing the overall levels of control that could be achieved both in direct emissions of PM, and in emissions of gaseous pollutants that can react to produce secondary PM. Secondary PM is produced mainly from sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), ammonia ($NH_3$), and volatile organic compounds (VOC). These precursor gases react with one another and with oxygen and water in the atmosphere to form condensible compounds. Appendix A gives a summary of control techniques documents and other EPA documents available to support the development of control strategies for primary $PM_{10}$ and $PM_{2.5}$ emissions, and emissions of precursor gases for secondary PM.

## 1.3 ORGANIZATION

This document is organized in seven sections, including this introduction. Section 2 gives background information on trends in PM air quality and emissions, projected future impacts of control programs, and major current sources of $PM_{10}$ and $PM_{2.5}$ emissions.

Section 3 discusses the methods available to measure PM emissions.  These techniques are needed to estimate the level of emissions from the source before and after control, as well as determine the control efficiency of the PM control devices/techniques.  This section discusses established as well as innovative procedures that have been developed to measure the mass and/or size of PM, especially for $PM_{10}$ and $PM_{2.5}$.  Techniques for identifying and measuring the chemical species of the PM are discussed as well.

Section 4 presents approaches for reducing PM emissions through the use of fuel substitution and source reduction techniques, i.e. process modifications or optimization.

Section 5 is the heart of this document, and contains detailed descriptions of the primary devices used to control PM at stationary sources: electrostatic precipitators (ESPs), fabric filters, wet scrubbers, and incinerators.  For each of these control devices, the various designs of the devices are discussed along with the principles of operation.  The range of control efficiencies for each device is then discussed and the source categories to which the devices are applicable are presented.  The capital and annual costs for each device are also included in Section 5 along with the energy and other secondary environmental impacts of the technologies.  Section 5 begins with a discussion of pretreatment techniques, that is similar in format to the primary device discussion. The pretreatment devices are used to reduce the PM loading on the primary PM collection devices, in order to reduce the size and, potentially, the costs of the primary control device, and to possibly increase the overall PM collection efficiency.

Section 6 discusses industrial fugitive emission controls that include enclosures, ventilation techniques, and optimization of equipment and operations.  Where available, the reported control efficiencies of the control measures are presented.

Section 7 discusses the emerging PM control technologies that are being investigated by the EPA and industry to increase the control efficiency of PM control and/or to target fine particles.  Many of these technologies have been implemented in pilot- or full-scale operation.

## 1.4 REFERENCES FOR SECTION 1

1. Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information - External Review Draft. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1996.

2. Control Techniques for Particulate Emissions from Stationary Sources--Volume 1. (EPA-450/3-81-005a). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 1982.

# 2. BACKGROUND

National ambient air quality standards (NAAQS) for particulate matter (PM) were first established in 1971. These standards applied to total suspended PM (TSP) as measured by a high volume sampler. The sampler design favored the collection of particles with aerodynamic diameters up to 50 $\mu$m. In 1987, the EPA changed the indicator for PM from TSP to $PM_{10}$. The NAAQS levels for $PM_{10}$ were set at a 24-hour average of 150 $\mu g/m^3$ (with no more than one expected exceedance per year), and an annual average of 50 $\mu g/m^3$ (expected arithmetic mean).[1] In 1997, the EPA revised the form of the 24-hour (daily) $PM_{10}$ NAAQS and established $PM_{2.5}$ as a new fine PM indicator.

Prior to the revision, the 24-hour $PM_{10}$ NAAQS was met when the expected number of days per calendar year with a 24-hour average concentration above 150 $\mu g/m^3$ was less than or equal to one (averaged over 3 calendar years). The revised 24-hour $PM_{10}$ standard is met when the 99th percentile of the distribution of 24-hour concentrations at each monitor in an area for a period of one year (averaged over 3 calendar years) does not exceed 150 $\mu g/m^3$. The annual $PM_{10}$ standard was not impacted by the 1997 revisions.

The new $PM_{2.5}$ NAAQS are set at an annual mean concentration of less than or equal to 15 $\mu g/m^3$ and a 24-hour (daily) concentration less than or equal to 65 $\mu g/m^3$. The annual standard is met when the three year average of the annual arithmetic mean of the 24-hour concentrations from single or multiple community-oriented monitors does not exceed 15 $\mu g/m^3$. The daily standard is met when the 98th percentile of the distribution of the 24-hour concentrations for a period of one year (averaged over 3 calendar years) does not exceed 65 $\mu g/m^3$ at each monitor within an area.

## 2.1 TRENDS IN AMBIENT PARTICULATE MATTER CONCENTRATIONS AND PARTICULATE MATTER EMISSIONS

The most recent EPA report on trends in ambient PM concentrations covers $PM_{10}$ for the years 1988 through 1996.[2] Complete data on ambient $PM_{10}$ concentrations are available from 900 monitoring sites with urban, suburban and rural locations. The annual arithmetic mean $PM_{10}$ concentration for all sites (national average) during 1988 was 32 $\mu g/m^3$. By 1996, the annual arithmetic mean concentration had decreased to 24 $\mu g/m^3$, a 25 percent improvement over 1988 levels. The trend of $PM_{10}$ concentrations at urban and suburban sites was essentially the same with the annual mean decreasing from about 34 $\mu g/m^3$ in 1988 to about 26 $\mu g/m^3$ in 1996. The annual arithmetic mean at rural sites in 1988 was 25 $\mu g/m^3$. The mean decreased 20 percent to 20 $\mu g/m^3$ in 1996.

An independent analysis of $PM_{10}$ trends, conducted by Darlington, et.al., found the same improvements in concentrations.[3] Data from monitoring sites that reported at least one reading each year from 1988 through 1995 (585 sites) to the Atmospheric Information Retrieval System (AIRS) were used in this analysis. Nationwide, the analysis indicated a 24 percent reduction in

$PM_{10}$ concentrations from 34 $\mu$g/m$^3$ in 1988 to 26 $\mu$g/m$^3$ in 1995. About 160 of the monitoring sites used by Darlington were located in counties designated as nonattainment for $PM_{10}$ and 425 were located in attainment counties. The annual mean concentration for all the nonattainment counties in 1988 was 41 $\mu$g/m$^3$. This was reduced by 26 percent to 31 $\mu$g/m$^3$ in 1995. The mean in the attainment counties decreased 20 percent, from 30 $\mu$g/m$^3$ in 1988 to 24 $\mu$g/m$^3$ in 1995.

Table 2-1 shows trends in $PM_{10}$ emissions for major emission sources from 1987 to 1996. The table shows a good deal of fluctuation in emissions, mainly due to changes in natural wind erosion. It must also be noted that fugitive dust emissions estimates in the table are subject to a high degree of uncertainty (e.g. paved and unpaved roads, construction, agricultural operations, and wind erosion). These fugitive dust emissions are overestimated when compared to ambient measurements of the mineral-related components of $PM_{2.5}$.

Ambient concentration data are not available to assess historical trends in $PM_{2.5}$ ambient concentrations or emissions. However, visibility can be viewed as a surrogate measure of trends in fine particles in the range of 2.5 micrometers and under. Particles in this size range contribute greatly to the scattering and absorption of light (known as light extinction). There are two large contiguous haze areas in the continental U.S. One encompasses the eastern U.S. and the other includes the western Pacific states. There has been a marked decrease in haze over the 30 year period from 1960 to 1990 in the western Pacific states. The mid-continent section of the eastern haze area has remained relatively constant over this period, whereas the eastern U.S. has shown a change from winter-dominated haze to summer-dominated haze.[2]

## 2.2 PROJECTIONS FOR FUTURE CONTROL PROGRAMS AND EMISSIONS

The EPA's Office of Policy, Planning, and Evaluation (OPPE) has projected emission levels for $PM_{10}$ and $PM_{2.5}$ based on implementation of control programs required under the Clean Air Act Amendments (CAAA) of 1990. Control programs for PM under Title I of the CAAA are projected to have only a small impact on overall future emissions--a reduction of about 3 percent for $PM_{10}$ and less than 0.1 percent for $PM_{2.5}$.[2]

Because of a lack of available data, OPPE's projections did not take into account the impact of regulations for hazardous air pollutants (HAPs) under Title III of the CAAA. However, a number of the Title III HAPs are metals that are emitted in fine PM, both in bulk and trace quantities. Standards implemented for these particulate HAPs will have some impacts on $PM_{10}$ and $PM_{2.5}$ emissions.

Substantial reductions in $SO_2$ emissions are projected by OPPE as a result of acid rain control programs implemented under Title IV of the CAAA. In addition, reductions in $NO_x$ emissions are projected as a result of Title IV, and reductions in both $NO_x$ and VOC are projected as a result of ozone control programs under Title I. All of these pollutants are precursors of secondary PM. Therefore, emission reductions for these pollutants are expected to produce reductions in the formation of secondary PM.

Table 2-1. Summary of Trends in PM-10 Emissions from 1987 through 1996 (Reference 2)

| | Estimated Emissions (million tons) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 |
| Fuel combustion - utility and industrial | 0.5 | 0.5 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 |
| Fuel combustion - residential wood and other | 0.8 | 0.9 | 0.9 | 0.6 | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 |
| Metals processing | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Other industrial | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Open burning and other waste disposal | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Motor vehicles and off-highway engines | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 1.0 | 0.9 | 0.9 |
| Wildfires and managed burning | 1.0 | 1.7 | 0.9 | 1.2 | 0.9 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 |
| *Agriculture | 7.3 | 7.5 | 7.3 | 5.1 | 5.1 | 4.9 | 4.5 | 4.7 | 4.7 | 4.7 |
| *Natural wind erosion | 1.6 | 18.1 | 12.1 | 2.1 | 2.1 | 2.2 | 0.5 | 2.2 | 1.1 | 5.3 |
| *Paved and unpaved roads | 16.6 | 18.3 | 17.6 | 13.5 | 13.6 | 13.3 | 13.9 | 13.9 | 12.8 | 12.7 |
| *Construction, mining, and quarrying | 12.5 | 12.0 | 11.7 | 4.6 | 4.4 | 4.8 | 5.1 | 5.8 | 4.2 | 4.5 |
| Total | 42.5 | 61.3 | 53.2 | 29.9 | 29.6 | 29.5 | 28.0 | 30.9 | 26.9 | 31.3 |

* Emissions from agricultural operations, wind erosion, paved and unpaved roads, and construction are far too large when reconciled with levels of the mineral-related components of $PM_{2.5}$ measured in the ambient air.

## 2.3 SOURCES OF $PM_{10}$ AND $PM_{2.5}$ EMISSIONS

Emission sources can be broadly classified as point sources and area sources. Point sources are large emission sources that are treated on a point-by-point basis in emissions inventories. These are typically industrial facilities, utilities, or large commercial or institutional emission sources. Area sources are defined as emission sources that are too numerous or dispersed to be treated individually in an emissions inventory. This category also includes highway vehicles and nonroad engines and equipment.

The emissions discussed in the next two sections are based on the 1990 National Inventory. The 1990 National Inventory attributed approximately 90 percent of $PM_{10}$ and 70 percent of $PM_{2.5}$ emissions to fugitive dust from agriculture, paved roads, unpaved roads, and construction activities. While these are certainly major sources of PM emissions, the confidence in these estimates is low. These estimates are believed to be high, and the inventory is being reviewed and revised to improve these estimates. For this reason, the following two sections discuss important sources of PM emissions in general terms without estimates of impact on emissions.

### 2.3.1 Point Sources

Particulate matter emissions from utility, industrial and commercial/institutional combustion sources are small in comparison with emissions from area combustion sources. This is due both to superior combustion conditions, which result in higher combustion efficiencies, and also to add-on PM controls for coal combustion and some oil combustion sources. Utility, industrial, and commercial/institutional combustion were the most significant point sources of $PM_{10}$ and $PM_{2.5}$ in 1990. Other significant industrial sources included metal processing, mineral products processing, and wood products processing.[2]

### 2.3.2 Area Sources

Fugitive emissions from agriculture, paved roads, unpaved roads, and construction activities represent a major portion of $PM_{10}$ and $PM_{2.5}$ emissions. However, as stated above, these emissions appear to be overestimated when reconciled to ambient measurements of the mineral-related components of $PM_{2.5.}$ In addition to these fugitive dust emission sources, area source combustion categories including residential wood burning, wildfires, and prescribed burning of forest residues were important sources. Highway vehicles, nonroad engines and equipment, and open burning of wastes also made significant contributions.[2]

## 2.4 CHARACTERIZATION OF $PM_{2.5}$ CONCENTRATIONS

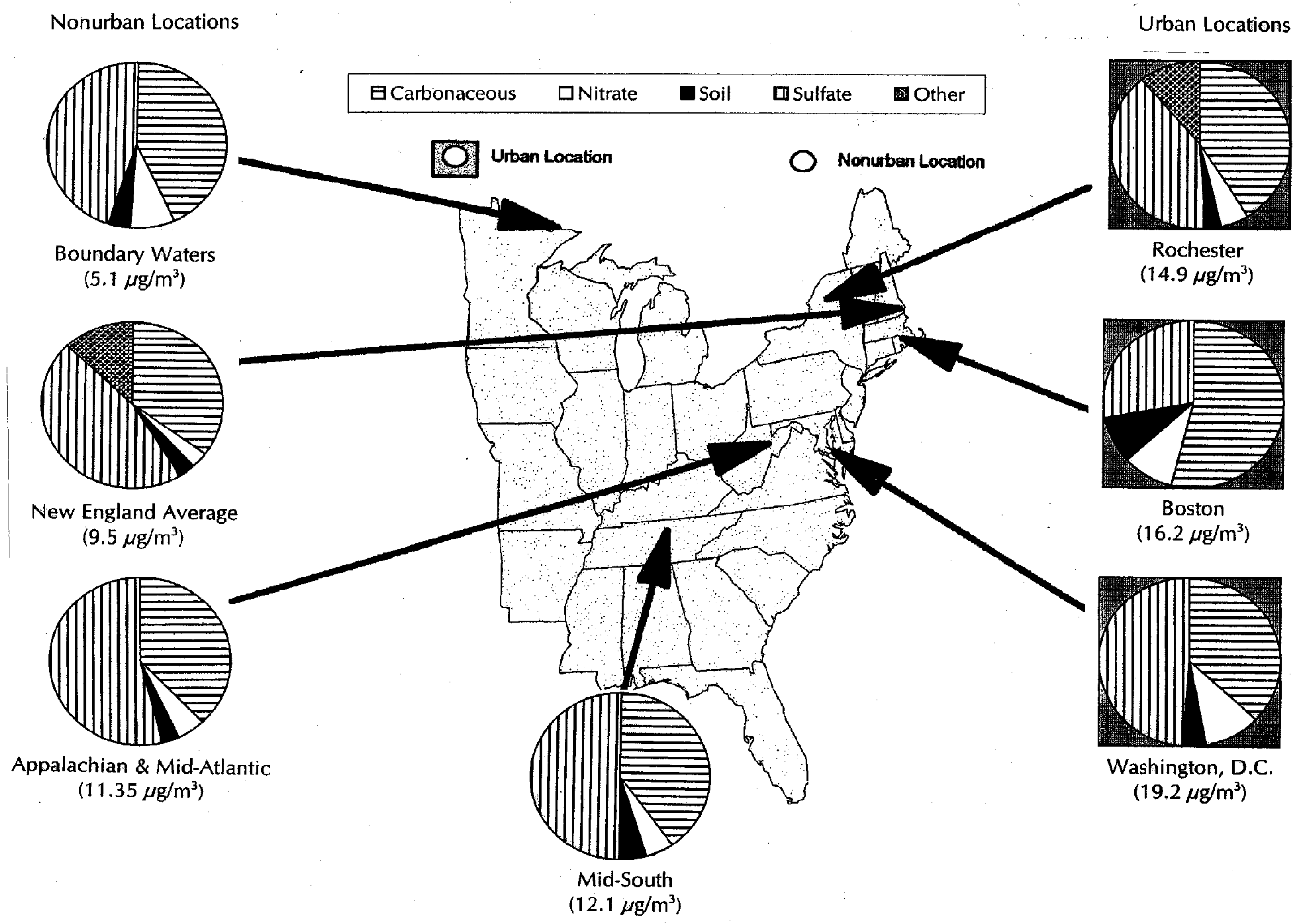
Ambient samples of $PM_{2.5}$ from eight research studies are summarized in Figures 1 and 2.[4,5] The $PM_{2.5}$ samples were chemically analyzed to determine the amounts of ammonium sulfate, ammonium nitrate, carbon, and soil present. Ammonium sulfate and ammonium nitrate are secondary particles formed in the atmosphere from the reaction of ammonia with sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_X$), respectively. Carbon and soil are primary particles. These are generally emitted directly into the atmosphere, or generated by processes such as wind erosion, construction, or traffic on paved or unpaved roads. The results of these analyses for eastern states are shown in Figure 1. Figure 2 summarizes the results for western states.

Figure 1 indicates that in the eastern states, $PM_{2.5}$ was dominated by ammonium sulfate particles which accounted for 40 to 60 percent of the total mass. Ammonium nitrate particles contributed another 5 to 15 percent. Carbon particles, from sources such as incomplete combustion, accounted for 30 to 40 percent of the $PM_{2.5}$ mass. The fraction of soil in the eastern samples ranged from 5 to 10 percent.[5]

Figure 2 shows that only 5 to 15 percent of the $PM_{2.5}$ was ammonium sulfate, and ammonium nitrate accounted for 1 to 35 percent of the total mass. The percentage of carbon from incomplete combustion ranged from 35 to 65 percent of the western samples. Soil content in the western samples contributed 5 to 15 percent of the total mass of $PM_{2.5}$.[5]

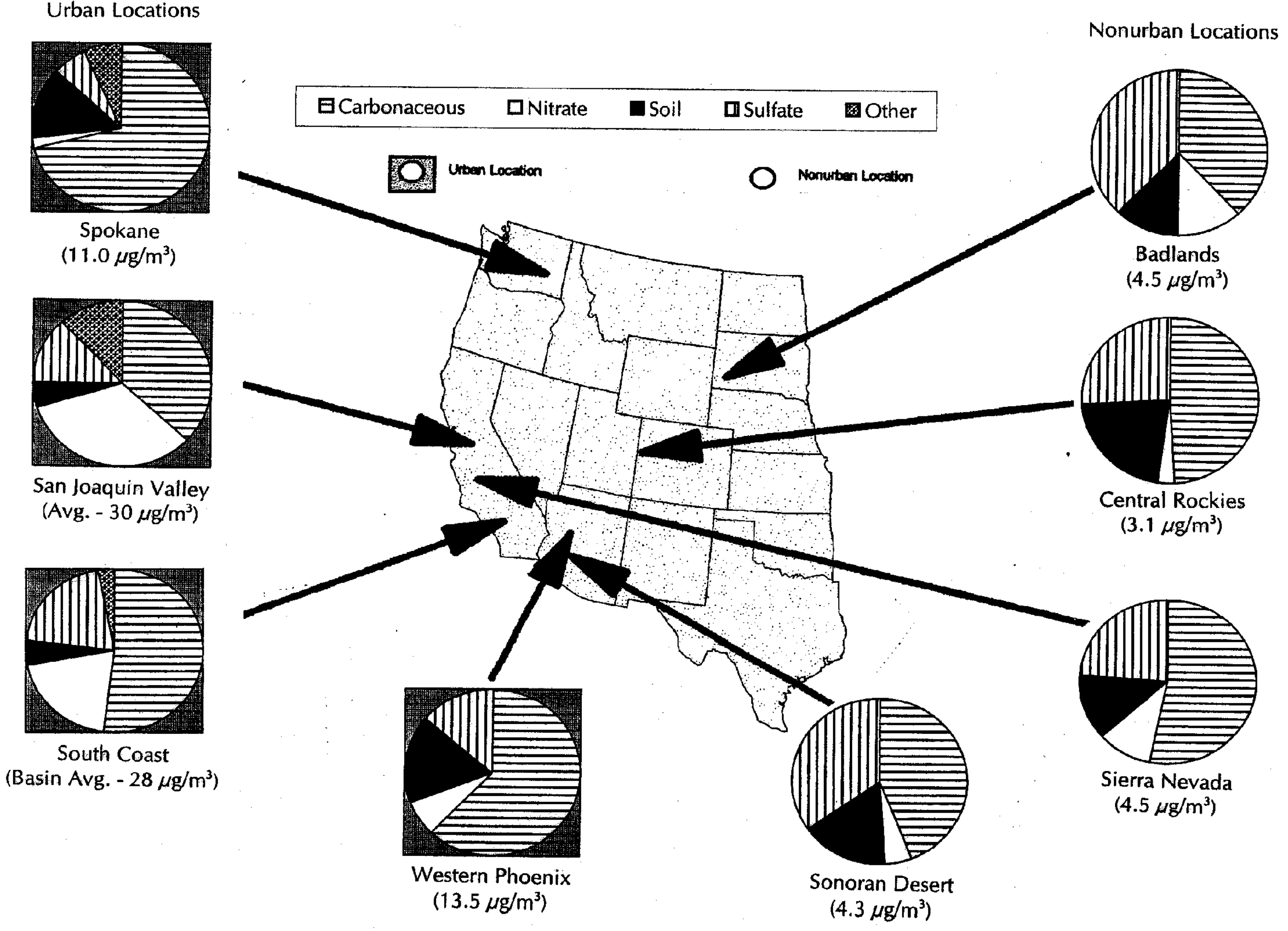
The following sections of this document address techniques for reducing primary particulate emissions from stationary combustion sources and industrial processes. As illustrated above, secondary particles (ammonium sulfate and ammonium nitrate) comprise a large percentage of the $PM_{2.5}$ samples in both the Eastern and Western United States. This is indicative of the need to address emissions of sulfur dioxide, nitrogen oxides, and ammonia when considering means of reducing $PM_{2.5}$ concentrations in the future.

Figure 1. $PM_{2.5}$ Composition in the Eastern United States



Note: $PM_{2.5}$ mass concentrations are determined on at least one year of monitoring at each location using a variety of non-Federal reference methods. They should not be used to determine compliance with the $PM_{2.5}$ NAAQS.

**Figure 2. $PM_{2.5}$ Composition in the Western United States**



Note: $PM_{2.5}$ mass concentrations are determined on at least one year of monitoring at each location using a variety of non-Federal reference methods. They should not be used to determine compliance with the $PM_{2.5}$ NAAQS.

## 2.5 REFERENCES FOR SECTION 2

1. Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information - External Review Draft. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1996.

2. National Air Quality and Emissions Trends Report: Report Number EPA-454/R-97-013. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. January 1998.

3. Darlington, T.L., Kahlbaum, D.F., Heuss, J.M., and Wolff, G.T. *Analysis of* $PM_{10}$ *Trends in the United States from 1988 through 1995*. Journal of the Air & Waste Management Association. October 1997. 1070-1078.

4. Pace, T.G. "$PM_{2.5}$ in the Ambient Air". Proceedings on the AWMA Specialty Conference $PM_{2.5}$ - A Fine Particle Standard. Long Beach, California. January, 1997.

5. Pace, T.G. and Kuykendal, W.B. "Planning Tools for PM2.5 Emission Factors and Inventories". Proceedings of the Air & Waste Management Association's 91st Annual Meeting and Exhibition. San Diego, California. June 1998.

# 3 MEASUREMENT

The determination of the control efficiency of PM control devices requires the use of methods to determine the control device inlet and outlet PM emissions. This section discusses established as well as innovative procedures that have been developed to measure the mass and/or size of PM, especially for $PM_{10}$ and $PM_{2.5}$. Techniques for identifying and measuring the chemical species of the PM are discussed as well.

The most precise method of determining the mass concentration of PM is to collect the entire volume of gas (and PM) and to determine the mass concentration from this sample. This procedure, however, is feasible only with a few sources where there are very low flow rates. Procedures have been developed to sample small portions of the gas stream to obtain a representative sample so that estimates of PM mass emissions can be made. These procedures are called "extractive" methods, since a portion of the gas stream is removed from the source and sampled elsewhere. Other more innovative procedures are being used to determine PM mass concentrations *in situ*. Also, as part of a PM emission characterization of a source or control device, the size distribution of the PM may be needed. This is especially true for $PM_{2.5}$ emission determinations, since procedures to determine $PM_{2.5}$ mass emissions directly are still under development (see Section 3.5, below).

In the measurement of PM during extractive methods, it is important that the gas be sampled isokinetically so that a representative sample of PM enters the sampling device. The term "isokinetic" refers to the situation where the gas streamlines of the source gas are preserved within the sampling probe so that the concentration and size distribution of the PM in the sample probe is the same as that in the source effluent duct. The parameter that must be controlled to establish isokinetics is the gas velocity within the sample probe, which must be equal to the actual gas velocity at the sample point in the source exhaust duct. Since the sample probe will have a smaller diameter than the source exhaust duct and possibly a lower temperature, the actual gas flow rate used to extract gas through the sampling probe must be controlled to establish an isokinetic sampling velocity.

Anisokinetics, or the lack of isokinetics, can lead to either over or under sampling of particles of a certain size. Sampling velocities less than isokinetic will lead to an overestimation of larger-sized particles and a higher than actual PM mass concentration; conversely, sampling velocities higher than isokinetic will lead to an overestimation of smaller particles with a lower than actual PM mass concentration.

## 3.1 List of EPA PM Mass Measurement Test Methods

Table 3-1 lists the EPA test methods applicable to the measurement of PM mass emissions. These methods are discussed further in the next section. To obtain a detailed

Table 3-1. EPA Test Methods for PM

| EPA Method | *Federal Register* Reference | | Description of Method |
|---|---|---|---|
| Method 5 | 36 FR 24877 | 12/23/71 | PM from stationary sources |
| Method 5A | 47 FR 34137 | 08/06/82 | PM from asphalt processing and asphalt roofing |
| Method 5B | 51 FR 42839 | 11/26/86 | Nonsulfuric acid PM |
| Method 5C | tentative | | PM from small ducts |
| Method 5D | 49 FR 43847 | 10/31/84 | PM from (positive pressure) fabric filters |
| Method 5E | 50 FR 07701 | 02/25/85 | PM from wool fiberglass plants |
| Method 5F | 51 FR 42839 | 11/26/86 | Nonsulfate PM |
| Method 5G | 53 FR 05860 | 02/26/88 | PM from wood heaters - dilution tunnel |
| Method 5H | 53 FR 05860 | 02/26/88 | PM from wood heaters - stack |
| Method 201 | 55 FR 14246 | 04/17/90 | PM/PM-10 - exhaust gas recycle (EGR) procedure |
| Method 201A | 55 FR 14246 | 04/17/90 | PM/PM-10 - constant sampling rate (CSR) pocedure |
| Method 17 | 43 FR 07568 | 02/23/78 | In-stack filtration method for PM |
| Method 202 | 56 FR 65433 | 12/17/91 | Condensible particulate emissions from stationary sources |
| Method 9 | 39 FR 39872 | 11/12/74 | Visual determination of stack opacity; remote Lidar |
| Performance Specification 1 | 36 FR 24877 | 12/23/71 | CEMS for opacity at stationary sources |
| Method 29 | 59 FR 48259 | 09/20/94 | Metal emissions (and PM) |

description of these methods, the EPA's Technology Transfer Network, an electronic bulletin board, can be viewed at http://www.epa.gov/ttn.

## 3.2 EPA Stationary (Point) Source PM Mass Measurement Test Methods

The following sections describe the EPA Test Methods for the sampling and analysis of PM mass that include test methods for the measurement of total PM, $PM_{10}$, condensible PM, and opacity.

EPA Test Method 5, that measures total PM from stationary sources, is the predominant test procedure used to measure PM mass emissions. The sampling train and isokinetic sampling procedures described in Method 5 are also the basis for many other EPA test methods. The Method 5 sampling train and procedures also has been modified and adapted into test methods that are designed to measure other gas constituents, such as semi-volatile compounds, in exhaust gases where PM is likely to also exist. In some cases, this is because PM mass measurements are desired in addition to the target compounds; in other cases, the PM is collected so as to remove the potential for interference with the measurement of the target compounds.

Method 5 and the other stationary source measurement methods described below rely on the use of EPA Test Methods 1 through 4. These methods describe the appropriate techniques to be used to sample the exhaust gas from stationary sources, and also the techniques used to obtain data on the physical and chemical characteristics of the exhaust gas which are needed to calculate PM emissions. These auxiliary test methods and their variations are listed in Table 3-2.

### 3.2.1 EPA Test Method 5 for Total PM Mass

This method is applicable for the determination of PM mass emissions from stationary sources. Particulate matter (PM) is withdrawn isokinetically from the source and collected on a glass fiber filter maintained at a temperature in the range of l20 ± l4°C or another temperature as specified in a regulation or approved for special purposes by the EPA for the specific application. The PM mass, which includes any material that condenses at or above the filtration temperature, is determined gravimetrically after removal of uncombined water.

A schematic of the sampling train used in this method is shown in Figure 3-l. Complete construction details are given in "APTD-0581: Construction Details of Isokinetic Source-Sampling Equipment;"[1] commercial models of this train are also available. Changes from APTD-058l and allowable modifications of the train shown in Figure 3-l can be obtained

Table 3-2. EPA Test Methods 1 through 4: General Stack Sampling Procedures

| EPA Test Method | Description of Method |
|---|---|
| Method 1 | Sample and velocity traverses for stationary sources |
| Method 1A | Sample and velocity traverses for stationary sources with small stacks or ducts |
| Method 2 | Determination of stack gas velocity and volumetric flow rate (Type S pitot tube) |
| Method 2A | Direct measurement of gas volume through pipes and small ducts |
| Method 2B | Determination of exhaust gas flow rate from gasoline vapor incinerators |
| Method 2C | Determination of stack gas velocity and volumetric flow rate in small stacks or ducts (standard pitot tube) |
| Method 2D | Measurement of gas volumetric flow rates in small pipes and ducts |
| Method 2E | Determination of landfill gas; gas production flow rate |
| Method 3 | Gas analysis for carbon dioxide, oxygen, excess air, and dry molecular weight |
| Method 3A | Determination of oxygen and carbon dioxide concentrations in emissions from stationary sources (instrumental analyzer procedure) |
| Method 3B | Gas analysis for the determination of emission rate correction factor or excess air |
| Method 3C | Determination of carbon dioxide, methane, nitrogen, and oxygen from stationary sources |
| Method 4 | Determination of moisture content in stack gases |

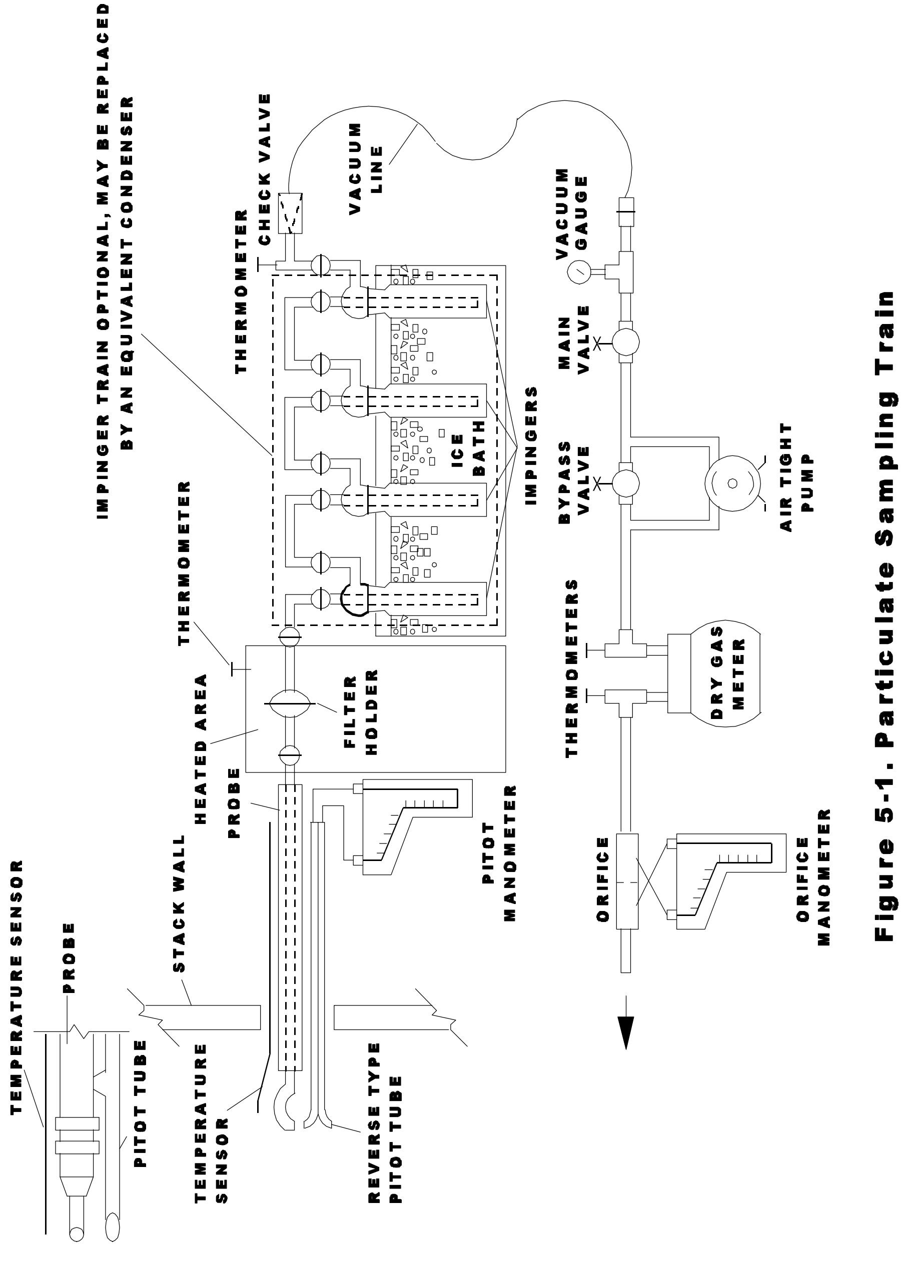


Figure 3-1. EPA Test Method 5 Sampling Train.

from the EPA's Emission Measurement Technical Information Center.[a] The operating and maintenance procedures for the sampling train are described in APTD-0576: "Maintenance, Calibration, and Operation of Isokinetic Source Sampling Equipment."[2] Correct usage of the sampling train is important in obtaining valid results with this method.

### 3.2.2 EPA Test Method 5 Variations: 5A - 5H

The following methods are considered variations of Method 5 that target a specific industry or type of PM emissions. The specifics of each method are summarized below and include the differences between the method and Method 5, and any other noteworthy details. Otherwise, the methods are largely identical to Method 5.

- **Method 5A: Determination of PM Emissions from the Asphalt Processing and Asphalt Roofing Industry**. This method is similar to Method 5 except that in this method the PM catch is maintained at a slightly lower temperature in Method 5A, 42°C vs. 120°C in Method 5, and a precollector cyclone is used.

- **Method 5B: Determination of Nonsulfuric Acid PM from Stationary Sources**. This method is similar to Method 5 except that the sample train is maintained at a higher temperature in Method 5B, 160°C vs. 120°C in Method 5, and the collected sample is heated in the oven for 6 hours to volatilize any sulfuric acid that may have collected. The nonsulfuric acid PM is then determined by the method.

- **Method 5C: Determination of PM in Small Ducts**. A test method to address PM measurement in small ducts is tentatively planned; no information about the method is currently available.

- **Method 5D: Determination of PM Emissions from Positive Pressure Fabric Filters**. Method 5D is similar to Method 5, except that it provides alternatives to Method 1 in terms of determining the measurement site, and location and number of sampling (traverse) points. Since the velocities of the exhaust gases from positive pressure fabric filters are often too low to measure accurately with the type S pitot specified in Method 2, alternative velocity determinations are presented in Method 5D. Because of the allowable changes to site selection and velocity determination in Method 5D, alternative calculations for PM concentration and gas flow are presented with the method.

- **Method 5E: Determination of PM Emissions from the Wool Fiberglass Insulation Manufacturing Industry**. This method is similar to Method 5 except

---

[a] Emission Monitoring and Analysis Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 27711

that it measures both filterable and condensed PM enabling the determination of total PM. A sodium hydroxide impinger solution is used to collect the condensed PM.

- **Method 5F: Determination of Nonsulfate PM Emissions from Stationary Sources**. This method is similar to Method 5 except that the sample train is maintained at a higher temperature in Method 5F, 160°C vs. 120°C in Method 5, and the collected sample is extracted with water to analyze for sulfate content.

- **Method 5G: Determination of PM Emissions from Wood Heaters from a Dilution Tunnel Sampling Location**. This method differs substantially from Method 5 in that there are different sampling trains specified for Method 5G and that the PM is withdrawn from a single point from a total collection hood and sampling tunnel that combines the wood heater exhaust with ambient dilution air. The PM is collected on two glass fiber filters in series, as opposed to only one used in Method 5. The fiber filters are also maintained at a much lower temperature in Method 5G, 32°C vs. 120°C in Method 5.

- **Method 5H**: Determination of PM Emissions from Wood Heaters from a Stack Location. This method is more similar than Method 5G to Method 5, since the filter is maintained at 120°C. Although, a dual filter sampling train from a single point is used, as in Method 5G, the two filters are separated by the impingers.

### 3.2.3 EPA Test Methods for $PM_{10}$ from Stationary Sources

The following are two methods to measure $PM_{10}$ emissions from stationary sources. Both methods are in-stack procedures; one method uses exhaust gas recycling and the other constant sampling. Since condensible emissions not collected by these methods are also $PM_{10}$ that contribute to ambient $PM_{10}$ levels, the EPA suggests that source $PM_{10}$ measurements include both in-stack $PM_{10}$ methods, such as method 201 or 201A, and condensible emissions measurements to establish source contributions to ambient levels of $PM_{10}$, such as for emission inventory purposes. Condensible emissions may be measured by an impinger analysis in combination with Method 201 and 201A, or by Method 202. Method 202 is discussed below in Section 3.2.5

#### 3.2.3.1 Method 201: Determination of $PM_{10}$ Emissions--Exhaust Gas Recycle Procedure

Method 201 applies to the in-stack measurement of $PM_{10}$ emissions. In Method 201, a gas sample is isokinetically extracted from the source. An in-stack cyclone is used to separate PM greater than $PM_{10}$, and an in-stack glass fiber filter is used to collect the $PM_{10}$. To maintain isokinetic flow rate conditions at the tip of the probe and a constant flow rate through the cyclone, a clean dried portion of the sample gas at stack temperature is recycled into the nozzle. The particulate mass is then determined gravimetrically after removal of uncombined water. Further information on this method can be found in the EPA document *Application Guide for Source* $PM_{10}$ *Measurement with Exhaust Gas Recycle Sampling System*.[3]

#### 3.2.3.2 Methods 201A: Determination of $PM_{10}$ Emissions--Constant Sampling Rate Procedure

Method 201A is a variation of Method 201, and may be used for the same purposes as Method 201. In Method 201A, a gas sample is extracted at a constant flow rate through an in-stack sizing device, which separates PM greater than $PM_{10}$, attached to a PM sampling train. The sizing device can be either a cyclone that meets the specifications in the method or a cascade impactor that has been calibrated using a specified procedure. Variations from isokinetic sampling conditions are maintained in the sampling train within well-defined limits. With the exception of the $PM_{10}$ sizing device and in-stack filter, this train is the same as an EPA Method 17 train. The particulate mass collected with the sampling train is then determined gravimetrically after removal of uncombined water. Further information on this method can be found in the EPA document *Application Guide for Source* $PM_{10}$ *Measurement with Constant Sampling Rate*.[4]

### 3.2.4 EPA Test Method 17: Determination of PM Emissions from Stationary Sources--In-Stack Filtration Method

This method describes an in-stack gas sampling method that can be used in situations where PM concentrations are not influenced by stack temperatures, over the normal range of temperatures associated with the source category. Therefore, Method 17 eliminates the use of the heated glass sampling probe and heated filter holder required in the "out-of-stack" Method 5, that is cumbersome and requires careful operation by usually trained operators. Method 17 can only be used to fulfill EPA requirements when specified by an EPA standard, and only used within the stack temperature range also specified by the EPA. Method 17 is especially not applicable to gas streams containing liquid droplets or which are saturated with water vapor. Also, Method 17 should not be used if the projected cross-sectional area of the probe/filter holder assembly covers more than 5 percent of the stack cross-sectional area.

### 3.2.5 Method 202 for Condensible PM Measurement

This method applies to the determination of condensible particulate matter (CPM) emissions from stationary sources. It is intended to represent condensible matter as material that condenses after passing through a filter. In Method 202, condensible PM is collected in the impinger portion of a Method 17 type sampling train. The impinger contents are immediately purged after the run with nitrogen gas to remove dissolved sulfur dioxide gases from the impinger contents. The impinger solution is then extracted with methylene chloride. The organic and aqueous fractions are then taken to dryness and the residues weighed. The total of both fractions represents the condensible PM.

There is the potential for low collection efficiency at oil-fired boilers with this method. To improve the collection efficiency at these sources, an additional filter should be placed between the second and third impinger. In sources that use ammonia ($NH_3$) injection as a control technique for hydrogen chloride (HCl), $NH_3$ can interfere with the determination of condensible PM by Method 202 by reacting with HCl in the gas stream to form ammonium chloride, which is then measured as condensible PM. The method describes measures that can be taken to correct for this interference.

The filter catch of this method can be analyzed according to the appropriate method to speciate the PM. Method 202 also may be used in conjunction with the methods designed to measure $PM_{10}$ (Method 201 or 201A) if the probes are glass-lined. If Method 202 is used in conjunction with Method 201 or 201A, the impinger train configuration and analysis specified in Method 202 should be used in conjunction with a sample train operation and front end recovery and analysis conducted according to Method 201 or 201A. Method 202 may also be modified to measure material that condenses at other temperatures by specifying the filter and probe temperature. A heated Method 5 out-of-stack filter may be used instead of the in-stack filter to determine condensible emissions at wet sources.

The following documents discuss the measurement of condensible PM and the development of this method in more detail: *Measurement of Condensible Vapor Contribution to* $PM_{10}$ *Emissions*,[5] *A Review of Current Methods for Measuring Particulate Matter Including Condensibles from Stationary Sources*,[6] and *Method Development and Evaluation of Draft Protocol for Measurement of Condensible Particulate Emissions*.[7]

### 3.2.6 EPA Test Method 9: Visual Determination of the Opacity of Emissions from Stationary Sources, and Alternate Method 1 for the Use of Remote Lidar

This method involves the determination of plume opacity by qualified observers that are trained and certified according to procedures described in the method. Method 9 describes the procedures that are to be used by these observers to determine plume opacity in the field. The method also includes performance criteria that are applicable to the method variables which, unless controlled, may exert significant influence upon plume appearance to the observer.

Alternate Method 1 to Method 9 provides for the remote determination of opacity using a Lidar (laser radar light detection and ranging) system that employs a ruby (red) laser. The Lidar uses its own light source and, therefore, can be used in the day or night. The Alternative Method includes design, calibration, and performance evaluation procedures for the Lidar system. The method is applicable to a stationary or mobile Lidar system.

### 3.2.7 Performance Specifications for Continuous Emissions Monitoring Systems (CEM) Used to Monitor Opacity

The EPA has published performance specifications (PS 1) for the use of CEMS to monitor opacity at new stationary sources (40 CFR 60, Appendix B). This performance specification applies to opacity monitors installed after March 30, 1996. The CEMS monitors PM using the principle of transmissometry of light. Light that has specific spectral characteristics is projected from a lamp in the CEMS through the stack gas. The intensity of the light after passing through the gas is attenuated (absorbed and scattered) by the PM and then measured by a sensor. The percentage of the projected light attenuated is defined to be the opacity. Transmittance is defined to be the opposite of opacity, i.e., opaque stack emissions that attenuate all of the light will have a transmittance of zero and an opacity of 100 percent, and transparent stack emissions have a transmittance of 100 percent and opacity of zero.

This performance specification establishes specific design criteria for an opacity monitor/transmissometer CEMS. The performance specification also specifies installation, calibration, and evaluating criteria to ensure proper performance of the CEMS.

## 3.3 Other Stationary (Point) Source PM Mass Measurement Test Methods

Other test methods for the measurement of PM mass include ASTM Method D3685/D3685M[8] and ASME Power Test Code 27.[9] A piezoelectric quart crystal has been used to measure "quasi-continuous" PM mass emissions.[10] The device directly measures the electrical frequency shift of the crystal due to the accumulating PM mass.

A triboelectric instrument has been developed for use as a continuous PM mass emissions monitor by Auburn International, called the Triboflow CEM 2604. The triboelectric effect is the transfer of electrical charge that takes place when two objects rub or abrade each other. In the Triboflow CEM, the tribolelectrical charge that is transferred from PM in a duct to a stainless steel probe is monitored as a current flow. Note that the triboelectric effect is different from static electricity, which is the storage as opposed to the transfer of charge. The Triboflow CEM is suited for monitoring the PM mass emissions of a relatively low level PM source, such as at the exit of a high efficiency PM control device.[11]

The use of CEMs for PM mass measurement is currently being investigated by EPA's Office of Research and Development. An EPA "Application Guide" for the mass measurement of $PM_{2.5}$ is also under development, but has not been validated yet.[12]

## 3.4 Fugitive PM Measurement Methods

The following are brief descriptions of eight methods that are available to measure $PM_{10}$ from fugitive dust sources. These methods are described in detail in the EPA document: *A Review of Methods for Measuring Fugitive PM-10 Emission Rates*.[13] Some of these methods have been available for a long time while others have been developed recently. Many are not frequently used and/or they were developed for other purposes (e.g., soil science). Guidance on selecting the most appropriate method for a given source type has been developed[14] and can be found as an appendix in the above EPA review document (Reference 13). Another document that discusses many of the methods described below is *Techniques and Equipment for Measuring Inhalable Particulate Fugitive Emissions.*[15]

Other documents that discuss the individual methods are referenced below with the description of each method. Because many of these methods were developed before $PM_{10}$ was a concern, some of the methods manuals referenced here describe only the measurement of total suspended PM. Therefore, although these earlier documents contain a substantial amount of valuable information, the equipment described for use in the methods are likely to be outdated. More current documents are referenced where available.

- **Quasi-stack Method**. This method consists of enclosing or hooding the fugitive dust source, on either a permanent or temporary basis, with the use of a fan and then sampling the exhaust isokinetically using EPA Test Methods 201 or 201A. This method is considered to be potentially the most accurate because the entire plume is captured and measured close to the source. Care must be taken, however, not to artificially generate emissions from the source with the sampling equipment. Additional information about this method can be found in *Technical Manual for the Measurement of Fugitive Emissions: Quasi-Stack Sampling Method*.[16] More current equipment is described in *Technical Manual: Hood System Capture of Process Fugitive Emissions*[17] and *Evaluation of an Air Curtain Hooding System for a Primary Copper Converter, Volume I.*[18]

- **Roof Monitor Method**.[19] This method may be the best means of measuring fugitive PM when a number of processes are located within a building. The PM is measured from all openings in the building and the total fugitive emission rate is the sum of the emission rates from all the openings. This method is best used when the building itself is construed as the "source." The method involves the measurement of the $PM_{10}$ concentration (with EPA Test Method 201 or 201A) in the duct exhaust, which is then multiplied times the air exit velocity and the opening cross-sectional area to produce the emission rate. Since the dust concentration may vary across the duct opening, a number of sites along the cross section of each duct should be sampled, as in stack testing (EPA Test Method 1). If sampling is performed in an actual roof monitor vent, it is recommended that sampling be done according to EPA Method 5D.

  In the event that isokinetic sampling is not feasible because of the variation in air velocity in the openings, ambient $PM_{10}$ measurement techniques may be used. Ambient samplers that have met EPA criteria are described in the "List of Designated Reference and Equivalent Methods" issued by the EPA's Atmospheric

Research and Exposure Assessment Laboratory.[b] Reference 13 contains the list as of February 8, 1993.

- **Upwind-downwind Method**.[20] In this method, ambient $PM_{10}$ concentrations are measured upwind and downwind of a dust source. The difference between the two concentrations is considered to be the $PM_{10}$ concentration due to the fugitive emission source. Using wind speed, direction, and other meteorological data obtained during the $PM_{10}$ sampling period, the emission rate is determined using dispersion models. The EPA "Industrial Source Complex" model is being revised to develop an improved deposition term to make it more accurate for use with PM.

  While the upwind-downwind method is considered the most versatile of the fugitive measurement methods, it has also been considered the least accurate, since only a small portion of a greatly diluted plume is sampled. Recent studies, however, have found that fugitive emission rates estimated using the upwind-downwind method are within a factor of two 80 percent of the time as with the quasi-stack method.[21]

- **Exposure Profile Method**.[22] This method consists of using a number of ambient samplers (typically 4 or 5) at several heights along a vertical tower (4 to 10 meters in height) equipped with nozzles and flow rate adjustments to sample the fugitive PM plume isokinetically. The tower is also equipped to measure wind speed and direction. The towers are placed downwind of the source, with ambient samplers (1 to 4) also placed upwind of the source to determine the background PM concentration. Ambient data obtained from these samplers are used to determine the total mass flux of dust emitted from the source; this is done by integration of the dust exposure values obtained from the various sampling points.[23]

  The Exposure Profile Method is largely constrained to situations where sampling close to the source is possible, except where extensions to the towers are used.[24] However, even with these extensions, the exposure profiling method may not be practical for sampling large area sources. Losses of $PM_{10}$ may occur if the source is close to the ground, but since this dust would not become airborne and contribute to emissions, the measurement of these "relevant emissions" is possibly just as desirable as the actual emissions from the source.[13] The exposure profiling method is considered more accurate than the upwind-downwind method and is considered to be comparable to the roof monitor method[13] and is considered well suited to roads.[13]

---

[b] U.S. Environmental Protection Agency, Office of Research and Development, Atmospheric Research and Exposure Assessment Laboratory, Methods Research and Development Division (MD-77), Research Triangle Park, North Carolina. 27711. (919)541-2622 or 4599.

- **Portable Wind Tunnel Method**. This method is applicable to wind-generated fugitive emissions only. It was developed in the 1970's to study the effects of wind-blown sand on vegetation and to quantify the sources of wind erosion. It has been used since to quantify wind-generated emissions from exposed soil and coal storage piles.[25,26,27] The portable wind tunnel consists of a vacuum cleaner-shaped device, the mouth of which is placed directly on the surface to be tested using an airtight seal. A fan draws air through the mouth of the tunnel, through a long tube into a raised duct section where PM sampling can occur. Sampling can be performed using EPA Method 201 or 201A. The fugitive dust emission rate is equal to the particle concentration times the tunnel flow rate. Over flat ground, the tunnel centerline wind speed can be related to wind speed at 10 meters altitude.

- **Scale-Model Wind Tunnel Method**. This method involves creating a wind tunnel that resembles the source or terrain to be sampled with the use of, in many cases, a to-scale recreation of the source within the wind tunnel. Parameters such as turbulence, velocity profile, wind shear, and other physical quantities, such as air moisture and terrain roughness, are usually duplicated within the wind tunnel. The advantage of using a scale-model wind tunnel is that the individual parameters affecting dust emissions can then be controlled. The disadvantage is that the relationship between the tests and actual field measurements is "uncertain."

- **Tracer Method**. This method uses either a gas or particles as a tracer for dust from the source to be measured. Common tracers are sulfur hexafluoride ($SF_6$)[28] and fluorescent or phosphorescent materials or coatings. The assumption is that the tracer plume will strongly resemble the dust plume if the tracer is released in the same place and time as the dust. Downwind measurements of the tracer and dust concentrations are used to quantify the (upwind) dust emission rate by a direct proportion using the (upwind) tracer release rate (i.e. emission rate). A study was done to determine the accuracy of the gas tracer method. This study determined that using a correction factor of 1.03 to calculate the source emission rate increases the accuracy of the method.[29]

- **Balloon Method**.[30,25] This method is a variation of the exposure profiling method, discussed above. In the Balloon Method, a balloon is used to suspend ambient samplers at varying heights instead of the sampling tower used in the exposure profiling method. This method is especially suited for sampling large area sources and/or sources which may not be closely approached. The problem with the Balloon method is that often the sampling is not done isokinetically, since once the balloon is aloft, nozzles cannot be changed. If variable flow rate sampling is not possible, the fixed flow rate in the samplers may also contribute to anisokinetics. However, isokinetic sampling is less critical to accurate measurement of $PM_{10}$ than for total suspended PM.[31]

## 3.5 Particle Size Analysis

The size distribution of a particulate dust stream is sometimes desired to determine the emissions from a source or collection efficiency of a PM control device. Various measurement approaches are available to determining the size distribution of a particulate stream that include cascade impactors, sampling cyclones, centrifugal separators, and more advanced techniques that utilize lasers. Note that EPA Test Method 201 and 201A can be used directly to determine $PM_{10}$ emissions and collection efficiency; however, for $PM_{2.5}$ and other particle sizes, one of the methods discussed below is needed to determine emissions or collection efficiency.[32]

### 3.5.1 Cascade Impactors

Cascade impactors are a widely used method to size particles that have been commercially available for source testing since the early 1970's,[33] and have a relatively well-developed theoretical basis.[32,34] Impactors collect particles by inertial impaction and utilize a series of plates (discs) or stages with various-sized holes (jets) that alter the velocity of the gas passing onto the next stage. Particles of a specific size or larger will impact each plate, while smaller particles will pass through to the next plate. The plates are coated with a sticky material (substrate) that causes the PM impacting the plates to be irreversibly collected. The selection of cascade impactor substrates is an important part of impactor use.[32,35]

Cascade impactors generally can determine particle sizes between 0.3 to 16 $\mu$m,[32] with low pressure impactors commercially available (Pollution Control Systems Corp.)[c] that measure particles between 0.02 and 10 $\mu$m.[36,37] The major limitation of cascade impactors is that only a small amount of PM (usually less than 10 mg) can be collected on each stage;[32] therefore, the gas sampling volume/time must be adjusted to accommodate for this upper limit. Cascade impactors may also be subject to biases towards small particles because of particle bounce and reentrainment, and because of fracturing of larger particles during impaction.

The proper operation of cascade impactors for source testing is described in the EPA document, *Procedures for Cascade Impactor Calibration and Operation in Process Streams*.[38]

### 3.5.2 Sampling Cyclones

Cyclone samplers operate in the same manner as cyclones used for PM collection, in that the gas with PM is forced to spin so that some of the PM hits the cyclone walls and is collected. PM above a certain size specific to the cyclone will be largely collected and particles below a certain size will mostly pass through the cyclone uncollected. Individual sampling cyclones are only able to determine the mass of particles either above and below a specific size. However, if various-sized sampling cyclones are used in series, PM sizes over a (relatively broad) range can be

---

[c] Pollution Control Systems Corporation, Seattle, Washington.

determined. The limitations of the sampling cyclones are that they are inadequate for sampling gases with low PM concentrations.[32]

In the late 1970's, the EPA developed the Source Assessment Sampling System (SASS) as a broad source assessment tool to screen for PM, organics, and inorganics in one sampling train.[39,40] The SASS train included a series of three cyclones and a back-up filter that separated PM into the following size categories: >10 $\mu$m, 3 to 10 $\mu$m, 1 to 3 $\mu$m, and <1 $\mu$m. Because the SASS train was constructed out of stainless steel to better withstand field conditions, the recovery rates for the chemical analyses were not as high as sampling trains made out of glass, such as the Office of Solid Waste's method, SW846-Method 0010 (Modified Method 5) described in Section 3.6.2.[41] The OSW method, however, does not fractionate PM by size.

A system of five cyclones nested in series has also been developed[42,43] and is commercially available from vendors, including Sierra Instruments, Inc.[d] The five cyclones have progressively smaller cut points, with reported $d_{50}$'s of 5.4, 2.1, 1.4, 0.65, and 0.32 $\mu$m.

### 3.5.3 Real-Time Size Distribution Measurement

An Aerodynamic Particle Sizer (APS) has been developed that can determines the "real-time" size of particles by measuring their velocity as the particles accelerate through a plate orifice.[44] The particle velocity measurements are made with a laser Doppler velocimeter.[45,46] The instrument is commercially available from TSI Inc.[e]

The *in situ* measurement of PM using lasers have been reported to be successful for small particles, less than 1 $\mu$m.[47] The laser is used to heat the PM and, based on the PM cooling rates, size differentiation is possible. This method has the advantage of a very short measurement time period (microseconds), so that the effect of rapidly changing processes on the particle size distribution can be determined.

Acoustical techniques are also being used to size PM. This technique relies on the detection and measurement of elastic waves arising from the impact of the particles on a surface, such as a plate,[48] or other particles.[49] The acoustic signal can be measured inexpensively by a high fidelity piezoelectric transducer[48] or with the use of a simple microphone.[49] The latter method is better suited to regularly-shaped PM, while the former is not recommended for high number concentration particle streams (>$10^9$ per $m^3$).

An optical method has been developed from an EPA funded study by Insitec Measurement Systems.[f] The method, known as “Transform method for Extinction-Scattering with Spatial

---

[d] Sierra Instruments, Inc., Carmel Valley, California.

[e] TSI Inc., St. Paul, Minnesota.

[f] Insitec Measurement Systems, San Ramon, California.

resolution" (TESS), is a patented technique based on laser light scattering.[50] TESS measures total particle concentration. The measurement is independent of particle composition, velocity, and size distribution. The particle concentration is measured as a ratio of scattered to transmitted light.

A diffusion battery that can be used in a source situation has been developed.[51] Diffusion batteries utilize arrays of screens, tubes, or plates, which present a large surface area for the deposition of particles by Brownian diffusion. Particulate matter of different sizes can be classified with diffusion batteries because of the difference in diffusion coefficients for particles of different sizes.[52,53]

Other real-time particle sizing/counting methods are available. These devices include optical devices, condensation nuclei counters, and electrical mobility analyzers. [54,55,56, 57,58,59] Some of these devices may not be appropriate for source level PM concentrations and/or can not properly account for particle refractive index or shape.

### 3.5.4 Size Distribution of Bulk Samples

Particulate matter can be collected from the source and later analyzed for the particle size distribution in the laboratory using various available techniques. These techniques should be used with caution, however, because the original flue gas particle distribution may be altered by agglomeration, particle breakup, chemical reactions, or loss of volatiles that occur during sample collection and storage. Also, artifact mass may be formed from filter materials, such as glass fiber, that oxidize in contact with acid gases in the sample air. Therefore, the size distribution results obtained with these methods are meaningful only if the effects of sample collection and storage are negligible or clearly known.

Particle size of PM collected on filters can be determined with scanning electron microscopes (SEM)[60]. The particle volume size distribution is estimated from the size distribution determined by the SEM. SEM can be used down to 0.01 $\mu$m.[61]

Another device used for particle sizing electrically stimulates the particles that are resuspended in a conductive fluid. The amplitude of the resulting electrical pulse generated by each particle is measured as the particles pass individually through an orifice or aperture. Because the electrical pulse is proportional to the particle volume, particle diameter can be estimated by assuming a spherically-shaped particle. Instruments such as a Coulter®[g] Counter[62] and Elzone®[h] Electrozone[63] are commercially available to provide this type of analysis.[64,65] These devices can provide analysis of particle with sizes >20 $\mu$m and as low as 0.35$\mu$m.[62]

---

[g] Coulter Electronics, Hialeah, Florida.

[h] Particle Data Laboratories, Ltd., Elmhurst, Illinois.

A *Bahco Micro-Particle Classifier* is the particle sizing device recommended by the Industrial Gas Cleaning Institute[i] to determine particle size and collection efficiency of mechanical collectors, for particles of 1 to over 20 $\mu$m in diameter. Procedures for calibration of the Bahco are found in the American Society of Mechanical Engineers Power Test Code 28[9] that describes procedures to be used for determining the size of fine PM found in dust and smoke. The Bahco is one of a class of instruments called centrifugal classifiers, that in effect determine the terminal velocity distribution of the PM, which can be related to particle size using Stokes' Law. In reality, these instruments determine the diameter of equivalent solid spherical particles and, therefore, may not provide useful information if the PM is significantly nonspherical.

An across-duct laminar flow device has been developed that collects PM for later size analysis by a Malvern laser diffraction size analyzer.[66] This instrument also measures the electric charge of the particles so that it can be used to optimize ESP operation.

## 3.6 Speciation

Extractive PM sampling procedures, such as EPA Test Method 5, allow for the chemical speciation of the collected PM. Most methods for speciation of PM use spectroscopic detection, although other analytical procedures can also be used. The following sections discuss the various techniques that can be used to speciate PM. Descriptions of two EPA test methods that detail procedures to collect as well as analyze PM for individual species are also included below.

### 3.6.1 EPA Test Method 29 for Metals and PM

Method 29 is applicable to the determination of antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), phosphorus (P), selenium (Se), silver (Ag), thallium (Tl), and zinc (Zn) emissions from stationary sources. This method may be used to determine total PM emissions, in addition to the metals emissions, if the prescribed procedures and precautions are followed.

In Method 29, a stack sample is withdrawn isokinetically from the source; PM emissions are collected in the probe and on a heated filter, and gaseous emissions are then collected in an aqueous acidic solution of hydrogen peroxide (analyzed for all metals including Hg) and an aqueous acidic solution of potassium permanganate (analyzed only for Hg). The recovered samples are digested, and appropriate fractions are analyzed for Hg by cold vapor atomic absorption spectroscopy (CVAAS) and for Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Ni, P, Se, Ag, Tl, and Zn by inductively coupled argon plasma emission spectroscopy (ICAP) or atomic absorption spectroscopy (AAS). Iron (Fe) can be a spectral interference during the analysis of As, Cr, and Cd by ICAP. Aluminum (Al) can be a spectral interference during the analysis of As and Pb by ICAP.

---

[i] Industrial Gas Cleaning Institute, Inc., Stamford, Connecticut.

Graphite furnace atomic absorption spectroscopy (GFAAS) is used for analysis of Sb, As, Cd, Co, Pb, Se, and Tl if these elements require greater analytical sensitivity than can be obtained by ICAP. If desired, AAS may be used for analysis of all listed metals if the resulting in-stack method detection limits meet the goal of the testing program. Similarly, inductively coupled plasma-mass spectroscopy (ICP-MS) may be used for analysis of Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Ni, As, Tl and Zn.

Method 29 is discussed in more detail in the EPA document *Multiple Metals Stack Emissions Measurement Methodology*.[67] Method 29 is virtually identical to two other EPA methods:

- EPA's Office of Solid Waste method SW-848-0012,[68] "Methodology for the Determination of Metals Emissions from Hazardous Waste Incineration and Similar Combustion Sources;" and
- EPA's Office of Solid Waste method: "Methodology for the Determination of Metals Emissions from Hazardous Waste Incineration and Similar Combustion Sources," that was developed for boilers and industrial furnaces (BIF)[69].

### 3.6.2 EPA Office of Solid Waste Test Method 0010 (SW-846)[41]

This method is used to determine the amount of semivolatile organic constituents in exhaust gas, as well as to determine total PM, as per EPA Method 5; hence, the common name of "Modified Method 5." OSW Test Method 0010 can be used to detect polychlorinated biphenyls, chlorinated dibenzodioxins and dibenzofurans, polycyclic organic matter, and other semivolatile organic compounds. The method is used by OSW to determine the destruction and removal efficiency of the principle organic hazardous constituents from waste incinerators.

Test Method 0010 is an EPA Test Method 5 sampling train modified to include a high efficiency filter and a packed bed of XAD-2 or foam resin. The filter collects the organic-laden PM and the packed bed adsorbs the semivolatile organic species in the flue gas. The method includes a description of a variety of comprehensive chemical analyses to determine the identity and concentration of the organic material. Analysis of the filter only yields PM speciation information.[70]

### 3.6.3 Spectrometry

Spectrometry is a common technique used to determine the species present in PM. However, since the spectrometric detectors respond to the presence of only the element, they provide no information about chemical compounds and, in most cases, do not indicate the oxidation state of the element.

#### 3.6.3.1 Atomic Absorption Spectrometry

Atomic absorption spectrometry (AAS)[71] usually involves some type of (acid) extraction of the analyte followed by excitation of the solution in a flame. Light with a wavelength characteristic of the element of interest traverses the flame. The amount of light absorbed is then related to the quantity of the element present. In AAS, individual elements must be determined sequentially. Thus, although any element can be determined for which a lamp is available to produce the characteristic light, most PM samples are large enough to allow only half a dozen determinations. Some elements, if present in the PM, (such as antimony and arsenic), may require the application of special methods. Atomic absorption is subject to interferences which can lead to substantial errors. If recognized, however, these errors generally can be accounted for or eliminated to produce good quantitative analyses.

#### 3.6.3.2 Optical Emission Spectrometry

Optical emission spectrometry (OES) involves the excitation of the loosely bound electrons in elements to observe their characteristic emissions as de-excitation occurs. The wavelength of the resultant light is characteristic of the element, and the intensity is an indication of the quantity of the element present.

The most desirable OES technique is argon plasma excitation.[72] Plasma spectrometry offers more advantages than AAS, with similar sample preparation, analysis rates, and detection limits. The OES techniques can simultaneously determine anywhere up to 50 elements. Optical emission spectrometry is, in general, more interference-free than atomic absorption.

#### 3.6.3.3 Mass Spectrometry

Mass spectrometry (MS) is a currently expanding field of analysis, whose growth has been fueled by the need for increased accuracy and detection of highly toxic pollutants that are present in small concentrations in the environment. Spectral interferences with MS are important, but generally can be overcome by use of a spectrometer with high resolution. As with any multi-element technique, the accuracy of MS depends on the elements to be analyzed and on the sample matrix. The advantage of MS is that every element in the periodic table can be simultaneously detected, with roughly equal sensitivity in the parts per million (ppm) and sub-ppm ranges. The MS techniques are also able to distinguish between isotopes, which is sometimes desirable in the determination of isotope ratios.

Two specific types of MS techniques applicable to PM samples are spark source mass spectrometry[73] and laser ion source MS, sometimes called laser microprobe mass analysis (LAMMA).[74] Both techniques use an energy source to vaporize and partly ionize small amounts of the PM which, under specially controlled conditions, are then accessible for MS analysis. LAMMA has the advantage in that it can also determine particle size and shape with the same resolution as a light microscope (approximately 0.13 $\mu$m).

#### 3.6.3.4 Neutron Activation Analysis

Neutron activation analysis (NAA) consists of a variety of distinct methods, all of which produce unstable nuclei that emit gamma radiation.[75,76] The energy and intensity of the gamma rays are indicators of the element and its quantity. Instrumental thermal NAA is the most commonly used method for PM. In this approach, a nuclear reactor is used to produce unstable nuclei. Neutron activation analysis can simultaneously determine up to 25 elements in on PM sample. Another advantage is that particles can be analyzed directly on the collecting filter surface.

#### 3.6.3.5 X-Ray Fluorescence Spectrometry

X-Ray fluorescence spectrometry involves excitation of tightly bound electrons and observation of the X-ray emission as de-excitation occurs.[75,77] Excitation may be done by a variety of techniques, but use of an x-ray generator is the most common. The technique may be either multielement (up to perhaps 30) energy dispersive detection or wavelength dispersive detection (up to perhaps 10 elements). Only elements with atomic numbers greater than that of magnesium can be analyzed. Particles can be analyzed nondestructively, directly on a filter. Interferences are common and calibration can be a problem.

### 3.6.4 Electrochemical

Electrochemical methods have been used to a limited extent to determine a small number of elements in PM samples. Some of these methods are: potentiometry with ion-selective electrodes, polarography, and anodic stripping voltametry.[75] Electrochemical methods have few advantages for PM analysis aside from the low initial capital costs of equipment relative to other techniques.

### 3.6.5 Chemical

Many wet chemical procedures constitute the classical methods used for trace element analysis of particulate. In general, a color-forming reagent is used, and the amount of an element is determined by the extent of color development. Probably the best known of these procedures is based on the use of dithiocarbazone (dithizone)[78] as the colorimetric reagent for lead. Wet chemical procedures are labor-intensive and slow, compared with spectral techniques, particularly since only one element can be determined at a time. Interferences can also be a problem.

Methods for estimating the total mass of benzene-extractable organic material in PM are available. In this technique, a portion of the front-half catch from EPA Test Method 5 is placed in a Soxhlet extractor and refluxed with benzene for several hours. The benzene is then volatilized and the mass of residue is measured.

Methods of identifying and determining individual organic species abound. These methods use different sequences of solvent extractions that separate groups of different organic species on the basis of solubility. Solutions are often subjected to chromatographic separation with mass spectral detection. For organic compounds that are volatile up to about 300°C, gas chromatography-mass spectrometry (GC-MS) can be used.[79] For organic species with lower volatility, liquid chromatography might be used. High-performance liquid chromatography (HPLC)[80] is typically used, but none of these procedures permits a high rate of analysis.

For analysis of one organic species of longstanding interest, benzo-a-pyrene (BaP), thin layer chromatography (TLC) with fluorescence detection has been used. This procedure requires a cyclohexane extraction, spotting, and development of a TLC plate, with fluorescence detection. This TLC procedure is more interference-free than some HPLC methods and has a higher yield rate.[81]

## 3.7 References for Section 3

1. Martin, R.M. Construction Details of Isokinetic Source-Sampling Equipment (APTD-058l). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. April l97l.

2. Rom, J.J. Maintenance, Calibration, and Operation of Isokinetic Source Sampling Equipment (APTD-0576). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. March l972.

3. Application Guide for Source $PM_{10}$ Measurement with Exhaust Gas Recycle Sampling System (EPA/600/3-88-058). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1988.

4. Application Guide for Source $PM_{10}$ Measurement with Constant Sampling Rate (EPA/600/3-88-057). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1988.

5. Measurement of Condensible Vapor Contribution to $PM_{10}$ Emissions (EPA-600/D-89/103; NTIS PB89-224521). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. June 1985.

6. A Review of Current Methods for Measuring Particulate Matter Including Condensibles from Stationary Sources (EPA-600/3-89/020; NTIS PB89-169973). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. February 1989.

7. Method Development and Evaluation of Draft Protocol for Measurement of Condensible Particulate Emissions (EPA-450/4-90-012; NTIS PB90-24805). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. May 1990.

8. 1995 Annual Book of Standards, Section 11: Water and Environmental Technology, Volume 11.03: Atmospheric Analyses. American Society of Testing and Materials, Philadelphia, Pennsylvania. 1995

9. Determining the Properties of Fine Particulate Matter: Power Test Codes. American Society of Mechanical Engineers, New York, New York. 1996.

10. Fissan, H. and D.F. Schulze-Froehlich. "A New Piezoelectric Quartz Crystal for Particle Mass Determination" in Proceedings: Advances in Particle Sampling and Measurement (EPA-600/9-89-004; NTIS PB89-166615), Daytona Beach, Florida, October 1981. February 1989.

11. Tacelli, R.W., R.E. Newton, and J.M. Andrews. "Triboelectric Instrument for Use as a Continuous Particulate Emission Rate Monitor," in *Continuous Emission Monitoring: A Technology for the 90s, Proceedings of an International Specialty Conference*. Air &

Waste Management Association, Pittsburgh, Pennsylvania. 1993.

12. Personal Communication. Ward, Tom, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, with Jones, Donna Lee, EC/R Inc., Durham, North Carolina. August 27, 1996.

13. A Review of Methods for Measuring Fugitive PM-10 Emission Rates (EPA/454-R-93-037; NTIS PB94-204203). Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. November 1993.

14. Protocol for the Measurement of Inhalable Particulate Fugitive Emissions from Stationary Sources. Draft report prepared under EPA Contract 68-04-3115 by TRC Environmental Consultants, Inc., Wethersfield, Connecticut, for Mr. D. Bruce Harris, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. March 1980.

15. Techniques and Equipment for Measuring Inhalable Particulate Fugitive Emissions (EPA-600/9-82-005d; NTIS PB-83-149617). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1982.

16. Technical Manual for the Measurement of Fugitive Emissions: Quasi-stack Sampling Method (EPA-600/2-76-089c). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1976.

17. Technical Manual: Hood System Capture of Process Fugitive Emissions (EPA-600/7-86-016; NTIS PB86-19044). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1986.

18. Evaluation of an Air Curtain Hooding System for a Primary Copper Converter, Volume I (EPA-600/2-84-042a: NTIS PB84-160514). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1984.

19. Technical Manual for the Measurement of Fugitive Emissions: Roof Monitor Sampling Method for Industrial Fugitive Emissions (EPA-600/2-76-089b). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1976.

20. Technical Manual for the Measurement of Fugitive Emissions: Upwind/Downwind Sampling Method for Industrial Emissions (EPA-600/2-76-089a). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1976.

21. Gengxin, H., X. Liguo, and H. Yanfeng. "A Study of Diffusion Models Applied to Dust Emissions from Industrial Complexes." Environmental Monitoring and Assessment. 22 (89-105). 1992.

22. Development of Emission Factors for Fugitive Dust Sources (EPA-450/3-74-037; NTIS PB-238262). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1974.

23. Garman, G and G.E. Muleski. Example Test Plan for Point or Nonuniform Line Sources. Prepared under EPA Contract 68-DO-0123, Work Assignment 11-44. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1993.

24. Clayton, P., S.C. Wallin, B.J. Davis, and A.C. Simmonds. Methods for Determining Particulate Fugitive Emissions from Stationary Sources (NTIS PB-85-181717). National Technical Information Service, Washington, DC. 1984.

25. Improved Emission factors for Fugitive Dust from Western Surface Coal Mining Sources (EPA-600/7-84-048; NTIS PB84-170802). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1984.

26. Cowherd, C. A New Approach to Estimating Wind-Generated Emissions from Coal Storage Piles. Air Pollution Control Association Specialty Conference Proceedings (SP-51): Fugitive Dust Issues in the Coal Use Cycle. Air & Waste Management Association, Pittsburgh, Pennsylvania. 1983.

27. Iron and Steel Plant Open Source Fugitive Emission Control Evaluation (EPA-600/2-83-110; NTIS PB84-110568). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1983.

28. On the Use of $SF_6$-Tracer Releases for the Determination of Fugitive Emissions (EPA-600/9-82-005d; NTIS PB83-149617). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1982.

29. Frankel, R.G. Fugitive Dust Emissions: Accuracy of Gas Tracer Determinations. Masters Report. University of North Carolina at Chapel Hill, Chapel Hill, North Carolina. 1995.

30. Balloon Sampling to Characterize Particle Emissions from Fugitive Sources (EPA-600/9-82-005d; NTIS PB83-149617). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1982.

31. Davies, C.N. The Entry of Aerosols in Sampling Heads and Tubes. British Journal of Applied Physics. 2:291. 1968.

32. Shendrikar, A.D. and D.S. Ensor. "Sampling and Measurement of Trace Element Emissions from Particulate Control Devices," in *Toxic Metals in the Atmosphere*, J.O. Nriagu and C.I. Davidson, Eds. John Wiley and Sons, New York, New York. 1986.

33. Pilat, M.J. D. S. Ensor, and J.C. Bosch. Source Test Cascade Impactor. Atmospheric Environment. 4:671-679. 1970.

34. Marple, V.A. and B.Y.H. Liu. Characteristics of Laminar Jet Impactors. Environmental Science and Technology. 8:648. 1974.

35. Felix, L.G., G.I. Clinard, G.E. Lacey, and J.D. McCain. Inertial Cascade Impactor Substrate Media for Flue Gas Sampling (EPA-600/7-77-060). U.S. Environmental Protection Agency, Washington, DC. 1977.

36. Pilat, M.J. G.A. Raemhild, E.B. Powell, G.M. Fiorette, and D.F. Meyer. Development of Cascade Impactor System for Sampling 0.02 to 20-micron Diameter Particles (FP-844, Volume 1). University of Seattle, Seattle Washington. 1978.

37. Nelson, P.A., D.S. Mummey, and W.D. Snowden. "Ultra-Fine Cascade Impactor Particle Size Data Relationships to Opacity: Case Histories" in Proceedings: Advances in Particle Sampling and Measurement (EPA-600/9-89-004; NTIS PB89-166615), Daytona Beach, Florida, October 1981. February 1989.

38. Procedures for Cascade Impactor Calibration and Operation in Process Streams (EPA-600/2-77-004). U.S. Environmental Protection Agency, Washington, DC. 1977.

39. Source Assessment Sampling System: Design and Development (EPA-600/7-78-018). U.S. Environmental Protection Agency, Washington, DC. February 1978.

40. Merrill, R.G., J. Lewtas, and R.E. Hall. "Source Assessment Sampling System (SASS) Versus Dilution Tunnel Sampling," in Proceedings: Advances in Particle Sampling and Measurement (EPA-600/9-89-004; NTIS PB89-166615), Daytona Beach, Florida, October 1981. February 1989.

41. Test Methods for Evaluating Solid Waste, Third Edition. Report No. SW-848. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. 1986.

42. Smith. W.B. and R.R. Wilson. Development and Laboratory Evaluation of a Five-Stage Cyclone System (EPA-600/7-78-008). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1978.

43. Smith, W.B. and R.R. Wilson. A Five-Stage Cyclone System for In Situ Sampling. Environmental Science and Technology. 13(11). November 1979.

44. Agarwal, J.K. and R.J. Remiarz. "Development of an Aerodynamic Particle Sizer" in Proceedings: Advances in Particle Sampling and Measurement (EPA-600/9-89-004; NTIS PB89-166615), Daytona Beach, Florida, October 1981. February 1989.

45. J.C. Wilson and B.Y.H. Liu. Aerodynamic Particle Size Measurement by Laser-Doppler Velocimetry. J. Aerosol Science. 11:139-150. 1980.

46. Agarwal, J.K. and L.M. Fingerson. Real-Time Aerodynamic Particle Size Measurement with a Laser Velocimeter. TSI Quarterly. V(1). 1979.

47. Roth, P. and V. Filippov. In Situ Ultrafine Particle Sizing by a Combination of Pulsed Laser Heatup and Particle Thermal Emission. J. Aerosol Science. 27(1):95-104. 1996.

48. Buttle, D.J., S.R. Martin, and C.B. Scruby. Particle Sizing by Quantitative Acoustic Emission. Research in Nondestructive Evaluation. 3(1):1-26. 1981.

49. M.F. Leach, G.A. Rubin, and J.C. Williams. Particle Size Distribution Characterization from Acoustic Emissions. Powder Technology. 19(2):157. March/April 1978.

50. Correspondence and product literature from Mr. Hugh North, Malvern/Insitec, San Ramon, California, to Mr. Kenneth Woodard, U.S. EPA. January 14, 1998.

51. Knapp, K.T. "Elemental Composition of Sized Profiles Emitted from Stationary Sources," in *Proceedings of the International Symposium on Recent Advances in Particulate Science and Technology* held on December 8-10, 1982, in Madras, India. Department of Chemical Engineering, Indian Institute of Technology, Madras, India. 1986.

52. Chen, B.T., Y.S. Cheng, and H.C. Yeh. Tests of the Size resolution and Size Accuracy of the Lovelace Parallel-Flow Diffusion Battery. Am. Ind. Hyg. Assoc. J. 52(2):75. February 1, 1991.

53. Barr, E.B., Y.S. Cheng, and H.C. Yeh. Size Characterization of Carbonaceous Particles Using a Lovelace Multijet Cascade Impactor/Parallel-Flow Diffusion Battery Serial Sampling Train. Aerosol Science and Technology. 10(1):205. 1989.

54. Hinds, W.C. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*. John Wiley and Sons, New York, New York. 1982.

55. "Particle Sizing--Past and Present" (Particle Sizing Editorial Review). Filtration and Separation. July/August 1993.

56. McCain, J.D., W.G. Kistler, J.W. Ragland, R.L. Merritt. "Aerosol Size and Chemistry at a Coal-Fired Power Plant" in Proceedings: Advances in Particle Sampling and Measurement (EPA-600/9-89-004; NTIS PB89-166615), Daytona Beach, Florida, October 1981. February 1989.

57. Cushing, K.M., R.R. Wilson, W.E. Farthing, and D.B. Harris. "A Comparison of Several Particle-Sizing Techniques" in Proceedings: Advances in Particle Sampling and Measurement (EPA-600/9-89-004; NTIS PB89-166615), Daytona Beach, Florida,

October 1981. February 1989.

58. Steele, W.J., W.B. Smith, W.E. Farthing, and R.C. Carr. "A Sensitive Particulate Monitor for Measuring the Approximate Opacity for Fabric Filter Systems" in Proceedings: Advances in Particle Sampling and Measurement (EPA-600/9-89-004; NTIS PB89-166615), Daytona Beach, Florida, October 1981. February 1989.

59. Sadakata. M., M. Motegi, Y. Mashio, T. Ishada, A. Harano, and H.J. Kim. Growth of Primary Soot Particles in an Atmospheric Premixed Methane Oxygen Flame. Chemical Engineering Research and Design, Part A: Transactions of the Institute of Chemical Engineers. 73(42):142-146. March 1995.

60. Huggins, F.E. D.A. Kosmack, G.P. Huffman, and R.J. Lee. "Coal Mineralogies by SEM Automatic Image Analyses," in *Scanning Electron Microscopy/I*. SEM Inc., AMF O'Hare, Chicago, Illinois. 1980.

61. Davidson, D.L. "The Analysis of particles by Electron Microscopy and Spectroscopy," in *Particle Characterization in Technology, Vol. I: Applications and Microanalysis,* J.K. Beddow, Ed. CRC Press, Inc., Boca Raton, Florida. 1984.

62. van de Plaats, G., H. Harps, and L. Willeams. Size Determination of Conductive Particles with a Coulter® Counter. Proceedings of the Particle Size Analysis Conference, Loughborough Tech. University, Loughborough, England. September 1981.

63. Berg, R.H. Electronic Size Analysis of Subsieve Particles by Flowing Through a Small Liquid Resistance (STP No. 234). American Society for Testing and Materials, Philadelphia, Pennsylvania. 1958.

64. Karuhn, R.F. and R.H. Berg. "Practical Aspects of Electrozone® Size Analysis," in *Particle Characterization in Technology, Vol. I: Applications and Microanalysis,* J.K. Beddow, Ed. CRC Press, Inc., Boca Raton, Florida. 1984.

65. Kinsman, S. "Particle Size Instrumentation--Coulter® Counter," in *Particle Characterization in Technology, Vol. I: Applications and Microanalysis,* J.K. Beddow, Ed. CRC Press, Inc., Boca Raton, Florida. 1984.

66. Corbin, R.G., J.K. Horrocks, D. Towell, and C. Wainwright. Measurement of Particle Size and Charge from an Electrostatic Filter. Filtration and Separation. 24(4):248-251. July-August 1988.

67. Multiple Metals Stack Emissions Measurement Methodology (EPA/600-A-93/089; NTIS PB93-185734). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1993.

68. "Methodology for the Determination of Metals Emissions in Exhaust Gases from Hazardous Waste Incineration and Similar Combustion Sources," in *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW-846, Third Edition)*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. September 1988.

69. "Methodology for the Determination of Metals Emissions from Hazardous Waste Incineration and Similar Combustion Sources," in Methods Manual for Compliance with the BIF Regulations Burning Hazardous Waste in Boilers and Industrial Furnaces (EPA/530-SW-91-010). U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. December 1990.

70. Screening Methods for the Development of Air Toxics Emission Factors (EPA-450/4-91-021). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 1991.

71. Ahearn, A.I. *Trace Analysis by Mass Spectrometry*. Academic Press, New York, New York. 1972.

72. Fassel, V. A. Quantitative Elemental Analyses by Plasma Emission Spectroscopy. Science, Vol. 202, 1978.

73. Morrison, G. H. Trace Analysis Physical Methods. Wiley Interscience, New York, 1965.

74. Kaufman, R. and P. Wieser. "Laser Microprobe Mass Analysis in Particle Analysis," in *Particle Characterization in Technology, Vol. I: Applications and Microanalysis*, J.K. Beddow, Ed. CRC Press, Inc., Boca Raton, Florida. 1984.

75. Priorities and Procedures for Development of Standards of Performance for New Stationary Sources of Atmospheric Emissions (EPA-450/3-76-020). U.S. Environmental Protection Agency, Research Triangle Park, NC. May 1976.

76. Lambert, J.P.F., and F.W. Wilshire. Neutron Activation Analysis for Simultaneous Determination of Trace Elements in Ambient Air Collected on Glass-Fiber Filters. Anal. Chem. 51. 1979.

77. Goold, R.W., C.S. Barrett, J.B. Newkirk, and C.O. Ruud. *Advances in X-ray Analysis*. Kendall/Hunt, Dubuque, Iowa. 1976.

78. Snell, F.D. *Photometric and Fluorometric Methods of Analysis: Metals, Part I.* John Wiley, New York, New York. 1978.

79. McFadden, W.H. *Techniques of Combined Gas Chromatography/Mass Spectrometry*. John Wiley, New York, New York. 1978.

80. Kirkland, J.J. *Modern Practice of Liquid Chromatography*. John Wiley, New York, New York. 1971.

81. Swanson, D., et al. *A Rapid Analytical Procedure for the Analysis of BaP in Environmental Samples*. Trends Fluoresc. 1. 1978.

# 4. FUEL SUBSTITUTION AND SOURCE REDUCTION APPROACHES FOR PARTICULATE MATTER

This section discusses the use of fuel substitution and process optimization to achieve reductions in PM emissions. In many cases, these practices can be easier and less expensive than upgrading existing control technology or investing in new add-on controls.

Fuel substitution, or fuel switching, is typically used as a means of reducing emissions from combustion sources, such as electric utilities and industrial boilers. It involves replacing the current fuel with a fuel which emits less of a given pollutant when burned. Common examples of this would be replacing coal with oil or natural gas at an electric utility plant. Source reduction techniques generally consist of modifying or optimizing a given process to improve its operation, since many PM emissions are the result of processes which are not performing to their potential. These emissions can be reduced or eliminated by altering the process.

## 4.1 Fuel Substitution

Fuel substitution can be an effective means of reducing emissions for many types of processes which use fuel combustion to provide heat for the process or to produce electricity. Fuel combustion is responsible for significant emissions of $PM_{10}$ and $PM_{2.5}$, as well as $SO_x$ and $NO_x$. Control devices, such as fabric filters and electrostatic precipitators are often the first option for PM control for fuel combustion sources. However, add-on PM controls can require a very large capital investment.

The type of fuel and process have a great impact on the PM emissions from combustion. Coal, oil, and natural gas are the most common fuels used. Of these fuels, coal combustion generally results in the highest PM emissions. The four major types of coal are bituminous, subbituminous, anthracite, and lignite;[1] their characteristics and emissions are very different. Oil is broadly classified as residual or distillate. Residual oils contain more sulfur and ash which contribute to higher emissions. Fuel oils are also described by numbers. Numbers 1 and 2 fuel oils are distillate, Nos. 5 and 6 are residual, and No. 4 fuel oil can be distillate or a mixture of residual and distillate.[1] Natural gas is a relatively clean-burning fuel and typically results in much less PM than oil or coal.[1]

### 4.1.1 Applicability

There are several considerations to determine if fuel switching is the best option for reducing emissions from a given combustion source. For many older boilers, the expense associated with new add-on PM controls or modifications to existing controls is not practical. Fuel switching is an especially attractive option for these boilers because the capital investment is usually small when compared to that of control devices.

For fuel substitution to be practical, there must be a suitable replacement fuel available at an acceptable cost. Prospective fuels must be evaluated using the criteria of performance, availability, and cost.[2] The first requirement is that the replacement fuel provides a significant reduction in emissions versus the original fuel. The effect that the replacement fuel has on emissions of other pollutants should be considered as well. For example, switching to low sulfur coal to reduce $SO_x$ emissions may increase PM emissions.[2] In many cases fuel substitution will reduce more than one type of pollutant. For instance, substituting natural gas for coal will reduce PM emissions and virtually eliminate $SO_x$.

While most industrialized areas have access to a variety of fuels, some fuels may not be practical in certain locations because of cost. Natural gas and fuel oil are generally supplied by pipeline. Locations which are not near existing pipelines may find it expensive to arrange for a natural gas or fuel oil supply. Smaller industrial or commercial units can rely on delivery by truck. Since coal is typically supplied by railroad and the characteristics of coal from different areas of the country vary widely, some types of coal may not be applicable as a replacement fuel for a given location because they must be shipped from an unreasonable distance.

In most cases, the process will have to be modified to accommodate switching to a different type of fuel. For certain types of coal fired boilers, such as stokers, it may be impractical to retrofit them to burn a liquid or gaseous fuel. Fuel switching will often require retrofitting the current control device in addition to the process. Fuel substitution therefore, would not be applicable to sources with excessive retrofit costs.

In addition to the requirements for source modification, fuel prices can be a determining cost factor for fuel switching. Since coal, oil, and natural gas all have different prices based on their heating values, fuel switching may also increase operating costs. The costs of fuel substitution will be discussed further in section 4.1.3.

### 4.1.2 Emission Reductions with Fuel Switching

If fuel substitution is applicable to a given combustion process, it can result in significant reductions in PM emissions. In general, PM and $SO_2$ emissions are highest for coal and lowest for natural gas. Tables 4.1 and 4.2 show potential $PM_{10}$ and $PM_{2.5}$ emission reductions, respectively, with fuel switching. The tables provide matrices showing the approximate emissions reductions for switching from bituminous coal to subbituminous coal, from coal to oil, and from oil to gas. Distillate oil was not provided as a replacement fuel for utility sources because it is not typically burned in utility boilers.

The emission reductions were calculated based on emission factors and fuel composition.[1] Emission factors are dependent on the type of fuel and the type of combustion process which is employed. The potential reductions achieved by switching from bituminous and subbituminous coal in Tables 4.1 and 4.2 were based on emissions from dry bottom

## Table 4.1. Potential $PM_{10}$ Emission Reductions with Fuel Switching (References 1, 4, and 5)

| | Estimated $PM_{10}$ Reductions with Replacement Fuel (percent) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Industrial | | | | Utility | | |
| Original Fuel | Subbituminous | Residual Oil[a] | Natural Gas | Distillate Oil[b] | Subbituminous | Residual Oil[a] | Natural Gas |
| Bituminous Coal | 21.4 | 62.9 | 98.2 | 99.0 | 21.4 | 69.5 | 99.3 |
| Subbituminous Coal | -- | 52.8 | 97.7 | 98.8 | -- | 61.2 | 99.2 |
| Residual Oil[a] | -- | -- | 95.1 | 97.4 | -- | -- | 97.9 |

[a] Residual Oil includes No. 4, 5, and 6 fuel oil.
[b] Distillate Oil is No. 2 fuel oil.

## Table 4.2. Potential $PM_{2.5}$ Emission Reductions with Fuel Switching (References 1, 4, and 5)

| | Estimated $PM_{2.5}$ Reductions with Replacement Fuel (percent) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Industrial | | | | Utility | | |
| Original Fuel | Subbituminous | Residual Oil[a] | Natural Gas | Distillate Oil[b] | Subbituminous | Residual Oil[a] | Natural Gas |
| Bituminous Coal | 21.4 | 7.4 | 93.1 | 99.1 | 21.4 | 14.8 | 97.5 |
| Subbituminous Coal | -- | -- | 91.2 | 98.8 | -- | -- | 96.8 |
| Residual Oil[a] | -- | -- | 92.5 | 99.0 | -- | -- | 97.0 |

[a] Residual Oil includes No. 4, 5, and 6 fuel oil.
[b] Distillate Oil is No. 2 fuel oil.

boilers, since dry bottom boilers are responsible for the highest percentage of PM emissions from coal combustion.[3] In addition, dry bottom boilers have lower $PM_{10}$ and $PM_{2.5}$ emission factors than wet bottom boilers and all types of stokers.[1] Emission factors for utility and industrial coal combustion in the same type of boilers were assumed to be the same.[1] Variation in PM emissions from oil combustion is due to differences in utility and industrial units. Utility units tend to operate more efficiently than industrial units and, therefore, have lower PM emissions. This is also the case with natural gas combustion.[1]

In terms of fuel composition, the ash content of the fuel is a major factor in determining PM emissions. In general, the higher ash content a given fuel, the more PM will be emitted when burned.[1] For these calculations, an average value of 8.6 weight percent ash (6.62 lb/$10^6$ Btu) in bituminous coal was used. The average ash content of subbituminous coal was assumed to be 5.2 percent (4 lb/$10^6$ Btu).[4] Particulate emissions from oil combustion are dependent on ash and sulfur content.[1] Increasing sulfur content will increase PM emissions from oil combustion because the sulfur inhibits complete combustion.[1] Also, a small percentage (1% to 3%) of the sulfur in oil is emitted as sulfate particulate.[1] Residual oil was estimated to have ash content of 0.03 weight percent (0.016 lb/$10^6$ Btu) and sulfur content of 2.5 percent (1.3 lb/$10^6$ Btu).[4] Distillate oil was estimated to have ash content of less than 0.01 percent (<0.005 lb/$10^6$ Btu) and sulfur content of 0.22 percent (0.115 lb/$10^6$ Btu).[4] A sample calculation of the potential $PM_{10}$ emission reduction associated with switching from bituminous coal to distillate oil follows.

The $PM_{10}$ emission factors for bituminous coal and distillate oil combustion in dry bottom boilers are 2.3(A) lb/ton and 1 lb/$10^3$ gallons, respectively.[1] In the coal emission factor, (A) refers to the ash content of the fuel. Because these factors are based on tons of coal and gallons of oil, they must be converted into factors based on the heating value of the fuel in order to be useful. This is done by dividing the emission factor by the heating value:

Bituminous coal: (2.3 lb/ton)(8.6)/(26,000,000 Btu/ton) = 0.761 lb/$10^6$ Btu
Distillate oil: (1 lb/$10^3$ gal)/(138,000,000 Btu/$10^3$ gal) = 0.007 lb/$10^6$ Btu

The potential reduction in $PM_{10}$ emissions when switching from bituminous coal to distillate oil is calculated by subtracting the emission factor for oil ($EF_{oil}$) from the emission factor for coal ($EF_{coal}$) and then dividing by the coal emission factor:

$$\text{Potential reduction} = [(EF_{coal}) - (EF_{oil})]/(EF_{coal})$$
$$= [(0.761 \text{ lb}/10^6 \text{ Btu}) - (0.007 \text{ lb}/10^6 \text{ Btu})]/(0.761 \text{ lb}/10^6 \text{ Btu})$$
$$= 0.99 \text{ or } 99 \text{ percent}$$

Tables 4.1 and 4.2 indicate that the maximum reductions in $PM_{10}$ and $PM_{2.5}$ emissions can be obtained by switching to from coal or residual oil to natural gas or distillate oil. The reductions presented in these tables were based on the average values discussed above; actual reductions will vary with specific fuel composition.

### 4.1.3 Costs

The costs associated with fuel substitution are related to retrofitting the current unit and purchasing the replacement fuel. Retrofitting the combustion process to burn another fuel can be a major undertaking, with the necessary modifications unique to each site. Generally, switching from one kind of coal or grade of oil to another is less costly than switching from coal to oil or natural gas. In some cases, the cost of modifying the combustion process to utilize the new fuel makes the fuel substitution impractical. Another possible retrofit cost is related to the existing control devices, which also may require modifications to accommodate the type of emissions associated with the new fuel.

A cost differential may also exist between fuels. If the replacement fuel is much more expensive than the fuel which is currently in use, operating costs may noticeably increase. Table 4.3 provides average prices for coal, oil, and natural gas, in terms of common units and heating value.[5,6,7] These prices will vary depending on the actual location in the U.S.

Table 4.3. Average Prices of Coal, Oil, and Natural Gas[a] (References 5, 6, and 7)

| | Average Price | |
|---|---|---|
| Fuel | Common Price | \$/MMBtu |
| Subbituminous coal[b] | | |
| Utility | \$27.01/ton | 1.35 |
| Industrial | \$32.37/ton | 1.62 |
| Bituminous coal[b] | | |
| Utility | \$27.01/ton | 1.04 |
| Industrial | \$32.37/ton | 1.25 |
| Residual oil[c] | \$390/$10^3$ gal | 2.60 |
| Distillate oil[c] | \$616/$10^3$ gal | 4.47 |
| Natural gas[c] | \$1680/$10^6$ scf | 1.68 |

[a] More current prices are available from the *Monthly Energy Review*, published by the U.S. Department of Energy, Washington, DC.

[b] 1995 average prices.

[c] Average prices as of September, 1996.

### 4.1.4 Other Impacts

In addition to reducing PM emissions, fuel substitution can also reduce emissions of other pollutants, such as $SO_x$ and $NO_x$. Potential $SO_x$ reductions with fuel switching are provided in Table 4.4. Natural gas is especially effective for $SO_x$ control, eliminating nearly 100 percent of $SO_x$. Coal burning power plants have been switching to Western coal as a means of reducing $SO_x$ emissions,[2] since western coals have lower sulfur contents than many otherwise comparable Eastern coals. Unfortunately, low sulfur ash is more difficult to collect in ESPs, so that switching to Western coal will usually require flue gas conditioning or a control device modification to maintain PM collection efficiency.[2]

Substituting natural gas for coal has been shown to be effective at reducing $NO_x$ emissions. In 1992, Public Service Electric and Gas (PSE&G) demonstrated seasonal control of $NO_x$ emissions by operating two utility boilers with natural gas instead of coal for the 3-month ozone season (June, July, and August).[8]

Table 4.4. Potential $SO_x$ Reductions with Fuel Switching

| | Estimated $SO_x$ Reductions with Replacement Fuel (percent) | | | | |
|---|---|---|---|---|---|
| Original Fuel | Subbituminous Coal | Lignite Coal[a] | No. 4 Fuel Oil[b] | No.2 Fuel Oil[c] | Natural Gas |
| Bituminous Coal | 72.9 | 80.2 | 47.4 | 91.2 | 99.9 |
| Subbituminous Coal | -- | 26.9 | -- | 69.5 | 99.9 |
| No. 6 Fuel Oil[d] | -- | -- | 46.2 | 91.5 | 99.9 |
| No. 4 Fuel Oil[b] | -- | -- | -- | 84.3 | 99.9 |
| No. 2 Fuel Oil[c] | -- | -- | -- | -- | 99.7 |

[a] Lignite coal with high sodium ash content and sulfur content of 0.4 percent by weight.
[b] Distillate/residual mixture with average sulfur content of 1.35 percent by weight.
[c] Distillate oil with average sulfur content of 0.22 percent by weight, typically not used in utility boilers.
[d] Residual oil with average sulfur content of 2.5 percent by weight.

## 4.2 Process Modification/Optimization

Process modification and/or optimization can be an effective means of reducing PM emissions. Some general examples of process optimization include reducing the frequency of mass transfer operations, improving operational efficiency, and the proper use of dust collection devices at the point of generation.

Manufacturing can require many individual process steps involving simple functions. Material transfer steps can cause fugitive PM emissions and costly loss of product. A careful analysis of all process steps may reveal some unnecessary or repetitive steps which can be eliminated, resulting in fewer fugitive PM emissions.[9]

Particle characteristics can also have a significant impact on PM emission rates. Particle size has a direct effect in that larger particles settle more quickly and are more easily collected in control devices. Therefore, wetting and agglomeration techniques in general increase particle size and the efficiency of control equipment.[9] The performance of some control devices, such as ESPs, is also influenced by the chemical composition of the particles. Flue gas conditioning (see Section 5.1) is a means of altering the composition of particles and improving the conditions for electrostatic precipitation.

Some specific process modification/optimization techniques to reduce PM emissions are:

- Changing from a cupola to an electric arc furnace.[9]

- Changing from an (open) bucket elevator to more efficient (closed) pneumatic conveyor.[9]

- Screening out undersized coke (<1 inch) to reduce blast furnace fugitive emissions in primary metal smelting.[10]

- Improving blast furnace combustion efficiency during primary lead smelting by improving the furnace water cooling system.[10]

- Eliminating fugitive PM from transporting, pouring, and stirring molten metal by the use of continuous kettle drossing rather than manual in primary metal smelting (as is currently done in only foreign facilities).[10]

- Improving raw material quality, e.g. improve the quality of coke and sinter concentrate used in primary metal production.[10]

- Cooling metal pots to reduce fume generation during kettle drossing in primary metal production.[10]

- Pumping (primary) metal directly to dross kettles using an electromagnetic pump.[10]

- Agglomerating blast furnace flue dust in an agglomerating furnace to reduce the load on the fabric filter to improve its performance. This process completely eliminates handling of the dust and the associated fugitive emissions, and eliminates fugitive emissions from flue dust storage piles.[10]

- Using permanent mold castings in gray iron foundries instead of green sand. This is reported to reduce PM emissions by 99 percent.[10]

- Pre-treating glass manufacturing raw materials to reduce the amount of fine particles. Pretreatments include: presintering, briquetting, pelletizing, or liquid alkali treatment.[10]

- Replacing grease and oil lubricants (e.g. in glass manufacturing) with silicone emulsions and water-soluble oils that eliminate the smoke generated from flash vaporization of hydrocarbons from greases and oils that come into contact with process materials.[10]

- Tuning industrial boilers to achieve more efficient combustion to reduce PM that occurs as a result of incomplete combustion.

- ABB Industry Oy of Finland's Burning Image analyZER (BIZER) that allows combustion control for kraft pulp mill recovery boilers. In this process, infrared cameras view the smelt pile and provide digital image processing to present burning information. This technique can be used for automatic burning control.[11]

- Hitachi, Ltd., of Japan's Oilless, Dry Centrifugal "Leak-Free" Compressors eliminate fugitive leaks and save energy. The PM reduction is achieved through energy efficiency. This device is currently being used at petroleum refineries.[11]

- Poland has developed a coal pyrolysis technique that produces a better fuel. Crushed dried coal is decomposed into gas and char in a circulating fluidized bed reactor. The gas is burned in a turbine and the char is mixed with coal and pressed into briquettes of smokeless fuel called ECOCOAL. ECOCOAL has 1.2 to 1.7 times the thermal efficiency of coal with PM emissions up to 50 percent lower.[11]

- Lurgi Metallurgie's (FRG) QSL Process for Secondary Lead Smelting. Use of a completely closed reactor designed to treat all grades results in >90 percent control of PM.[11]

- Fluidized-bed heat treatment technology for primary metal manufacturing developed by Quality Heat Treatment Pty, Ltd., of Australia. A gas-phase heat treatment process uses a fluidized bed of alumina particles and is completely enclosed, enabling collection of fugitive PM emissions.[11]

- Dow Chemical Ferroalloy Process. Pure oxygen is used instead of air in a closed furnace that produces no dust.

## 4.3 References for Section 4

1. Compilation of Air Pollutant Emission Factors (AP-42). volume I (Fifth Edition). U.S. Environmental Protection Agency, Research Triangle Park, NC. January 1995.

2. Rembold, D. and R. Rupinkas. CAA Compliance: Fuel Switching Can Be Complex, Yet Rewarding. Electrical World. April 1994.

3. Source Category Emission Reductions with Particulate Matter and Precursor Control Techniques. Prepared for K. Woodard, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina (AQSSD/IPSG), under Work Assignment II-16 (EPA Contract No. 68-03-0034), "Evaluation of Fine Particulate Matter Control." September 30, 1996.

4. Perry, R.H. and D.W. Green. Perry's Chemical Engineers' Handbook (6th Edition). McGraw-Hill Publishing Company, Inc., New York, New York. 1984.

5. Quarterly Coal Report, October-December 1995 (DOE/EIA-0121(95/4Q)). Energy Information Administration, Department of Energy, Washington, DC. May 1996.

6. Electric Power Monthly, April 1996 (DOE/EIA-0226(96/04)). Department of Energy, Washington, DC. April 1996.

7. Industry Statistics. Oil & Gas Journal. September 16, 1996.

8. Control Costs for VOC and NOx Measures for Non-Traditional Sources for Ozone NAAQS Review. Final Report for Work Assignment No. 06; EPA Contract No. 68-D3-0034. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 30, 1994.

9. Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-18-005a, NTIS PB83-127498). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. September 1982.

10. Estimating and Controlling Fugitive Lead Emissions from Industrial Sources (EPA-452/R-96-006). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. May 1996.

11. Assessment of International Air Pollution Prevention and Control Technology for Title IX of the Clean Air Act Amendments. Draft Report to Congress. Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC. July 1996.

# 5. EXHAUST GAS CLEANING SYSTEMS FOR STATIONARY SOURCES

This section discusses the exhaust gas cleaning systems for stationary sources that can be used in industries with particulate-bearing exhaust streams. The devices discussed are electrostatic precipitators (ESPs), fabric filters, wet scrubbers and incinerators (used for streams with especially high VOC contents as well as PM). The section begins with a discussion of pretreatment devices that can be used to reduce the PM loading onto the primary control device and flue gas conditioning which can enhance particle collection.

Each section includes a description of the device, the collection mechanisms, and discussion of different systems designs. Also included is a discussion of the applicability of the device to the various processes to which the controls can be applied. The effectiveness of the device, in terms of the range of efficiencies for various types of systems and applications, is then discussed, with a special focus on $PM_{10}$ and $PM_{2.5}$. General curves relating particle size and efficiency are included along with a discussion of the parameters influencing efficiency and their quantitative impacts. Two types of efficiency, fractional and cumulative, are discussed in this section. Fractional efficiency refers to the efficiency of a control device for a particular size of particle only, such as 10 $\mu$m in aerodynamic diameter. Cumulative efficiency is the efficiency of a control device for a particular particle size and all the particles smaller that size particle, such as $PM_{10}$, which includes all particles with aerodynamic diameters of 10 $\mu$m or smaller.

Costs of the devices are discussed, and include cost tables and curves derived using standard EPA protocol. A discussion of the parameters affecting cost and the relationship between costs and these parameters is included in each cost section. In many cases, the costs have been updated to fourth quarter 1996 using the Vatavuk Air Pollution Control Cost Index (VAPPCI). This index is provided in Appendix B. The index is also published monthly in Chemical Engineering. Finally, the energy and other secondary environmental impacts, such as water pollution and waste generation, are discussed along with potential mitigation measures.

## 5.1 PRETREATMENT

The performance of particulate control devices can often be improved through pretreatment of the gas stream. For PM control devices, pretreatment consists of two categories: precollection and flue gas conditioning. Precollection devices remove large particles from the gas stream, reducing the loading on the primary control device. Gas conditioning techniques alter the characteristics of the particles and/or the gas stream to allow the primary control device to function more effectively. Both types of pretreatment can lead to increased collection efficiency and operating life, while reducing operating costs. The performance of precollection devices is discussed in Section 5.1.2.

### 5.1.1 Precollection Devices

The vast majority of precollection devices are mechanical collectors. Mechanical collectors are a class of devices that rely on gravity and inertia for particle collection. They are used extensively in industry because of several advantages they possess. Mechanical collectors have low capital costs, the ability to operate in harsh environments, and low maintenance requirements because they lack moving parts.[1] There are also disadvantages associated with mechanical collectors, such as the relatively low collection efficiencies for small particles. While this does prevent their use as primary collection devices in many applications, it is not a major concern when mechanical collectors are used for precollection. Some mechanical collectors can achieve high collection efficiencies, but only with the high operating costs associated with large pressure drops.[1] The five major types of mechanical collectors are settling chambers, elutriators, momentum separators, mechanically aided collectors, and centrifugal separators (cyclones); these devices are discussed separately below.

#### 5.1.1.1 Settling Chambers

The simplest mechanical collectors are settling chambers, which rely on gravitational settling as a collection mechanism. Settling chambers prevent excessive abrasion and dust loading in primary collection devices by removing large particles from the gas stream.[2] Despite low collection efficiencies, settling chambers are still used extensively. They are particularly useful for industries that also need to cool the gas stream prior to treatment in a fabric filter. The mineral products and metals processing industries have several applications for settling chambers. There are two primary types of settling chambers: the expansion chamber and the multiple-tray chamber. In the expansion chamber, the velocity of the gas stream is significantly reduced as the gas expands into a large chamber. The reduction in velocity allows larger particles to settle out of the gas stream.[3] Figure 5.1-1 shows a schematic diagram of an expansion chamber, which consists of a simple chamber with collection hoppers.[2]

A multiple-tray settling chamber, shown in Figure 5.1-2, is an expansion chamber with a number of thin trays closely spaced within the chamber, which causes the gas to flow

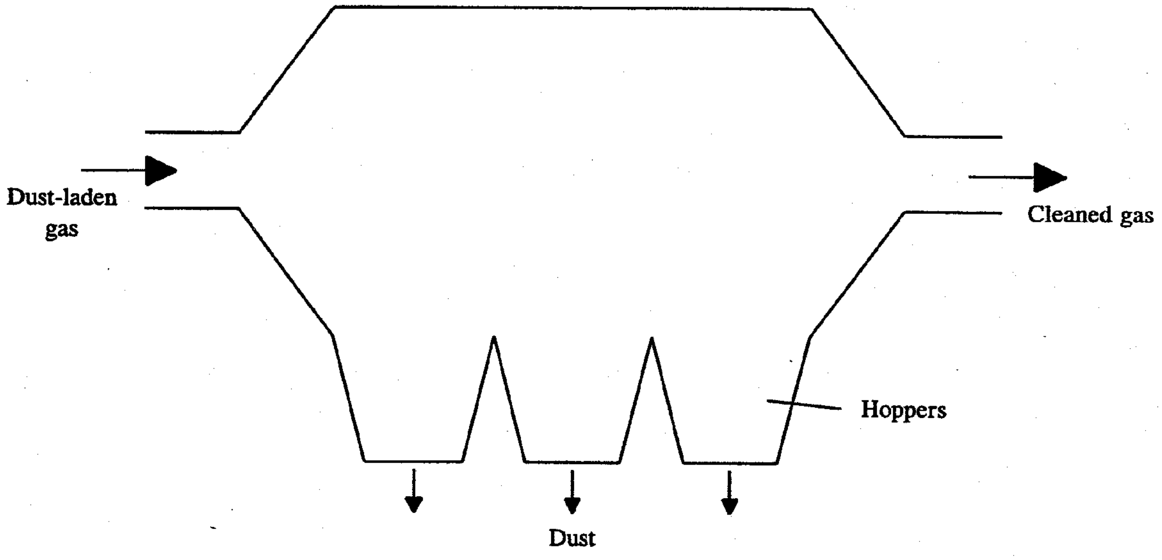


Figure 5.1-1. Expansion Settling Chamber (Adapted from Reference 2).

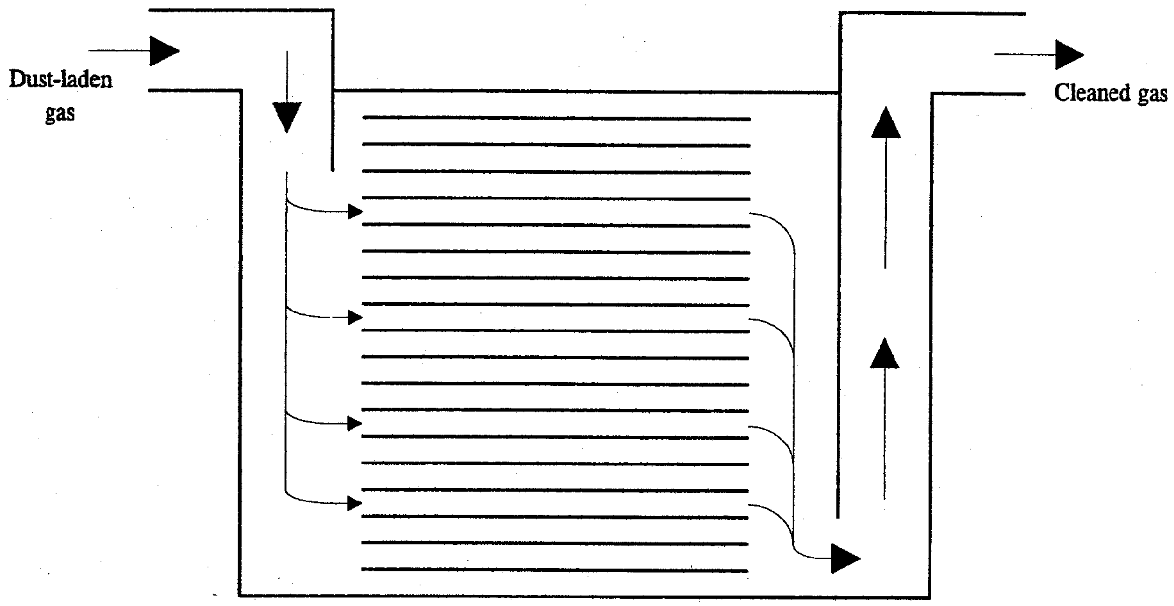


Figure 5.1-2. Multiple-Tray Settling Chamber (adapted from Reference 2).

horizontally between them.[2] While the gas velocity is increased slightly in a multiple-tray chamber, the collection efficiency generally improves because the particles have a much shorter distance to fall before they are collected. An expansion chamber must be very large to collect any small particles, but multiple-tray chambers have lower volume requirements for the collection of small particles ($\geq$15 µm).[3]

### 5.1.1.2 Elutriators

Like settling chambers, elutriators also rely on gravitational settling to collect particles. An elutriator is made up of one or more vertical tubes or towers in series, where the gas stream passes upward through the tubes. Larger particles whose terminal settling velocity is greater than the upward gas velocity are collected at the bottom of the tube, while smaller particles are carried out of the top of the tube. Size classification of the collected particles can be achieved by using a series of tubes with increasing diameters, as shown in Figure 5.1-3.[2,3]

### 5.1.1.3 Momentum Separators

Momentum separators utilize both gravity and inertia to separate particles from the gas stream. Separation is accomplished by forcing the gas flow to sharply change direction within a gravity settling chamber through the use of strategically placed baffles. Typically, the gas first flows downward and then is forced by the baffles to suddenly flow upwards. Inertial momentum and gravity act in the downward direction on the particles, which causes larger particles to cross the flow lines of the gas and collect in the bottom of the chamber.[2,3]

There are several common arrangements of baffles in momentum separators, as illustrated in Figure 5.1-4.[2,3] Momentum separators are capable of collecting particles as small as 10 µm at low efficiency (10-20 percent). These devices require less space than gravity settlers, but have higher pressure drops.[3]

### 5.1.1.4 Mechanically-Aided Separators

Mechanically-aided separators rely on inertia as a separation mechanism. The gas stream is accelerated mechanically, which increases the effectiveness of the inertia separation. As a result, mechanically-aided separators can collect smaller particles than momentum separators. Unfortunately, they also have higher operating costs as a result of higher pressure drops. A common type of mechanically-aided collector is the modified radial blade fan, shown in Figure 5.1-5.[3] In this device, the gas stream enters at the center of the fan, perpendicular to the blade rotation. The blades propel the particles across the gas flow lines, where they are concentrated on the inside wall of the casing. From there, the particles are diverted into a collection hopper while the gas continues out of the separator. Mechanically-aided separators are subject to abrasive wear from large particles and clogging from particles which cake or accumulate on the blades. Consequently, these devices have higher maintenance requirements than other separators.[2,3,4]

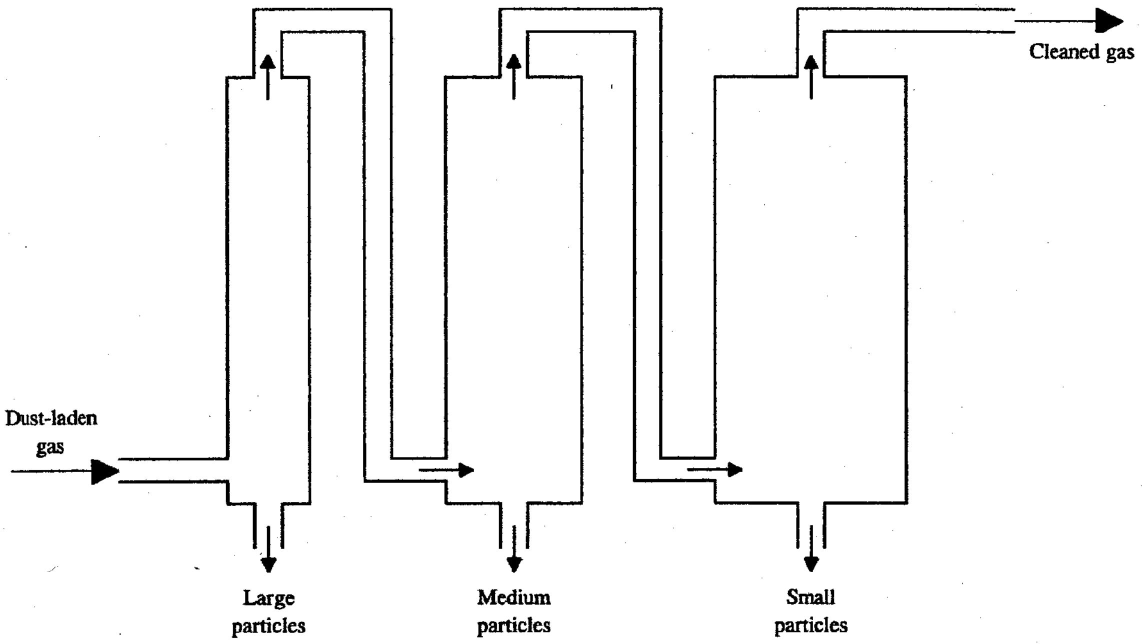


Figure 5.1-3. Elutriators in Series (Reference 3).

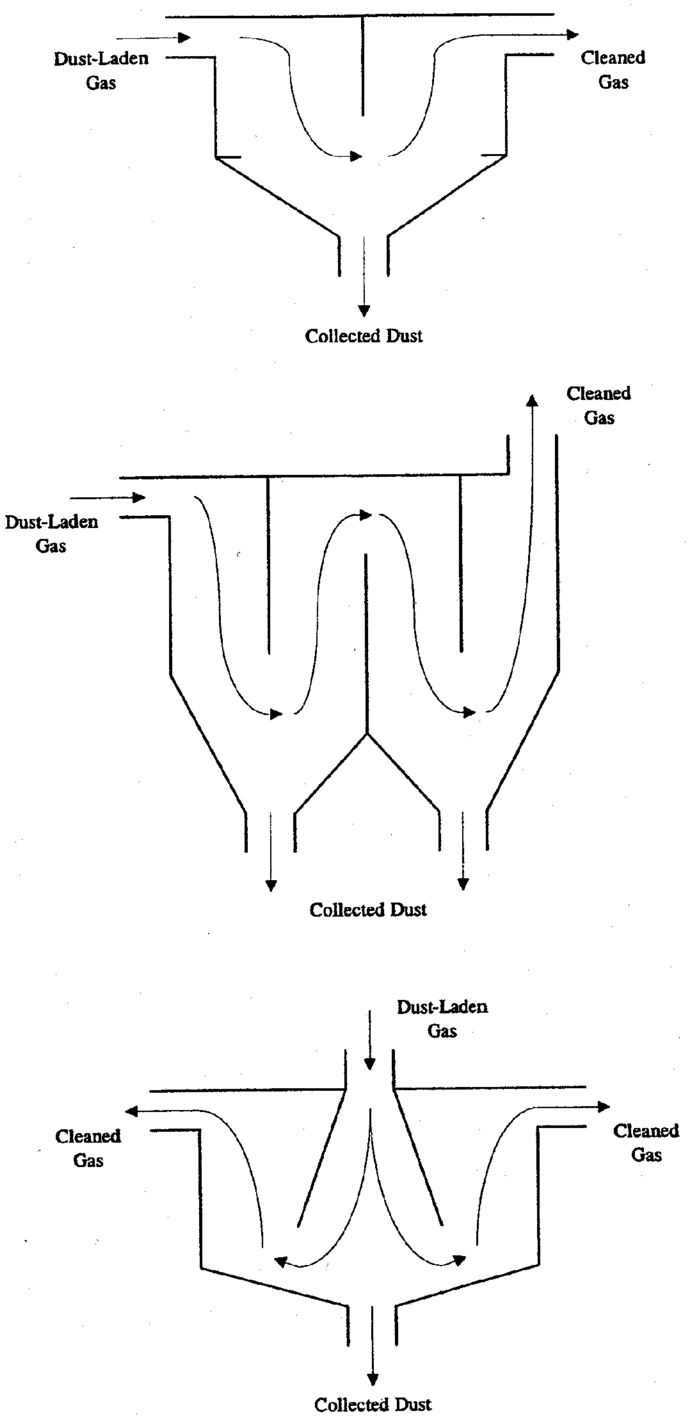


Figure 5.1-4. Momentum Separators (References 2 and 3).

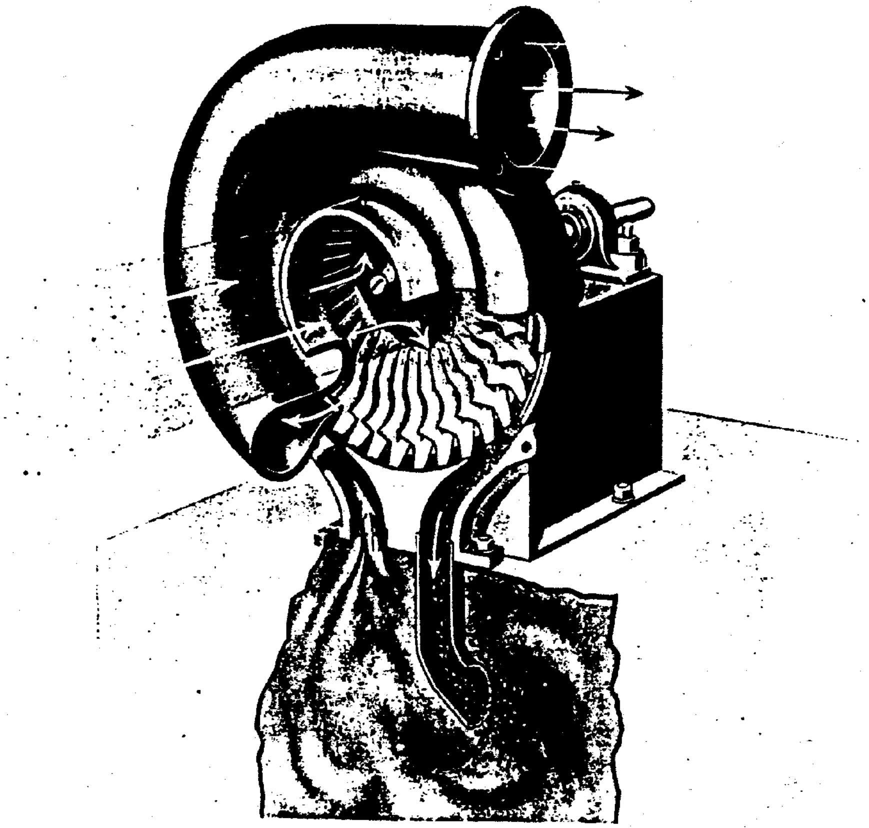


Figure 5.1-5. Mechanically-Aided Separator (Reference 3).

### 5.1.1.5 Cyclones

Cyclones use inertia to remove particles from a spinning gas stream. Within a cyclone, the gas stream is forced to spin within an usually conical-shaped chamber. Cyclones operate by creating a double vortex inside the cyclone body. The incoming gas is forced into circular motion either by tangential inlet or by turning vanes in the axial inlet. The gas spirals down the cyclone near the inner surface of the cyclone tube. At the bottom of the cyclone, the gas turns and spirals up through the center of the tube and out of the top of the cyclone. Figure 5.1-6 illustrates the double vortex operation in a cyclone.[1]

Particles in the gas stream are forced toward the cyclone walls by the centrifugal force of the spinning gas, but are opposed by the fluid drag force of the gas traveling through and out of the cyclone. For particles that are large, inertial momentum overcomes the fluid drag force so that the particles reach the cyclone walls and are collected; while for smaller particles, the fluid drag force overwhelms the inertial momentum and causes these particles to leave the cyclone with the exiting gas. Gravity also causes the larger particles that reach the cyclone walls to travel down into a bottom hopper. While they rely on the same separation mechanism as momentum separators, cyclones are more effective because they have a more complex gas flow pattern.[2,3]

Cyclone collectors are generally classified into four types, based on how the gas stream is introduced and how the collected dust is discharged:

- Tangential inlet, axial discharge
- Axial inlet, axial discharge
- Tangential inlet, peripheral discharge
- Axial inlet, peripheral discharge

The first two types are the most commonly used cyclones. Schematic diagrams of the four types of cyclones are provided in Figure 5.1-7.[2,3]

Cyclone collectors can be designed for many applications, and they are typically categorized as high efficiency, conventional, or high throughput. High efficiency cyclones are likely to have the highest pressure drops of the three cyclone types; high throughput cyclones can treat large volumes of gas with a low pressure drop.[1,5] Each of these three cyclone types have the same basic design. Different levels of collection efficiency and operation are achieved by varying the standard cyclone dimensions, identified in Figure 5.1-8,[6] according to the values[7,8,9] shown in Table 5.1-1.[1,6]

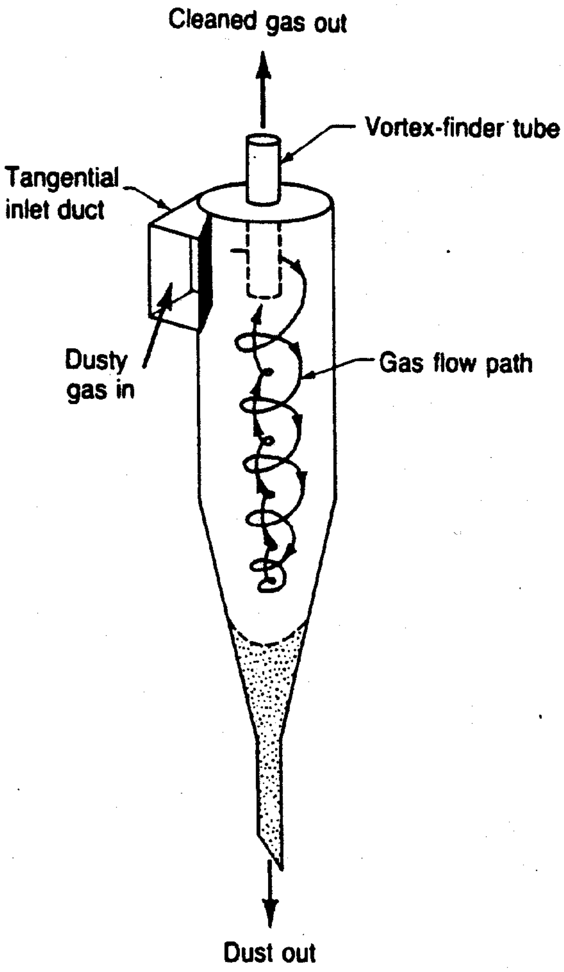


Figure 5.1-6. Illustration of the Double Vortex Within a Cyclone (Reference 1).

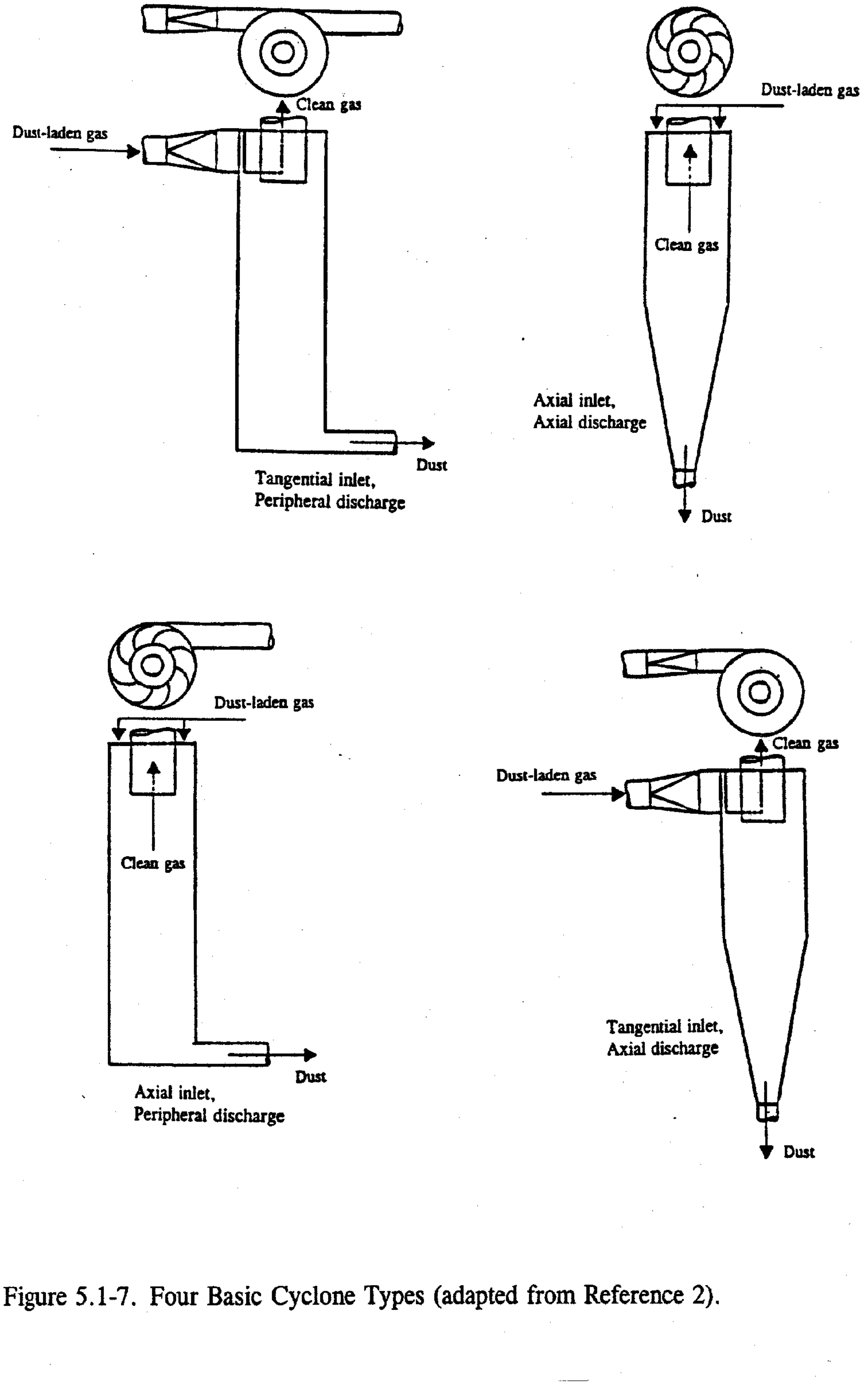


Figure 5.1-7. Four Basic Cyclone Types (adapted from Reference 2).

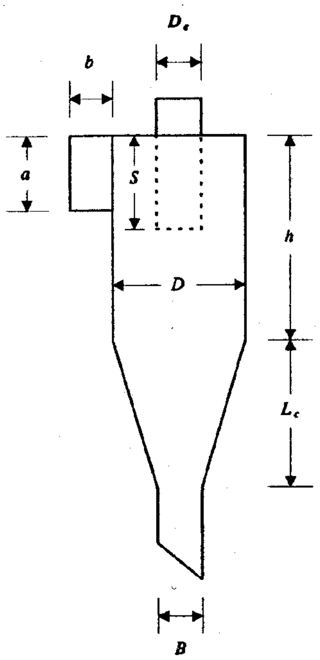


**Figure 5.1-8. Standard Dimensions of a Cyclone (Reference 6).**

Table 5.1-1 Characteristics of Common Cyclones

| | Cyclone Type | | | | | |
|---|---|---|---|---|---|---|
| | High Efficiency | | Conventional | | High Throughput | |
| Cyclone Dimension | (I) | (II) | (III) | (IV) | (V) | (VI) |
| Body Diameter, *D/D* | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Inlet Height, *a/D* | 0.5 | 0.44 | 0.5 | 0.5 | 0.75 | 0.8 |
| Inlet Width, *b/D* | 0.2 | 0.21 | 0.25 | 0.25 | 0.375 | 0.35 |
| Gas Exit Diameter, $D_e/D$ | 0.5 | 0.4 | 0.5 | 0.5 | 0.75 | 0.75 |
| Vortex Finder Length, *S/D* | 0.5 | 0.5 | 0.625 | 0.6 | 0.875 | 0.85 |
| Body Length, *h/D* | 1.5 | 1.4 | 2.0 | 1.75 | 1.5 | 1.7 |
| Cone Length, $L_c/D$ | 2.5 | 2.5 | 2.0 | 2.0 | 2.5 | 2.0 |
| Dust Outlet Diameter, *B/D* | 0.375 | 0.4 | 0.25 | 0.4 | 0.375 | 0.4 |

Note: The various cyclone designs correspond to the following literature references: cyclone I and V from Reference 7, cyclones II, IV, and VI from Reference 8, and cyclone III from Reference 9.

A multiple cyclone, shown in Figure 5.1-9, is a type of high efficiency cyclone which consists of many small diameter cyclones operating in parallel. This arrangement allows for the treatment of large flow rates at higher efficiencies than for single cyclones.[2]

The greatest limitation in the use of cyclones is the energy needed to force the gas through the narrow cyclone body. The pressure drop within the cyclone generally increases with increasing gas flow rate and decreasing cyclone diameter. Cyclone pressure drop can be estimated from a number of equations that are based on both theory and experimental data.[10]

### 5.1.2 Collection Efficiency of Precollectors

Mechanical precollectors have a wide range of collection efficiencies. Collectors which rely only on gravity settling, such as settling chambers and elutriators, typically have the lowest collection efficiencies. Cyclones are the most effective mechanical collectors, with multicyclones achieving the highest collection efficiencies.

#### 5.1.2.1 Gravity Settling

Gravity settling chambers are most effective for large and/or dense particles. Collection efficiency for $PM_{10}$ is very low, typically less than 10 percent. The efficiency of settling chambers increases with the residence time of gas in the chamber. Because of this, gravity settling chambers are often operated at the lowest possible gas velocities. Unfortunately, as the gas velocity decreases, the size of the chamber must increase. In reality, the gas velocity must be low enough to prevent dust from becoming reentrained, but not so low that the chamber becomes unreasonably large.[3] Figure 5.1-10 presents a typical fractional collection efficiency curve for settling chambers.[2] The impact of particle density is illustrated in Figure 5.1-11.[3] The more dense particles of iron oxide, with a specific gravity of 4.5, are collected more efficiently than the quartz dust which has a specific gravity of 2.6.[2,3]

#### 5.1.2.2 Momentum Separators

Because these devices utilize inertia in addition to gravity, momentum separators achieve collection efficiencies approaching 20 percent for $PM_{10}$. Collection efficiency for momentum separators will increase as the gas velocity increases. The pressure drop and corresponding operating costs will also increase with gas velocity, so the optimum velocity must be chosen to balance the efficiency and operating costs.[2,3] Figure 5.1-12 presents efficiency data for momentum separators collecting fly ash.

#### 5.1.2.3 Mechanically-Aided Separators

Figure 5.1-13 provides efficiency curves for two types of mechanically-aided separators.[2] Mechanically-aided separators are capable of collection efficiencies approaching 30 percent for $PM_{10}$.[2] Mechanically-aided separators generally produce more centrifugal

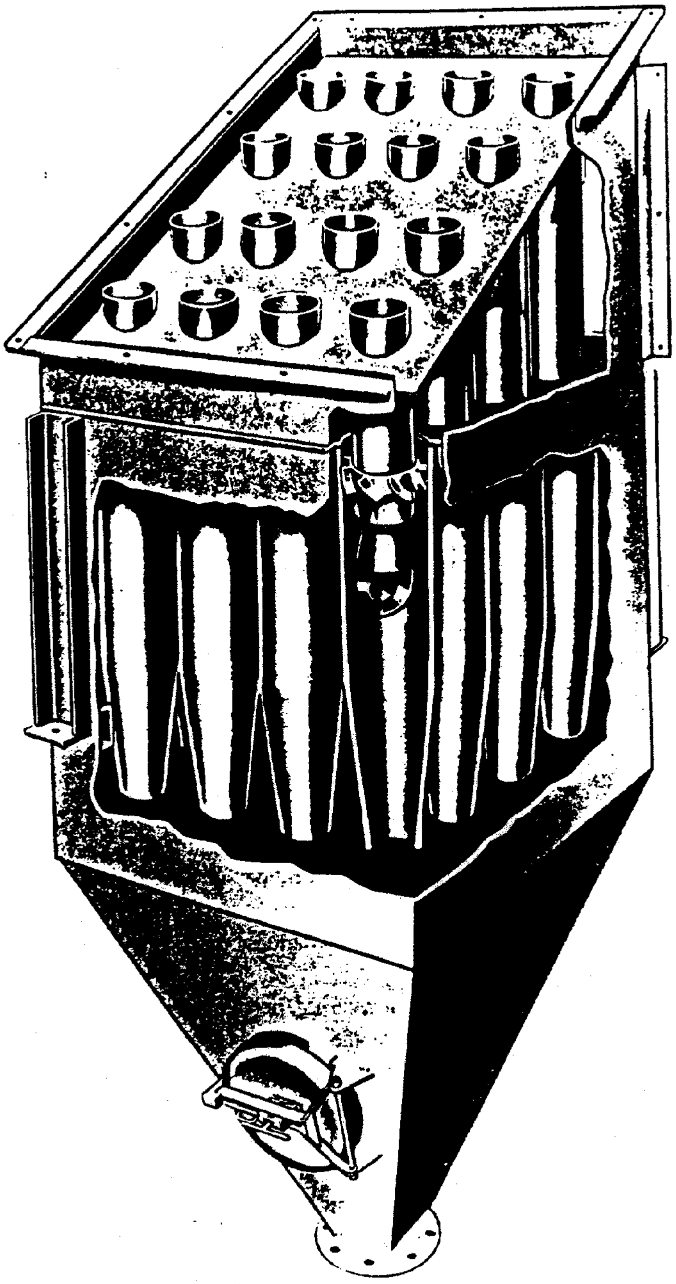


Figure 5.1-9. Typical Multiple Cyclone (Reference 3).

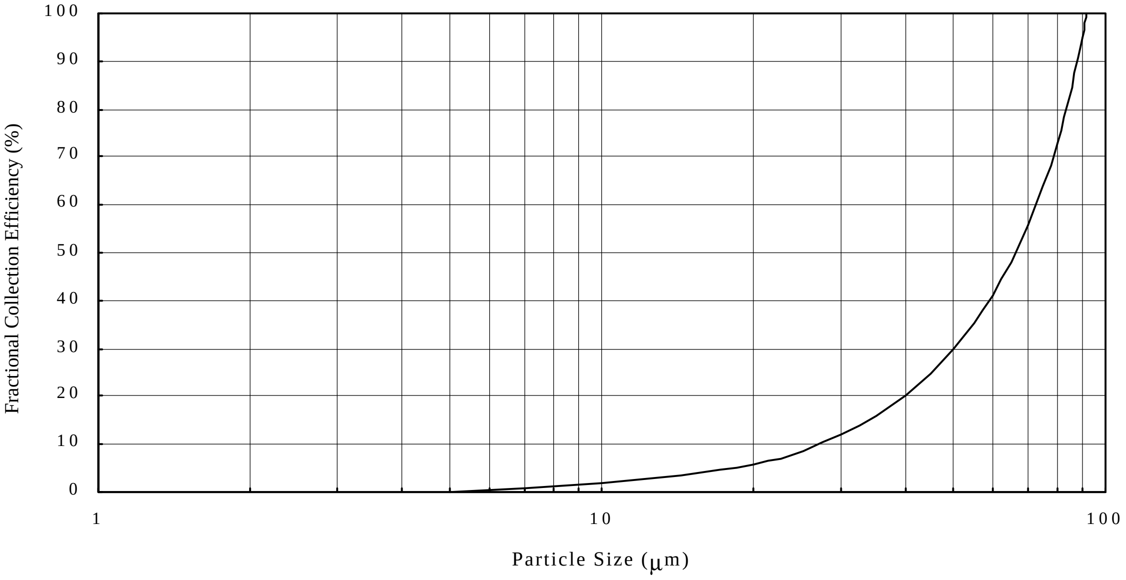


Figure 5.1-10. Typical Fractional Collection Efficiency Curve for Settling Chamber (Reference 2).

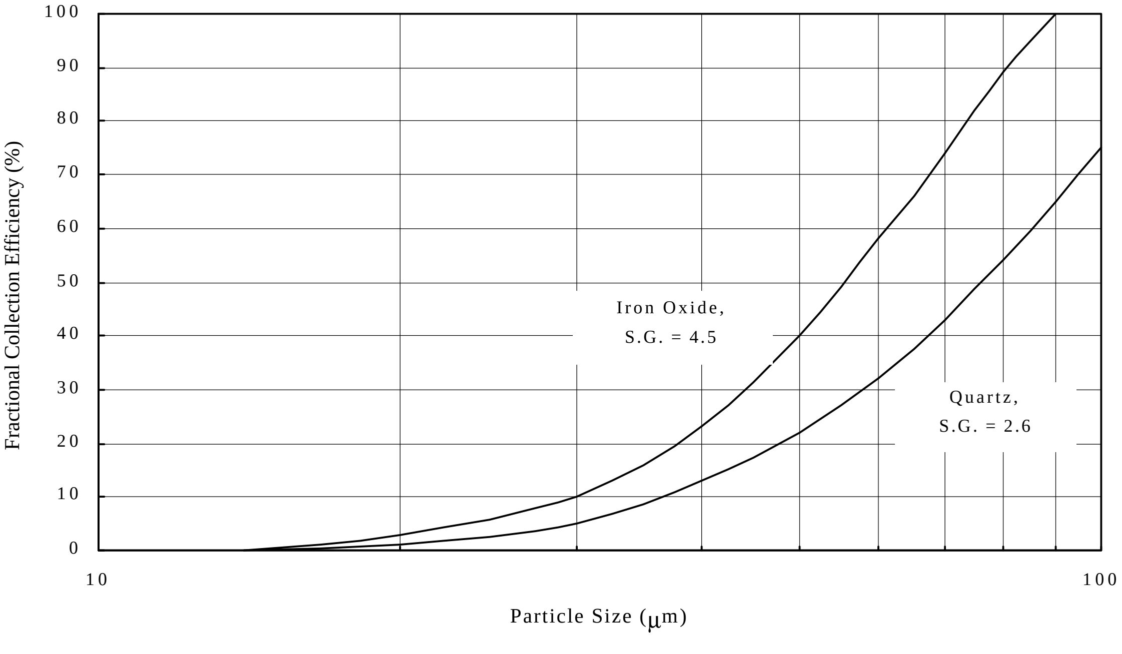


Figure 5.1-11. Impact of Particle Density on Settling Chamber Fractional Collection Efficiency (Reference 3).

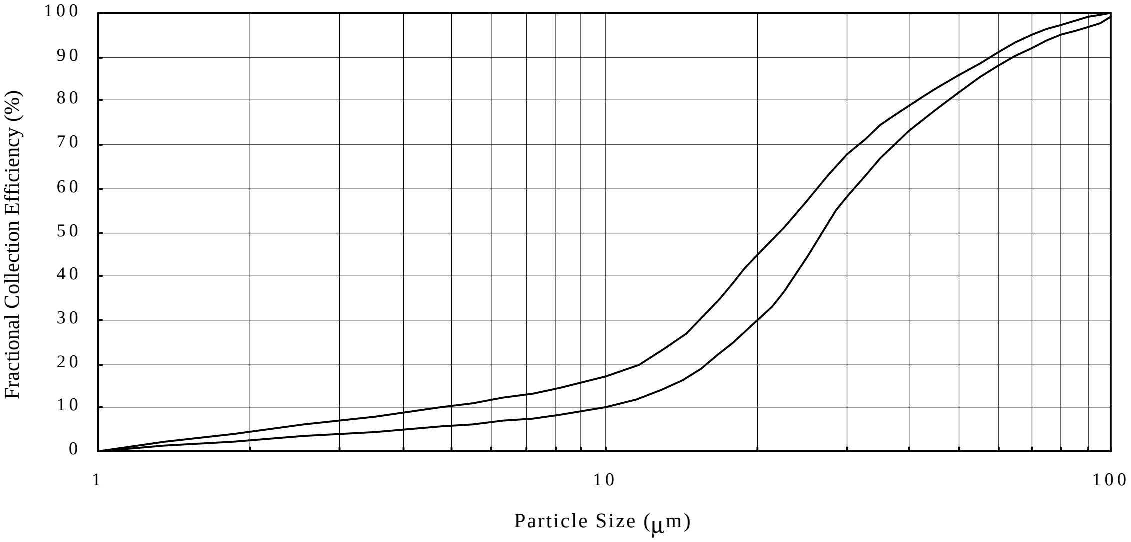


Figure 5.1-12. Typical Fractional Collection Efficiency Curve for a Momentum Separator (Reference 2).

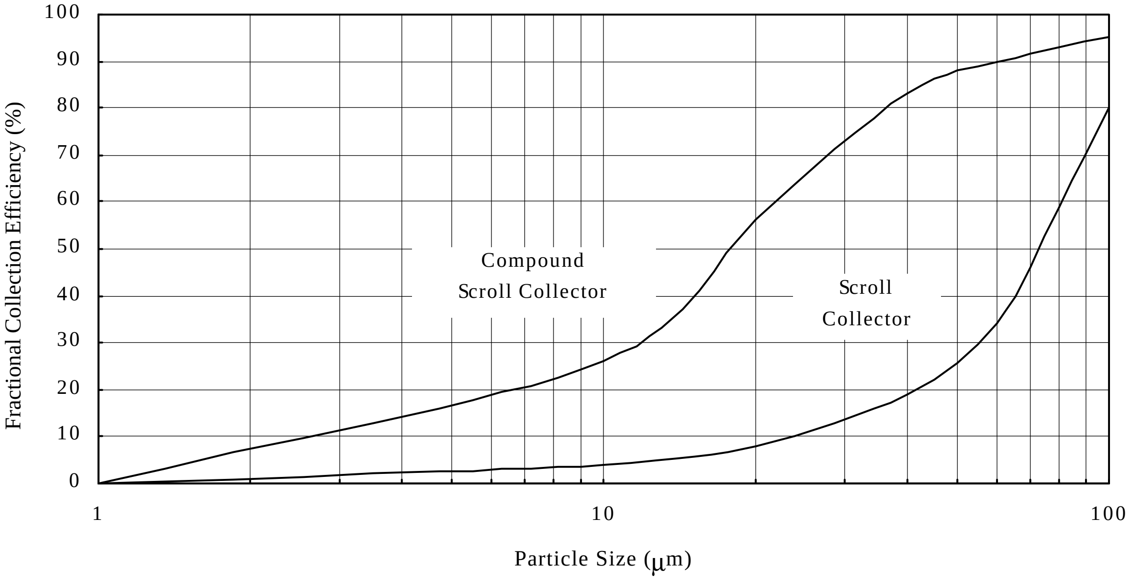


Figure 5.1-13. Typical Fractional Collection Efficiency Curve for a Mechanically-Aided Separator (Reference 2).

force than cyclones, but they also have shorter residence times and more reentrainment as a result of turbulence.  A major advantage of these separators is their compact size.[4]

#### 5.1.2.4 Cyclones

There are many factors which affect the collection efficiency of cyclones.  Cyclone efficiency has generally been shown to increase with the following parameters:  (1) particle size and/or density, (2) inlet duct velocity, (3) cyclone body length, (4) number of gas revolutions in the cyclone, (5) ratio of cyclone body diameter to gas exit diameter, (6) dust loading, and (7) smoothness of the cyclone inner wall.[11]

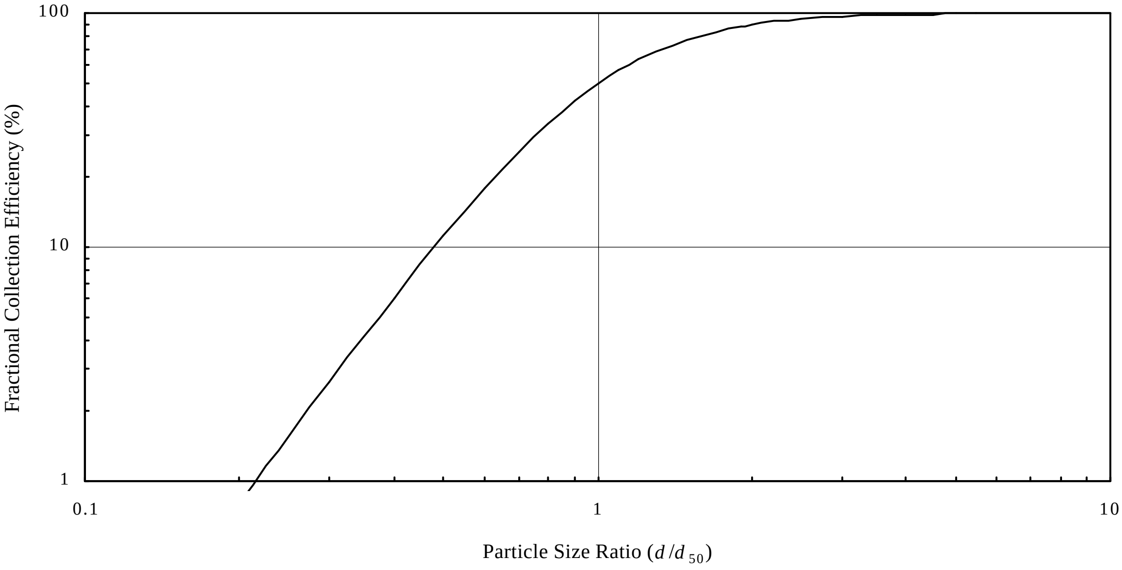
The cyclone efficiency will decrease with increases in the following parameters:  (1) gas viscosity, (2) cyclone body diameter, (3) gas exit diameter, (4) gas inlet duct area, and (5) gas density.  Another common cause of cyclone ineffectiveness is leakage of air into the dust outlet. Specifically, this will decrease the efficiency for fine particles.[11]

Several approaches for estimating cyclone efficiency have been developed.  Most cyclone theories utilize a particle size term, called a "particle cut size," that defines the particle size for a specific collection efficiency.  Particles greater than the cut size will be collected with greater than the specified efficiency, and smaller particles will be collected less efficiently.  Usually, the particle cut size corresponds to 50 percent collection efficiency and is called the "$d_{50}$."  Another important cyclone sizing parameter is the "critical particle size."  Particles of this size and larger are captured with 100 percent efficiency.  Two general types of cyclone fractional efficiency curves are shown in Figure 5.1-14; the first curve "A" is hyperbolic, the second curve "B" is sigmoid shaped.  Most cyclone efficiency theories will produce a curve similar to one of the two shown in this figure.[6,15]

Lapple[12] developed a relatively simple model to predict cyclone efficiency that was derived from particle motion theory and requires an assumption about the number of turns the gas makes within the cyclone.  Leith and Licht[13] developed an efficiency theory that was based on an approximate solution to theoretical particle motion equations using the assumption of turbulence within the cyclone.  Both these theories produce a cyclone efficiency curve of type "A" in Figure 5.1-14.  More recently, Iozia and Leith[14,15] developed a cyclone efficiency theory based on theoretical particle motion that uses empirically developed coefficients.  This theory produces a cyclone efficiency curve of type "B" in Figure 5.1-14.  The Iozia and Leith theory was shown to predict cyclone efficiency better than the theories of Lapple, and Leith and Licht, using cyclone laboratory test data available in the literature.[15]  The Lapple theory and the Iozia and Leith theory are discussed in more detail below.

According to the Lapple theory,[12] $d_{50}$ is calculated as follows:

$$d_{50} = [9\,\mu\,b\,/(2\,\pi\,N\,V_i\,(\rho_p - \rho_g))]^{1/2} \qquad \text{(Eq. 5.1-1)}$$



A: Log-log Scale
B: Linear Scale

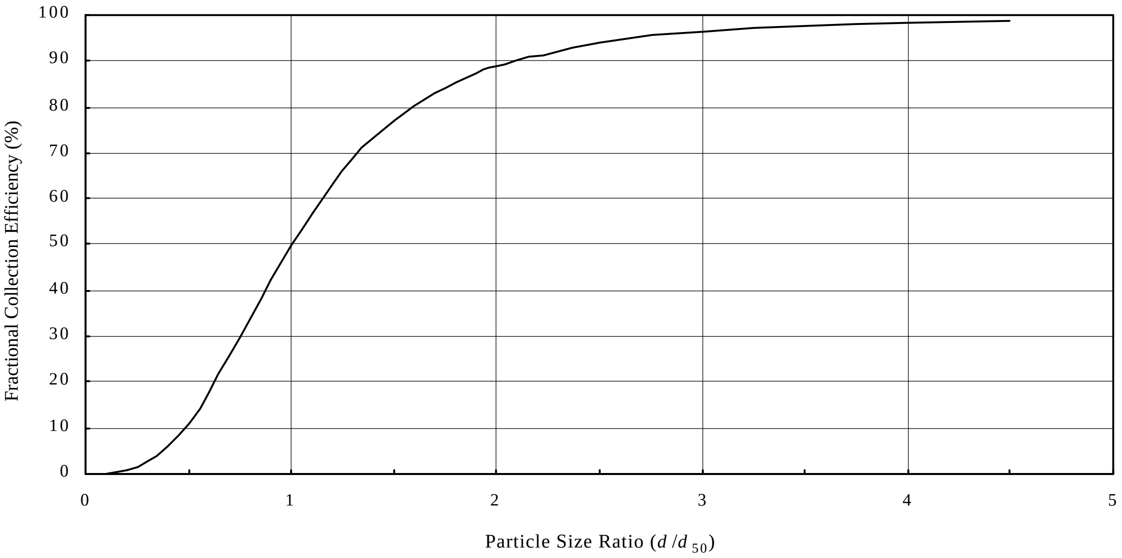


Figure 5.1-14. Typical Cyclone Efficiency Curve in Log-log (A) and Linear (B) Scales (References 6 and 15).

where $d_{50}$ is the diameter of particle collected with 50 percent efficiency (ft), $\mu$ is the gas viscosity (lb/sec-ft), b is the cyclone inlet duct width (ft), $N$ is the number of gas revolutions in cyclone (estimated to be between 0.3 and 10, with a mean value of approximately 5[16]), $V_i$ is the inlet duct gas velocity (ft/sec), $\rho_p$ is the particle density (lb/ft$^3$), and $\rho_g$ is the gas density (lb/ft$^3$). The limitation on this equation is that $N$, the number of gas revolutions within the cyclone, is unknown and estimates for this value do not take into account individual cyclone design or other operating conditions. Also, the Lapple theory does not allow for calculation of collection efficiency for other particle sizes.

The efficiency theory developed by Iozia and Leith[14,15] to predict cyclone fractional collection efficiency utilizes an equation, called a "logistic equation," that approximates a sigmoid-shaped efficiency curve:

$$\text{CE} = 1/(1 + (d_{50}/d)^{ß}) \qquad \text{(Eq. 5.1-2)}$$

where CE is the control efficiency (expressed as a fraction for a particle of diameter $d$, $d_{50}$ is the diameter of the particle collected with 50 percent efficiency, and beta (ß) is a coefficient. Iozia and Leith developed an equation to predict ß from cyclone dimensions using laboratory test data from a 25 cm diameter cyclone:[15]

$$\ln ß = 0.62 - 0.87 \ln (d_{50}) + 5.21 \ln (ab/D^2) + 1.05 (\ln (ab/D^2))^2 \qquad \text{(Eq. 5.1-3)}$$

where $d_{50}$, as above, is expressed in centimeters; $a$ is the cyclone inlet duct height, $b$ is the cyclone inlet duct width, and $D$ is the cyclone diameter. An equation to predict $d_{50}$ was also developed:

$$d_{50} = \{(9 \mu Q)/(\pi z \rho_p Vt_{max}^2)\} \qquad \text{(Eq. 5.1-4)}$$

where $\mu$ is gas viscosity, $Q$ is gas flow, $z$ is approximately equal to the cyclone height minus the height of the extension of the exit duct into the cyclone, $\rho_p$ is the particle density, and $Vt_{max}^2$ is the maximum tangential gas velocity within the cyclone and is calculated as below:

$$Vt_{max}^2 = 6.1V_i \{(ab/D^2)^{0.61} (De/D)^{-0.74} (H/D)^{-0.33}\} \qquad \text{(Eq. 5.1-5)}$$

where $V_i$ is the gas inlet duct velocity; $a$, $b$, and $D$ are as above; $De$ is cyclone outlet duct diameter; and $H$ is the cyclone overall height ($h + L_c$).

Iozia and Leith used their cyclone efficiency theory to optimize cyclone design.[17] Using a computerized cyclone optimization program, they developed curves to predict the cyclone dimensions of a cyclone with the highest efficiency possible for a given situation.[18] Figure 5.1-15 shows the inlet and outlet duct dimensions needed to achieve this optimized cyclone design.[17] The predictions of Iozia and Leith, however, have not yet been tested in full-scale industrial applications.

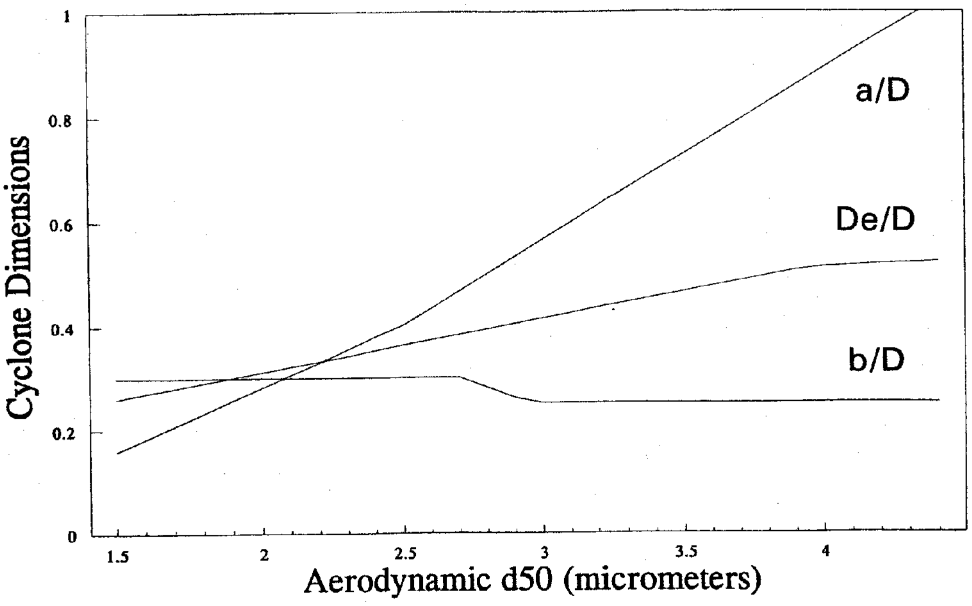


Figure 5.1-15. Dimensions of the Cyclone Inlet and Outlet Ducts for an Optimized Cyclone Design, According to the Iozia and Leith Cyclone Efficiency Theory (Reference 17).

For single cyclones, conventional cyclones can remove 10 µm particles with 85 to 90 percent efficiency, 5 µm particles with 75 - 85 percent efficiency, and 2.5 µm particles with 60 to 75 percent efficiency.[6] High efficiency single cyclones can remove 5 µm particles at up to 90 percent efficiency, with higher efficiencies achievable for larger particles.[1] High throughput cyclones are only guaranteed to remove particles greater than 20 µm, although collection of smaller particles does occur to some extent.[19]

Multicyclones are reported to achieve from 80 percent efficiency up to 95 percent efficiency for particles 5 µm.[1,5,19] In some cases, multiple cyclones have been used as primary collection devices.[19] Multiple cyclones are often used as precollectors at industrial combustion operations. Figure 5.1-16 shows the collection efficiency for multiple cyclones at a boiler that is burning oil. At many large industrial combustion units, PM emissions include significant amounts of carbon which was not fully combusted. To improve the efficiency of these units, collected fly ash from the multiple cyclones (or other precollection devices) is reinjected into the combustion unit. This operation, known as fly ash reinjection, increases the particulate loading considerably, and leads to lower collection efficiencies for small particles.[5] Figure 5.1-17 illustrates this effect, showing efficiency curves for multiple cyclones at coal and wood boilers with and without fly ash injection.

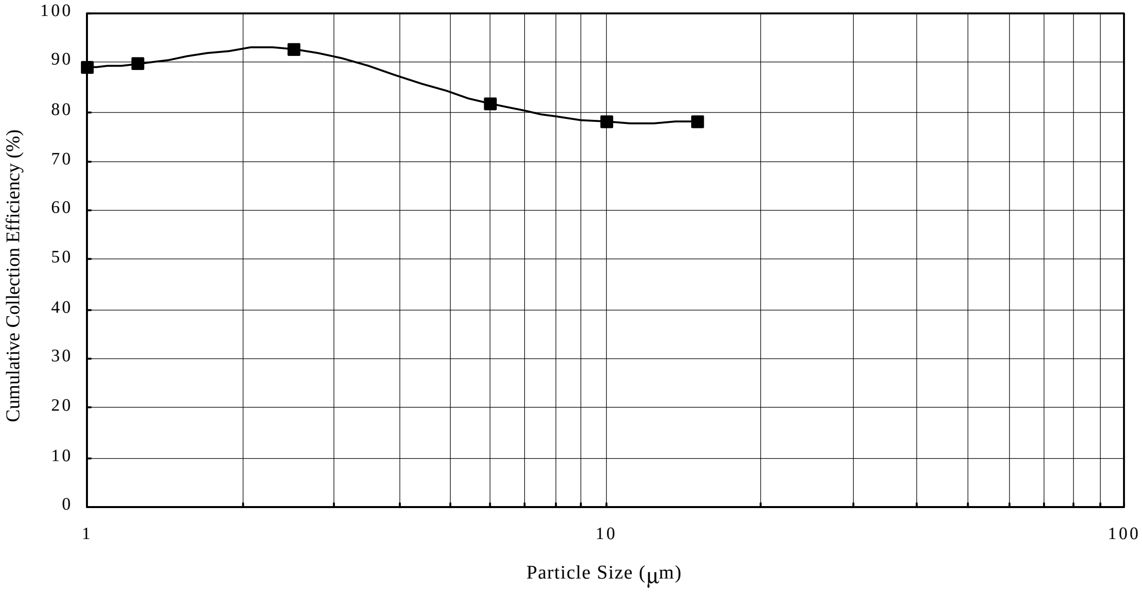
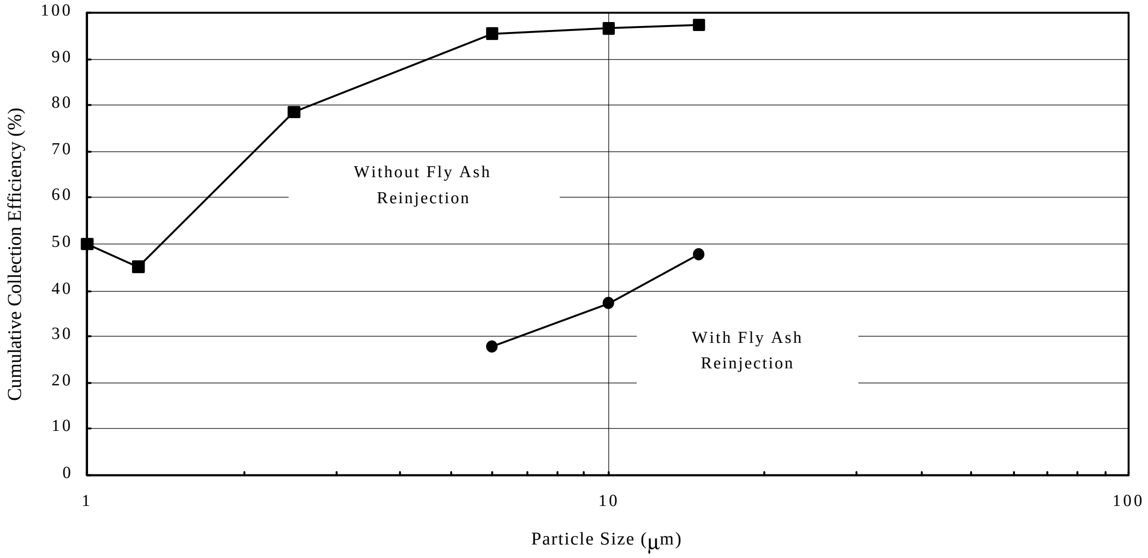


Figure 5.1-16. Cumulative Collection Efficiency Data for Multiple Cyclones at a Residual Oil-Fired Boiler (Reference 5).

### 5.1.3 Applicability

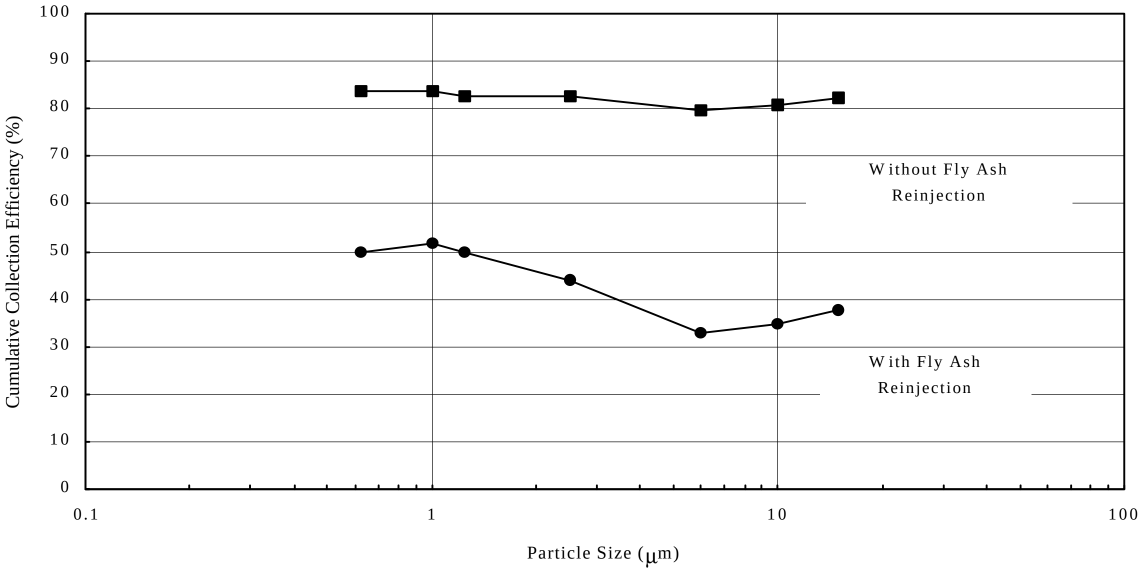
Mechanical precollectors have very few limitations in their application as precollectors, although they are not generally used where there is no coarse PM. Mechanical precollectors can be used to treat small and large flow rates and remove a wide range of particle sizes. Mechanical collectors are simple in design and inexpensive to purchase and operate. In addition, their use will reduce the particulate loading on primary collection devices which will extend operating life.[2]

The vast majority of dusts are suitable for collection in mechanical precollectors. One exception may be sticky dusts, which can clog cyclones. In addition, mechanical precollectors would not be effective for gas streams where the bulk of the PM is small (<3 $\mu$m). Mechanical collectors can be constructed out of various materials and are capable of operating under any conditions which the construction materials allow. Typically, any industry which uses large and relatively expensive control devices, such as a fabric filters or electrostatic precipitators (ESPs), will also employ mechanical precollectors. Multiple cyclones are the most common device for industrial applications, especially for boilers and other combustion units that generate smaller particles. Some industries also use mechanical collectors for product or catalyst recovery, since these collectors are nondestructive and allow reuse or sale of the recovered material.[2]



Coal (Spreader Stoker)

Figure 5.1-17. Cumulative Collection Efficiency Data for Multiple Cyclones at Coal and Wood



Wood Bark

Bark Boilers, With and Without Fly Ash Reinjection (Reference 5).

### 5.1.4 Costs of Precollectors

The costs of installing and operating a mechanical pre-collector include both capital and annual costs. Capital costs are all of the initial costs related to collector equipment and installation. Annual costs are the direct yearly costs of operating the device, plus indirect costs such as overhead; capital recovery; and taxes, insurance, and administrative charges. The following sections discuss capital and annual costs for mechanical collectors, referenced to the third quarter of 1995 unless otherwise noted. Since cyclones are the most common and generally most effective mechanical precollectors for industrial applications, this section will focus only on the costs of these devices.

#### 5.1.4.1 Capital Costs of Cyclones

The total capital investment (TCI) for cyclones includes all of the initial capital costs, both direct and indirect. Direct capital costs are the purchased equipment costs (PEC), and the costs of installation (supports, etc.). Indirect costs are related to the installation and include engineering, construction, contractors, start-up, testing, and contingencies. The PEC is calculated based on the cyclone specifications. The direct and indirect installation costs are calculated as factors of the PEC. For cyclones, installation costs are generally low, with the combination of direct and indirect costs assumed to be about 25 percent of the PEC. Hence, the TCI for cyclones is typically calculated as 1.25 times the PEC.[20]

The most important parameter for sizing cyclones is the inlet duct area (A), which can be calculated from the following equations:[19]

$$A = Q/V_i \qquad \text{(Eq. 5.1-6)}$$

$$A = (Q(\rho_p - \rho_g)/\mu)^{1.33}\, d_c^{2.67} \qquad \text{(Eq. 5.1-7)}$$

where A is the cyclone inlet duct area (ft$^2$), $Q$ is the cyclone gas flow rate (ACFM), $V_i$ is the cyclone inlet duct velocity (ft/min), $\rho_p$ is the particle density (lb/ft$^3$), $\rho_g$ is the gas density (lb/ft$^3$), $\mu$ is the gas viscosity (lb/ft-sec), and $d_c$ is the critical particle size ($\mu$m).

By selecting an inlet duct gas velocity ($V_i$) for Equation 5.1-2, the inlet duct area can be determined and Equation 5.1-3 can be solved for the critical particle size ($d_c$). The critical particle size is defined for this equation as the smallest particle that the cyclone can collect with 100 percent efficiency. Similarly, the inlet duct gas velocity can be calculated for a given critical particle size.[19]

Cyclone costs are based on the inlet duct area, and include the cyclone, fan, motor, supports, hopper (or drum), and rotary air lock. Figure 5.1-18 presents a cost curve for cyclones

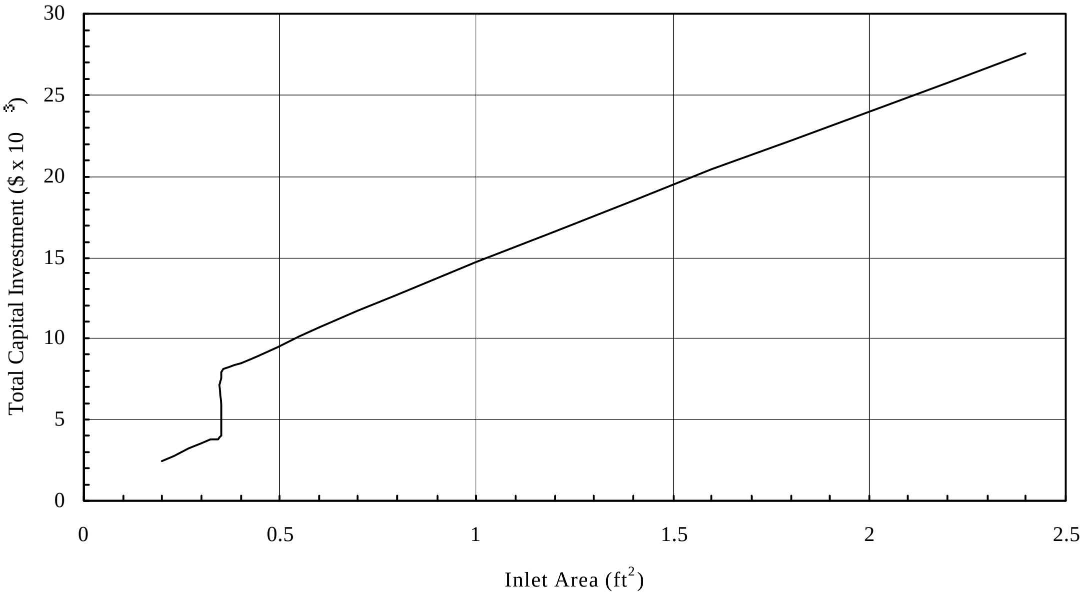


Figure 5.1-18. Total Capital Investment vs. Inlet Duct Area for $0.2\ ft^2$ < Duct Area < $2.64\ ft^2$ (Reference 19).

with inlet duct areas between 0.2 and 2.64 $ft^2$. The step in this curve at 0.35 $ft^2$ is a result of the fact that cyclones with inlet duct areas less than 0.35 $ft^2$ do not require air locks, which are dampers that prevent the gas in the cyclone from entering the dust hopper during dust removal.[19] For cyclones with required total inlet duct areas greater than 2.64 $ft^2$, the total inlet duct area must be divided equally between 2 or more cyclones, each with inlet duct areas less than 2.64 $ft^2$.

Figure 5.1-19 provides a cost curve for cyclones with total inlet duct areas greater than 2.64 $ft^2$.[19] The steps in this curve indicate the flow rates at which an additional cyclone becomes necessary. The step function approximates a straight line. The cost curves in this document are for carbon steel cyclones, other materials may increase costs.[20]

Capital costs obtained from this document can be escalated to more current values through the use of the Vatavuk Air Pollution Control Cost Indexes (VAPCCI), which are published monthly and updated quarterly in *Chemical Engineering* magazine. The VAPCCI updates the PEC and, since capital costs are based only on the PEC, capital costs can be easily adjusted using the VAPCCI. To escalate capital costs from one year ($Cost_{old}$) to another more recent year ($Cost_{new}$), a simple proportion can be used, as follows:[21]

$$Cost_{new} = Cost_{old}(VAPCCI_{new}/VAPCCI_{old}) \qquad \text{(Eq. 5.1-8)}$$

The VAPCCI for mechanical collectors from fourth quarter 1996 was 103.3.

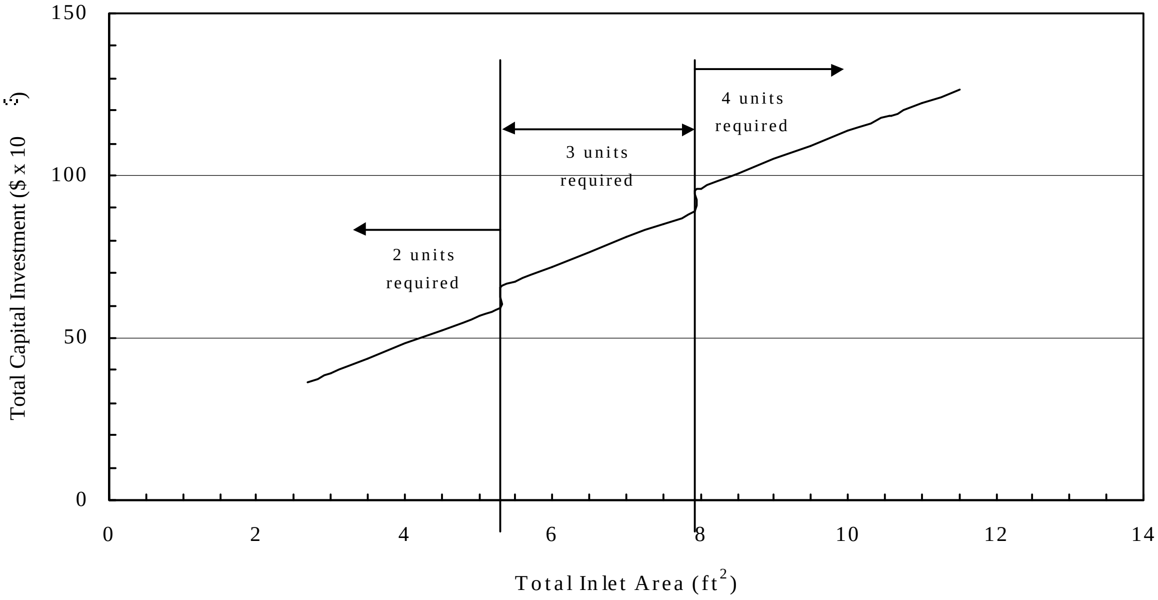


Figure 5.1-19. Total Capital Investment vs. Inlet Duct Area for Duct Area > 2.64 $ft^2$ (Reference 19).

### 5.1.4.2 Annual Costs of Cyclones

The total annual costs for a cyclone consist of both direct and indirect costs. Direct annual costs are those associated with the operation and maintenance of the cyclone. These include maintenance labor, maintenance materials, electricity, and dust disposal. Typical nonhazardous dust disposal costs are \$20-\$30/ton, excluding transportation costs. Hazardous dusts can cost ten times as much to dispose of.[22] Cyclones are assumed to have no need for operator and supervisor labor.[20]

The indirect annual costs for cyclones include taxes, insurance, administrative costs, overhead, and capital recovery. All of these costs but overhead are dependent on the TCI. Table 5.1-2 provides the parameters which impact annual costs and estimates of typical values. Table 5.1-3 provides the annual cost factors for cyclones.[20] Annual costs are very site-specific and, therefore, difficult to generalize.

Table 5.1-2. Annual Cost Parameters for Cyclones (Reference 9).

| Parameter | Description | Typical Values |
|---|---|---|
| Direct Cost Parameters | | |
| Operating factor (OF) | Hours of cyclone operation per year | 8,640 hr/yr |
| Maintenance labor rate (MR) | Maintenance labor pay rate | $14.00/hr[b] |
| Maintenance shift (MS) factor | Fraction of maintenance shift on cyclone | 0.25[b] |
| Maintenance materials factor (MF) | Fraction of maintenance labor cost | 1.0[b] |
| Electricity rate (ER) | Cost of electricity | $0.07/kW-hr[a] |
| Dust disposal cost (DC) | Cost of dust disposal | $20-$30/ton[a] |
| Indirect Cost Parameters | | |
| Overhead factor (OV) | Fraction of total labor and (MM) costs | 0.60[b] |
| Annual interest rate (I) | Opportunity cost of the capital | 7 percent[b] |
| Operating life (n) | Expected operating life of cyclone | 20 years[b] |
| Capital recovery factor (CRF) | Function of (n) and (I) | 0.0944[c] |
| Taxes (TAX) | Fraction of the TCI[d] | 0.01[b] |
| Insurance (INS) | Fraction of the TCI[d] | 0.01[b] |
| Administrative costs (AC) | Fraction of the TCI[d] | 0.02[b] |

[a] Estimated for 1996 from currently available information.

[b] Estimates from "CO$T-AIR" Control Cost Spreadsheets (Reference 20).

[c] Capital Recovery Factor is calculated from the following formula: $CRF = \{I(1 + I)^n\} \div \{(1 + I)^n - 1\}$, where $I$ = interest rate (fraction) and $n$ = operating life (years).

[d] The total capital investment (TCI) can be escalated to current values by using the Vatavuk Air Pollution Control Cost Indexes (VAPCCI), described in Section 5.1.4.1.

Table 5.1-3. Annual Cost Factors for Cyclones (Reference 20).

| Cost Item | Formula | Factor |
|---|---|---|
| Direct Costs | | |
| Maintenance labor (ML) | (OF)×(MR)×(MS) | A |
| Maintenance materials (MM) | (MF)×(ML) | A |
| Electricity (E) | Fan Power × (ER) | E |
| Dust disposal (D) | (DC) × Tons per year | D |
| Total Direct Cost (DC) | | 2 A + E + D |
| Indirect Costs | | |
| Overhead | (OV)×(ML+MM) | 1.2 A |
| Capital Recovery | (CRF)×(TCI) | 0.0944 TCI |
| Taxes | (TAX)×(TCI) | 0.01 TCI |
| Insurance | (INS)×(TCI) | 0.01 TCI |
| Administrative Costs | (AC)×(TCI) | 0.02 TCI |
| Total Indirect Cost (IC) | | 1.2 A + 0.1344 TCI |
| Total Annual Cost (DC + IC) | | 3.2 A + 0.1344 TCI + E + D |

Note: These values are also described in Table 5.1-2.

### 5.1.5 Energy and Other Secondary Environmental Impacts of Precollectors

The secondary environmental impacts of cyclone operation are related to energy consumption and solid waste generation. The energy demands for cyclones consist of electricity requirements for fan operation. The fan power needed for a specific cyclone is dependent on the pressure drop and can be estimated with the following equations:[19]

$$\Delta P = 2.36 \times 10^{-7}(V_i^2) \qquad \text{(Eq. 5.1-9)}$$

$$\text{Fan Power (kW-hr/yr)} = 1.81 \times 10^{-4}(Q)(\Delta P)(t) \qquad \text{(Eq. 5.1-10)}$$

where $\Delta P$ is the cyclone pressure drop (in. water), $V_i$ is the inlet duct gas velocity (ft/min), $Q$ is the gas flow rate (ACFM), and $t$ is the operating time (hr/yr).

Dust which is collected in mechanical collectors may be sold or recycled if it has intrinsic value or can be recycled by use in other materials, such as concrete. Otherwise, the fly ash must be disposed. Most inert, nonhazardous dusts can be landfilled. Dusts which are hazardous or reactive will typically require treatment or disposal in a secure landfill.

### 5.1.6 Flue Gas Conditioning

Gas conditioning is used to modify the characteristics of the gas stream and particles to enhance particle removal in the primary collection device. Flue gas conditioning at coal fired power plants is the most widespread application of this practice. Usually, flue gas conditioning involves the use of chemicals that are added to the gas stream to improve the fly ash properties and electrical conditions in electrostatic precipitators. See Section 5.2 for a detailed discussion of ESP operation. Fabric filter and scrubber performance is far less dependent on the chemical composition of the gas and particles, so these devices typically do not employ chemical conditioning for particle removal. Any gas conditioning for fabric filters or scrubbers usually consists of controlling the temperature and moisture of the gas stream. Therefore, this section will only discuss flue gas conditioning for ESPs.

Flue gas conditioning is most often used to retrofit ESP's which are not operating up to the design efficiency. This often occurs as a result of switching to low-sulfur coal,[1,11] which produces a high resistivity fly ash that is difficult to collect in an ESP. Collection efficiency of an ESP is dependent on the electric field strength and ion density; the adhesive and cohesive properties of the fly ash; and the particle size and size distribution. Flue gas conditioning can influence all of these parameters.[23] Conditioning agents can improve ESP collection efficiency with one or more of the following mechanisms:[23]

- Adsorb on surface of fly ash and reduce surface resistivity
- Adsorb on fly ash and change adhesion/cohesion properties
- Increase ultrafine particle concentration for space charge improvement

- Increase sparkover voltage of flue gas (reduce back corona)
- Increase mean particle size
- Decrease acid dew point in flue gas

Common conditioning agents include sulfur trioxide ($SO_3$), ammonia, ammonium compounds, organic amines, and dry alkalis.[11]

The effect of flue gas conditioning on collection efficiency is difficult to quantify because it differs greatly between applications. In some cases, a small dose of conditioning agent will provide a significant improvement in collection efficiency while subsequently larger doses show little additional improvement. Other users have reported steady increases in collection efficiency with increasing doses.[23] In *Flue Gas Conditioning* (Reference 23), a variety of $SO_3$ conditioning users reported increases in collection efficiency ranging from 1.7 percent up to 18 percent with $SO_3$ doses ranging from 5 ppmv to 64 ppmv.[23]

### 5.1.6.1 Sulfur Trioxide Conditioning

The most commonly used flue gas conditioning agent for power plants in the U.S. is $SO_3$. Sulfur trioxide is injected into the gas stream after the air preheater, which is a heat exchanger that uses the hot flue gases to preheat the combustion intake air. Sulfuric acid is actually the active agent in conditioning. Virtually all of the $SO_3$ is hydrated to sulfuric acid at the temperature and humidity of the flue gas stream. Sulfuric acid has a strong affinity for water and readily dissociates to two hydrogen ions and one sulfate ion in solution. This property makes the solution highly conductive. Sulfuric acid also has a low vapor pressure; as a result, sulfuric acid will not easily vaporize, even from a concentrated solution to a dilute vapor phase. This combination of low volatility and high conductivity make sulfuric acid very effective at lowering the resistivity of fly ash.[11,23]

Sulfuric acid reduces the resistivity of particles in ESP's by establishing a layer of conductive solution on the particle surface through adsorption and/or condensation of sulfuric acid and water. A layer of acid solution also forms on particles which have already been collected on the collection plate.[11,23]

Sulfur trioxide used for gas conditioning is commonly generated by one of the following four methods: 1) vaporization of sulfuric acid solution, 2) vaporization of liquid $SO_3$, 3) vaporization of liquid sulfur dioxide ($SO_2$) and subsequent catalytic oxidation to $SO_3$, and 4) combustion of liquid sulfur in air to produce $SO_2$ with subsequent oxidation to $SO_3$. Methods 3 and 4 are the most reliable, with method 3 the most economical.[11,23]

A typical dosage of $SO_3$ ranges from 5 to 30 ppmv, though the dose may be as high as 70 ppmv. A dosage of 20 ppmv can decrease fly ash resistivity by two orders of magnitude.[11,23]

The flue gas temperature and PM composition of the gas stream determine how effective $SO_3$/sulfuric acid will be in reducing resistivity. At high temperatures (>200°C), sulfuric acid is less effective for two reasons. First, temperatures above the acid dew point prevent sulfuric acid from adsorbing or condensing in appreciable quantities on the particles. Second, volume conduction through the bulk of the particles becomes dominant over surface conduction at high temperatures. A conductive layer of sulfuric acid will only improve surface conduction. If the PM includes a large amount of alkaline compounds, the PM will react with the acid to form a nonconductive layer of salts. A higher dosage of $SO_3$ will provide excess acid to adsorb or condense on top of the salt layer.[11,23]

Users of $SO_3$ conditioning have reported problems with corrosion, catalyst deactivation, and over conditioning. At temperatures below the acid dew point, sulfuric acid will condense in the pipes leading to the injection nozzles. This can lead to corrosion and clogging of the lines. Installations that rely on catalytic oxidation of sulfur dioxide to produce $SO_3$ have found it necessary to replace the catalyst approximately once a year. Conditioning with excessive doses of sulfuric acid can also over-condition the ash. In such cases, the resistivity becomes too low and particles are easily reentrained. In addition, the acid can form a solution which binds particles to the plates, making them difficult to remove with normal rapping.[11,23]

### 5.1.6.2 Ammonia Conditioning

Ammonia conditioning has been shown to be an effective gas conditioning agent for ESPs operating with low sulfur coals. In Australia, ammonia is the most popular ESP conditioning agent, because Australian coal produces ash with very high resistivity. In the U.S., ammonia conditioning has become important with the increased use of low sulfur coals, that are being used to offset the generation of acid rain precursors, like $SO_2$.[11,23]
Ammonia is also being used to optimize the operation of fabric filters.[24] Both of these applications are discussed below.

Ammonia Conditioning in ESPs. In an ESP, ammonia can be injected either as a vapor or in solution before or after the air preheater. While the conditioning mechanisms of ammonia have not been fully explained, two distinct effects have been reported. The first effect is the enhancement of the space charge in the ESP. The ammonia reacts with sulfuric acid vapor in the flue gas and forms a fume of fine ammonium salt particles. The fine particles increase the resistivity of the gas phase in the interelectrode space. The increased gas resistivity increases the voltage drop and the field strength between the electrodes, allowing for operation at higher voltages. The second effect is an increase in the cohesiveness of the particles. Condensation of sulfuric acid in the presence of ammonium salts contributes to the adsorption of acid and salts to water on the surface of particles. The layer of surface deposits is very sticky and increases the cohesive force between particles on the collection plate, reducing reentrainment.[11,23]

The effects of ammonia on resistivity are not entirely clear. Evidence has shown that fly ash conditioned with ammonia may have resistivity that is less than, the same as, or greater than unconditioned ash. Ammonia conditioning is very sensitive to temperature, and is more effective at low temperatures (<110°C). Ammonia conditioning has generally been shown to increase collection efficiency; however, the increase in ESP efficiency does not necessarily correlate with a decrease in fly ash resistivity. Users of ammonia have reported problems with plugging of nozzles and build-up of deposits on the discharge electrodes.[11,23]

Ammonia Conditioning in Fabric Filters.[24] Ammonia additions to flue gas containing $SO_3$ produces ammonium sulfate compounds. These byproducts have been found to increase ash cohesivity, thereby reducing PM emissions during the cleaning cycle of fabric filters. The presence of ammonium sulfate compounds also produces a higher porosity dust cake that results in a lower pressure drop in the fabric filter. In addition, ammonia conditioning reduces the corrosion and bag failure that results with $SO_3$ condensation.

### 5.1.6.3 Ammonium Compound Conditioning

Ammonium compounds provide a more convenient method of conditioning with ammonia. Sulfamic acid ($NH_3SO_2OH$), ammonium sulfate [$(NH_4)_2SO_4$], and ammonium bisulfate ($NH_4HSO_4$) are the most common ammonium compounds for conditioning. Several proprietary conditioning agents also contain ammonium compounds. These compounds can dissociate into ammonia and sulfuric acid in the gas stream, and may provide the effects of both ammonia and sulfuric acid (from $SO_3$) conditioning. Ammonium compounds can be introduced upstream or downstream of the air preheater.[11,23]

Ammonium compounds can enhance ESP performance by decreasing particle resistivity, increasing space charge, and/or increasing particle cohesion. Particle resistivity can be reduced by ammonium sulfate and ammonium bisulfate. Both compounds behave like sulfuric acid, forming a layer of conductive solution on the surface of the collected fly ash.
The sulfuric acid and ammonia formed when ammonium compounds decompose can react to form fine salt particles which increase the space charge. These particles increase the gas resistivity, which increases the voltage drop between the electrodes and allows for ESP operation at higher applied voltage. The cohesion of the particles is also increased, which increases collection efficiency, through condensation of sulfuric acid and through the adsorption of compounds that form a viscous, sticky layer on the particles.[11,23]

Ammonium sulfate, ammonium bisulfate, and sulfamic acid are effective in reducing ash resistivity because they can form a layer of conductive solution on the particles or decompose into $SO_3$. Ammonium compounds can reduce resistivity by approximately a factor of 5. While ammonium compounds are effective in reducing resistivity, they are not as effective as $SO_3$. Problems of plugging in the air preheater have been reported when the agents are injected prior to the preheater.[11,23]

Apollo LPA-445, a proprietary conditioning agent containing ammonium compounds, effectively increases ash cohesiveness. Apollo LPA-445 has also demonstrated that it increases the number of fine particles when used as a conditioning agent. Space charge increases with an increase in fine particles.[11,23]

### 5.1.6.4 Organic Amine Conditioning

Research on organic amines as conditioning agents has been conducted in laboratories and pilot-scale ESP's. Of all the amines, triethylamine [$N(C_2H_5)_3$] has been studied most extensively. Triethylamine is an organic nitrogen compound which behaves similar to ammonia, but is a stronger base than ammonia. The conditioning mechanism for triethylamine is not completely understood, but it appears to also reduce the fly ash resistivity by forming a conductive layer on the surface of the fly ash.[11,23]

A dose of 60 ppm triethylamine has been demonstrated to reduce ash resistivity from $3 \times 10^9$ ohm-m to $5 \times 10^7$ ohm-m in a pilot scale boiler. A laboratory study has shown resistivity reductions of 1 to 2 orders of magnitude for a 25 ppm dose at temperatures of 102°C to 150°C. Triethylamine is more effective with lower temperatures, less basic ash, and higher doses of the agent.[11,23]

### 5.1.6.5 Alkali Conditioning

Many coals from the western U.S. produce fly ash with high resistivity when combusted. It has been determined that the fly ash has low alkali content. Fly ash resistivity has been found to be inversely proportional to the concentration of lithium and sodium in the ash. Hence, alkali conditioning is used to reduce resistivity by increasing alkali concentration in the ash. Sodium compounds are the most widely used conditioning agents. Sodium sulfate and sodium carbonate are commonly used. Sodium chloride has shown to be effective in laboratory tests, but it is not used industrially because of its potential for corrosion.[11,23]

Sodium compounds can reduce resistivity in two ways. The compound can be injected prior to the ESP and collected with the fly ash. In this case, the sodium compound mixes with the ash and serves as a conductive medium. It also reduces the resistivity of the layer of dust which collects on the plates. The second means of reducing fly ash resistivity is unique to alkali conditioning. Sodium compounds can be injected into the boiler and combusted with the coal. In this method, the sodium is bound to the fly ash and reduces resistivity as the presence of natural sodium would.[11,23]

Compounds of sodium are effective at reducing the resistivity of fly ash if the sodium and ash are well mixed. A 1.0 to 1.5 percent concentration of sodium carbonate has been demonstrated to reduce resistivity from $2.1 \times 10^{10}$ to $3.7 \times 10^9$ in a pilot scale ESP. Ash resistivity reductions of two orders of magnitude have been reported from field tests. Problems with boiler fouling may occur when sodium compounds are introduced to the coal prior to combustion.[11,23]

### 5.1.7 Costs of Flue Gas Conditioning

Costs of flue gas conditioning vary with the size of the power plant and the type of conditioning installed. There are also several site specific factors which will influence flue gas conditioning costs, such as the sulfur content of the fuel, fly ash resistivity, and the initial collection efficiency of the ESP prior to flue gas conditioning. Table 5.1-4 provides estimates of capital and annual costs for flue gas conditioning at electric utility plants.[23,25] The cost data in Table 5.1-4 has been escalated to February 1996 where possible through the use of *Chemical Engineering* magazine's "Plant Cost Index."[26] No cost data were available for ammonium compounds and organic amines; this is probably due to the limited industrial experience with these conditioning agents.[11,23]

### 5.1.8 Energy and Other Secondary Environmental Impacts of Flue Gas Conditioning

Flue gas conditioning can lead to air emissions from compounds formed by the conditioning agents.[11,23] No energy impacts, however, are associated with flue gas conditioning.

Sulfur trioxide conditioning can lead to emissions of sulfuric acid mist and particulate sulfate compounds caused by the condensation of acid and formation of sulfate on fly ash particles. The ESP performance, ash composition, and gas temperature effect the emission rates of these compounds.[11,23]

Ammonium sulfate conditioning can result in increased sulfate emissions. Most sulfate particle emissions are smaller than 1 µm. Ammonium phosphates can decompose to form ammonia and either phosphorous pentoxide or condensed phosphates.[11,23]

Although ammonia conditioning in the presence of $SO_3$ forms ammonium bisulfate aerosol, the ammonium bisulfate should be collected by the ESP. A secondary benefit of ammonia conditioning is that large amounts of ammonia will react with nitrogen oxides to form elemental nitrogen.[11,23]

Table 5.1-4. Costs of Flue Gas Conditioning

| Conditioning Agent | Capital Cost ($/kW)[a,c] | Annual Cost (mills/kWh)[a,b] | Comments |
|---|---|---|---|
| Sulfur trioxide | 6.24 | 0.191 | Capital costs developed from 1982 data (Reference 23). Annual costs based on current costs for sulfur ($300/Mg) from Reference 25. |
| Ammonia | 0.25 | 0.024[c] | Capital costs data from Reference 23. Annual costs based on 1996 costs for ammonia ($325/Mg) from Reference 25, and costs for steam ($17.22/Mg) escalated from 1982 data from Reference 23. |
| Alkali | 2.47 - 4.78 | 0.03 | Capital costs from Reference 23. Annual costs based on 1979 data from Reference 23; available information not detailed enough to allow for escalation to current prices. |

[a] Kilowatts of power plant capacity.
[b] 1 mill = $0.001.
[c] Escalated to February 1996 using the *Chemical Engineering* Plant Cost Index (Reference 26).

### 5.1.9 References for Section 5.1

1. Cooper, C.D. and F.C. Alley. *Air Pollution Control: A Design Approach*. Second edition. Waveland Press, Prospect Heights, Illinois. 1994.

2. Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-81-005a; NTIS PB83-127498). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. September 1982.

3. Theodore, L. and A.J. Buonicore. *Air Pollution Control Equipment, Volume I: Particulates*. CRC Press, Boca Raton, Florida. 1988.

4. Perry, R.H. and D.W. Green. *Perry's Chemical Engineers' Handbook*. Sixth edition. McGraw-Hill Publishing Company, New York, New York. 1984.

5. Compilation of Air Pollution Emission Factors (AP-42). Volume I (5th Edition). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. January 1995.

6. *Air Pollution Engineering Manual*. A.J. Buonicore, and W.T. Davis, Eds. Air & Waste Management Association, Pittsburgh, Pennsylvania; and Van Nostrand Reinhold, New York, New York. 1992.

7. Stairmand, C.J. "The Design and Performance of Cyclone Separators." Trans. Ind. Chem. Eng. 29. 1951.

8. Swift, P. "Dust Control in Industry." Steam Heating Engineering. 38. 1969.

9. Lapple, C.E. "Processes Use Many Collector Types." Chem. Eng. 58:144-151. 1951.

10. Leith, D. and D. Mehta. Atmospheric Environment. 7:527. 1973.

11. The Electrostatic Precipitator Manual (Revised). The McIlvaine Company. Northbrook, Illinois. January 1992.

12. Lapple, L.E. Industrial Hygiene Quarterly. 11:40. 1950.

13. Leith, D. and W. Licht. AIChE Symposium Series. 68:196. 1972.

14. Iozia, D.L. and D. Leith. "Effect of Cyclone Dimensions on Gas Flow Pattern." Aerosol Science and Technology. 10(3):491-500. 1989.

15. Iozia, D.L. and D. Leith. "The Logistic Equation and Cyclone Fractional Efficiency." Aerosol Science and Technology. 13(1). 1990.

16. Friedlander, S.K, L. Silverman, P. Drinker, and M.W. First. *Handbook on Air Cleaning*. USAEC (AECD-3361, NYO-1572), Washington, DC. 1952.

17. Iozia, D.L. and D. Leith. "Optimizing Cyclone Design and Performance." Filtration and Separation. 24(4):272-274. 1989.

18. Leith, D. and D.L. Jones. Chapter 15: "Cyclones," in Handbook of Powder Science and Technology, M.E. Fayed and L. Otten, Eds. Chapman and Hall, New York, New York. 1997.

19. Vatavuk, W.M. *Estimating Costs of Air Pollution Control*. Lewis Publishers, Chelsea, Michigan. 1990.

20. Vatavuk, W.M. "CO$T-AIR" Control Cost Spreadsheets. Innovative Strategies and Economics Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, North Carolina. February 1996.

21. Vatavuk, W.M. "Escalate Equipment Costs." Chemical Engineering. December 1995.

22. OAQPS Control Cost Manual (Fourth Edition, EPA 450/3-90-006) U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. January 1990.

23. Flue Gas Conditioning (EPA-600/7-85-005, NTIS PB85-173912). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. February 1985.

24. Oglesby, S., Jr. Future Directions of Particulate Control Technology: A Perspective. J. Air Waste Management Assoc. 40(8): 1184-1185. August 1990.

25. "Chemical Prices." Chemical Marketing Reporter. 250:7. August 12, 1996.

26. "Plant Cost Index." Chemical Engineering. July 1996.

## 5.2 ELECTROSTATIC PRECIPITATORS

This section discusses the basic operating principles, typical designs, industrial applications, and costs of electrostatic precipitators (ESPs). Collection of particles by electrostatic precipitation involves the ionization of the stream passing though the ESP, the charging, migration, and collection of particles on oppositely charged surfaces, and the removal of particles from the collection surfaces. In dry ESPs the particulate is removed by rappers which vibrate the collection surface. Wet ESPs use water to rinse the particles off.

Electrostatic precipitators have several advantages when compared with other control devices. They are very efficient collectors, even for small particles. Because the collection forces act only on the particles, ESPs can treat large volumes of gas with low pressure drops. They can collect dry materials, fumes, or mists. Electrostatic precipitators can also operate over a wide range of temperatures and generally have low operating costs. Possible disadvantages of ESPs include high capital costs, large space requirements, inflexibility with regard to operating conditions, and difficulty in controlling particles with high resistivity.[1]
Disadvantages of ESPs can be controlled with proper design.

### 5.2.1 Particle Collection

Particle collection during electrostatic precipitation is the end result of several steps. These steps include the establishment of an electric field, corona generation, gas stream ionization, particulate charging, and migration to the collection electrode. One typical ESP arrangement is shown in Figure 5.2-1.[2] In this illustration, the discharge electrode is a weighted wire and the collection electrode is a pipe. A wire-pipe ESP would contain many such wires and pipes.

#### 5.2.1.1 Electric Field

The electric field plays an important role in the precipitation process in that it provides the basis for generation of corona required for charging and the necessary conditions for establishing a force to separate particulate from the gas streams.[2] An electric field is formed from application of high voltage to the ESP discharge electrodes; the strength of this electric field is a critical factor in ESP performance.[3]

The electric field develops in the interelectrode space of an ESP and serves a three-fold purpose. First, the high electric field in the vicinity of the discharge electrode causes the generation of the charging ions in an electrical corona; second, the field provides the driving force that moves these ions to impact with and attach their charge to the particles; and thirdly, it provides the force that drives the charged particulate to the collection electrode for removal from the effluent gas stream.[2]

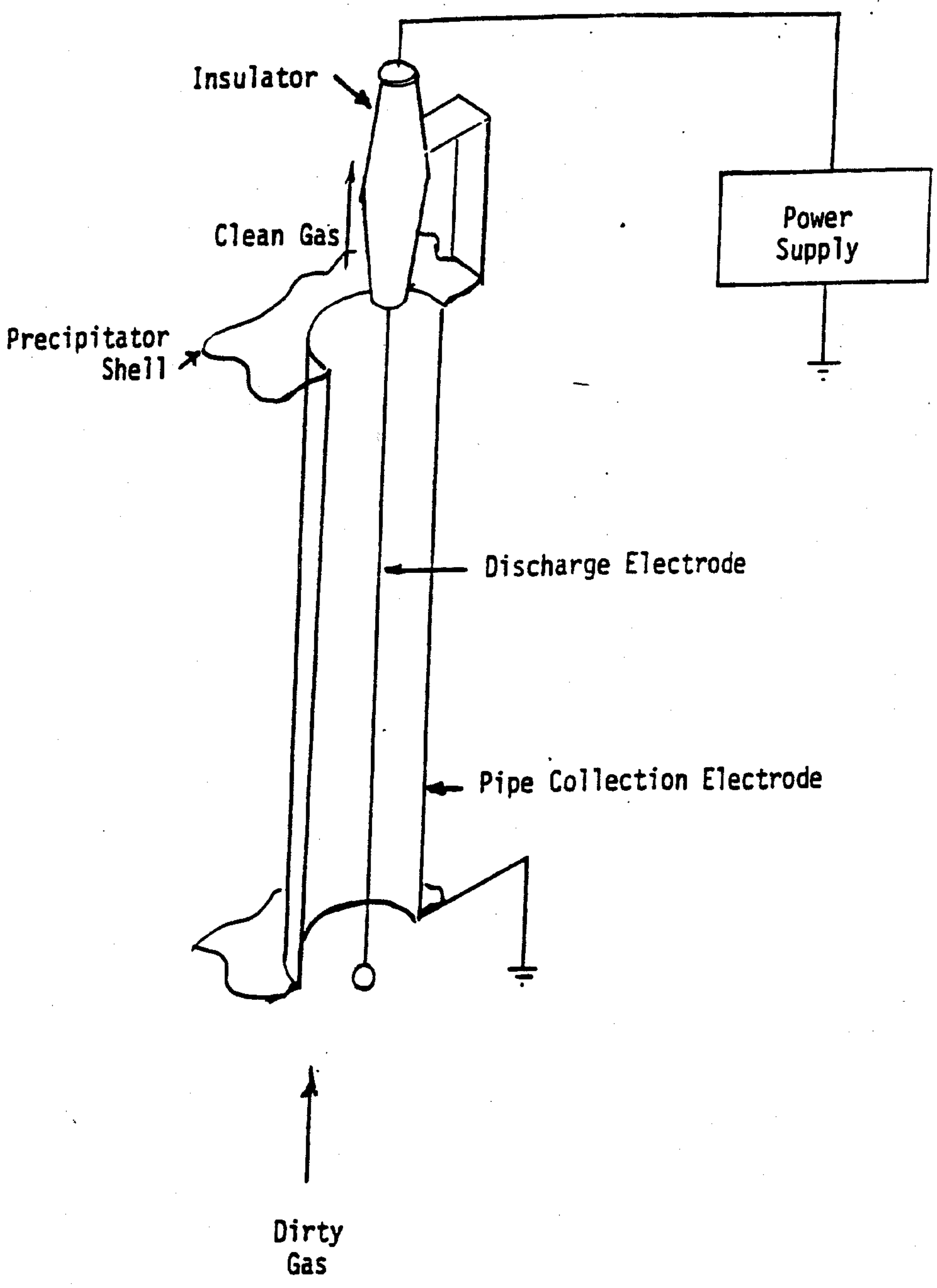


Figure 5.2-1. Cutaway view of Wire-Pipe Electrostatic Precipitator (Reference 2).

The electric field in an ESP is the result of three contributing factors: the electrostatic component resulting from the application of a voltage in a dual electrode system, the component resulting from the space charge from the ions and free electrons, and the component resulting from the charged particulate. Each of these factors may assume a dominant role in the determination of the field in a given set of circumstances. For example, the electric field in the vicinity of the first few feet of the inlet section of an ESP collecting particulate from a heavily particulate-laden gas stream may be dominated by the particle space charge; while the field in the outlet section of a highly efficient ESP is usually dominated by the ionic space charge.[2]

The strength or magnitude of the electric field is an indication of the effectiveness of an ESP.[3] Two factors are critical to the attainable magnitude of the electric field in an ESP. First, the mechanical alignment of the unit is important. If a misalignment occurs in a localized region that results in a close approach between the corona and collection electrodes, the sparking voltage for that entire electrical section will be limited. The second is the resistivity of the collected particulate, which can limit the operating current density and applied voltage that results in a reduced electric field.[2]

### 5.2.1.2 Corona Generation

The corona is the electrically active region of a gas stream, formed by the electric field, where electrons are stripped from neutral gas molecules leaving positive ions. The positive ions are driven in one direction and the free electrons in another. The necessary conditions for corona formation include the presence of an electric field with a magnitude sufficient to accelerate a free electron to an energy required to ionize a neutral gas molecule on impact, and a source of electrons to act as initiating electrons for the process.[2]

Details of electric field generation were discussed above. In terms of electron sources, there is always a supply of free electrons available from the ionization of gas molecules by either cosmic rays, natural radioactivity, photoionization, or the thermal energy of the gas.[2]
The corona is generated by a mechanism which is commonly referred to as electron avalanche. This mechanism occurs when the magnitude of the applied electric field is great enough to accelerate the free electrons. When free electrons attain sufficient velocity, they collide with and ionize neutral gas molecules. Ionization occurs when the force of the collision removes an electron from the gas molecule, resulting in a positively charged gas molecule and another free electron. These newly-freed electrons are also accelerated and cause additional ionization.[2]

The corona can be either positive or negative; but the negative corona is used in most industrial ESPs since it has inherently superior electrical characteristics that enhance collection efficiency under most operating conditions.[3]

### 5.2.1.3 Particle Charging

Particle charging in an ESP (and subsequent collection) takes place in the region between the boundary of the corona glow and the collection electrode, where gas particles are subject to the generation of negative ions from the (negative) corona process.[3]

Upon entering the ESP, the uncharged dust particles suspended in the effluent gas stream are exposed to a region of space filled with ions and, in the case of negative corona, perhaps some free electrons. As these electrical charges approach the electrically neutral dust particles, an induced dipole is established in the particulate matter by the separation of charge within the particles.[2] As a dipole, the particle itself remains neutral while positive and negative charges within the particle concentrate within separate areas. The positive charges within the particle are drawn to the area of the particle closest to the approaching negative ion. As a negative ion contacts the particulate matter, the induced positive charges will retain some electrical charge from the ion. This results in a net negative charge on the previously neutral particulate. The presence of an electrical charge is required in order for the electric field to exert a force on the particle and remove the particulate from the gas stream.[2]

Charging is generally done by both field and diffusion mechanisms. The dominant mechanism varies with particle size. In field charging, ions from the corona are driven onto the particles by the electric field. As the ions continue to impinge on the dust particles, the charge on it increases until the local field developed by the charge on the particle causes a distortion of the electric field lines so that they no longer intercept the particle and no further charging takes place. This is the dominant mechanism for particles larger than about 0.5 µm.[3]

Diffusion charging is associated with ion attachment resulting from random thermal motion; this is the dominant charging mechanism for particles below about 0.2 µm. As with field charging, diffusion charging is influenced by the magnitude of the electric field, since ion movement is governed by electrical as well as diffusional forces. Neglecting electrical forces, diffusion charging results when the thermal motion of molecules causes them to diffuse through the gas and contact the particles. The charging rate decreases as the particle acquires charge and repels additional gas ions, but charging continues to a certain extent.[3]

The particle size range of approximately 0.2 to 0.5 µm is a transitional region in which both charging mechanisms are present but neither dominates. Fractional efficiency test data for ESPs have shown reduced collection efficiency in this transitional size range, where diffusion and field charging overlap.[3]

### 5.2.1.4 Particle Collection

The final step in particle collection in an ESP involves the movement of the charged particles towards an oppositely-charged electrode that holds the particles in place until the electrode is cleaned.  Typically, the collection electrodes are parallel flat plates or pipes that are cylindrical, square, or hexagonal.[2]

The movement of particles toward the collection electrode is driven by the electric field. The motion of larger particles (greater than 10 to 20 $\mu$m) will more or less follow a trajectory determined by the average gas velocity and average particle electrical velocity.[2] The trajectory for smaller particles (<10 $\mu$m) will be less direct, since the inertial effects of the turbulent gas flow predominate over the electrical velocity induced by the relatively smaller electric charge.  The overall movement of smaller particles, however, will be towards the collection electrode.  The cumulative collection efficiency of an ESP is generally dependent upon the fractional collection efficiency of these smaller particles, especially between 0.2 to 2.0 $\mu$m in size.[2]

### 5.2.2 Penetration Mechanisms

There are several conditions which can reduce the effectiveness of ESPs and lead to penetration of particulate.  These conditions include back corona, dust reentrainment, erosion, saltation, and gas sneakage.

#### 5.2.2.1 Back Corona

Back corona or reverse ionization describes the conditions where an electrical breakdown occurs in an ESP.  Normally in an ESP, a corona is formed at the discharge electrode, creating electrons and negative ions which are driven toward the (positive) collection electrode by the electric field.  This situation is reversed if the corona is formed at the (positive) collection electrode.  A corona at this electrode generates positive ions that are projected into the interelectrode space and driven toward the discharge electrode.[2]

As the positive ions flow into the interelectrode space in an ESP, they encounter negatively charged particulate and negative ions.  The electric field from the charged particulate exceeds that of an ion at most distances.  Therefore, the majority of the positive ions flow toward the negatively-charged dust particles, neutralizing their charge.  This neutralization of charge causes a proportionate reduction in the electrical force acting to collect these particles.[2]

A second mechanism by which back corona may be disruptive to ESP collection is due to a neutralization of a portion of the space charge that contributes to the electric field adjacent to the collection electrode.  The space charge component of the electric field near the collection zone may be as much as 50 percent of the total field.  Neutralization of the space charge reduces the total collection force by the same fraction.[2]

#### 5.2.2.2 Dust Reentrainment

Dust reentrainment associated with dry ESP collection may occur after the dust layer is rapped clear of the plates.  The first opportunity for rapping reentrainment occurs when the dust layer begins to fall and break up while falling. Dust particles are swept back into the circulating gas stream. The second opportunity occurs as the dust falls into the hopper, impacts the collected dust, and puffs up to form a dust cloud. Portions of this dust cloud are picked up by the circulating gas stream. Some of the dust may be recollected.[2]

Direct erosion of the collected dust from the collection electrode can occur when gas velocities exceed 10 feet per second (fps). Most ESPs have gas velocities less than 8 fps, while newer installations have velocities less than 4 fps. Saltation is theorized to be a minor form of reentrainment which occurs as particles are collected. As a particle is captured and strikes the collection electrode, it may loosen other particles which are resuspended in the gas stream. Other causes of reentrainment in an ESP are electric sparking, air leakage through the hopper, and electrical reentrainment associated with low resistivity particles.[2]

#### 5.2.2.3 Dust Sneakage

The construction of an ESP is such that nonelectrified regions exist in the top of the ESP where the electrical distribution, plate support, and rapper systems are located. Similarly, portions of the collection hopper and the bottom of the electrode system contain nonelectrified regions. Particle-laden gas streams flowing through these regions will not be subjected to the collection forces and tend to pass through the ESP uncollected. The amount of gas sneakage and bypassing through nonelectrified regions will place an upper limit on the collection efficiency of an ESP.[2]

### 5.2.3 Types of Electrostatic Precipitators

Electrostatic precipitators are generally divided into two broad groups, dry ESPs and wet ESPs. The distinction is based on what method is used to remove particulate from the collection electrodes. In both cases, particulate collection occurs in the same manner. In addition to wet and dry options, there are variations of internal ESP designs available. The two most common designs are wire-plate and wire-pipe collectors. Electrostatic precipitators are often designed with several compartments, to facilitate cleaning and maintenance.

#### 5.2.3.1 Dry ESPs

Dry ESPs remove dust from the collection electrodes by vibrating the electrodes through the use of rappers. Common types of rappers are gravity impact hammers and electric vibrators. For a given ESP, the rapping intensity and frequency must be adjusted to optimize performance. Sonic energy is also used to assist dust removal in some dry ESPs. The main components of dry ESPs are an outside shell to house the unit, high voltage discharge electrodes, grounded collection electrodes, a high voltage source, a rapping system, and hoppers. Dry ESPs can be designed to operate in many different stream conditions, temperatures, and pressures. However, once an ESP is designed and installed, changes in operating conditions are likely to degrade performance.[1,2,3]

### 5.2.3.2 Wet ESPs

The basic components of a wet ESP are the same as those of a dry ESP with the exception that a wet ESP requires a water spray system rather than a system of rappers. Because the dust is removed from a wet ESP in the form of a slurry, hoppers are typically replaced with a drainage system. Wet ESPs have several advantages over dry ESPs. They can adsorb gases, cause some pollutants to condense, are easily integrated with scrubbers, and eliminate reentrainment of captured particles. Wet ESPs are not limited by the resistivity of particles since the humidity in a wet ESP lowers the resistivity of normally high resistivity particles.[2,4]

Previously, the use of wet ESPs was restricted to a few specialized applications. As higher efficiencies have currently become more desirable, wet ESP applications have been increasing. Wet ESPs are limited to operating at stream temperatures under approximately 170°F. In a wet ESP, collected particulate is washed from the collection electrodes with water or another suitable liquid. Some ESP applications require that liquid is sprayed continuously into the gas stream; in other cases, the liquid may be sprayed intermittently. Since the liquid spray saturates the gas stream in a wet ESP, it also provides gas cooling and conditioning. The liquid droplets in the gas stream are collected along with particles and provide another means of rinsing the collection electrodes. Some ESP designs establish a thin film of liquid which continuously rinses the collection electrodes.[2,3]

### 5.2.3.3 Wire-Plate ESPs

Wire-plate ESPs are by far the most common design of an ESP. In a wire-plate ESP, a series of wires are suspended from a frame at the top of the unit. The wires are usually weighted at the bottom to keep them straight. In some designs, a frame is also provided at the bottom of the wires to maintain their spacing. The wires, arranged in rows, act as discharge electrodes and are centered between large parallel plates, which act as collection electrodes. The flow areas between the plates of wire-plate ESPs are called ducts. Duct heights are typically 20 to 45 feet.[2] A typical wire-plate ESP is shown in Figure 5.2-2.[2]

Wire-plate ESPs can be designed for wet or dry cleaning. Most large wire-plate ESPs, which are constructed on-site, are dry. Wet wire-plate ESPs are more common among smaller units that are pre-assembled and packaged for delivery to the site.[4] In a wet wire-plate ESP, the wash system is located above the electrodes.[2]

### 5.2.3.4 Wire-Pipe ESPs

In a wire-pipe ESP, a wire that functions as the discharge electrode runs through the axis of a long pipe, which serves as the collection electrode. The weighted wires are suspended from a frame in the upper part of the ESP. The pipes can be cylindrical, square, or hexagonal. An example of a wire-pipe design is provided in Figure 5.2-3. Previously, only cylindrical pipes were used; square and hexagonal pipes have currently grown in popularity. The space between cylindrical tubes creates a great deal of wasted collection area. Square and hexagonal pipes can be packed closer together, so that the inside wall of one tube is the outside wall of another.[4] This situation is illustrated in Figure 5.2-4.

Wire-pipe collectors are very effective for low gas flow rates and for collecting mists. They can use dry or wet cleaning methods, but the vast majority are cleaned by a liquid wash. As with wire-plate collectors, the cleaning mechanism in a wire-pipe ESP is located above the electrodes. These pipes are generally 6 to 12 inches in diameter and 6 to 15 feet in length.[2]

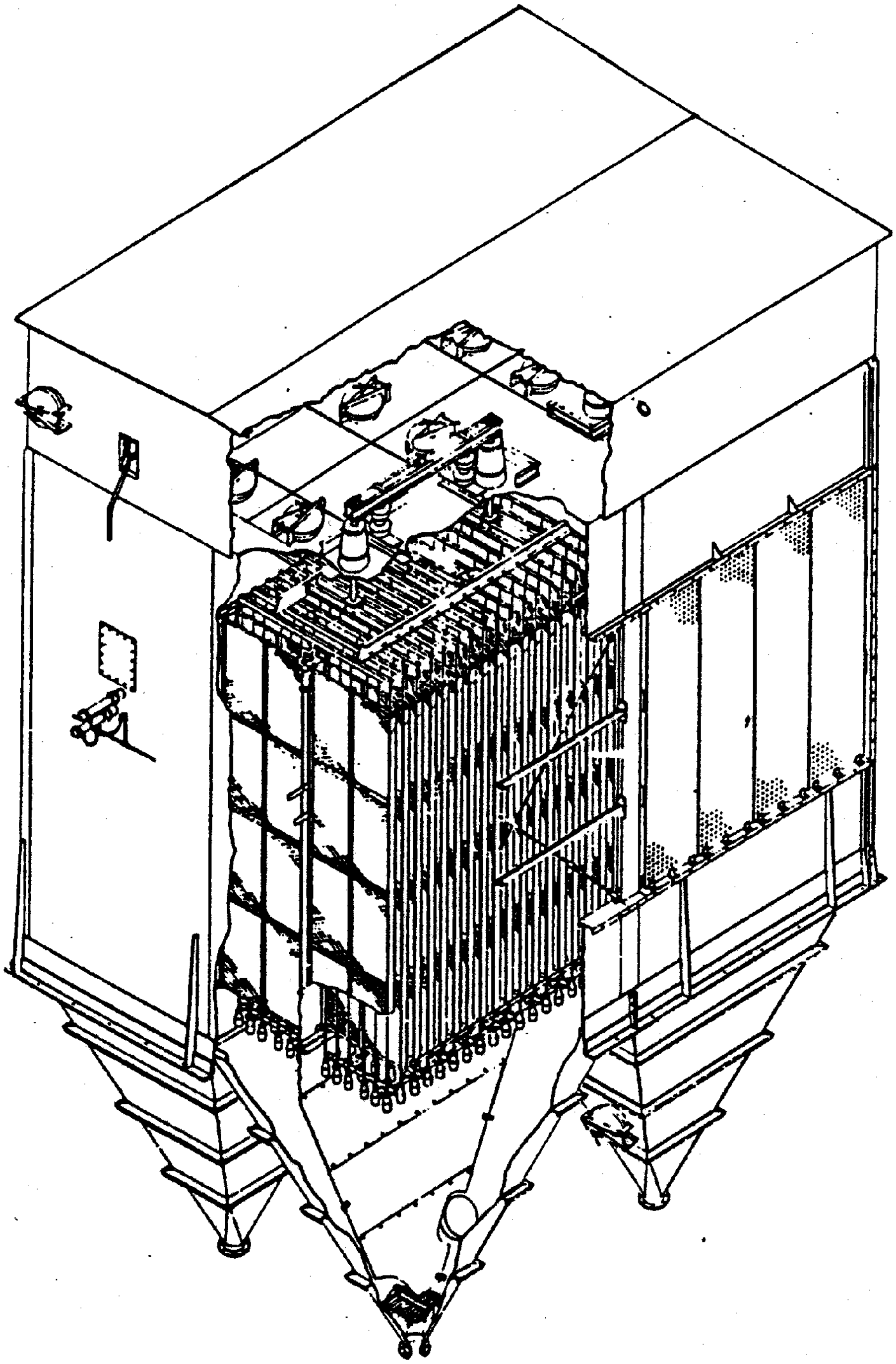


Figure 5.2-2. Wire-Plate Electrostatic Precipitator (Reference 2).

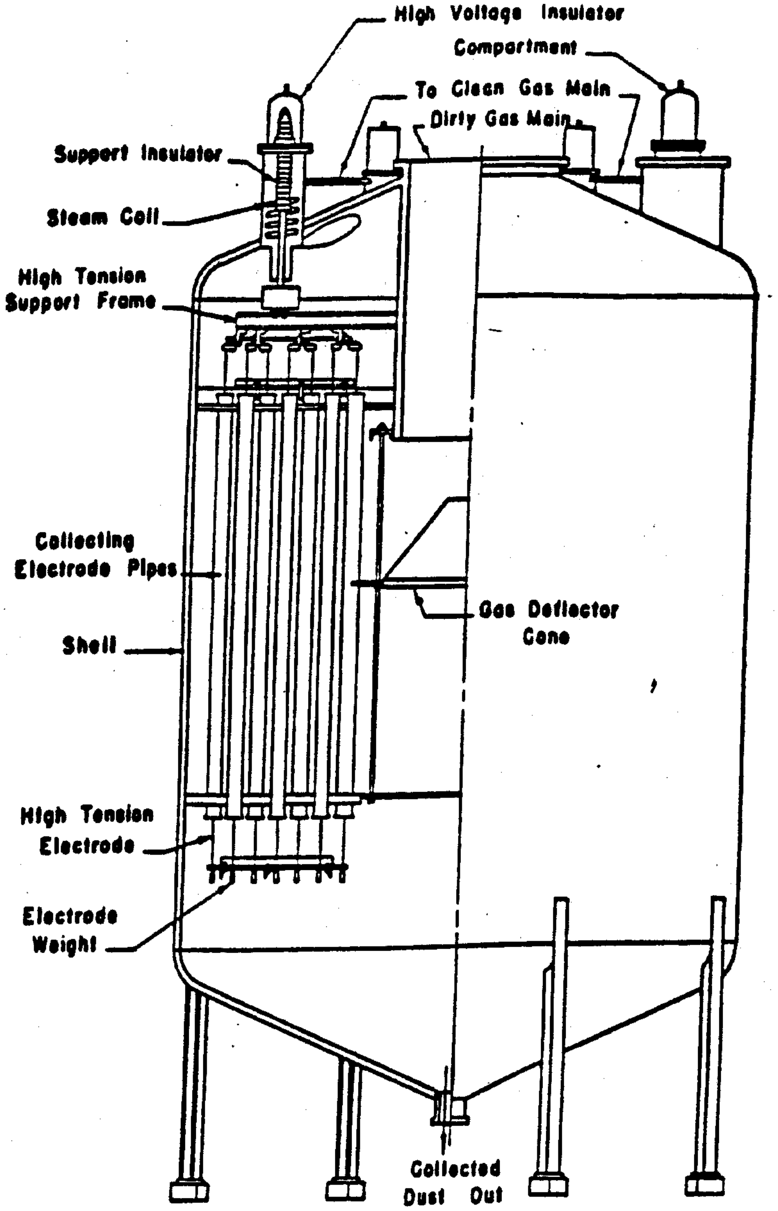


Figure 5.2-3. Wire-Pipe Electrostatic Precipitator (Reference 2).

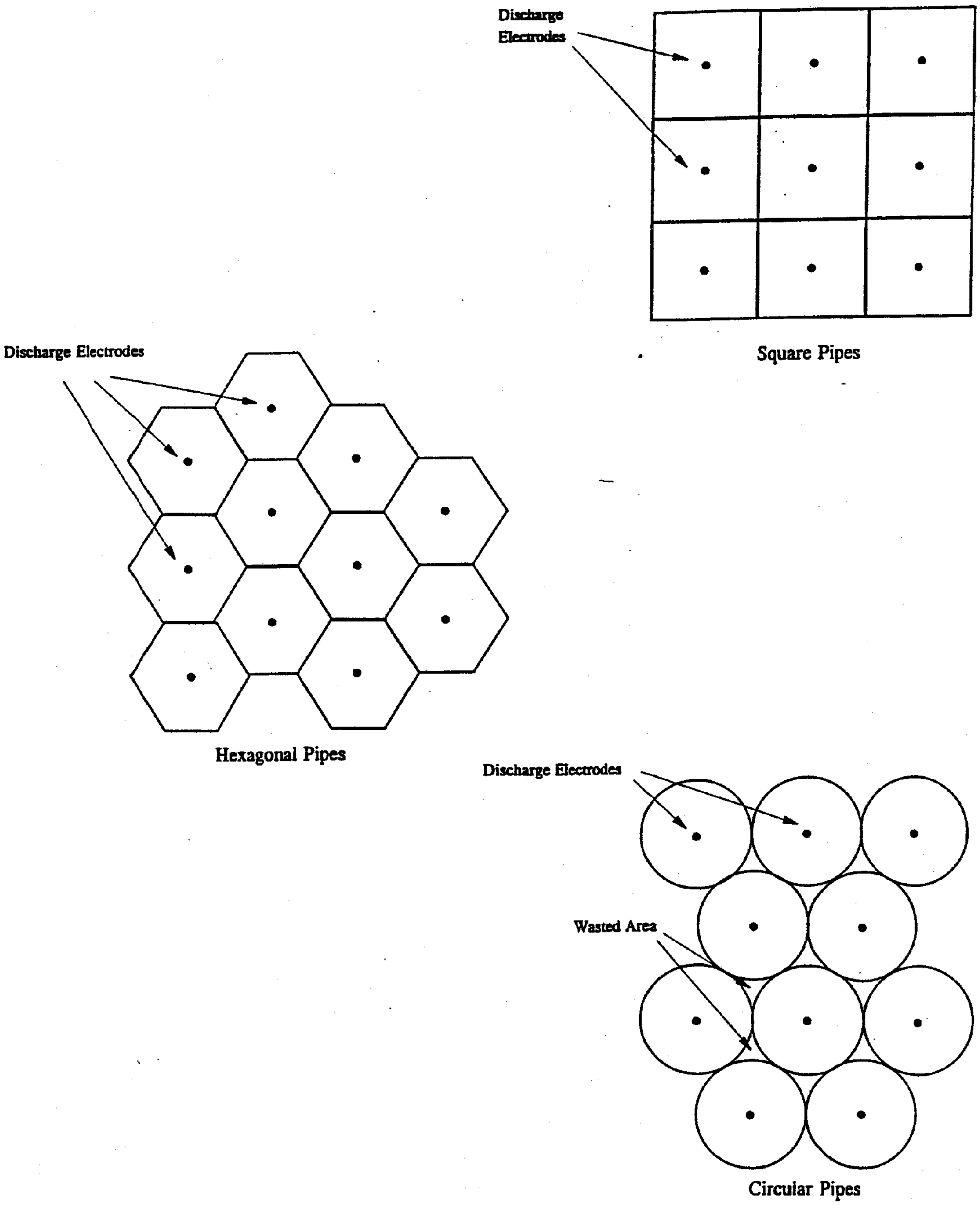


Figure 5.2-4. Square, Hexagonal, and Circular Pipe Arrangements for Wire-Pipe Precipitators (adapted from Reference 4).

### 5.2.3.5 Other ESP Designs

Rigid-Frame Plate. This ESP design is very similar to the wire-plate ESP, with the exception that the discharge electrode is a rigid frame, rather than a series of weighted wires, that is placed between plates. The frame supports wire discharge electrodes. This type of ESP operates in the same manner as the wire-plate and can be wet or dry. In general, the rigid frame design is more durable than weighted wires, but has higher initial (capital) expense.[2,3] Rigid frames have become the preferred design in some industries, such as pulp and paper.[5] Figure 5.2-5 provides an example of a rigid frame-plate ESP.

Wide-Plate Spacing.[6] The flow areas between the plates of a conventional wire-plate ESP usually vary from 8 to 12 inches in width. A recent enhancement in these units has been wide-plate spacings of up to 20 inches. Wide spacing gives a higher collecting field strength due to the resultant increase in space charge, a more uniform current density, and higher migration velocities. More variation in the discharge electrode geometry is also possible with wide-plate spacing. Because of the increased efficiency associated with this technique, less plate area is needed, thereby reducing the overall size and cost of the ESP.[7]

Electrode Variations.[1,2] In addition to the rigid frames, there are several other variations of electrodes that are not as common. In some cases, completely rigid discharge electrodes are preferred over weighted wires or rigid frames with wires.[1] Other discharge electrode designs are square wires, barbed wires, serrated strips of metal, and strips of metal with needles at regular intervals. The barbs, serration, and needles on the discharge electrodes help to establish a uniform electric field. In some cases, flat plates are used both as discharge and collection electrodes. Collection electrodes are often modified with baffles to improve gas flow and particle collection. Some ESPs use wire mesh rather than flat plates as collection electrodes. Examples of discharge electrodes and collection plates are shown in Figure 5.2-6.

Concentric Plate.[3] In this design, the ESP consists of vertical cylinders that are arranged concentrically and act as collection electrodes. The walls of the cylinders are continually rinsed by a thin film of liquid which is supplied by a system above the electrodes. The discharge electrodes are made of wire mesh located between the cylinders. This type of ESP is only operated as a wet ESP. The gas stream is wetted in a scrubber before it reaches the ESP. The concentric plate ESP is illustrated in Figure 5.2-7.

Pulsed Energization.[2] Some ESPs have experienced success with pulsed energization. Conventional ESPs rely on a constant base voltage applied to the discharge electrode to generate the corona and electric field. In pulse energization, high voltage pulses of short duration (of a few microseconds) are applied to the discharge electrodes. A typical pulse energization system will operate with pulse voltages on the order of 100 kilovolts (kV) rather than the 50 kV used with conventional energization. The pulses produce a more uniformly current distribution on the collection electrode.[8] Pulses can be used alone or in addition to a base voltage and have been shown to increase the collection efficiency of ESPs with poor energization. Pulse energization has been used successfully in the electric utility industry. The Ion Physics Corp. has performed tests of this procedure at Madison Gas and Electric, Madison, Wisconsin.[9] This technique is,

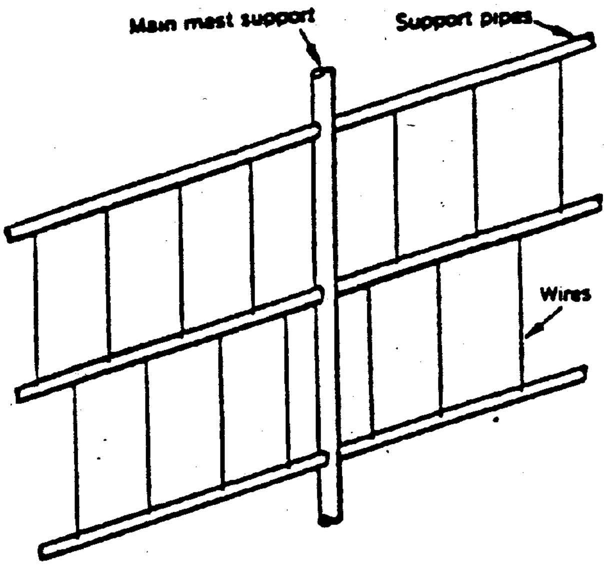


Figure 5.2-5. Rigid Frame Electrode (Reference 2).

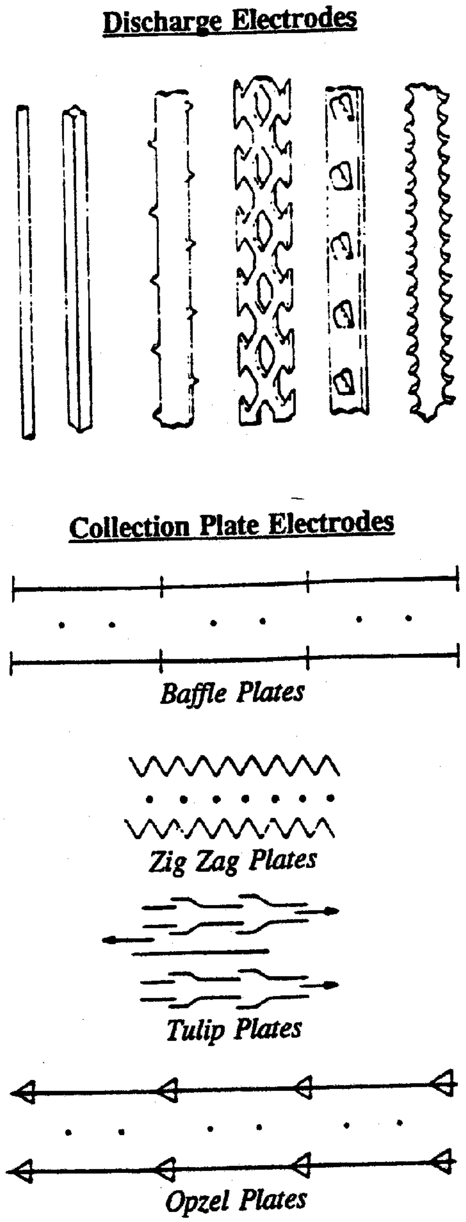


Figure 5.2-6. Various Discharge Electrodes and Collection Plate Designs (Reference 2).

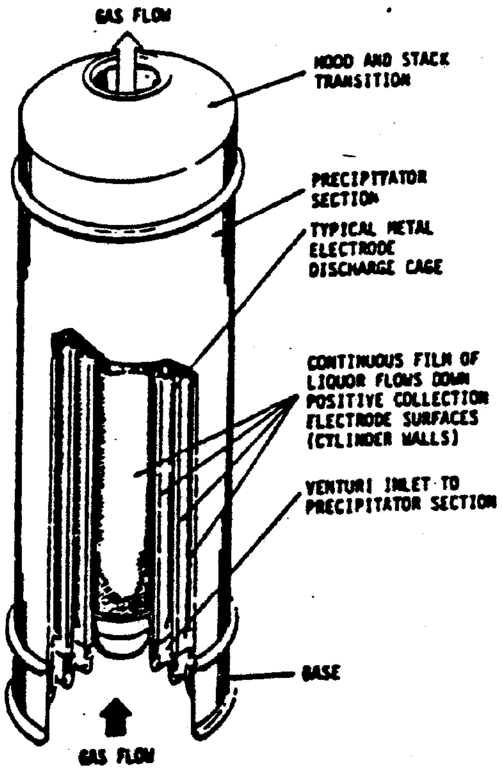


Figure 5.2-7. Concentric Plate Electrostatic Precipitator (Reference 3).

however, still evolving to permit a more rational approach to pulse energization and, perhaps, to reduce the cost.[6]

Two-Stage ESP.[2,3] All of the ESP designs mentioned previously have been single-stage ESPs. In a single stage ESP, particle charging and collection take place simultaneously in the same physical location. Two-stage ESPs are different in that particle charging takes place in a separate section which precedes collection. Two-stage ESPs are best suited for low dust loadings and fine particles. It is often used for cleaning air in buildings.

### 5.2.4 Collection Efficiency

Electrostatic precipitators are capable of collecting greater than 99 percent of all sizes of particulate.[1] Collection efficiency is effected by several factors including dust resistivity, gas temperature, chemical composition (of the dust and gas), and particle size distribution.

The resistivity of a dust is a measure of its resistance to electrical conduction and it has a great effect on the performance of dry ESPs. The efficiency of an ESP is limited by the strength of the electric field it can generate, which in turn is dependent upon the voltage applied to the discharge electrodes. The maximum voltage that can be applied is determined by the sparking voltage. At this voltage, a path between the discharge and collection electrodes is ionized and sparking occurs. Highly resistive dusts increase sparking, which forces the ESP to operate at a lower voltage. The effectiveness of an ESP decreases as a result of the reduced operating voltage.[2]

High resistivity dusts also hold their electrical charge for a relatively long period of time. This characteristic makes it difficult to remove the dust from the collection electrodes. In order to loosen the dust, rapping intensity must be increased. High intensity rapping can damage the ESP and cause severe reentrainment, leading to reduced collection efficiency. Low dust resistivities can also have a negative impact on ESP performance. Low resistivity dust quickly loses its charge once collected. When the collection electrodes are cleaned, even with light rapping, serious reentrainment can occur.[2]

Temperature and the chemical composition of the dust and gas stream are factors which can influence dust resistivity. Current is conducted through dust by two means, volume conduction and surface conduction. Volume conduction takes place through the material itself, and is dependent on the chemical composition of the dust. Surface conduction occurs through gases or liquids adsorbed by the particles, and is dependent on the chemical composition of the gas stream. Volume resistivity increases with increasing temperatures and is the dominant resistant force at temperatures above approximately 350°F. Surface resistivity decreases as temperature increases and predominates at temperatures below about 250°F. Between 250 and 350°F, volume and surface resistivity exert a combined effect, with total resistivity highest in this temperature range.[2,3]

For coal fly ash, surface resistance is greatly influenced by the sulfur content of the coal. Low sulfur coals have high resistivity, because there is decreased adsorption of conductive gases (such as $SO_3$) by the fly ash. The collection efficiency for high-resistance dusts can be improved with chemical flue gas conditioning that involves the addition of small amounts of chemicals into the gas stream (discussed in Section 5.1, Pretreatment). Typical chemicals include sulfur dioxide ($SO_2$), ammonia ($NH_3$), and sodium carbonate. These chemicals provide conductive gases which can substantially reduce the surface resistivity of the fly ash.[?,10] Resistivity can also be reduced by the injection of steam or water into the gas stream.[2]

In general, dry ESPs operate most efficiently with dust resistivities between $5 \times 10^3$ and $2 \times 10^{10}$ ohm-cm.[2] Electrostatic precipitator design and operation is difficult for dust resistivities above $10^{11}$ ohm-cm.[2] Dust resistivity is generally not a factor for wet ESPs.[1,2] The particle size distribution impacts on the overall performance of an ESP. In general, the most difficult particles to collect are those with aerodynamic diameters between 0.1 and 1.0 µm. Particles between 0.2 and 0.4 µm usually show the most penetration. This is most likely a result of the transition region between field and diffusion charging. Figure 5.2-8 provides cumulative collection efficiency curves for ESPs operating in the utility, copper, and iron and steel industries. The curves were derived from emission factors.[11] Table 5.2-1 presents the cumulative collection efficiencies for $PM_{10}$ and $PM_{2.5}$.

### 5.2.5 Applicability

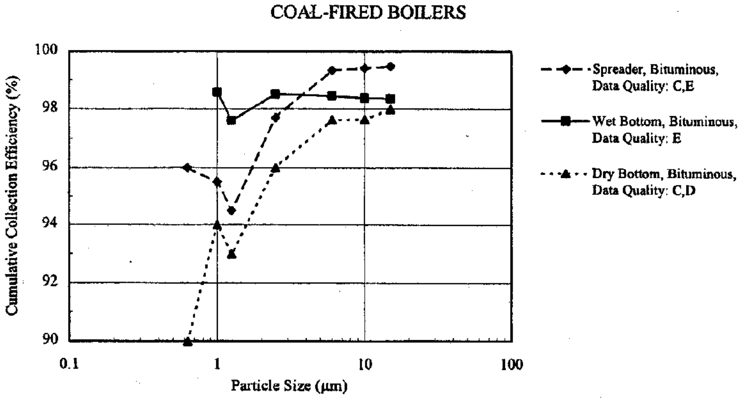
Approximately 80 percent of all ESPs in the U.S. are used in the electric utility industry. Many ESPs are also used in pulp and paper (7 percent), cement and other minerals (3 percent), iron and steel (3 percent), and nonferrous metals industries (1 percent).[1] Table 5.2-2 lists common applications of ESPs.[12]

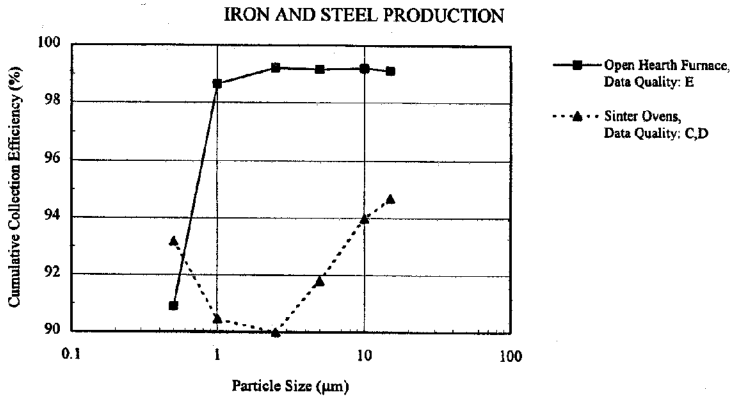
The dust characteristics can be a limiting factor in the applicability of dry ESPs to various industrial operations. Sticky or moist particles and mists can be easily collected, but often prove difficult to remove from the collection electrodes of dry ESPs. Dusts with very high resistivities are also not well suited for collection in dry ESPs. Dry ESPs are susceptible to explosion in applications where flammable or explosive dusts are found.[2]

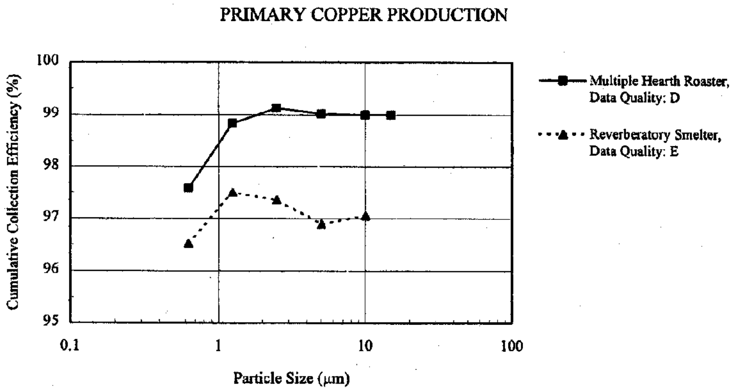
Wet ESPs can collect sticky particles and mists, as well as highly resistive or explosive dusts. Wet ESPs are generally not limited by dust characteristics, but are limited by gas temperatures. Typically, the operating temperatures of wet ESPs cannot exceed 170°F. When collecting a valuable dust which can be sold or recycled into the process, wet ESPs also may not be desirable, since the dust is collected as a wet slurry that would likely need additional treatment.[2,4]

Electrostatic precipitators are usually not suited for use on processes which are highly variable, since frequent changes in operating conditions are likely to degrade ESP performance. Electrostatic precipitators are also difficult to install on sites which have limited space because

ESPs must be relatively large to obtain the low gas velocities necessary for efficient particle collection.[1]







Note: Data quality refers to the data quality ratings assigned to the emission factors from which the efficiencies were calculated (from Reference 8).

A = excellent
B = above average
C = average
D = below average
E = poor

Figure 5.2-8. Cumulative Collection Efficiency Data for Electrostatic Precipitators at Coal-Fired Boilers, Primary Copper Producters, and Iron and Steel Production Operations (Reference 8).

### Table 5.2-1. $PM_{10}$ and $PM_{2.5}$ Cumulative Collection Efficiencies for ESPs at Coal Combustors, Primary Copper Operations, and Iron and Steel Production Operations (from Reference 11)

| Application | Collection Efficiency (percent) | |
|---|---|---|
| | $PM_{10}$ | $PM_{2.5}$ |
| Coal-Fired Boilers | | |
| Dry bottom (bituminous) | 97.7 | 96.0 |
| Spreader stoker (bituminous) | 99.4 | 97.7 |
| Spreader stoker (anthracite) | 98.4 | 98.5 |
| Primary Copper Production | | |
| Multiple hearth roaster | 99.0 | 99.1 |
| Reverberatory smelter | 97.1 | 97.4 |
| Iron and Steel Production | | |
| Open hearth furnace | 99.2 | 99.2 |
| Sinter oven | 94.0 | 90.0 |

### Table 5.2-2. Typical Industrial Applications of Electrostatic Precipitators (from References 2 and 12)

| Application | Source Category Code | Type of ESP[a] |
|---|---|---|
| Utility Boilers<br>(Coal, Oil) | 1-01-002...004 | DESP, Wire-Plate |
| Industrial Boilers<br>(Coal, Oil, Wood, Liq. Waste) | 1-02-001...005<br>1-02-009, -013 | DESP, Wire-Plate |
| Commercial/Institutional Boilers<br>(Coal, Oil, Wood) | 1-03-001...005<br>1-03-009 | DESP, Wire-Plate |

| Application | Source Category Code | Type of ESP[a] |
|---|---|---|
| Chemical Manufacture | 3-01-001...999 | Site specific |
| Non-Ferrous Metals Processing (Primary and Secondary) | | |
| Copper | 3-03-005<br>3-04-002 | DESP, WESP, Plate-Plate, Wire-Plate, Wire-Pipe, Rigid Frame-Plate |
| Lead | 3-03-010<br>3-04-004 | DESP, WESP, Plate-Plate, Wire-Plate, Wire-Pipe, Rigid Frame-Plate |
| Zinc | 3-03-030<br>3-04-008 | DESP, WESP, Plate-Plate, Wire-Plate, Wire-Pipe, Rigid Frame-Plate |
| Aluminum | 3-03-000...002<br>3-04-001 | DESP, WESP, Wire-Plate, Wire-Pipe Rigid Frame-Plate |
| Other | 3-03-011...014<br>3-04-005...006<br>3-04-010...022 | DESP, WESP, Wire-Plate, Wire-Pipe |
| Ferrous Metals Processing | | |
| Coke Production | 3-03-003...004 | WESP, Wire-Pipe |
| Ferroalloy Production | 3-03-006...007 | DESP, Wire-Plate |
| Iron and Steel Production | 3-03-008...009 | DESP, WESP, Wire-Plate, Wire-Pipe |
| Gray Iron Foundries | 3-04-003 | DESP, Wire-Plate |
| Steel Foundries | 3-04-007, -009 | DESP, WESP, Wire-Plate, Wire-Pipe |
| Petroleum Refineries and Related Industries | 3-06-001...999 | DESP, Wire-Plate |
| Mineral Products | | |
| Cement Manufacturing | 3-05-006...007 | DESP, Wire-Plate |
| Stone Quarrying and Processing | 3-05-020 | Site specific |
| Other | 3-05-003...999 | DESP, WESP, Wire-Plate, Needle-Plate |
| Wood, Pulp, and Paper | 3-07-001 | DESP, Wire-Plate, Rigid Frame-Plate |
| Incineration (Municipal Waste) | 5-01-001 | DESP, Wire-Plate, Rigid Frame-Plate |

[a] DESP = Dry ESP, WESP = Wet ESP.

Table 5.2-2, continued

## 5.2.6 Costs of Electrostatic Precipitators

The costs of installing and operating an ESP include both capital and annual costs. Capital costs are all of the initial equipment-related costs of the ESP. Annual costs are the direct costs of operating and maintaining the ESP for one year, plus such indirect costs as overhead; capital recovery; and taxes, insurance, and administrative charges. Please refer to Chapter 6 of the *OAQPS Control Cost Manual* for cost equations.[13]

### 5.2.6.1 Capital Costs

The total capital investment (TCI) for ESPs includes all of the initial capital costs, both direct and indirect. Direct capital costs are the purchased equipment costs (PEC), and the costs of installation (foundations, electrical, piping, etc.). Indirect costs are related to the installation and include engineering, construction, contractors, start-up, testing, and contingencies. The direct and indirect installation costs are calculated as factors of the PEC.[13] Table 5.2-3 presents the TCI cost factors for ESPs. There are several aspects of ESPs which impact the PEC. These factors include inlet gas flow rate, collection efficiency, dust and gas characteristics, and various standard design features. The PEC is estimated based on the ESP specifications and is typically correlated with the collecting area in two ways, the Deutsch-Anderson equation or the sectional method.[13] Please refer to Chapter 6 of the OAQPS Cost Manual (Reference 13) for ESP cost estimation equations.

Inlet Flow Rate. The inlet flow rate has the greatest effect on TCI because it determines the overall size of the ESP. As the gas flow rate increases so does the ESP size and, in turn, the costs. Typical gas flow rates for ESPs are 10,000 to 1,000,000 actual cubic feet per minute (ACFM).[2] Electrostatic precipitator costs increase approximately linearly with gas flow rate, with the slope of the cost curves dependent on the other factors discussed below.

Collection Efficiency. Electrostatic precipitators are designed to achieve a specific collection efficiency. The TCI costs of ESPs increase as greater efficiencies are achieved. To attain higher collection efficiencies, ESPs must be larger to provide greater collection areas. In addition, extremely high efficiencies may require special control instrumentation and internal modifications to improve gas flow and rapping efficiency. Figure 5.2-9 shows the effect of collection efficiency on TCI costs for an ESP.[14]

Dust Characteristics. Particle size distribution, adhesiveness, and resistivity are dust characteristics that affect ESP costs. The size distribution of the dust influences the overall ESP collection efficiency. For example, particles in the range of 0.1 to 1.0 µm are the most difficult for an ESP to collect. If many of the particles are in this range, it will be more difficult to achieve a given collection efficiency and a larger, more expensive ESP will be required. If the dust is very sticky, dry ESPs will need to be made of more durable (and costly) materials to withstand the intense rapping needed to remove the dust from the collection electrodes. For this reason, a wet ESP is often preferred for very sticky dusts, which drives costs higher. Dust resistivity influences costs, since highly resistive particles will require the added operating expense of flue gas conditioning or the use of wet ESPs.[13]

Table 5.2-3. Capital Cost Factors for Electrostatic Precipitators (from Reference 10)

| Cost Item | Factor |
|---|---|
| Direct Costs | |
| Purchased equipment costs | |
| ESP + auxiliary equipment | As estimated (A) |
| Instrumentation | 0.10 A |
| Sales taxes | 0.03 A |
| Freight | 0.05 A |
| Total Purchased Equipment Cost, (PEC) | B = 1.18 A |
| Direct installation costs | |
| Foundations and supports | 0.04 B |
| Handling and erection | 0.50 B |
| Electrical | 0.08 B |
| Piping | 0.01 B |
| Insulation for ductwork | 0.02 B |
| Painting | 0.02 B |
| Total direct installation cost | 0.67 B |
| Site Preparation and Buildings | As required (Site) |
| Total Direct Cost, DC | 1.67 B + Site |
| Indirect Costs (installation) | |
| Engineering | 0.20 B |
| Construction and field expense | 0.20 B |
| Contractor fees | 0.10 B |
| Start-up | 0.01 B |
| Performance test | 0.01 B |
| Model study | 0.02 B |
| Contingencies | 0.03 B |
| Total Indirect Cost (IC) | 0.57 B |
| Total Capital Investment = DC + IC | 2.24 B + Site |

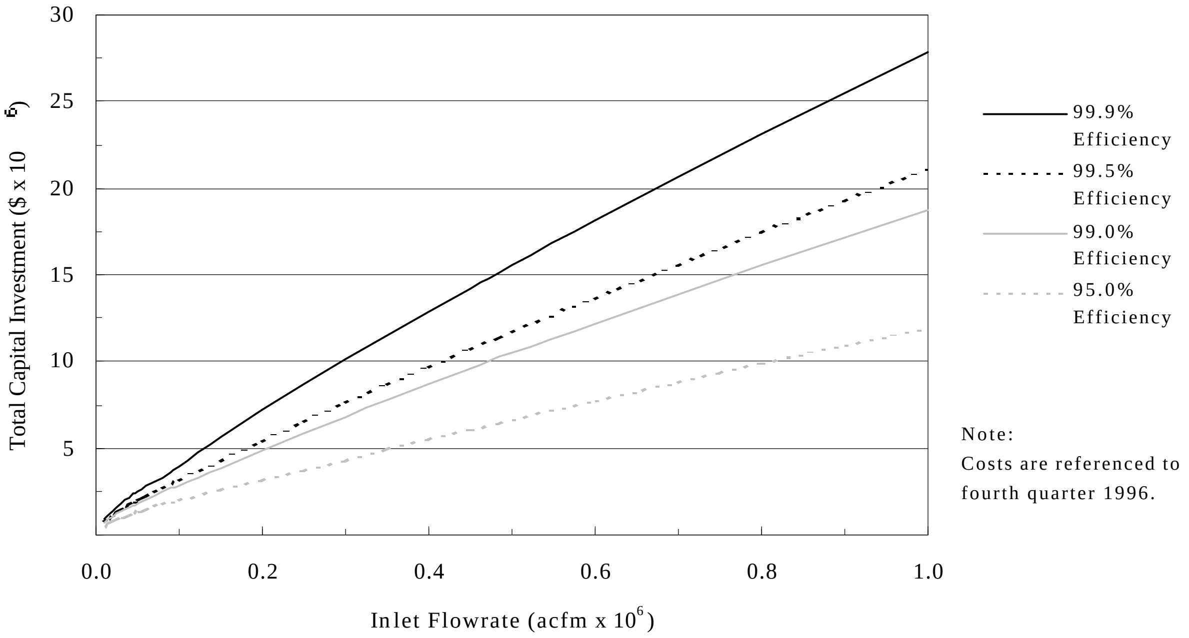


Figure 5.2-9. Effect of Design Collection Efficiency on ESP TCI Costs (Reference 14).

Gas Stream Characteristics. Important gas stream characteristics are temperature, moisture, and chemical composition. Gas stream temperature affects particle resistivity and, consequently, ESP efficiency and costs. Very moist streams and mists generally require the use of wet ESPs. The chemical composition of the gas stream may restrict the construction materials appropriate for the ESP. Most ESPs are constructed of carbon steel; however when the stream is highly corrosive, more costly corrosion resistant materials such as stainless steel, carpenter, monel, nickel, and titanium are needed.[13] Figure 5.2-10 shows the impact of the use of corrosion resistant materials on ESP TCI costs.[14]

Design Features. There are several design features that are considered standard for most ESPs and which can add up to 50 percent of the PEC. These options include inlet and outlet nozzles, diffuser plates, hopper auxiliaries (heaters, level detectors, etc.), weather enclosures, stair access, structural supports, and insulation.[13] Figure 5.2-11 shows ESP costs with and without these standard design features.[14] Wet ESPs and rigid-frame designs typically have higher initial (capital) expenses than dry and wire-plate ESPs.

### 5.2.6.2 Annual Costs

The total annual cost of an ESP consists of both direct and indirect costs. Direct annual costs are those associated with the operation and maintenance of the ESP. These include labor (operating, supervisory, coordinating, and maintenance), maintenance materials, operating

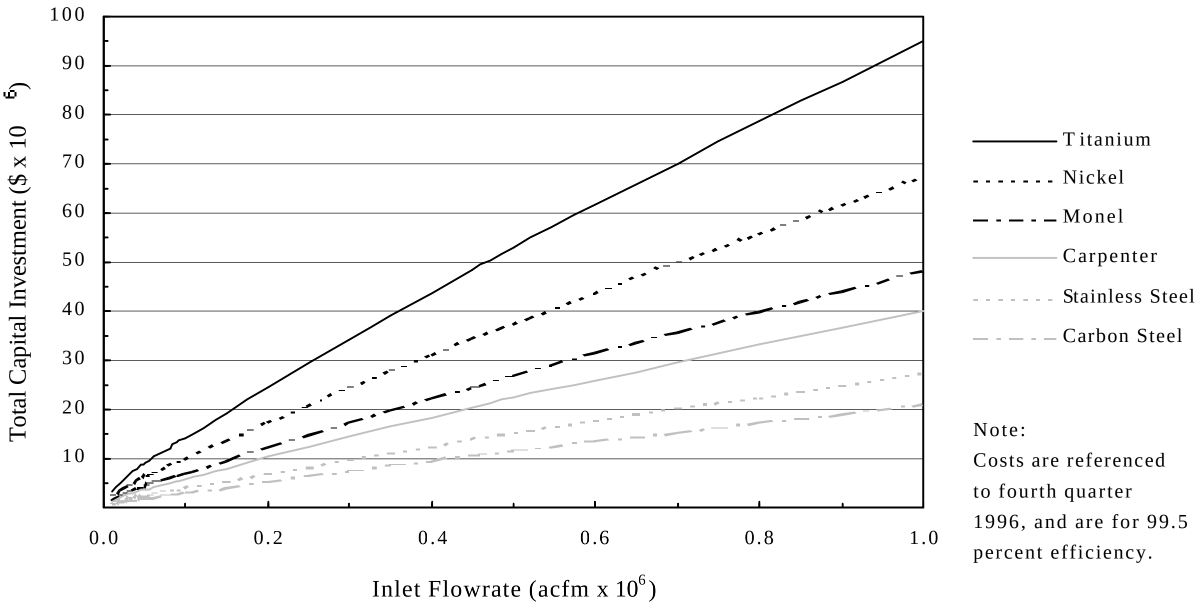


Figure 5.2-10. Effect of the Use of Corrosion Resistant Materials on ESP TCI Costs (Reference 14)

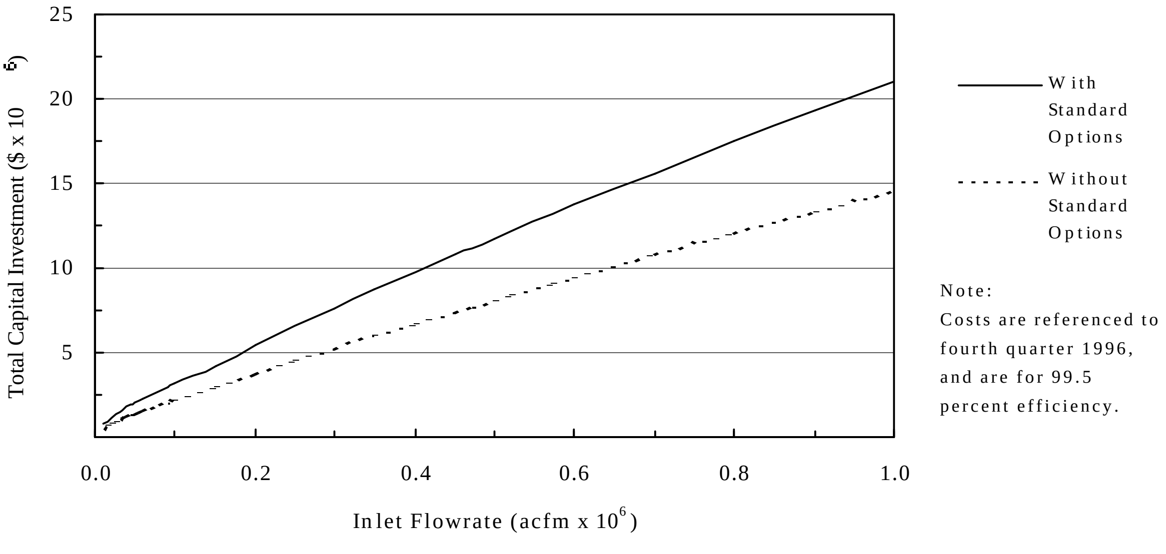


Figure 5.2-11. TCI Costs for ESPs With and Without Various Standard Design Features (Reference 14).

materials, electricity, dust disposal, wastewater treatment (wet ESPs), compressed air (for rappers), conditioning agents, and heating or cooling costs.[13] Some operating costs are not applicable to all ESPs. For ESPs collecting dusts which have no value, dust disposal can be expensive. Gas conditioning agents are used for ESPs that need to collect highly resistive dusts. Some ESP installations also require heating or cooling of the gas stream for effective operation. The cost of the heating fuel can be significant; cooling water costs generally are not.[13]

Indirect annual costs include taxes, insurance, administrative costs, overhead, and capital recovery. All of these costs except overhead are dependent on the TCI. Table 5.2-4 lists the annual cost parameters that impact ESP costs, with typical values provided for each parameter. Table 5.2-5 provides the annual cost factors for ESPs. It is difficult to generalize these costs for all ESPs, since annual costs are very site-specific.[13]

### 5.2.7 Energy and Other Secondary Environmental Impacts

The environmental impacts of ESP operation include those associated with energy demand, solid waste generation in the form of the collected dust, and water pollution for wet ESPs. The energy requirements for operation of an ESP consist mainly of electricity demand for fan operation, and electric field generation, and cleaning. Fan power is dependent on the pressure drop across the ESP, the flow rate, and the operating time. Assuming a fan-motor efficiency of 65 percent and a ratio of the gas specific gravity to that of air equal to 1.0, the fan power requirement can be estimated from the following equation:[13]

$$\text{Fan Power (kW-hr/yr)} = 1.81 \times 10^{-4}\, (V)(\Delta P)(t) \qquad \text{(Eq. 5.2-1)}$$

where $V$ is gas flow rate (ACFM), $\Delta P$ is pressure drop (inches $H_2O$), $t$ is annual operating time (hr/yr), and $1.81 \times 10^{-4}$ is a unit conversion factor.

The operating power requirements for the electrodes and the energy for the rapper systems can be estimated from the following relationship:[13]

$$\text{Operating Power (kW-hr/yr)} = 1.94 \times 10^{-3}\, (A)(t) \qquad \text{(Eq. 5.2-2)}$$

where $A$ is ESP plate area ($ft^2$), $t$ is annual operating time (in hr/yr), and $1.94 \times 10^{-3}$ is a unit conversion factor.

Wet ESPs have the additional energy requirement of pumping the rinse liquid into the ESP. Pump power requirements can be calculated as follows:[13]

$$\text{Pump Power (kW-hr/yr)} = (0.746(Q_l)(Z)(S_g)(t)) \,/\, (3{,}960\ \eta) \qquad \text{(Eq. 5.2-3)}$$

where $Q_l$ is the liquid flow rate (gal/min), $Z$ is the fluid head (ft), $S_g$ is the specific gravity of the liquid, $t$ is the annual operating time (hr/yr), $\eta$ is the pump-motor efficiency, and 0.746 and 3,960 are unit conversion factors.

Table 5.2-4. Annual Cost Parameters for Electrostatic Precipitators (Reference 14).

| Parameter | Description | Typical Values |
|---|---|---|
| Direct Cost Parameters | | |
| Operating factor (OF) | Hours of scrubber operation per year | 8,640 hr/yr |
| Operator labor rate (OR) | Operator labor pay rate | $12.50/hr[a] |
| Operator shift factor (OS) | Fraction of operator shift on scrubber | 0.25[b] |
| Supervisor labor factor (SF) | Fraction of operator labor cost | 0.15[b] |
| Coordinator labor factor (CF) | Fraction of operator labor cost | 0.33[b] |
| Maintenance labor (ML) | Dependent on plate collector area | Site specific |
| Maintenance materials factor (MF) | Fraction of Purchased Equipment Cost | 0.01[b] |
| Electricity rate (ER) | Cost of electricity | $0.07/kW-hr[a] |
| Chemicals (C) | Cost of chemical conditioning agents | Site specific (sect. 5.1) |
| Compressed air (CA) | Cost of compressed air for rappers | $0.18/1000 scf[a] |
| Wastewater treatment (W) | Cost of treating wet ESP effluent | $1.55-$2.55/1000 gal[a] |
| Waste disposal (D) | Cost of disposing of dust/sludge | $20-30/ton[a] |
| Indirect Cost Parameters | | |
| Overhead factor (OV) | Fraction of total labor and (MM) costs | 0.60[b] |
| Annual interest rate (I) | Opportunity cost of the capital | 7 percent[b] |
| Operating life (n) | Expected operating life of scrubber | 20 years[b] |
| Capital recovery factor (CRF) | Function of (n) and (I) | 0.0944[c] |
| Taxes (TAX) | Fraction of the TCI[d] | 0.01[b] |
| Insurance (INS) | Fraction of the TCI[d] | 0.01[b] |
| Administrative costs (AC) | Fraction of the TCI[d] | 0.02[b] |

[a] Estimated for 1996 from currently available information.

[b] Estimates from "CO$T-AIR" Control Cost Spreadsheets (Reference 14).

[c] Capital Recovery Factor is calculated from the following formula: $CRF = \{I(1 + I)^n\} \div \{(1 + I)^n - 1\}$, where $I$ = interest rate (fraction) and $n$ = operating life (years).

[d] The total capital investment (TCI) can be escalated to current values by using the Vatavuk Air Pollution Control Cost Indicies (VAPCCI), described in Appendix B.

Table 5.2-5. Annual Cost Factors for Electrostatic Precipitators (Reference 14).

| Cost Item | Formula[a] | Factor |
|---|---|---|
| Direct Costs | | |
| Labor | | |
| Operator (OL) | (OF)×(OR)×(OS) | A |
| Supervisor (SL) | (SF)×(OL) | 0.15 A |
| Coordinator (CL) | (CF)×(OL) | 0.33 A |
| Maintenance (ML) | Site specific | ML |
| Maintenance materials (MM) | (MF)×(PEC) | 0.01 PEC |
| Electricity (E) | Power[b] × (ER) | E |
| Chemicals (C) | Site specific | C |
| Compressed air (CA) | (CA) | CA |
| Wastewater treatment (W) | (W) | W |
| Waste disposal (D) | (D) | D |
| Total Direct Cost (DC) | | 1.48 A + ML + 0.01 PEC + E + C + CA + W + D |
| Indirect Costs | | |
| Overhead | (OV)×(OL+SL+CL +ML+MM) | 0.89 A + 0.6 ML + 0.006 PEC |
| Capital Recovery | (CRF)×(TCI) | 0.1424 TCI |
| Taxes | (TAX)×(TCI) | 0.01 TCI |
| Insurance | (INS)×(TCI) | 0.01 TCI |
| Administrative Costs | (AC)×(TCI) | 0.02 TCI |
| Total Indirect Cost (IC) | | 0.89 A +0.6 ML + 0.006 PEC + 0.1824 TCI |
| Total Annual Cost (DC + IC) | | 2.37 A + 1.6 ML + 0.016 PEC + 0.1824 TCI + E + C + CA + W + D |

[a] Includes values also described in Table 5.2-4.

[b] Equal to total power requirements, e.g. fan, pump, etc.

Solid waste is generated from ESP operation in the form of the collected dust. Although the dust is usually inert and nontoxic, dust disposal is a major factor of ESP operation. With some ESP operations, the dust can be reused in the process or on the facility or sold. Otherwise, the dust must be shipped offsite. Water pollution is a concern for wet ESPs. Some installations may require water treatment facilities and other modifications to handle the slurry discharge from wet ESPs.[2,13]

### 5.2.8 References for Section 5.2

1. Cooper, C.D and F.C. Alley. *Air Pollution Control: A Design Approach.* 2nd ed. Waveland Press, Prospect Heights, Illinois. 1994.

2. The Electrostatic Precipitator Manual (Revised). The McIlvaine Company, Northbrook, Illinois. March 1996.

3. Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-81-005a, NTIS PB83-127498). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. September 1982.

4. Steinsvaag, R. Overview of Electrostatic Precipitators. Plant Engineering. July 10, 1995.

5. Mastropietro, T. and P. Dhargalkar. Electrostatic Precipitator Designs Evolve to meet Tighter Regulations. Pulp & Paper. September 1991.

6. Oglesby, S., Jr. Future Directions of Particulate Control Technology: A Perspective. J. Air Waste Management Assoc. 40(8): 1184-1185. August 1990.

7. Scholtens, M.J. Air Pollution Control: A Comprehensive Look. Pollution Engineering. May 1991.

8. C. Sedman, N. Plaks, W. Marchant, and G. Nichols. Advances in Fine Particle Control Technology. Presented at the Ukraine Ministry of Energy and Electrification Conference on Power Plant Air Pollution Control Technology, in Kiev, The Ukraine, September 9 - 10, 1996.

9. ESP Newsletter. The McIlvaine Company, Northbrook, Illinois. May 1996.

10. Rikhter, L.A. et. al. Improving the Efficiency of Removal of High-resistance Ash in Electrostatic Precipitators by Chemical Conditioning of Flue Gases. Thermal Engineering. 38:3. March 1991.

11. Compilation of Air Pollutant Emission Factors (AP-42). Volume I (Fifth Edition). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. January 1995.

12. Source Category Emission Reductions with Particulate Matter and Precursor Control Techniques. Prepared for K. Woodard, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina (AQSSD/IPSG), under Work Assignment II-16 (EPA Contract No. 68-03-0034), "Evaluation of Fine Particulate Matter Control." *September 30, 1996.*

13. OAQPS Control Cost Manual (Fourth Edition, EPA 450/3-90-006) U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. January 1990.

14. Vatavuk, W.M. "CO$T-AIR" Control Cost Spreadsheets. Provided by the Innovative Strategies and Economics Group of the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. February 1996.

## 5.3 FABRIC FILTERS

This section addresses the basic operating principles of fabric filters, the cleaning methods, fabric selection, costs, and applicability to various industries. Fabric filters are a popular means of separating particles from a gas stream because of their relatively high efficiency and applicability to many situations. Fabric filters can be made of either woven or felted fabrics and may be in the form of sheets, cartridges, or bags, with a number of the individual fabric filter units housed together in a group. Bags are by far the most common type of fabric filter, hence the use of the term "baghouses" to describe fabric filters in general.

The major particle collection mechanisms of fabric filters are inertial impaction, diffusion from Brownian motion, and interception. During fabric filtration, dusty gas is drawn through the fabric by forced-draft fans. The fabric is responsible for some filtration, but more significantly it acts as support for the dust layer that accumulates. The layer of dust, also known as a filter cake, is a highly efficient filter, even for submicrometer particles. Woven fabrics rely on the filtration abilities of the dust cake much more than felted fabrics.

Fabric filters possess some key advantages over other types of particle collection devices. Along with the very high collection efficiencies, they also have the flexibility to treat many types of dusts and a wide range of volumetric gas flows. Fabric filters can be operated with low pressure drops. Fabric filters also have some potential disadvantages. In general, they are limited to filtering dry streams. Also, high temperatures and certain chemicals can damage some fabrics. Fabric filters also have the potential for fire or explosion, and can require a large area for installation.[1] Proper design can minimize or eliminate these disadvantages.

### 5.3.1 Particle Collection and Penetration Mechanisms

Particle capture during fabric filtration is mainly due to some combination of inertial impaction, diffusion, and direct interception. Collection may also occur due to gravitational sedimentation and electrostatic attraction, but usually to a lesser extent.[2] Figure 5.3-1 illustrates these five particle collection mechanisms.[3]

Inertial impaction occurs as a result of a change in velocity between a fluid, such as air, and a particle suspended in the fluid. As the fluid approaches an obstacle it will accelerate and change direction to pass around the object. Depending on the mass of the particle, it may not be able to adapt to the fluid acceleration and a difference in velocity will develop between the particle and fluid stream. Inertia will maintain the forward motion of the particle towards the object, but the fluid will attempt to drag the particle around the obstacle. The resultant particle motion is a combination of these forces of fluid drag and inertia. This results in impaction for the particles where inertia dominates, and by-pass for those particles overwhelmed by fluid drag.[2]

Collection by diffusion occurs as a result of both fluid motion and the Brownian (random) motion of particles. Diffusional collection effects are most significant for particles less than 1 micrometer ($\mu$m) in diameter.[2] Another collection mechanism, direct interception, occurs when a particle comes within one particle radius of an obstacle. The path that the particle takes can be a result of inertia, diffusion, or fluid motion.[2]

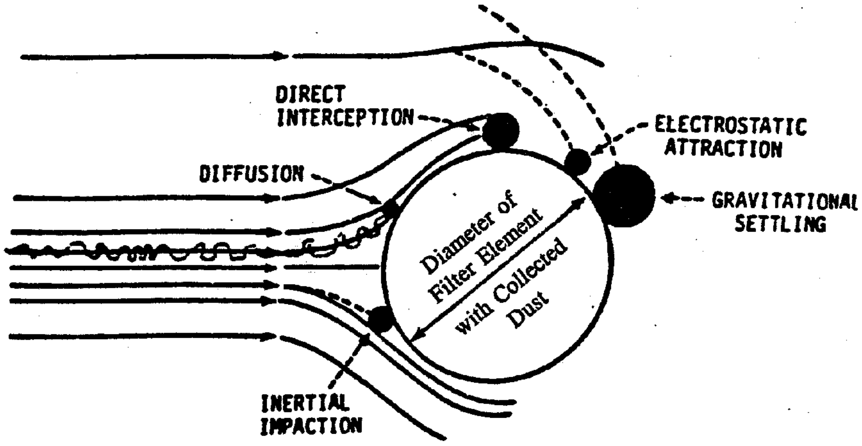


Figure 5.3-1. Collection Mechanisms of Fabric Filtration (from Reference 3).

Gravitational sedimentation, i.e. the falling of individual or agglomerated particles, is a minor collection mechanism for fabric filter operations.[2] Electrostatic charge can play an important role in particle collection and agglomeration in some situations. In order to maximize the electrostatic effect, the characteristics of the particles must be understood before the fabric is selected. See Section 6, Emerging Technologies, for more discussion of electrostatic effects in fabric filtration.

Because of the physics of each collection mechanism, the particle size will determine the predominance of one collection mechanism over another. Generally, as particle size decreases, the predominance of the diffusion collection mechanism increases, assuming other parameters remain constant. As particle size increases, the impaction collection mechanism will most likely increase. The combination of these two major particle collection effects contributes to a minimum efficiency at a given particle size, as illustrated in Figure 5.3-2, a plot of fractional fabric filter collection efficiency versus aerodynamic particle size.[2]

The fabric itself is also a factor in particle collection and penetration. In the initial stages of filtration where the fabric is usually bare, the fabric is responsible for some filtration. More significantly, however, it acts as support for the dust layer that accumulates over the course of operation of the fabric filter. The dust or filter cake is a highly efficient filter, even for submicrometer particles. In terms of fabric type, woven fabrics rely on the filtration abilities of the dust cake much more than felted fabrics.

The structure of the fabric, particularly for woven fabrics, is also very important to particle collection. Large pores and a high free-space area within the fabric contribute to low particle removal. Particle capture in woven fabrics is enhanced by small fibers (known as fibrils) which project into the pores. Dust can deposit on the fibrils and bridge across the pores, which allows a filter cake to build up and increases collection efficiency. Fabrics can have similar pore sizes and very different collection characteristics because of the number of fibrils they possess. The electrostatic properties of fibers are also critical. Different fibers have different electrostatic and surface characteristics. The intensity of the electrostatic charge of the fabric has a distinct effect on particle collection efficiency and is a function of the fabric properties and surface roughness. The resistivity of the fabric influences charge dissipation once particles have been captured. The rate of charge dissipation affects how the dust releases from the fabric and how easily the fabric can be cleaned.

The gas-to-cloth (G/C) ratio is an important design consideration and has a major effect on particle collection mechanisms. This is a ratio of the volumetric flow rate of gas per unit of filtering area, and is usually expressed in the units of cubic feet per minute of gas per square foot of fabric [$(\mathrm{ft}^3/\mathrm{min})/\mathrm{ft}^2$]. Since these units can be reduced to feet per minute (ft/min), the G/C ratio is also referred to as the face velocity.[4] In general, as the face velocity increases, the efficiency of impaction collection increases and diffusional collection efficiency decreases.[2] Higher face velocities allow for smaller fabric filters, all other things being constant. However, as the face velocity increases, there is increased pressure drop, increased particle penetration, blinding of fabric, more frequent cleaning, and reduced bag life. Table 5.3-1 shows recommended G/C ratios for various industrial dusts.[4,16]

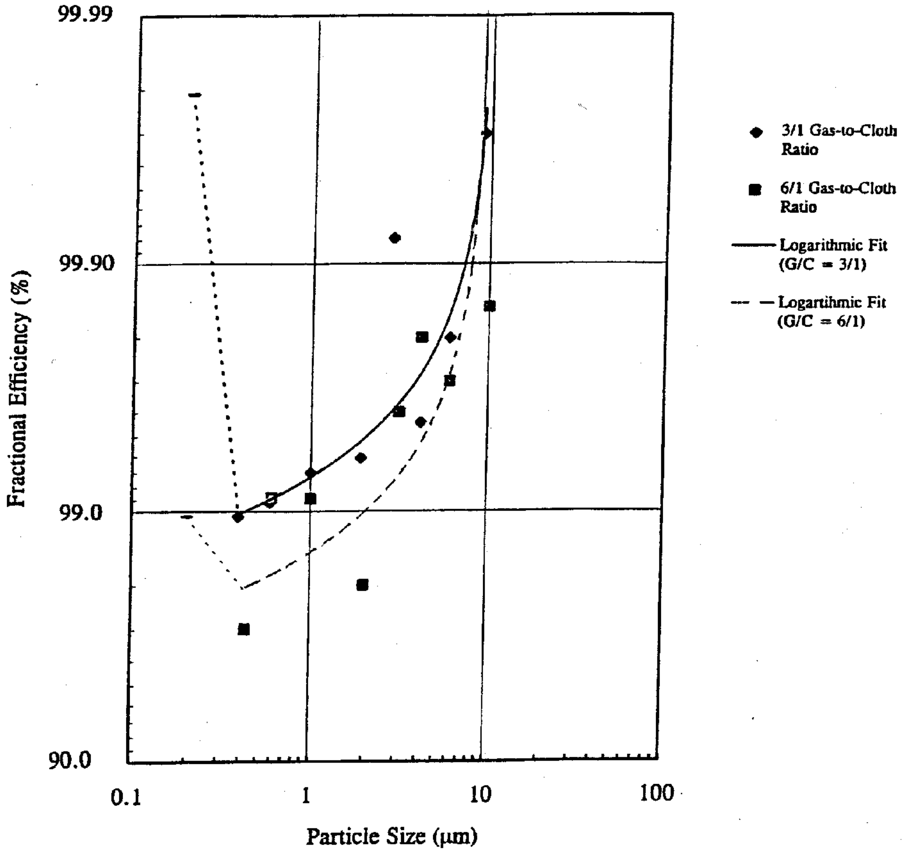


Figure 5.3-2. Fractional Efficiency of Fabric Filters vs. Particle Size (from Reference 2).

## Table 5.3-1. Recommended Gas-to-Cloth Ratios (acfm/ft$^2$) for Common Industrial Applications of Fabric Filters (References 4 and 13)

| Dust | Shaker or Reverse-Air Woven Fabric | Pulse-Jet Felted Fabric |
|---|---|---|
| Alumina | 2.5 | 8 |
| Asbestos | 3.0 | 10 |
| Bauxite | 2.5 | 8 |
| Carbon Black | 1.5 | 5 |
| Coal | 2.5 | 8 |
| Cocoa | 2.8 | 12 |
| Clay | 2.5 | 9 |
| Cement | 2.0 | 8 |
| Cosmetics | 1.5 | 10 |
| Enamel Frit | 2.5 | 9 |
| Feeds, Grain | 3.5 | 14 |
| Feldspar | 2.2 | 9 |
| Fertilizer | 3.0 | 8 |
| Flour | 3.0 | 12 |
| Fly Ash | 2.5 | 5 |
| Graphite | 2.0 | 5 |
| Gypsum | 2.0 | 10 |
| Iron Ore | 3.0 | 11 |
| Iron Oxide | 2.5 | 7 |
| Iron Sulfate | 2.0 | 6 |
| Lead Oxide | 2.0 | 6 |
| Leather Dust | 3.5 | 12 |
| Lime | 2.5 | 10 |
| Limestone | 2.7 | 8 |
| Mica | 2.7 | 9 |
| Paint Pigment | 2.5 | 7 |
| Paper | 3.5 | 10 |
| Plastics | 2.5 | 7 |
| Quartz | 2.8 | 9 |
| Rock Dust | 3.0 | 9 |
| Sand | 2.5 | 10 |
| Sawdust | 3.5 | 12 |
| Silica | 2.5 | 7 |
| Slate | 3.5 | 12 |
| Soap, Detergents | 2.0 | 5 |
| Spices | 2.7 | 10 |
| Starch | 3.0 | 8 |
| Sugar | 2.0 | 7 |
| Talc | 2.5 | 10 |
| Tobacco | 3.5 | 13 |
| Zinc Oxide | 2.0 | 5 |

The majority of the dust that penetrates the filter is a result of dust that is dislodged during cleaning and penetrates to the clean side, and dust that is loosened during cleaning and cannot resist dislodging when the flow resumes.[2] The majority of submicrometer particles penetrate the fabric by passing directly through the pores or by seepage.[2] Seepage occurs when particles migrate through the filter cake and the fabric by continuous capture and reentrainment. Seepage is more common with smooth particles and with a lack of significant electrostatic forces.[2]

### 5.3.2 Types of Fabric Filters

There are a wide variety of materials which can be woven or felted into effective fabrics, and there are many different sizes and arrangements of bags that can be utilized. Although the presence of a filter cake increases collection efficiency as the cake becomes thicker, it also restricts the flow of gas. This increases the pressure drop and energy requirements. To operate a fabric filter continuously, the dust must be cleaned from the filters and removed from the fabric filter on a regular basis. Fabric filters are frequently classified by their cleaning method. The three major types of fabric filter cleaning mechanisms are mechanical shaker, reverse-air, and pulse-jet. These types are discussed below along with a brief discussion of other less common types of cleaning methods and fabric filter configurations.

#### 5.3.2.1 Shaker-Cleaned Fabric Filters

Shaking has been a popular cleaning method for many years because of its simplicity as well as its effectiveness. Shaker-cleaned fabric filters utilizing specially chosen woven fabrics are more effective than other types of fabric filters for many applications.[2] For small units, shaking can be accomplished manually. Large fabric filters require mechanical shaking. For both cases, the operation is basically the same. In general, dusty gas enters an inlet pipe to the shaker-cleaned fabric filter and very large particles are removed from the stream when they strike the baffle plate in the inlet duct and fall into the hopper. The particulate-laden gas is drawn from beneath a cell plate in the floor and into the filter bags. The gas proceeds from the inside of the bags to the outside and through the outlet pipe. The particles are collected on the inside surface of the bags and a filter cake accumulates.

A typical mechanical shaker-cleaned fabric filter unit is shown in Figure 5.3-3.[1] In mechanical shaking units, the tops of the bags are attached to a shaker bar. When the bags are cleaned, the bar is moved briskly, usually in a horizontal direction. This movement flexes the fabric, causing the dust cake to crack and fall away from the fabric and into the hopper. A typical shaker mechanism is shown in Figure 5.3-4.[2] Some amount of filter cake will remain on the inside of the filter bag; as discussed above, this is desirable and also necessary to maintain a consistently high collection efficiency. The amount of dust that is removed during cleaning can be controlled by regulating the frequency, amplitude, and duration of the shaking cycles. In some designs, reverse-air flow is used to enhance dust removal.

The flow of gas through the bags must be stopped during the cleaning cycle to allow the filter cake to release from the fabric and to prevent dust from working through the bag during the

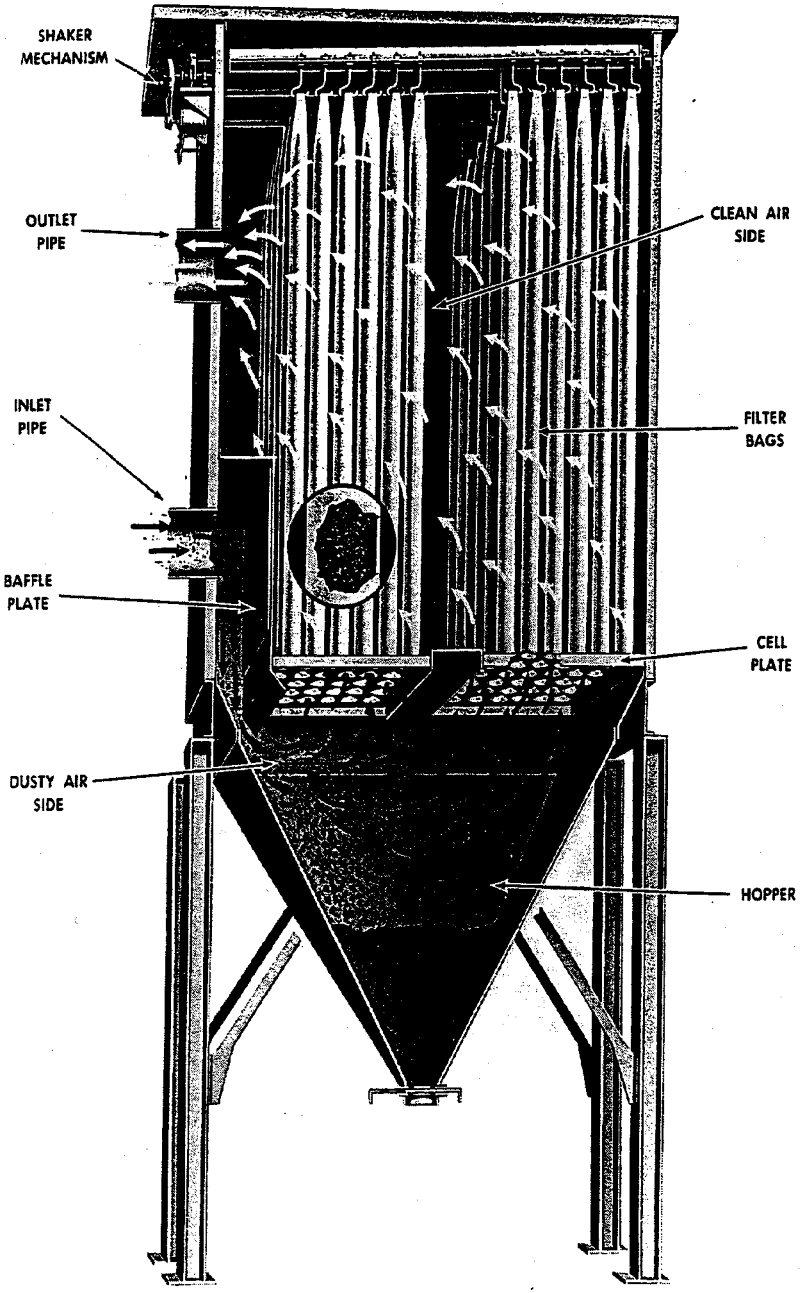
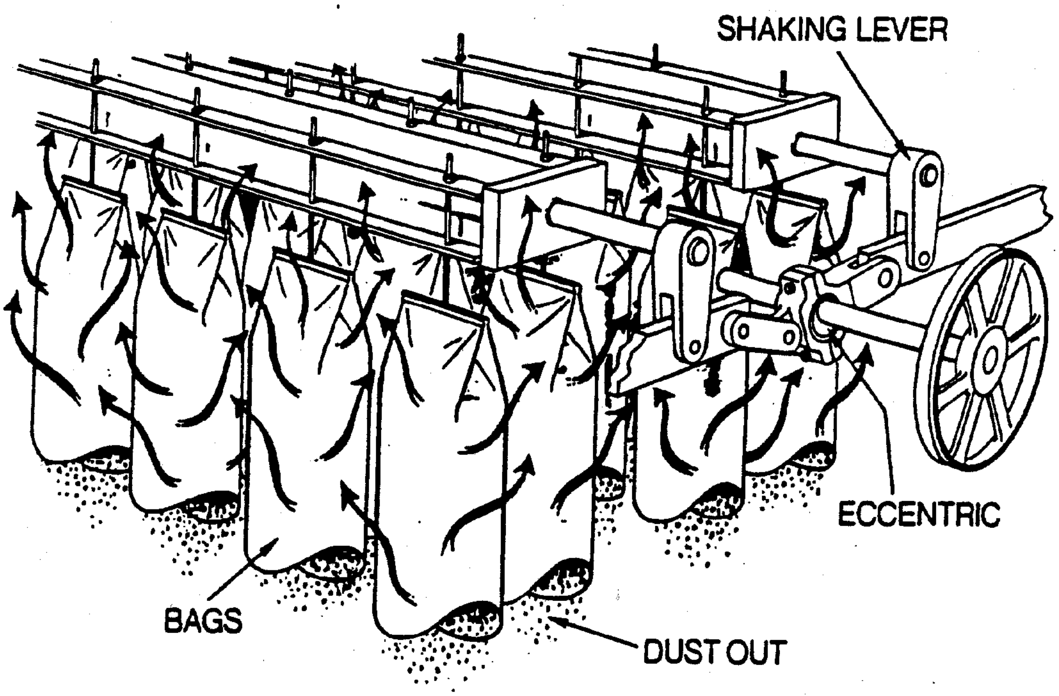


Figure 5.3-3. Cutaway View of a Typical Shaker Fabric Filter (from Reference 1).



5.3-4. Typical Shaker Mechanism (from Reference 2).

shaking. In order to accomplish this, shaker-cleaned fabric filters are often designed with several separate compartments. Each compartment can then be isolated from the gas flow and cleaned while the other compartments continue to filter the stream.

Shaker-cleaned fabric filters are very flexible in design, allowing for different types of fabrics, bag arrangements, and fabric filter sizes. This enables shaker-cleaned fabric filters to have many applications, with only some limitations. Shaker-cleaning fabric filters need a dust that releases fairly easily from the fabric, or the fabric will be damaged from over shaking and bag failure will result. Glass fabrics in particular are susceptible to degradation from shaking.[2] Most other filter fabrics are less brittle than glass and have longer service lives in shaker-cleaned applications. The shaker mechanism itself also must be well designed and maintained or it will quickly wear and lose effectiveness. As the shaker mechanism loses effectiveness, the operator will often increase shaking intensity in order to clean the bags satisfactorily. Continuing this practice can eventually destroy the shaking mechanism.[2]

### 5.3.2.2 Reverse-Air Cleaned Fabric Filter

Reverse-air cleaning is another popular fabric filter cleaning method that has been used extensively and improved over the years.[5] It is a gentler but sometimes less effective cleaning mechanism than mechanical shaking.[1] Most reverse-air fabric filters operate in a manner similar to shaker-cleaned fabric filters. The bags are open on the bottom, closed on top and the gas flows from the inside to the outside of the bags with dust being captured on the inside. However, some reverse-air designs collect dust on the outside of the bags. In either design, reverse-air cleaning is performed by forcing clean air through the filters in the opposite direction of the dusty gas flow. The change in direction of the gas flow causes the bag to flex and crack the filter cake. In internal cake collection, the bags are allowed to collapse to some extent during reverse-air cleaning. The bags are usually prevented from collapsing entirely by some kind of support, such as rings that are sewn into the bags. The support enables the dust cake to fall off the bags and into the hopper. Cake release is also aided by the reverse flow of the gas. Because felted fabrics retain dust more than woven fabrics and thus, are more difficult to clean, felts are usually not used in reverse-air systems.[2]

There are several methods of reversing the flow through the filters. As with mechanical shaker-cleaned fabric filters, the most common approach is to have separate compartments within the fabric filter so that each compartment can be isolated and cleaned separately while the other compartments continue to treat the dusty gas. A typical design of one compartment of a reverse-air cleaning fabric filter is shown in Figure 5.3-5.[2] One method of providing the reverse flow air is by the use of a secondary fan or cleaned gas from the other compartments. A second method is with a traveling air mechanism. An example of such a mechanism is shown in Figure 5.3-6.[3] In this design, the dust is collected on the outside of the bags. The air manifolds rotate around the fabric filter and provide reverse air to each bag, allowing most of the bags to operate while a few of the bags are being cleaned.

Reverse-air cleaning alone is used only in cases where the dust releases easily from the fabric. In many instances, reverse-air is used in conjunction with shaking or pulsing. A

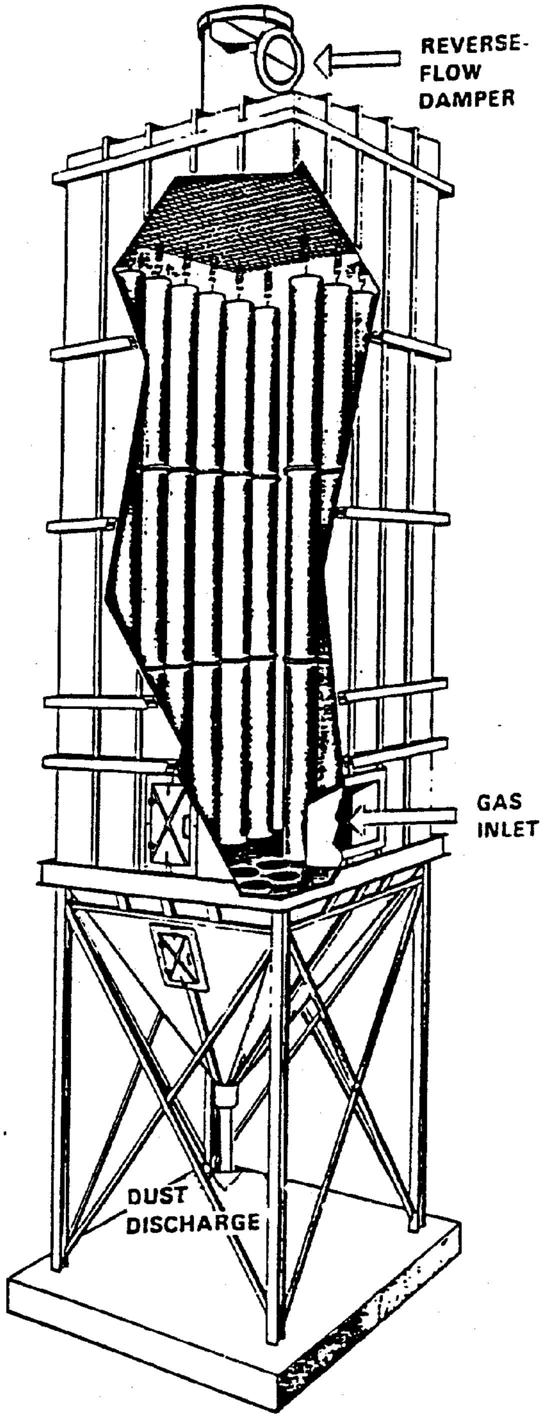


Figure 5.3-5. Typical Design of One Compartment of a Reverse-air Cleaning Fabric Filter (from Reference 2).

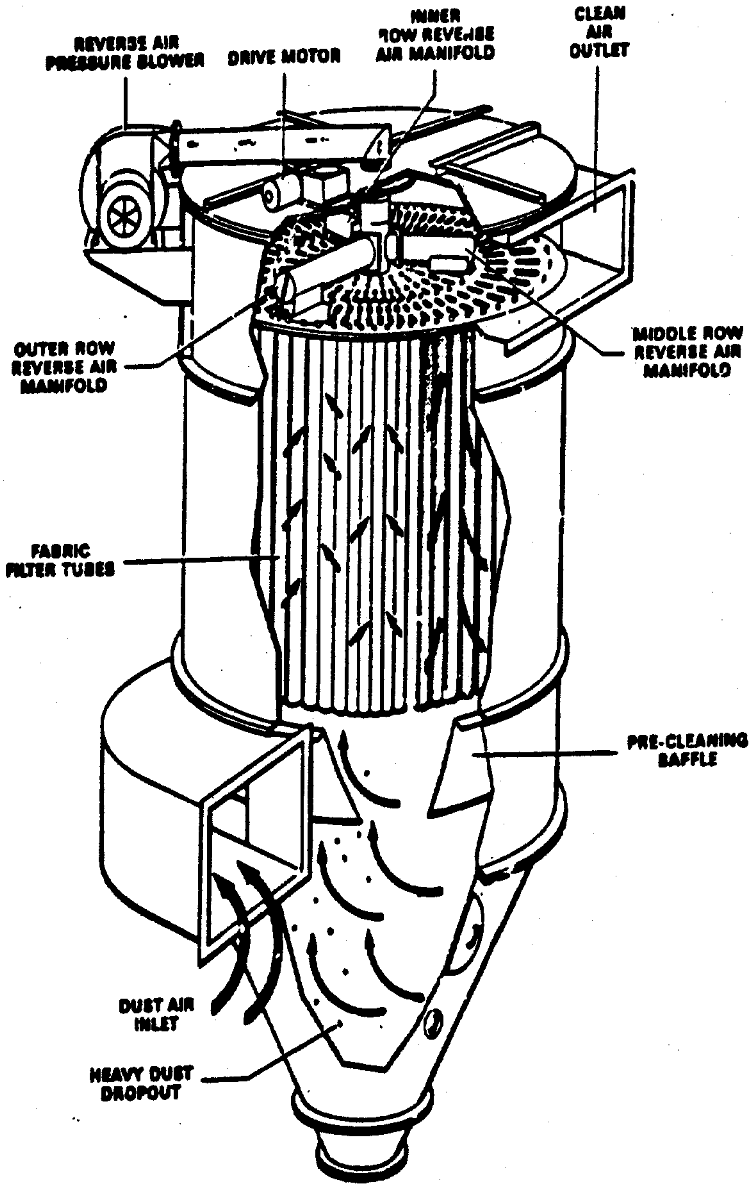


Figure 5.3-6. Reverse-Air Fabric filter with Travelling Mechanism and External Cake Collection (from Reference 3).

relatively recent development has been the use of sonic horns to aid cleaning (see Section 5.3.2.4). During cleaning, sonic blasts from horns mounted in the fabric filter assist in the removal of dust from the bags. This is an important enhancement to fabric filtration.[6,7] Sonic assistance is a very popular method for fabric filters at coal-burning utilities.[1]

### 5.3.2.3 Pulse-Jet Cleaned Fabric Filter

Pulse-jet cleaning of fabric filters is relatively new compared to other types of fabric filters, since they have only been used for the past 30 years. This cleaning mechanism has consistently gained in popularity because it can treat high dust loadings, operate at constant pressure drop, and occupy less space than other types of fabric filters.[8] Pulse-jet cleaned fabric filters can only operate as external cake collection devices. A schematic of a pulse-jet cleaned fabric filter is shown in Figure 5.3-7.[1] The bags are closed at the bottom, open at the top, and supported by internal retainers, called cages. Particulate-laden gas flows into the bag, with diffusers often used to prevent oversized particles from damaging the bags. The gas flows from the outside to the inside of the bags, and then out the gas exhaust. The particles are collected on the outside of the bags and drop into a hopper below the fabric filter.

During pulse-jet cleaning a short (0.03 to 0.1 second) burst of high pressure (90 - 100 psig) air is injected into the bags. The pulse is blown through a venturi nozzle at the top of the bags and establishes a shock wave that continues on to the bottom of the bag. The wave flexes the fabric, pushing it away from the cage, and then snaps it back dislodging the dust cake. The cleaning cycle is regulated by a remote timer connected to a solenoid valve. The burst of air is controlled by the solenoid valve and is released into blow pipes that have nozzles located above the bags. The bags are usually cleaned row by row.

There are several unique attributes of pulse-jet cleaning. Because the cleaning pulse is very brief, the flow of dusty gas does not have to be stopped during cleaning. The other bags continue to filter, taking on extra duty because of the bags being cleaned.[9] In general, there is no change in fabric filter pressure drop or performance as a result of pulse-jet cleaning. This enables the pulse-jet fabric filters to operate on a continuous basis with solenoid valves as the only significant moving parts.[2] Pulse-jet cleaning is also more intense and occurs with greater frequency than the other fabric filter cleaning methods. This intense cleaning dislodges nearly all of the dust cake each time the bag is pulsed. As a result, pulse-jet filters do not rely on a dust cake to provide filtration. Felted fabrics are used in pulse-jet fabric filters because they do not require a dust cake to achieve high collection efficiencies. It has been found that woven fabrics used with pulse-jet fabric filters leak a great deal of dust after they are cleaned.

Since bags cleaned by pulse-jet do not need to be isolated for cleaning, pulse-jet cleaning fabric filters do not need extra compartments to maintain adequate filtration during cleaning. Also, because of the intense and frequent nature of the cleaning, they can treat higher gas flow rates with higher dust loadings. Consequently, fabric filters cleaned by pulse jet can be smaller than other types of fabric filters in the treatment of the same amount of gas and dust, making higher gas-to-cloth ratios achievable.

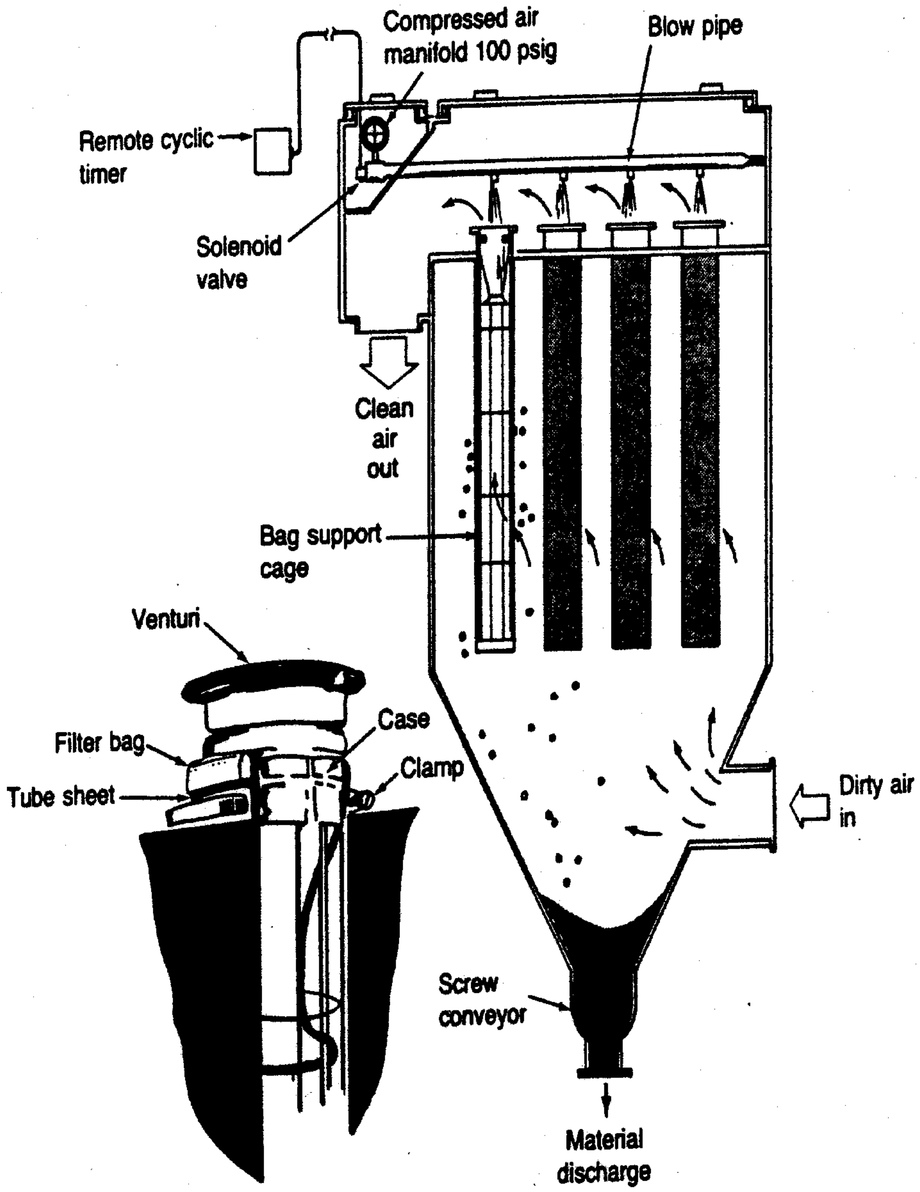


Figure 5.3-7. Schematic of a Pulse-Jet Fabric Filter with Enlarged View of Pulse Inlet Area (Reference 1).

A disadvantage of pulse-jet units that use very high gas velocities is that the dust from the cleaned bags can be drawn immediately to the other bags.[2] If this occurs, little of the dust falls into the hopper and the dust layers on the bags becomes too thick. To prevent this, pulse-jet fabric filters can be designed with separate compartments that can be isolated for cleaning.

### 5.3.2.4 Other Fabric Filter Designs

The less common fabric filter designs of reverse-jet, vibrational, and sonic cleaning, and cartridge filters are briefly described below.

Reverse-Jet Cleaning:[2] Reverse-jet fabric filters have internal cake collection and employ felted fabrics. Each bag is cleaned by a jet ring which travels up and down the outside of the bag on a carriage. The rings blow a small jet of moderately pressurized air through the felt, dislodging the dust on the inside of the bags. Reverse-jet designs are generally used when high-efficiency collection is required for fine particles at low dust loadings, such as toxic or valuable dusts. This fabric filter cleaning method mechanism provides high efficiency at high G/C ratios, but its industrial application seems to be declining.

Vibration Cleaning:[2] Vibration cleaning is similar to mechanical shaker cleaning. However, in vibrational cleaning, the tops of the bags are attached to one plate, rather than a series of shaker bars as with mechanical shaker cleaning. To clean the bags, the plate is oscillated in a horizontal direction at a high frequency. This creates a ripple in the bags which dislodges the filter cake. Vibration cleaning is most effective for medium- to large-sized particles with weak adhesive properties, therefore this cleaning method is limited to applications where fine particle collection is not needed.

Sonic Cleaning:[6,10] Sonic cleaning is generally used to assist another cleaning method, such as reverse air cleaning. Sonic horns are installed inside the fabric filter compartments, where the bags are periodically blasted with sonic energy. The frequency and amplitude of the soundwaves can be adjusted to maximize the effect for a given dust. The soundwave shock causes a boundary layer to form in the filter cake; this allows more of the cake to be dislodged during cleaning and, hence, improves cleaning efficiency. Over half of the reverse gas fabric filters also use sonic horns, either continuously or intermittently.[11]

Cartridge Dust Collectors:[2,12] Cartridge collectors are pleated fabrics that are contained in completed closed containers, or cartridges. These collectors offer high efficiency filtration combined with a significant size reduction in the fabric filter unit. A cartridge filter occupies much less space than filter bags with the same amount of filtration media. In addition, cartridge collectors can operate at higher G/C ratios than fabric filters. Cartridges can be pulse cleaned, and some types can be washed and reused. Cartridge replacement is also much simpler than filter bag replacement. However, this type of fabric filter has been limited to low flow rate and low temperature applications. New filter materials and collector designs are increasing the applications of cartridge filters.

### 5.3.3 Fabric Characteristics

Fabric selection is a very important feature of fabric filter operation. There are many fibers that can be used effectively used as filters, with different properties that determine their appropriate applications. In general, fibers can be made into woven or felted fabrics. The cleaning method affects the fiber choice, since some fibers wear quickly and lose their effectiveness as a result of frequent flexing or shaking. The fabric type must also fit the cleaning method, and the stream and particle characteristics. Woven fabrics are preferred for shaker and reverse-air fabric filters. Felted fabrics are recommended for pulse-jet and reverse-jet fabric filters. The use of felt is generally limited to external surface dust collection styles.[2]

The major gas stream characteristics to consider when selecting fabrics are temperature and chemical composition. Most fabrics are degraded by high temperatures.[2] Among the variety of available fabrics, there is a wide range of maximum operating temperatures that can be matched to the range of temperatures in the different applications. Some fabrics are also easily degraded by acids, whereas others are highly resistant to acids. Alkalis, oxidizers, and solvents are other types of chemicals that can damage filter materials.[2] New fibers, such as Ryton®, Gore-Tex®, and Chem-Pro®, are continually in development for high temperature and other demanding applications.[13] Ceramic fabrics, Nextel® for example, have recently been developed and can function at temperatures up to 1000°F.[13,14] Table 5.3-2 lists the maximum operating temperatures, and physical and chemical resistances of various industrial-used fabrics.[2]

The important particle characteristics to consider in fabric selection are size, abrasion potential, and release potential. The average sizes of the particles can be a factor in the selection of the type of weave or felt that is chosen for a particular application. With very abrasive dusts, care must be taken to insure that the fabric will not wear out too quickly. Moist or sticky dusts require a fabric that will easily release the dust cake, or that is coated with some type of lubricant layer.[2]

Several different finishes and textures have been developed for fiberglass fabrics to increase their use in filtration. There are also many coatings and chemical treatments available to provide lubrication and other properties to fibers to improve their performance.

### 5.3.4 Collection Efficiency

Well-designed and maintained fabric filters that are operated correctly should collect greater than 99 percent of particles ranging in size from submicrometer to hundreds of micrometers.[1] There are several factors which can affect the collection efficiency of fabric filters. These factors include gas filtration velocity, particle characteristics, fabric characteristics, and cleaning mechanism. In general, collection efficiency increases with increasing filtration velocity and particle size. Other particle characteristics, as well as the type of cleaning method, are key variables in fabric filter design.  An improperly designed fabric filter will not function as well as possible and will oftentimes impact efficiency.

## Table 5.3-2. Temperature Ranges, and Physical and Chemical Resistances of Common Industrial Fabrics (from Reference 2 and 14)

| | | Physical Resistance | | | | | Chemical Resistance | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fabric Type | Maximum Operating Temperature (°F) | Dry Heat | Moist Heat | Abrasion | Shaking | Flexing | Mineral Acids | Organic Acids | Alkalies | Oxidizers | Solvents |
| Cotton | 180 | G | G | F | G | G | P | G | F | F | E |
| Dacron | 275 | G | F | G | E | E | G | G | F | G | E |
| Orlon | 275 | G | G | G | G | E | G | G | F | G | E |
| Nylon | 225 | G | G | E | E | E | P | F | G | F | E |
| Dynel | 160 | F | F | F | F-P | G | G | G | G | G | G |
| Polypropylene | 200 | G | F | E | E | G | E | E | E | G | G |
| Creslan | 275 | G | G | G | G | E | G | G | F | G | E |
| Vycron | 300 | G | F | G | E | E | G | G | G | G | E |
| Nomex® | 400 | E | E | E | E | E | F-P | E | G | G | E |
| Teflon® | 450 | E | E | F-P | G | G | E | E | E | E | E |
| Nextel™ | 1000 | E | E | NA | NA | NA | E | E | E | E | E |
| Wool | 215 | F | F | G | F | G | F | F | P | P | F |
| Glass | 550 | E | E | P | P | F | E | E | G | E | E |

Note: E = Excellent, G = Good, F = Fair, P = Poor, NA = Not available.

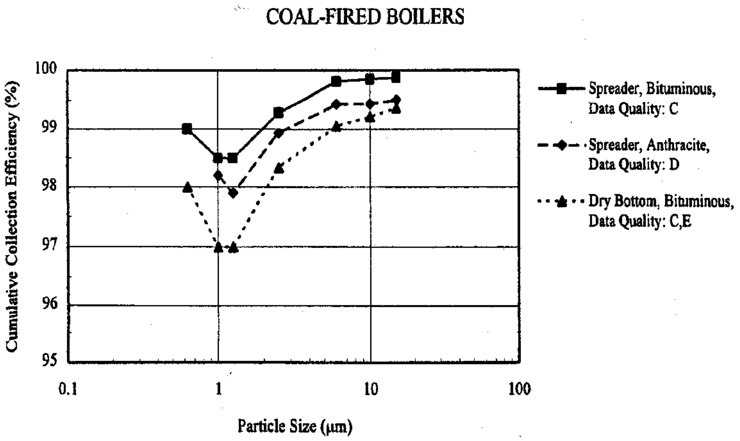
For a given combination of filter design and dust, the effluent particle concentration from a fabric filter is nearly constant whereas the overall efficiency of a fabric filter is more likely to vary with particulate loading.[2] For this reason, fabric filters can be considered constant outlet devices rather than constant efficiency devices. Constant effluent concentration is achieved because at any given time part of the fabric filter is being cleaned. Unlike cyclones, scrubbers, and electrostatic precipitators, fabric filters never really achieve a steady state of particle collection.[2] As a result of the cleaning mechanisms used in fabric filters, the collection efficiency at a given time is always changing. Each cleaning cycle removes at least some of the filter cake and loosens particles which remain on the filter. When filtration resumes, the filtering capability has been reduced because of the lost filter cake and loose particles are pushed through the filter by the flow of gas. This reduces the collection efficiency. As particles are captured the efficiency increases until the next cleaning cycle. Average collection efficiencies for fabric filters are usually determined from tests that cover a number of cleaning cycles at a constant inlet loading.[2]

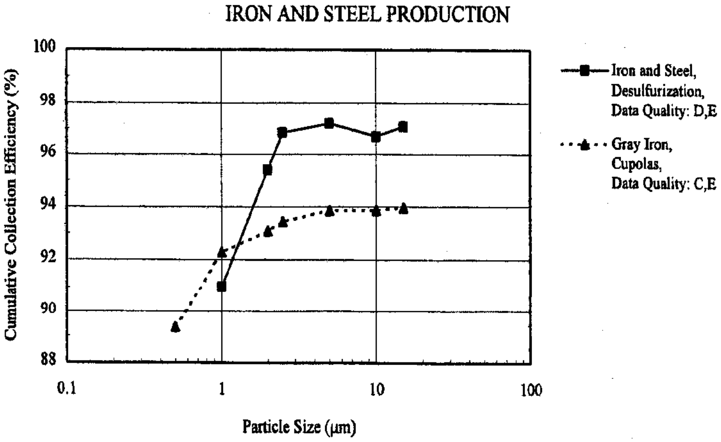
Earlier, Figure 5.3-2 showed typical fractional collection efficiency curves versus particle size for fabric filters. Figure 5.3-8 shows cumulative collection efficiency curves for fabric filters in operation in the utility, ferroalloys, and the iron and steel industry industries, respectively, that were calculated from reported test data.[15] The collection efficiency data for $PM_{10}$ and $PM_{2.5}$ are provided in Table 5.3-3.

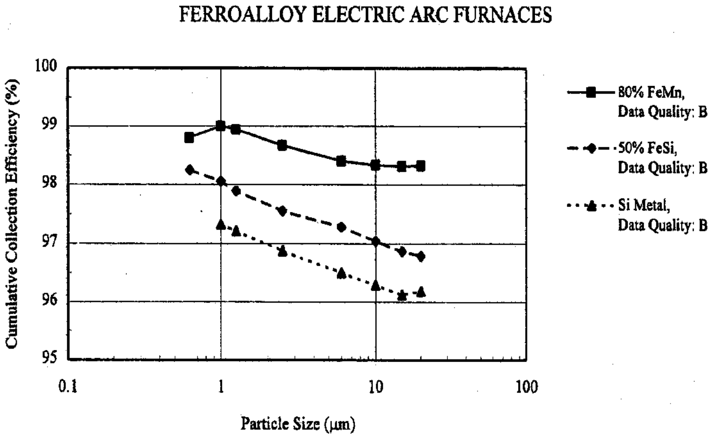
## 5.3.5 Applicability

Fabric filters can perform very effectively in many different applications. The variety of designs and fabrics allows for adaptability to most situations. For most applications, there are several combinations of cleaning method and filter fabric that are appropriate. Table 5.3-4 lists common applications of fabric filters and their recommended cleaning methods and fabrics. Table 5.3-1 above provided the recommended G/C ratios for various applications of fabric filters. There are also empirical methods for determining G/C ratios for a given application, which are described in Chapter 5 of the *OAQPS Cost Manual*.

Although fabric filters can be used in many different conditions, there are some factors which limit their applications. The characteristics of the dust are one factor. Some particles are too adhesive for fabric filters. While such particles are easily collected, they are too difficult to remove from the bags. Particles from oil combustion are an example of a very sticky dust, most of which is thought to be heavy hydrocarbons. For this reason, fabric filters are not recommended for boilers which fire oil exclusively;[4] however, fabric filters are often used with boilers which fire oil as a secondary fuel.


COAL-FIRED BOILERS


IRON AND STEEL PRODUCTION


FERROALLOY ELECTRIC ARC FURNACES

Note: Data quality refers to the data quality ratings assigned to the emission factors from which the efficiencies were calculated (from Reference 8).

A = excellent
B = above average
C = average
D = below average
E = poor

Figure 5.3-8. Cumulative Collection Efficiency Data for Fabric Filters at Coal Combustors, Ferroalloy Electric Arc Furnaces, and Iron and Steel Production Operations (from Reference 15).

## Table 5.3-3. $PM_{10}$ and $PM_{2.5}$ Cumulative Collection Efficiencies for Fabric Filters at Coal Combustors, Ferroalloy Electric Arc Furnaces, and Iron and Steel Production Operations (from Reference 15).

| | Collection Efficiency (percent) | |
|---|---|---|
| Application | $PM_{10}$ | $PM_{2.5}$ |
| Coal-fired Boilers | | |
| Dry bottom (bituminous) | 99.2 | 98.3 |
| Spreader stoker (bituminous) | 99.9 | 99.3 |
| Spreader stoker (anthracite) | 99.4 | 98.4 |
| Ferroalloy Electric Arc Furnaces | | |
| Iron silicate | 97.0 | 97.6 |
| Iron manganese | 98.3 | 98.7 |
| Silica | 96.3 | 96.9 |
| Iron and Steel Production | | |
| Desulfurization | 96.7 | 96.8 |
| Gray iron cupolas | 93.9 | 93.4 |

## Table 5.3-4. Typical Cleaning Methods and Fabrics for Industrial Applications of Fabric Filters (from Reference 2)

| Application | Source Category Code | Typical Cleaning Methods[a] | Typical Fabrics[b] |
|---|---|---|---|
| Utility Boilers (Coal) | 1-01-002...003 | MS, PJ, RA with SA | Fiberglass, Teflon, Teflon treated Glass |
| Industrial Boilers (Coal, Wood) | 1-02-001...003<br>1-02-009 | PJ, RA | Fiberglass, Teflon, Teflon treated Glass |
| Commercial/Institutional Boilers (Coal, Wood) | 1-03-001...003<br>1-03-009 | PJ, RA | Fiberglass, Teflon, Teflon treated Glass |
| Non-Ferrous Metals Processing (Primary and Secondary) | | | |

| Application | Source Category Code | Typical Cleaning Methods[a] | Typical Fabrics[b] |
|---|---|---|---|
| Copper | 3-03-005<br>3-04-002 | MS, RA | Fiberglass, Dacron, Polypropylene, Nomex, Teflon |
| Lead | 3-03-010<br>3-04-004 | MS, RA | Polypropylene, Nomex, Teflon, Dacron, Orlon |
| Zinc | 3-03-030<br>3-04-008 | MS, RA | Polypropylene, Nomex, Teflon, Dacron |
| Aluminum | 3-03-000...002<br>3-04-001 | MS, RA | Nomex, Dacron, Teflon, Polypropylene |
| Other | 3-03-011...014<br>3-04-005...006<br>3-04-010...022 | MS, RA | Nomex, Dacron, Teflon, Polypropylene |
| Ferrous Metals Processing | | | |
| Coke | 3-03-003...004 | MS, RA | Dacron Combination, Teflon |
| Ferroalloy | 3-03-006...007 | RA, MS | Fiberglass (coated with graphite, silicone, Teflon), Dacron, Nomex |
| Iron and Steel | 3-03-008...009 | RA, MS, PJ | Fiberglass with lubricant (silicone, graphite, Teflon) |
| Gray Iron Foundries | 3-04-003 | MS, RA | Fiberglass (with silicone), Nomex, Orlon |
| Steel Foundries | 3-04-007<br>3-04-009 | RA, MS, PJ | Fiberglass, Nomex, Dacron, Teflon |
| Mineral Products | | | |
| Cement | 3-05-006...007 | MS, PJ, RA | Dacron, Cotton, Wool, Nomex, Fiberglass |
| Coal Cleaning | 3-05-010 | | |
| Stone Quarrying and Processing | 3-05-020 | MS, PJ, RA | Cotton, Orlon, Dacron |
| Other | 3-05-003...999<br>(except above) | MS, PJ, RA | Fiberglass, Nomex, Teflon, Orlon, Nylon, Dacron, Dynel, Cotton |
| Asphalt Manufacture | 3-05-001...002 | PJ, RA, MS | Nomex, Fiberglass |
| Grain and Feed Milling | | PJ, RA | Dacron |

[a] MS = Mechanical Shaking, RA = Reverse Air, PJ = Pulse Jet, SA = Sonic Assistance

Table 5.3-4. (continued)

[b] Fabrics are not specified as woven or felted. Felted fabrics are generally recommended for pulse-jet cleaning, woven fabrics are usually utilized for reverse-air and mechanical shaker cleaning.

The potential for explosion is also a concern for certain fabric filters applications. Some fabrics are flammable, and some dusts and stream components may form explosive mixtures. If a fabric filter is chosen to control explosive mixtures, care must be taken when designing and operating the fabric filters to eliminate conditions which could ignite the dust, the stream, and the bags. In addition, the fabric filters should be designed to prevent operator injuries in the event of an explosion.

Temperature and humidity are also limiting factors in the use of fabric filters. Currently, there are few fabric filters in applications where temperatures exceed 500°F for long periods of time. However, new fibers which can operate at temperatures in the 900 to 1000°F range are commercially available and in use at some installations. An example of such a fabric is the ceramic fabric Nextel®. This fabric is very effective, but is also very expensive and is priced much higher than Teflon®, the most expensive of the commonly used filter fabrics.[13] The high cost of new filter fabrics may discourage the use of fabric filters in very high temperature applications. Humidity can also be a problem when considering fabric filters. Moist particles can be difficult to clean from the bags and can bridge over and clog the hopper.[1] Streams with high humidity can also require baghouses with insulation to maintain temperatures well above the dew point to prevent condensation.

### 5.3.6 Costs of Fabric Filters

The costs of installing and operating a fabric filter includes capital and annual costs. Capital costs include all of the initial equipment-related costs of the fabric filter. Annual costs are the direct costs of operating and maintaining the fabric filter for one year, plus such indirect costs as overhead; capital recovery; and taxes, insurance, and administrative charges. The following sections discuss capital and annual costs for various fabric filter designs. Capital costs have been referenced to the third quarter of 1995. The major design consideration, regarding cost, is the G/C ratio (G/C). The G/C is dependent on several factors and must be optimized to balance the capital costs, in terms of the fabric filters size, and the annual operating costs, in particular the pressure drop.[1]

#### 5.3.6.1 Capital Costs

The total capital investment (TCI) for fabric filters includes all of the initial capital costs of the fabric filter, both direct and indirect. Direct capital costs are the purchased equipment costs (PEC) and the costs of physically installing the equipment (foundations and supports, electrical wiring, piping, etc.). Indirect capital costs are also related to installation and include engineering, contractor fees, start-up, testing, and contingencies. The PEC is dependent upon the fabric filter design specifications; direct and indirect installation costs are generally calculated as a factors of the PEC.[16] Commonly used factors for estimating fabric filter capital costs are provided in Table 5.3-5.

There are several design factors which influence fabric filter PEC, and in turn the TCI of fabric filters. Important factors include the inlet gas flow rate, the cleaning mechanism, the type

Table 5.3-5. Capital Cost Factors for Fabric Filters (from Reference 16)

| Cost Item | Factor |
|---|---|
| Direct Costs | |
| Purchased equipment costs | |
| Fabric filter + bags + auxiliary equipment | As estimated (A) |
| Instrumentation | 0.10 A |
| Sales taxes | 0.03 A |
| Freight | 0.05 A |
| Total purchased equipment cost (PEC) | B = 1.18 A |
| Direct installation costs | |
| Foundations and supports | 0.04 B |
| Handling and erection | 0.50 B |
| Electrical | 0.08 B |
| Piping | 0.01 B |
| Insulation for ductwork | 0.07 B |
| Painting | 0.02 B |
| Total direct installation cost | 0.72 B |
| Site Preparation and Buildings | As required (Site) |
| Total Direct Cost (DC) | 1.72 B + Site |
| Indirect Costs (installation) | |
| Engineering | 0.10 B |
| Construction and field expense | 0.20 B |
| Contractor fees | 0.10 B |
| Start-up | 0.01 B |
| Performance test | 0.01 B |
| Contingencies | 0.03 B |
| Total Indirect Cost (IC) | 0.45 B |
| Total Capital Investment = DC + IC | 2.17 B + Site |

of dust, the dust loading, particle characteristics, gas stream characteristics, and fabric type. Please refer to Chapter 5 of the *OAQPS Control Cost Manual* for cost equations.[16]

Gas Flow Rate: The inlet flow rate has the greatest impact on the costs of a fabric filter, since it affects the necessary fabric filter size. For any one fabric filter cleaning type, as the gas flow rate increases so does the fabric filter size and, consequently, the costs. Fabric filters typically treat flow rates from 10,000 to over 1,000,000 acfm.[2] Although fabric filter costs increase approximately linearly with gas flow rate, the slope of the cost curve depends on the other design features that are discussed below.

Cleaning Mechanism: The fabric filter cleaning mechanism is the next most important design feature in terms of costs. Figure 5.3-9 presents cost versus gas flow rate curves for different fabric filters cleaning mechanisms with Nomex® fabric treating similar streams.[17] Cost curves for two different types of pulse-jet fabric filters, common-housing and modular, are provided in Figure 5.3-9, along with reverse air and mechanical shaker cleaning cost information. Pulse-jet common-housing fabric filters are fabric filter that not taken off-line for cleaning. Modular pulse-jet fabric filters are constructed with bags in separate compartments which can be taken off-line for cleaning.[16] Figure 5.3-9 illustrates that reverse air and mechanical shaker cleaning fabric filters have higher TCI costs than pulse-jet (with reverse air units the highest), largely due to the much lower G/C ratios, which raises capital costs. In terms of pulse-jet cleaning fabric filters, modular pulse-jet units are slightly more expensive than common-housing units in terms of TCI.

Although different cleaning mechanisms can operate over different ranges of G/C ratios, pulse-jet fabric filters generally operate at higher G/C ratios compared to shaker and reverse-air models. For this reason, pulse-jet fabric filters are usually smaller (with lower TCI costs) than other fabric filter designs that treat the same flow rate. However, the cleaning mechanism is not chosen simply because of the resultant fabric filter size. Some cleaning mechanisms may not be recommended for certain dust types (See Table 5.3-4 above). In addition, the choice of cleaning mechanism also affects the choice (and resultant costs) for fabric and auxiliary equipment. When choosing between cleaning mechanisms, the PEC is calculated for all applicable designs to determine the least expensive option.

Gas-to-Cloth Ratio: Dust type is most responsible for determining the correct G/C ratio for a particular fabric filter. Each combination of dust and fabric filter cleaning method has a recommended G/C ratio that in most cases has been arrived at through actual fabric filter operations. For a given flow rate, a higher G/C ratios will result in a smaller fabric filter and lower TCI costs. Figure 5.3-10 shows typical cost curves for mechanical shaker and pulse-jet fabric filters operating at G/C ratios appropriate for each cleaning type.[17] Although mechanical shaker cost curves are generally higher than pulse-jet (modular) cost curves, a fabric filter with mechanical shaker cleaning and a high G/C ratio (curve C) has similar TCI costs to a pulse-jet cleaned fabric filter with a low G/C ratio (curve D).

Dust Loading: The dust loading is a measure of the amount of dust per volume of gas being treated that is generally expressed as the weight of dust per unit volume of gas (e.g. grams per cubic foot (g/ft$^3$)). While the type of dust generally determines the best G/C ratio, the dust loading may cause adjustments to the recommended ratio. For high dust loadings, the G/C ratio should be decreased so that more fabric is available to handle the high dust levels.[1] With low dust loadings, the G/C ratio can be increased, which in turn will reduce the fabric filter size.

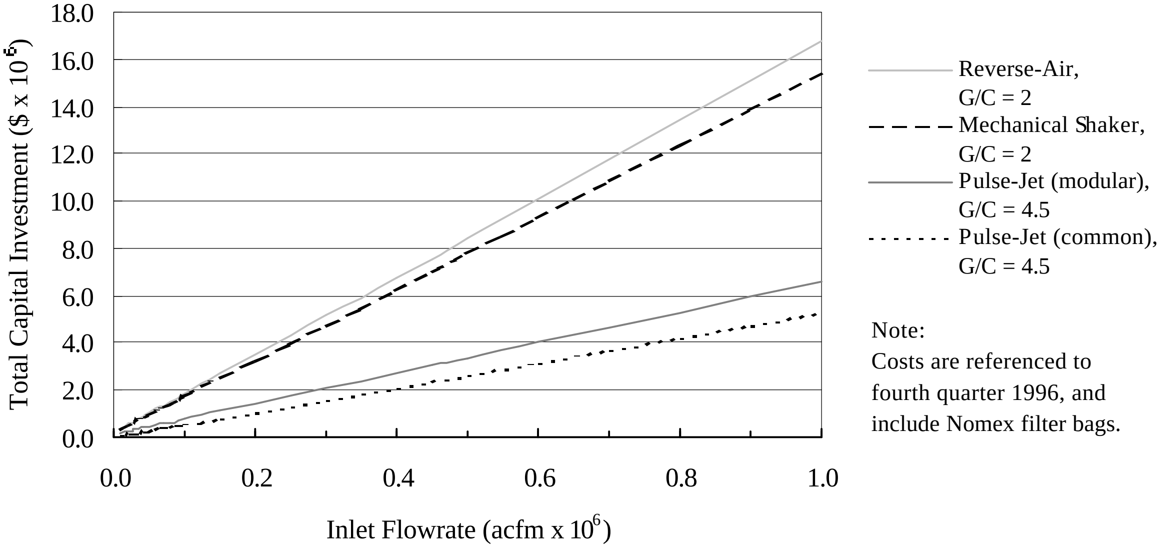


Figure 5.3-9. Effect of Cleaning Mechanism on Fabric Filter TCI (Reference 17).

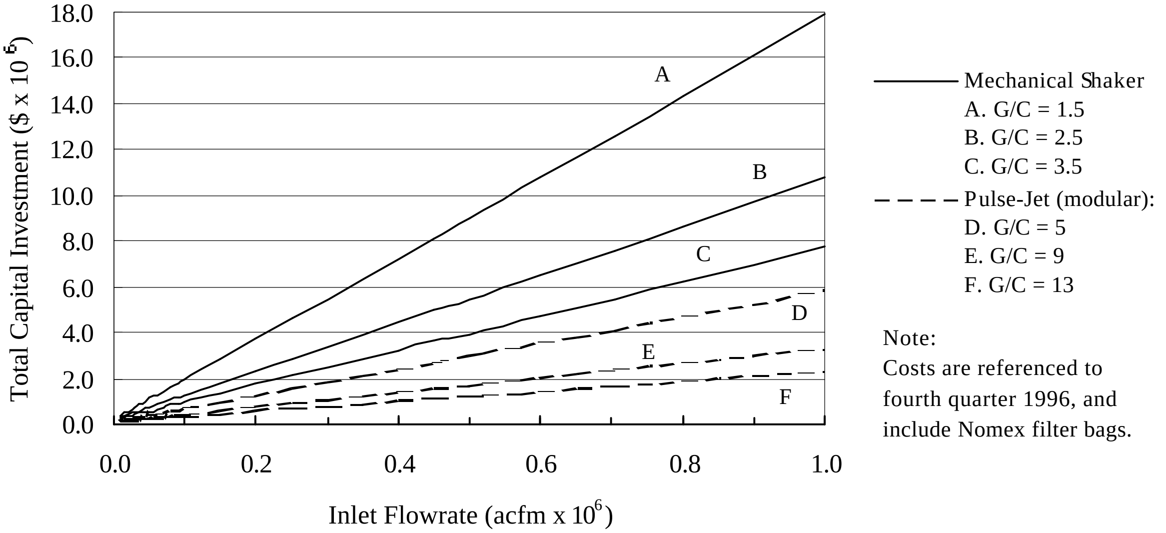
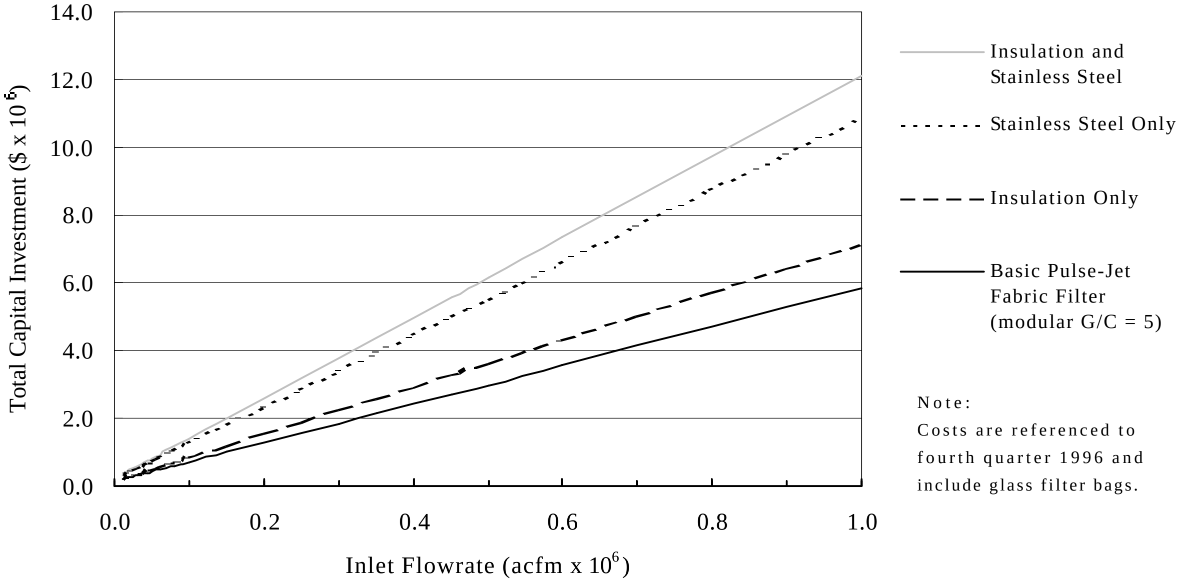


Figure 5.3-10. Effect of Gas-to-Cloth Ratio on Fabric Filter TCI (Reference 17).

Particle Characteristics: Particle size and adhesiveness are particle characteristics that will influence fabric filter design and costs. The G/C ratio should be decreased for small particles and increased for large particles.[1] The adhesive properties of the dust will affect the fabric and cleaning mechanism selection. Higher intensity cleaning mechanisms, like pulse-jet, work best with sticky particles, as well as fabrics with coatings such as teflon or other lubricants.

Gas Stream Characteristics: The two primary stream characteristics that influence fabric filter design and capital costs are the temperature and chemical properties of the gas stream. Both characteristics can have a major impact on the fabric selection, since the available fabrics have widely varying resistances to heat and chemical degradation (see Table 5.3-2 above). In addition, gas stream properties can affect the construction of the fabric filter. High temperature streams require insulation of the fabric filters. Streams with highly corrosive components will need a fabric filter constructed of corrosion-resistant stainless steel. Insulation and corrosion-resistant materials can be very expensive additions to the cost of a fabric filter, as shown in Figure 5.3-11; the use of stainless steel, however, has a greater cost impact on fabric filters than insulation.[17]

Fabric Type: Fabric type is usually selected to a great extent by the type of fabric filter cleaning method, dust type, and the characteristics of the particles and the gas stream. While these factors may limit the choices, there are usually at least two fabrics that can perform satisfactorily in a given situation. There is a wide range of prices among the typical fabrics, but it is not recommended that fabrics be chosen based on cost alone. Some higher priced fabrics



Note:
Costs are referenced to fourth quarter 1996 and include glass filter bags.

Figure 5.3-11. Effect of Insulation and Stainless Steel on Fabric Filter TCI (Reference 17).

have longer operating lives, resulting in lower maintenance and replacement and costs.[4] Figures 5.3-12 and 5.3-13 show capital cost curves for reverse-air and pulse-jet fabric filters, respectively, with typical fabric types.[17]

### 5.3.6.2 Annual Costs

The total annual cost of a fabric filter consists of both direct and indirect costs. Direct annual costs are those associated with the operation and maintenance of the fabric filter. These include labor (operating, supervisory, and maintenance), operating materials, replacement parts, electricity, compressed air (for pulse-jet), and dust disposal.

Disposal costs for collected dusts that have no reuse value can be high, comprising sometimes over 50 percent of the annual costs. Indirect annual costs include taxes, insurance, administrative costs, overhead, and capital recovery costs. All indirect annual costs except overhead are dependent on the TCI. In most cases, annual costs are difficult to generalize because they depend on many factors which can vary widely, even among similar fabric filters. Table 5.3-6 lists the annual cost parameters that impact fabric filter costs, with typical values provided for each parameter. Table 5.3-7 provides the annual cost factors for fabric filters. It is difficult to generalize these costs for all fabric filters, since annual costs are very site-specific.[16]

Electricity costs, however, are a significant portion of the annual costs for most fabric filters. The fabric filters fans consume the majority of the electrical power; the cleaning equipment also requires power. Fan power consumption is directly related to the pressure drop across the fabric filter, which in turn is directly dependent upon the G/C ratio. As the G/C ratio increases, so does the pressure drop and resultant electricity costs. As mentioned above, increasing the G/C ratio will decrease the fabric filters size and capital costs. Fabric filters are generally designed to operate at a specific pressure drop. The G/C ratio should be selected to minimize the annual costs while maintaining the design pressure drop. Power requirements for fans can be calculated by the following relationship:

$$\text{Fan Power (kW-hr/yr)} = 1.81 \times 10^{-4}(V)(\Delta P)(t) \qquad \text{(Eq. 5.3-1)}$$

where $V$ is the gas flow rate (ACFM), $\Delta P$ is the pressure drop (in. $H_2O$), $t$ is the operating hours per year, and $1.81 \times 10^{-4}$ is a unit conversion factor. Once the fan power is determined, it can be multiplied by the cost of electricity (in \$/kW-hr) to determine the electrical costs.[16]

Figure 5.3-14 shows annual operating cost curves for four different fabric filter types.[17] The curves represent annual costs for the same fabric filter designs used in Figure 5.3-9. For each fabric filter type, identical values for the design parameter listed in Table 5.3-6 were used to prepare the curves in both figures. Although the same trend in costs is observed for annual costs as for TCI costs, where reverse-air fabric filter costs are highest and pulse-jet lowest, the advantage of pulse-jet fabric filters in terms of annual costs is not as distinct as with capital costs.

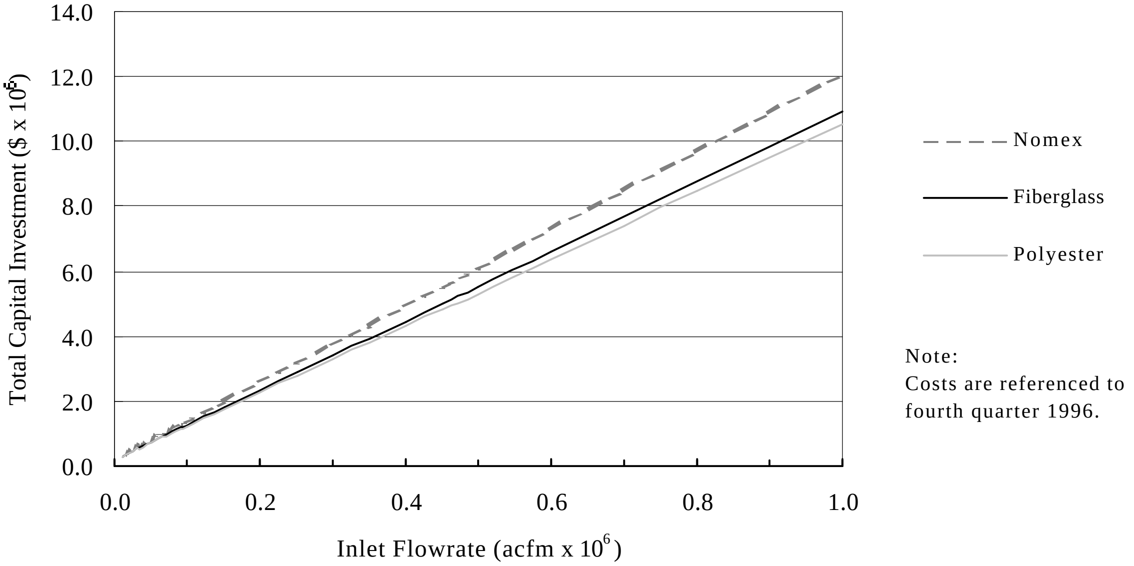


Figure 5.3-12. Effect of Fabric Type on TCI - Reverse-Air Fabric Filter, G/C=2.5 (Reference 17).

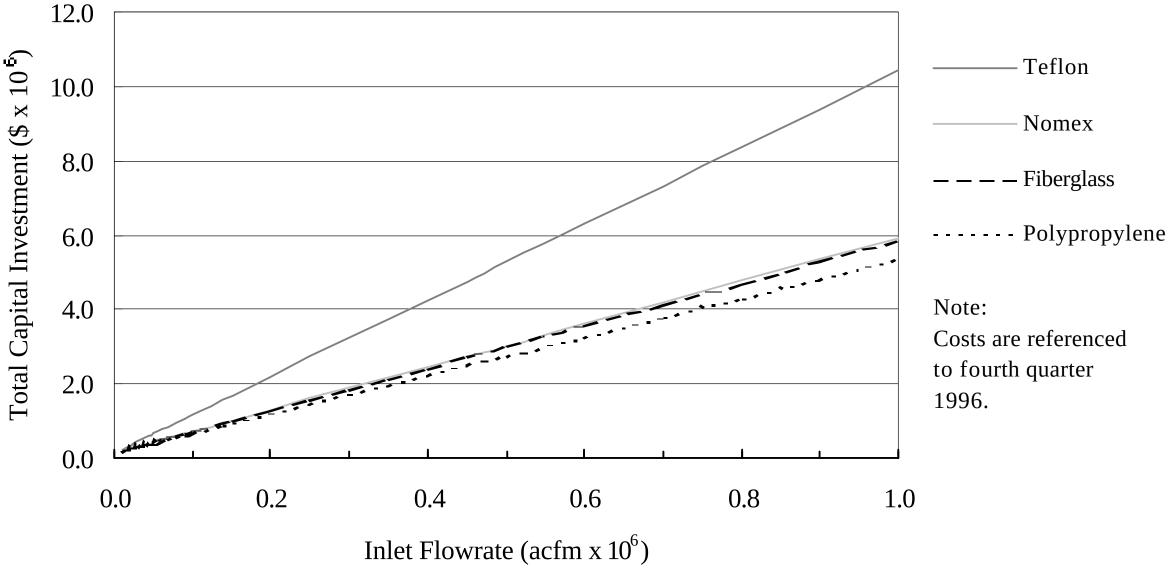


Figure 5.3-13. Effect of Fabric Type on TCI - Pulse-Jet Fabric Filter, G/C=5 (Reference 17).

Table 5.3-6. Annual Cost Parameters for Fabric Filters (Reference 17)

| Parameter | Description | Typical Values |
|---|---|---|
| Direct Cost Parameters | | |
| Operating factor (OF) | Hours of fabric filter operation per year | 8,640 hr/yr |
| Operator labor rate (OR) | Operator labor pay rate | \$12.50/hr[a] |
| Operator shift factor (OS) | Fraction of operator shift on fabric filter | 0.25[b] |
| Maintenance labor rate (MR) | Maintenance labor pay rate | 1.1 x OR[b] |
| Maintenance shift (MS) factor | Fraction of maintenance shift on f.f. | 0.125[b] |
| Electricity rate (ER) | Cost of electricity | \$0.07/kW-hr[a] |
| Compressed air (CA) | Cost of compressed air | \$0.18/1000 scf[a] |
| Dust disposal (DD) | Cost of disposing of dust | \$20-30/ton[a] |
| Bag capital rec. factor (BCRF) | Function of (b) and (i) | 0.5531[c] |
| Indirect Cost Parameters | | |
| Overhead factor (OV) | Fraction of total labor costs | 0.60[b] |
| Annual interest rate (I) | Opportunity cost of the capital | 7 percent[b] |
| Operating life (n) | Expected operating life of fabric filter | 20 years[b] |
| Capital recovery factor (CRF) | Function of (n) and (i) | 0.0944[c] |
| Bag life (b) | Expected operating life of filter bags | 2 years[b] |
| Taxes (TAX) | Fraction of the TCI[d] | 0.01[b] |
| Insurance (INS) | Fraction of the TCI[d] | 0.01[b] |
| Administrative costs (AC) | Fraction of the TCI[d] | 0.02[b] |

[a] Estimated for 1996 from currently available information.

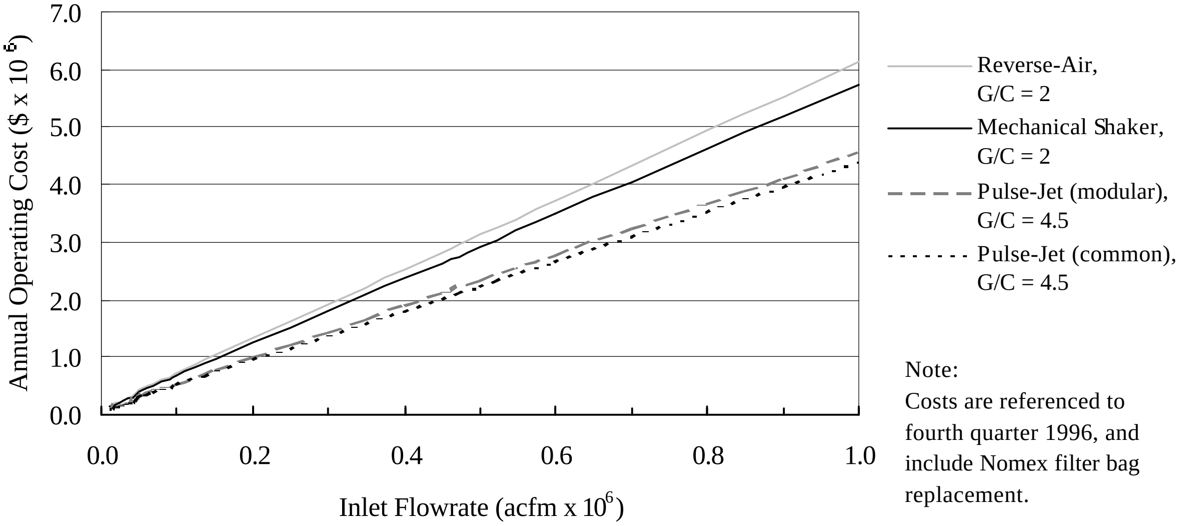
[b] Estimates from "CO$T-AIR" Control Cost Spreadsheets (Reference 17).

[c] Capital Recovery Factor is calculated from the following formula:

$$CRF = \{i(1 + i)n\} \div \{(1 + i)n - 1\},$$

where $i$ = interest rate (fraction) and $n$ (or $b$) = operating life (years).

[d] The total capital investment (TCI) can be escalated to current values by using the Vatavuk Air Pollution Control Cost Indicies (VAPCCI), described in Appendix B.



Note:
Costs are referenced to fourth quarter 1996, and include Nomex filter bag replacement.

Figure 5.3-14. Annual Fabric Filter Operating Costs (Reference 17).

Table 5.3-7. Annual Cost Factors for Fabric Filters (Reference 17).

| Cost Item | Formula[a] | Factor |
|---|---|---|
| Direct Costs | | |
| Labor | | |
| Operator (OL) | (OF)×(OR)×(OS) | A |
| Maintenance (ML) | (OF)×(MR)×(MS) | 0.55 A |
| Electricity (E) | Power[b] × (ER) | E |
| Compressed air (C) | (CA) × scf per year | C |
| Dust disposal (D) | (DD) × tons per year | D |
| Bag Capital Recovery | (BCRF)×(BAG)[c] | 0.5531 BAG |
| Total Direct Cost (DC) | | 1.55 A + E + C + D + 0.5531 BAG |
| Indirect Costs | | |
| Overhead | (OV)×(OL+ML) | 0.93 A |
| Capital Recovery | (CRF)×(TCI) | 0.0944 TCI |
| Taxes | (TAX)×(TCI) | 0.01 TCI |
| Insurance | (INS)×(TCI) | 0.01 TCI |
| Administrative Costs | (AC)×(TCI) | 0.02 TCI |
| Total Indirect Cost (IC) | | 0.93 A + 0.1344 TCI |
| Total Annual Cost (DC + IC) | | 2.48 A + 0.1344 TCI + 0.5531 BAG + E + C + D |

[a] Includes values also described in Table 5.3-6.

[b] Equal to total power requirements, e.g. fan, shaker, etc.

[c] BAG = the capital cost of the filter bags only.

### 5.3.7 Energy and Other Secondary Environmental Impacts

The vast majority of energy demands for fabric filters are for fan operation. Other minor energy requirements are for cleaning mechanism operation and air compression. The fan power requirements can be calculated from the above mentioned formula. Energy requirements for cleaning mechanisms are very site specific.[16]

The major secondary environmental impact of fabric filters is the generation of solid waste. Fabric filters collect large amounts of particulate matter, which must be disposed of in many cases. The characteristics of the waste are ultimately dependent on the specific installation. In most applications fabric filters collect dust which is nontoxic and suitable for landfilling, but some dusts are valuable and can be recycled or sold. In some applications, fabric filters may collect dusts which are toxic or hazardous. Such dusts will require special handling and treatment prior to disposal.[2]

### 5.3.8 References for Section 5.3

1. Cooper, C.D and F.C. Alley. *Air Pollution Control: A Design Approach.* 2nd ed. Waveland Press, Prospect Heights, Illinois. 1994.

2. The Fabric Filter Manual (Revised). The McIlvaine Company, Northbrook, Illinois. March 1996.

3. Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-81-005a, NTIS PB83-127498). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. September 1982.

4. McKenna, J.D. and J.H. Turner. *Fabric Filter-Baghouses I: Theory, Design, and Selection (A Reference Text).* ETS Inc., Roanoke, Virginia. 1993.

5. Jensen, R.M. Give Reverse-air Fabric Filters a Closer Look. Power, 139:2. February 1995.

6. Schlotens, M.J. Air Pollution Control: A Comprehensive Look. Pollution Engineering. May 1991.

7. Pontius, D.H. Characterization of Sonic Devices Used for Cleaning Fabric Filters. J. Air Pollution Control Association. 35:1301. December 1985.

8. Belba, V.H., W.T. Grubb, and R. Chang. The Potential of Pulse-Jet Baghouses for Utility Boilers. Part 1: A Worldwide Survey of Users. Journal of the Air and Waste Management Association. 42:2. February 1992.

9. Carr, R.C. Pulse-Jet Fabric Filters Vie for Utility Service. Power. December 1988.

10. Carr, R.C. and W.B. Smith. Fabric Filter Technology for Utility Coal-Fired Power Plants, Part V: Development and Evaluation of Bag Cleaning Methods in Utility Baghouses. J. Air Poll. Control Assoc. 34(5):584. May 1984.

11. Oglesby, S., Jr. Future Directions of Particulate Control Technology: A Perspective. J. Air Waste Management Assoc. 40(8): 1184-1185. August 1990.

12. Grafe, T. and K. Gregg. Baghouse and Cartridge Dust Collectors: A Comparison. American Ceramic Society Bulletin. 72:9. September 1993.

13. Parkinson, G. A Hot and Dirty Future For Baghouses. Chemical Engineering. April 1989.

14. Croom, M.L. New Developments in Filter Dust Collection. Chemical Engineering. February 1996.

15. Compilation of Air Pollutant Emission Factors (AP-42). Volume I (Fifth Edition). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. January 1995.

16. OAQPS Control Cost Manual (Fourth Edition, EPA 450/3-90-006) U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. January 1990.

17. Vatavuk, W.M. "CO$T-AIR" Control Cost Spreadsheets. Provided by the Innovative Strategies and Economics Group of the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. February 1996.

## 5.4 WET SCRUBBERS

Wet scrubbers are PM control devices that rely on direct and irreversible contact of a liquid (droplets, foam, or bubbles) with the PM. The liquid with the collected PM is then easily collected. Scrubbers can be very specialized and designed in many different configurations. Wet scrubbers are generally classified by the method that is used to induce contact between the liquid and the PM, e.g. spray, packed-bed, plate. Scrubbers are also often described as low-, medium-, or high-energy, where energy is often expressed as the pressure drop across the scrubber. This section addresses the basic operating principles, designs, collection efficiency, applicability, and costs of wet scrubbers.

Wet scrubbers have important advantages when compared to other PM collection devices. They can collect flammable and explosive dusts safely, absorb gaseous pollutants, and collect mists. Scrubbers can also cool hot gas streams. There are also some disadvantages associated with wet scrubbers. For example, scrubbers have the potential for corrosion and freezing. Additionally, the use of wet scrubbers can lead to water and solid waste pollution problems.[1] These disadvantages can be minimized or avoided with good scrubber design.

### 5.4.1 Particle Collection and Penetration Mechanisms

The dominant means of PM capture in most industrial wet scrubbers is inertial impaction of the PM onto liquid droplets. Brownian diffusion also leads to particle collection, but its effects are only significant for particles approximately 0.1 micrometer (μm) in diameter or less.[2] Direct interception is another scrubber collection mechanism. Less important scrubber collection mechanisms utilize gravitation, electrostatics, and condensation.[2]

Inertial impaction in wet scrubbers occurs as a result of a change in velocity between PM suspended in a gas, and the gas itself. As the gas approaches an obstacle, such as a liquid droplet, the gas changes direction and flows around the droplet. The particles in the gas will also accelerate and attempt to change direction to pass around the droplet. Inertial forces will attempt to maintain the forward motion of the particle towards the object, but the fluid force will attempt to drag the particle around the droplet with the gas. The resultant particle motion is a combination of these forces of fluid drag and inertia. This results in impaction for the particles where inertia dominates, and by-pass for those particles overwhelmed by fluid drag.[2] Large particles, particles i.e. greater than 10 $\mu$m are more easily collected by inertial impaction because these particles have more inertial momentum to resist changes in the flow of the gas and, therefore, impact the droplet. Small particles (i.e. particles <1 $\mu$m) are more difficult to collect by inertial impaction because they remain in the flow lines of the gas due to the predominance of the fluid drag force.

Collection by diffusion occurs as a result of both fluid motion and the Brownian (random) motion of particles. This particle motion in the scrubber chamber results in direct particle-liquid contact. Since this contact is irreversible, collection of the PM by the liquid occurs. Diffusional collection effects are most significant for particles less than 0.1 μm in diameter.[2] Direct interception occurs when the path of a particle comes within one radius of the collection medium, which in a scrubber is a liquid droplet. The path can be the result of inertia, diffusion, or fluid motion.[2]

Gravitational collection as a result of falling droplets colliding with particles is closely related to impaction and interception, and is a minor mechanism in some scrubbers.[2] Gravitational settling of particles is usually not a factor because of high gas velocities and short residence times.[3] Generally, electrostatic attraction is not an important mechanism except in cases where the particles, liquid, or both, are being deliberately charged, or where the scrubber follows an electrostatic precipitator.[3] Some scrubbers are designed to enhance particle capture through condensation. In such cases, the dust-laden stream is supersaturated with liquid (usually water). The particles then act as condensation nuclei, growing in size as more liquid condenses around them and becoming easier to collect by inertial impaction.[2,4]

The collection mechanisms of wet scrubbers are highly dependent on particle size. Inertial impaction is the major collection mechanism for particles greater than approximately 0.1 µm in diameter. The effectiveness of inertial impaction increases with increasing particle size. Diffusion is generally effective only for particles less than 0.1 µm in diameter, with collection efficiency increasing with decreasing particle size. The combination of these two major scrubber collection mechanisms contributes to a minimum collection efficiency for PM approximately 0.1 µm in diameter.[5] The exact minimum efficiency for a specific scrubber will depend on the type of scrubber, operating conditions, and the particle size distribution in the gas stream. Scrubber collection efficiency is discussed in more detail in Section 5.4.3.

### 5.4.2 Types of Wet Scrubbers

There are a great variety of wet scrubbers that are either commercially available or can be custom designed. While all wet scrubbers are similar to some extent, there are several distinct methods of using the scrubbing liquid to achieve particle collection. Wet scrubbers are usually classified according to the method that is used to contact the gas and the liquid.

The most common scrubber design is the introduction of liquid droplets into a spray chamber, where the liquid is mixed with the gas stream to promote contact with the PM. In a packed-bed scrubber, layers of liquid are used to coat various shapes of packing material that become impaction surfaces for the particle-laden gas. Scrubber collection can also be achieved by forcing the gas at high velocities though a liquid to form jet streams. Liquids are also used to supersaturate the gas stream, leading to particle scrubbing by condensation.

#### 5.4.2.1 Spray Chambers

Spray chambers are very simple, low-energy wet scrubbers. In these scrubbers, the particulate-laden gas stream is introduced into a chamber where it comes into contact with liquid droplets generated by spray nozzles. These scrubbers are also known as pre-formed spray scrubbers, since the liquid is formed into droplets prior to contact with the gas stream. The size of the droplets generated by the spray nozzles is controlled to maximize liquid-particle contact and, consequently, scrubber collection efficiency.

The common types of spray chambers are spray towers and cyclonic chambers. Spray towers are cylindrical or rectangular chambers that can be installed vertically or horizontally. In vertical spray towers, the gas stream flows up through the chamber and encounters several sets of spray nozzles producing liquid droplets. A de-mister at the top of the spray tower removes liquid droplets and wetted PM from the exiting gas stream. Scrubbing liquid and wetted PM also drain from the bottom of the tower in the form of a slurry. Horizontal spray chambers operate in the same manner, except for the fact that the gas flows horizontally through the device. A typical spray tower is shown in Figure 5.4-1.[1,2,5]

A cyclonic spray chamber is similar to a spray tower with one major difference. The gas stream is introduced to produce cyclonic motion inside the chamber. This motion contributes to higher gas velocities, more effective particle and droplet separation, and higher collection efficiency.[1] Tangential inlet or turning vanes are common means of inducing cyclonic motion.[5] Figure 5.4-2 provides an example of a cyclonic spray chamber.

### 5.4.2.2 Packed-Bed Scrubbers

Packed-bed scrubbers consist of a chamber containing layers of variously-shaped packing material, such as raschig rings, spiral rings, and berl saddles, that provide a large surface area for liquid-particle contact. These and other types of packings are illustrated in Figure 5.4-3.[2,5] The packing is held in place by wire mesh retainers and supported by a plate near the bottom of the scrubber. Scrubbing liquid is evenly introduced above the packing and flows down through the bed. The liquid coats the packing and establishes a thin film. In vertical designs, the gas stream flows up the chamber (countercurrent to the liquid). Some packed beds are designed horizontally for gas flow across the packing (crosscurrent).

In packed-bed scrubbers, the gas stream is forced to follow a circuitous path through the packing, on which much of the PM impacts. The liquid on the packing collects the PM and flows down the chamber towards the drain at the bottom of the tower. A mist eliminator (also called a "de-mister") is typically positioned above/after the packing and scrubbing liquid supply. Any scrubbing liquid and wetted PM entrained in the exiting gas stream will be removed by the mist eliminator and returned to drain through the packed bed. A typical packed-bed scrubber is illustrated in Figure 5.4-4.[2,5]

In a packed-bed scrubber, high PM concentrations can clog the bed, hence, the limitation of these devices to streams with relatively low dust loadings.[5] Plugging is a serious problem for packed-bed scrubbers because the packing is more difficult to access and clean than other scrubber designs.[2] Mobile-bed scrubbers are available that are packed with low-density plastic spheres that are free to move within the packed bed.[5] These scrubbers are less susceptible to plugging because of the increased movement of the packing material. In general, packed-bed scrubbers are more suitable for gas scrubbing than particulate scrubbing because of the high maintenance requirements for control of PM.[1,2]

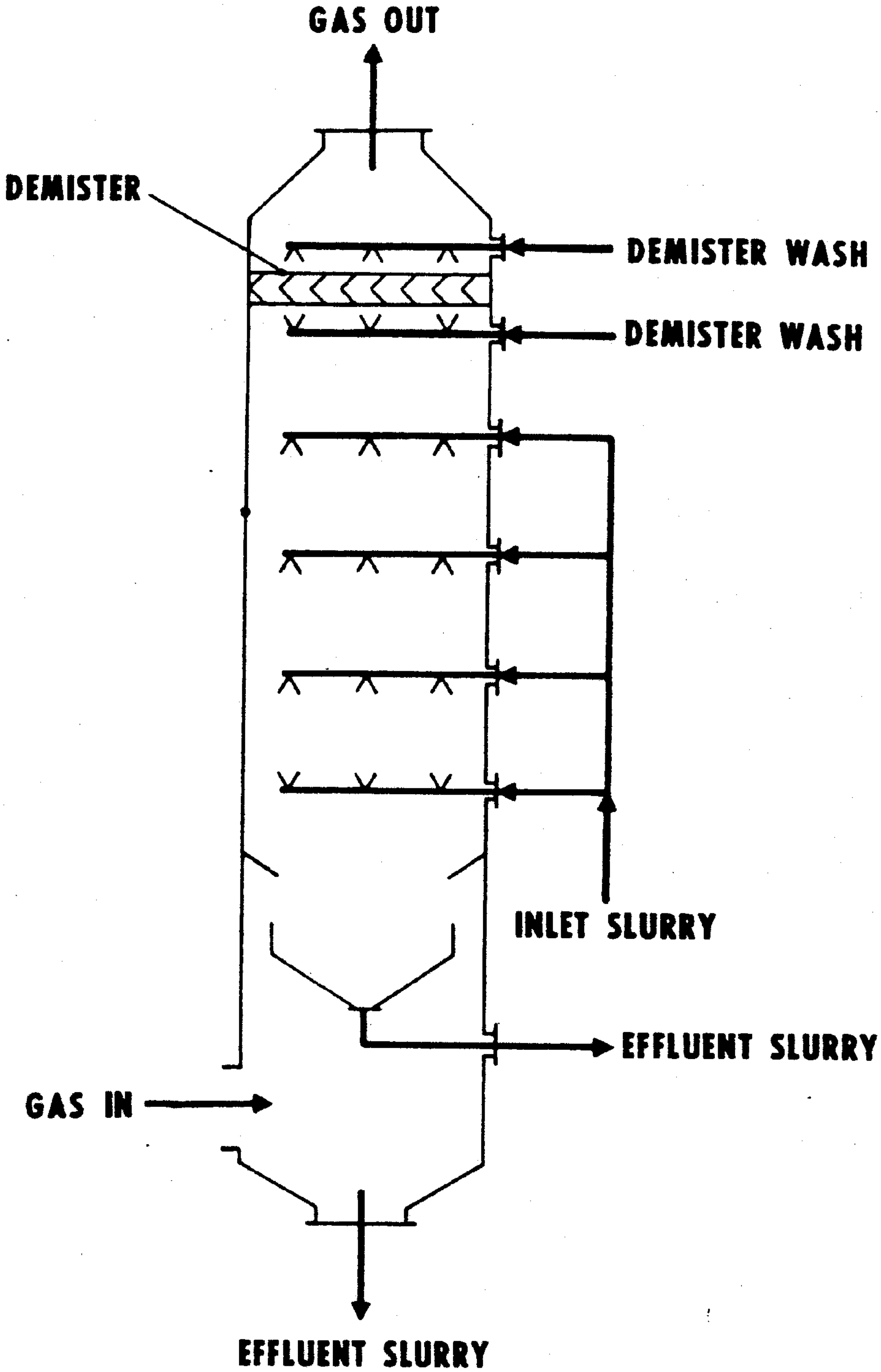


Figure 5.4-1. Schematic Diagram of a Spray Tower Scrubber (Reference 2).

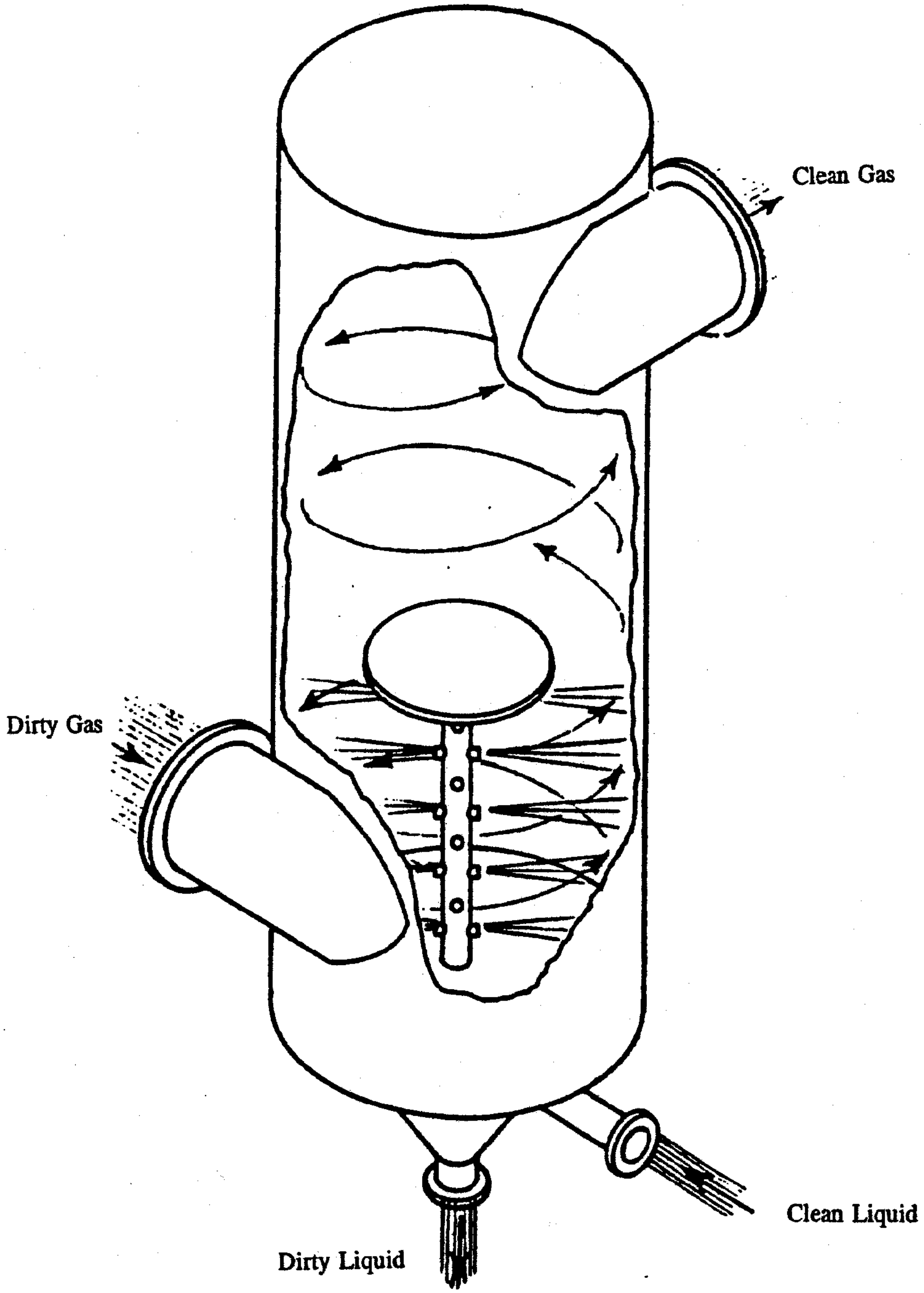


Figure 5.4-2. Schematic Diagram of a Cyclonic Spray Chamber Scrubber (Reference 1).

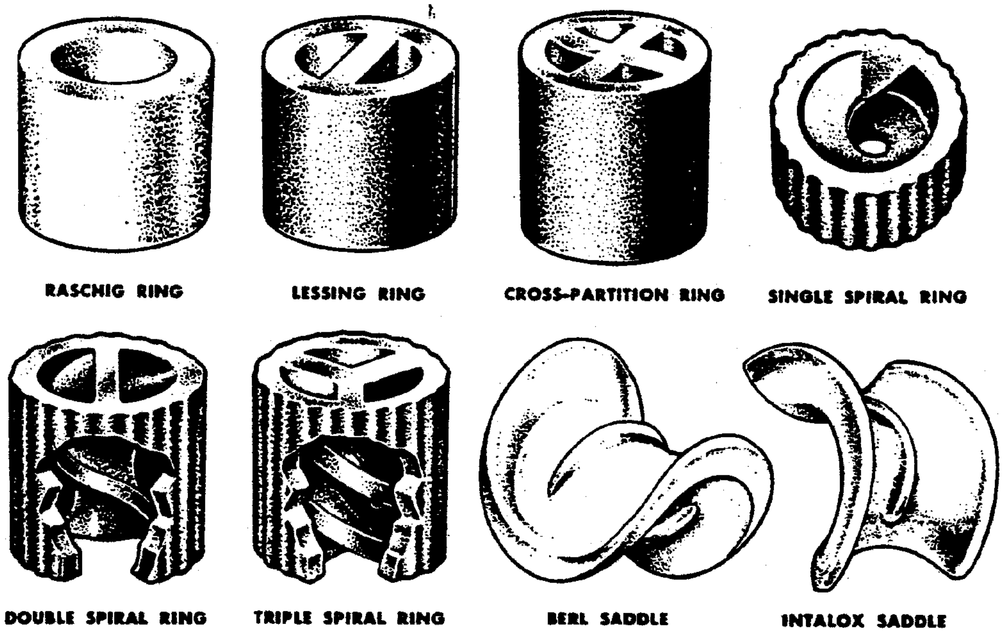


Figure 5.4-3. Typical Packing Materials for Packed Bed Scrubbers (Reference 2).

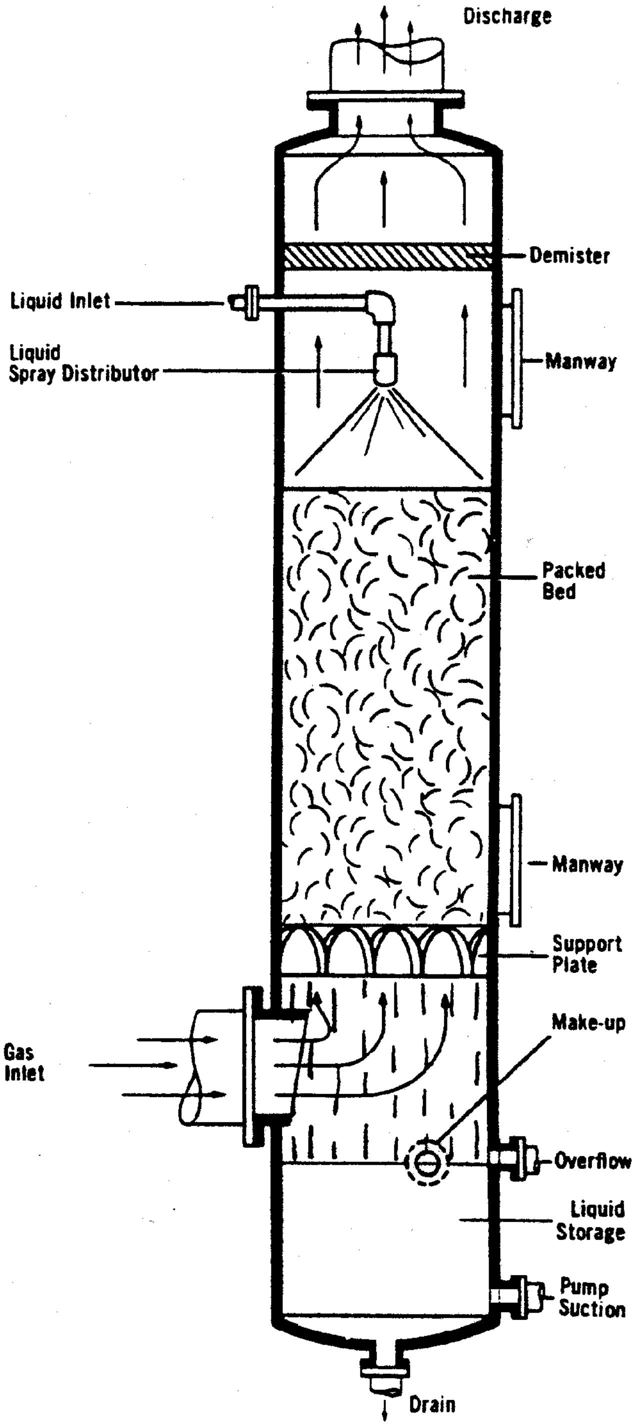


Figure 5.4-4. Schematic Diagram of a Packed Tower Scrubber (Reference 2).

### 5.4.2.3 Impingement Plate Scrubbers

An impingement plate scrubber is a vertical chamber with plates mounted horizontally inside a hollow shell. Impingement plate scrubbers operate as countercurrent PM collection devices. The scrubbing liquid flows down the tower while the gas stream flows upward. Contact between the liquid and the particle-laden gas occurs on the plates. The plates are equipped with openings that allow the gas to pass through. Some plates are perforated or slotted, while more complex plates have valve-like openings. Figure 5.4-5 shows common plate designs used in impingement plate scrubbers.[2,5]

The simplest impingement plate is the sieve plate, which has round perforations. In this type of scrubber, the scrubbing liquid flows over the plates and the gas flows up through the holes. The gas velocity prevents the liquid from flowing down through the perforations. Gas-liquid-particle contact is achieved within the froth generated by the gas passing through the liquid layer. Complex plates, such as bubble cap or baffle plates, introduce an additional means of collecting PM. The bubble caps and baffles placed above the plate perforations force the gas to turn before escaping the layer of liquid. While the gas turns to avoid the obstacles, most PM cannot and is collected by impaction on the caps or baffles. Bubble caps and the like also prevent liquid from flowing down the perforations if the gas flow is reduced.

In all types of impingement plate scrubbers, the scrubbing liquid flows across each plate and down the inside of the tower onto the plate below. After the bottom plate, the liquid and collected PM flow out of the bottom of the tower. A typical impingement plate scrubber is shown in Figure 5.4-6.[2,5] Impingement plate scrubbers are usually designed to provide operator access to each tray, making them relatively easy to clean and maintain.[2] Consequently, impingement plate scrubbers are more suitable for PM collection than packed-bed scrubbers. Particles greater than 1 µm in diameter can be collected effectively by impingement plate scrubbers, but many particles <1 $\mu$m will penetrate these devices.[5]

### 5.4.2.4 Mechanically-aided Scrubbers

Mechanically-aided scrubbers (MAS) employ a motor driven fan or impeller to enhance gas-liquid contact. Generally in MAS, the scrubbing liquid is sprayed onto the fan or impeller blades. Fans and impellers are capable of producing very fine liquid droplets with high velocities. These droplets are effective in contacting fine PM. Once PM has impacted on the droplets, it is normally removed by cyclonic motion. Mechanically aided scrubbers are capable of high collection efficiencies, but only with a commensurate high energy consumption. An example of a mechanically aided scrubber is provided in Figure 5.4-7.[1,2,5]

Because many moving parts are exposed to the gas and scrubbing liquid in a MAS, these scrubbers have high maintenance requirements. Mechanical parts are susceptible to corrosion, PM buildup, and wear. Consequently, mechanical scrubbers have limited applications for PM control.[2,5]

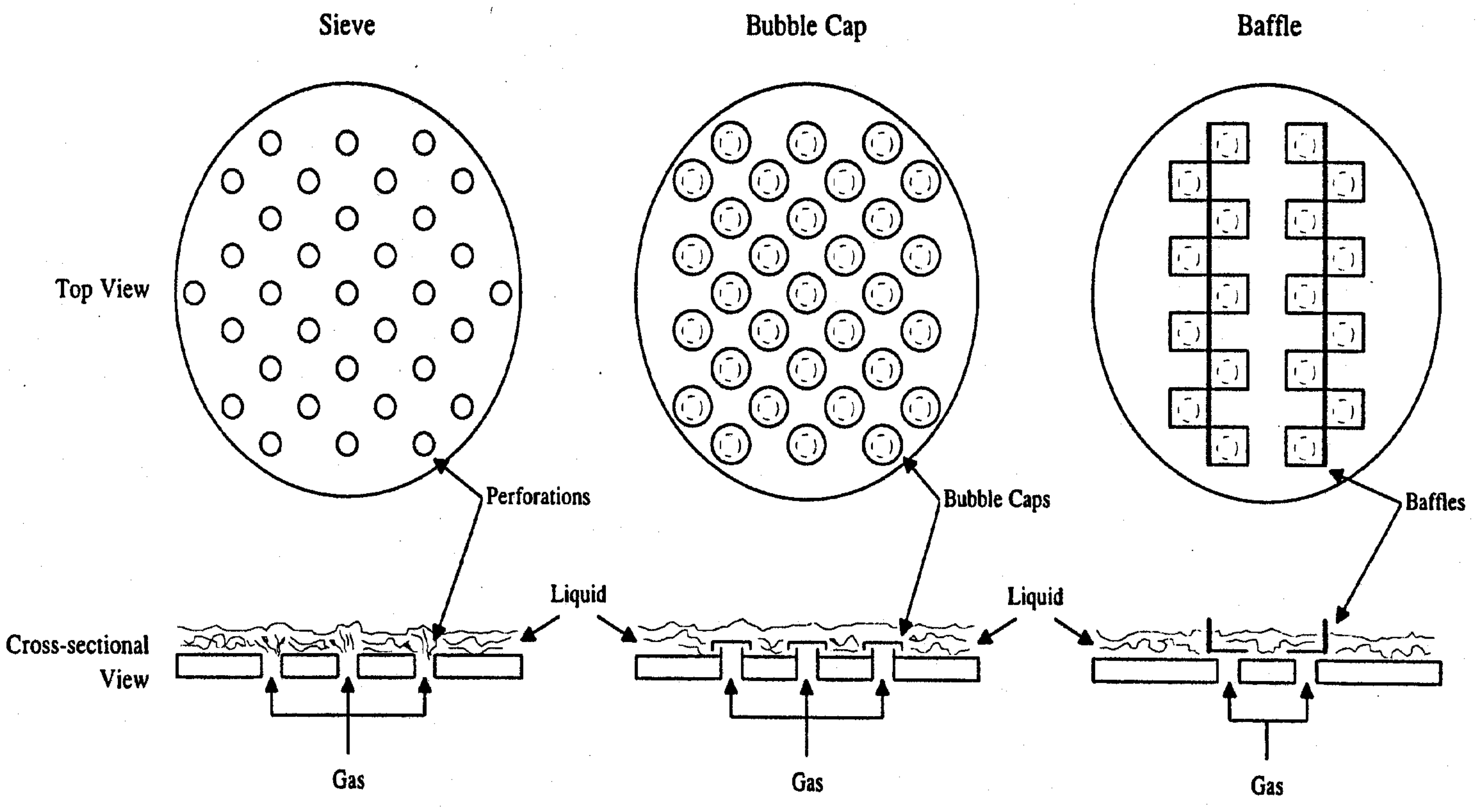


Figure 5.4-5. Common Plate Designs for Impingement Plate Scrubbers (adapted from Reference 2).

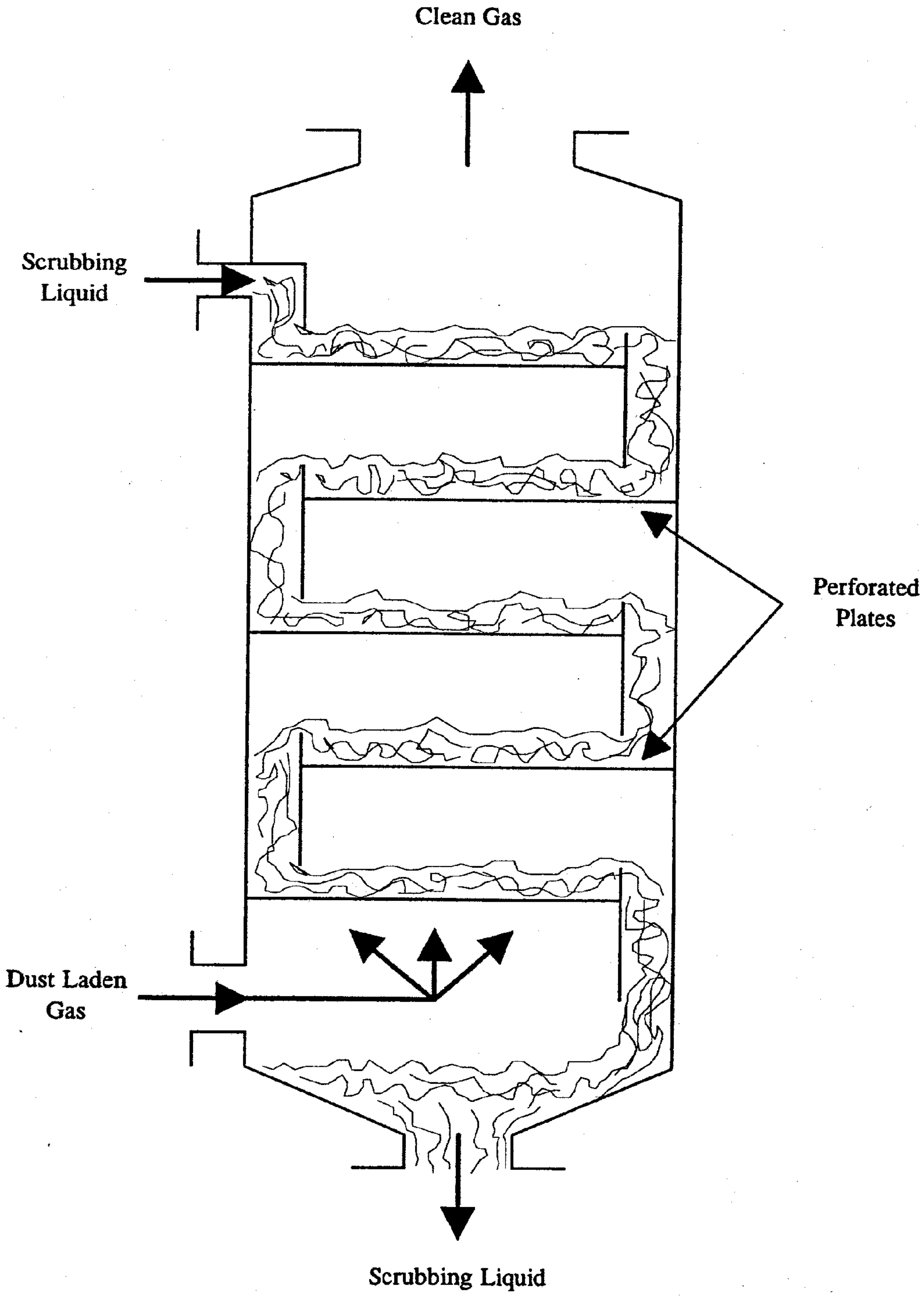


Figure 5.4-6. Schematic Diagram of a Plate Tower Scrubber (adapted from Reference 2).

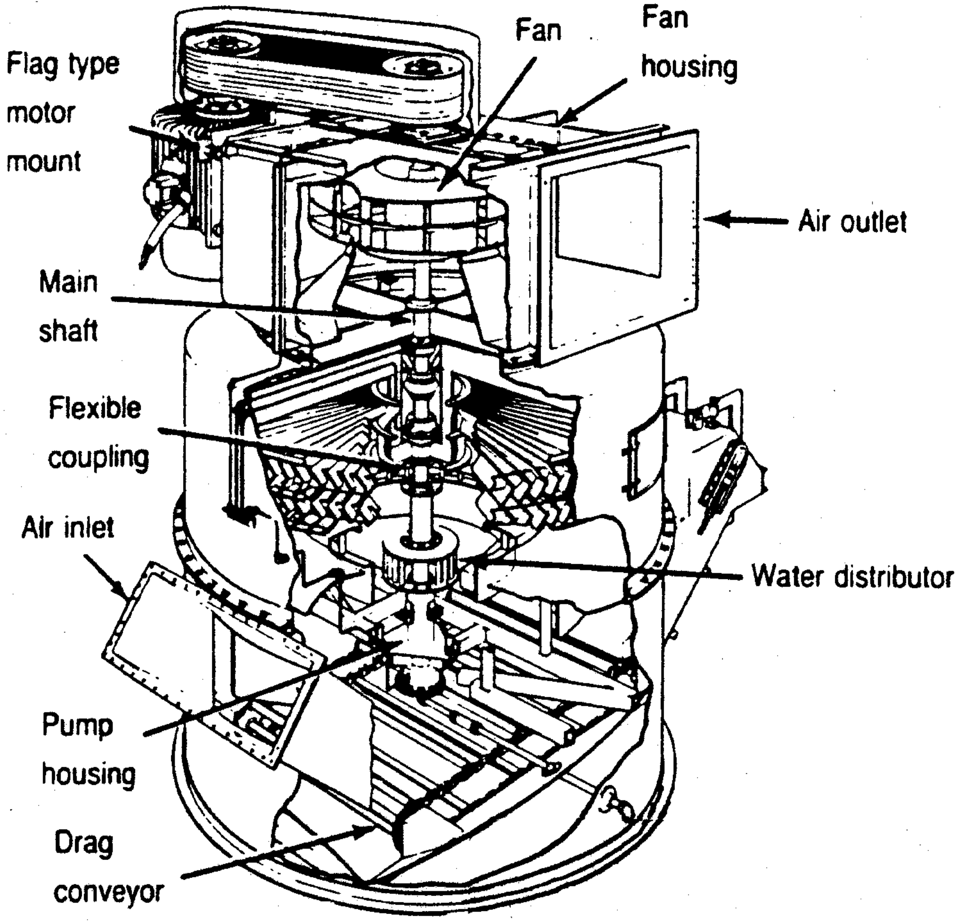


Figure 5.4-7. Diagram of a Mechanically-aided Scrubber (Reference 1).

### 5.4.2.5 Venturi Scrubbers

A venturi, or gas-atomized spray, scrubber accelerates the gas stream to atomize the scrubbing liquid and to improve gas-liquid contact. In a venturi scrubber, a "throat" section is built into the duct that forces the gas stream to accelerate as the duct narrows and then expands. As the gas enters the venturi throat, both gas velocity and turbulence increase. The scrubbing liquid is sprayed into the gas stream before the gas encounters the venturi throat. The scrubbing liquid is then atomized into small droplets by the turbulence in the throat and droplet-particle interaction is increased. After the throat section in a venturi scrubber, the wetted PM and excess liquid droplets are separated from the gas stream by cyclonic motion and/or a mist eliminator. Venturi scrubbers have the advantage of being simple in design, easy to install, and with low-maintenance requirements.[1] An example of a venturi scrubber is provided in Figure 5.4-8.

The performance of a venturi scrubber is dependent to some extent on the velocity of the gas through the throat. Several venturi scrubbers have been designed to allow velocity control by varying the width of the venturi throat.[2,5] Because of the high interaction between the PM and droplets, venturi scrubbers are capable of high collection efficiencies for small PM. Unfortunately, increasing the venturi scrubber efficiency requires increasing the pressure drop which, in turn, increases the energy consumption.[1]

### 5.4.2.6 Orifice Scrubbers

Orifice scrubbers, also known as entrainment or self-induced spray scrubbers, force the particle-laden gas stream to pass over the surface of a pool of scrubbing liquid as it enters an orifice. With the high gas velocities typical of this type of scrubber, the liquid from the pool becomes entrained in the gas stream as droplets. As the gas velocity and turbulence increases with the passing of the gas through the narrow orifice, the interaction between the PM and liquid droplets also increases. Particulate matter and droplets are then removed from the gas stream by impingement on a series of baffles that the gas encounters after the orifice. The collected liquid and PM drain from the baffles back into the liquid pool below the orifice.[2,5] Orifice scrubbers can effectively collect particles larger than 2 µm in diameter.[1,5] Some orifice scrubbers are designed with adjustable orifices to control the velocity of the gas stream. A typical orifice scrubber is shown in Figure 5.4-9.

Orifice scrubbers usually have low liquid demands, since they use the same scrubbing liquid for extended periods of time.[1] Because orifice scrubbers are relatively simple in design and usually have few moving parts, the major maintenance concern is the removal of the sludge which collects at the bottom of the scrubber. Orifice scrubbers rarely drain continually from the bottom because a static pool of scrubbing liquid is needed at all times. Therefore, the sludge is usually removed with a sludge ejector that operates like a conveyor belt. As the sludge settles to the bottom of the scrubber, it lands on the ejector and is conveyed up and out of the scrubber. Figure 5.4-10 shows a typical sludge ejector.[2]

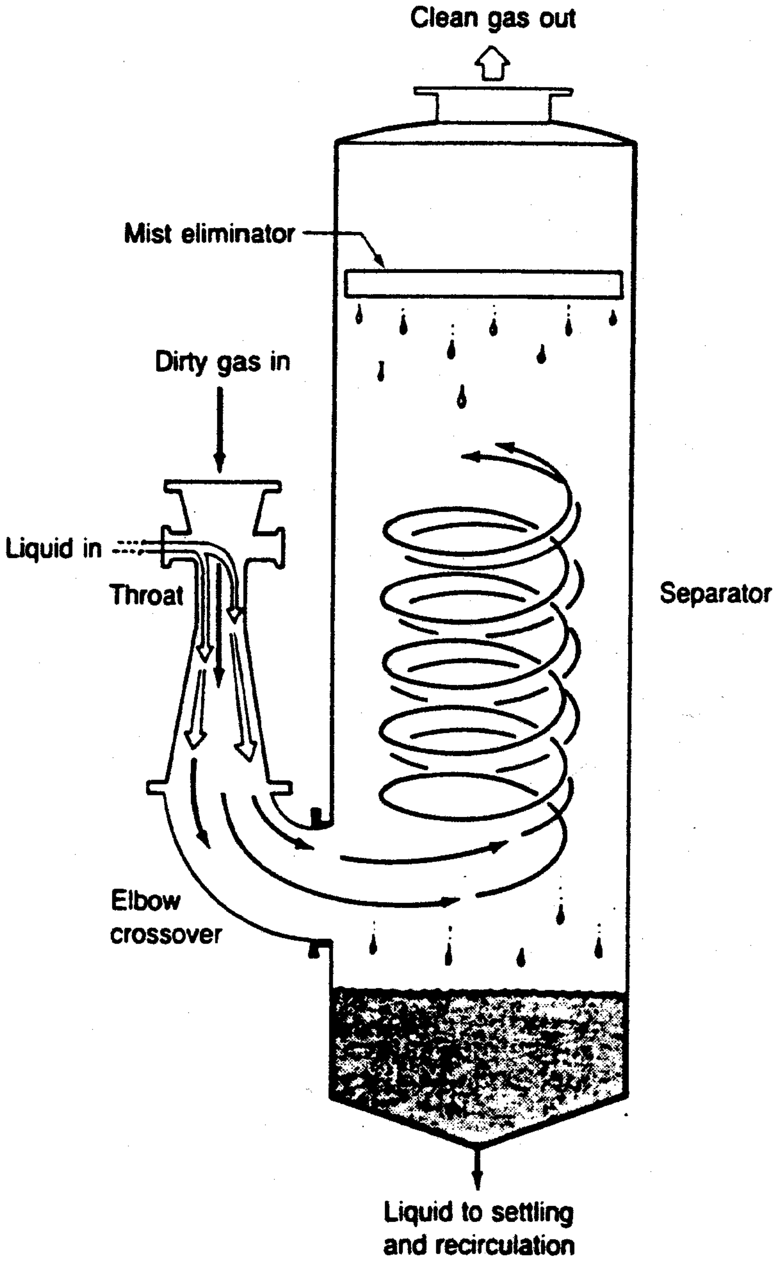


Figure 5.4-8. Schematic Diagram of a Venturi Scrubber with Cyclonic Separation (Reference 1).

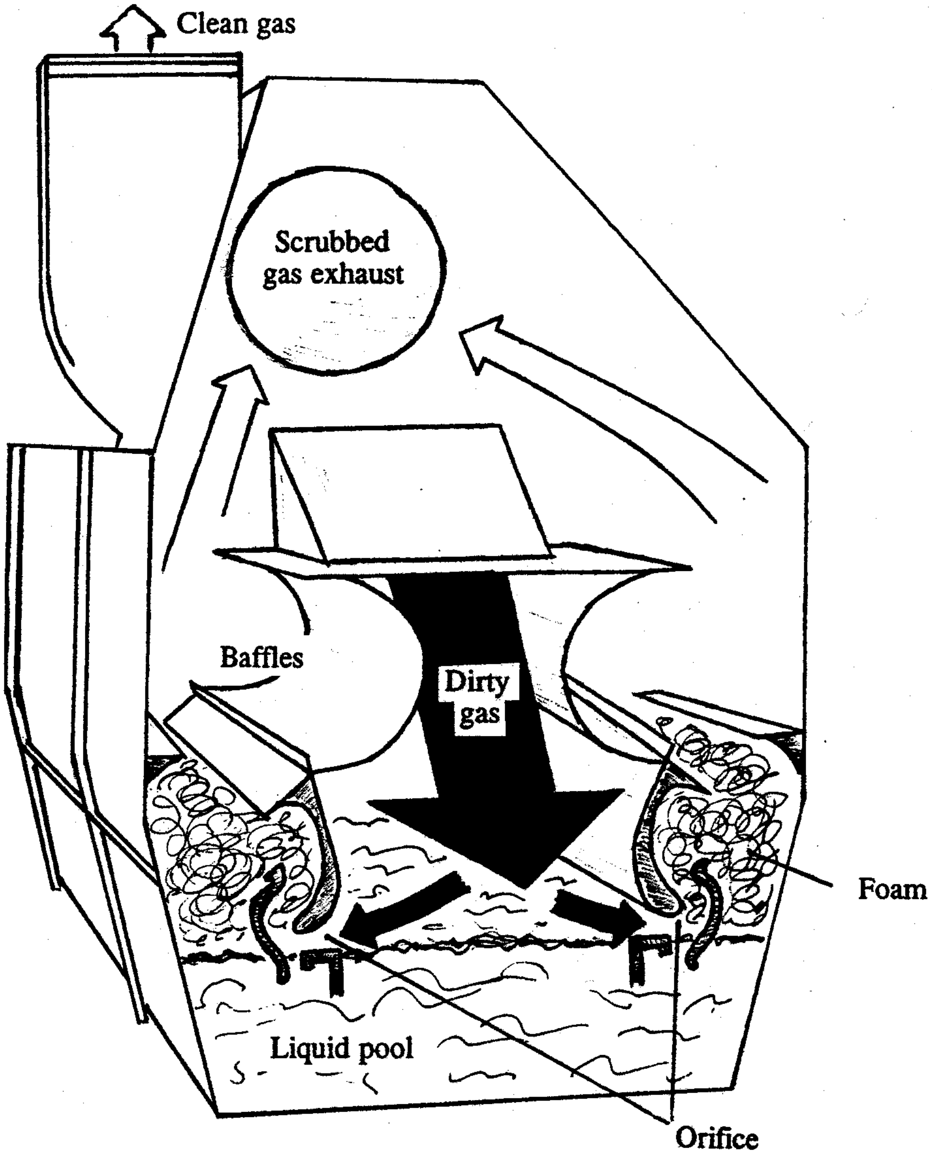


Figure 5.4-9. Diagram of an Orifice Scrubber (Reference 1).

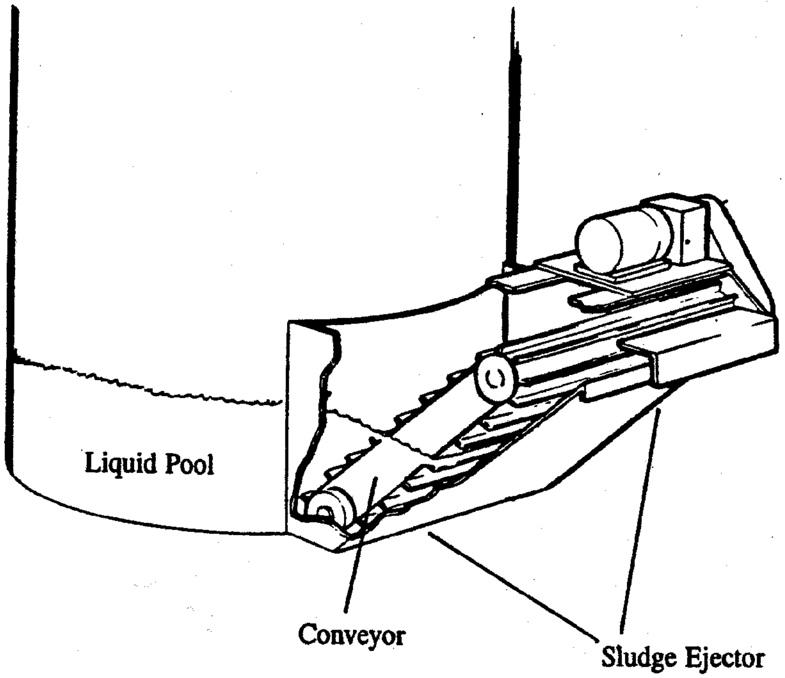


Figure 5.4-10. Diagram of a Sludge Ejector in an Orifice Scrubber (Reference 2).

### 5.4.2.7 Condensation Scrubbers

Condensation scrubbing is a relatively recent development in wet scrubber technology. Most conventional scrubbers rely on the mechanisms of impaction and diffusion to achieve contact between the PM and liquid droplets. In a condensation scrubber, the PM act as condensation nuclei for the formation of droplets. Generally, condensation scrubbing depends on first establishing saturation conditions in the gas stream. Once saturation is achieved, steam is injected into the gas stream. The steam creates a condition of supersaturation and leads to condensation of water on the fine PM in the gas stream. The large condensed droplets can be removed by several conventional devices. Typically, a high efficiency mist eliminator is also used.[2,4]

A high-efficiency condensation "growth" PM scrubber has been developed that is suitable for both new and retrofit installations, and is designed specifically to capture fine PM that escapes primary PM control devices. This type of scrubber utilizes a multistage process, including pretreatment and growth chambers, that provide an environment that encourages the fine PM to coagulate and form larger particles. A schematic diagram of this scrubber is provided in Figure 5.4-11.[4]

### 5.4.2.8 Charged Scrubbers

Charged, or electrically-augmented, wet scrubbers utilize electrostatic effects to improve collection efficiencies for fine PM with wet scrubbing. Since conventional wet scrubbers rely on the inertial impaction between PM and liquid droplets for PM collection, they are generally ineffective for particles with diameters less than 1 µm. Pre-charging of the PM in the gas stream can significantly increase scrubber collection efficiency for these submicrometer particles. When both the particles and droplets are charged, collection efficiencies for submicrometer particles are highest, approaching that of an ESP.[2]

There are several types of charged wet scrubbers. Particulate matter can be charged negatively or positively, with the droplets given the opposite charge. The droplets may also be bipolar (a mixture of positive and negative). In this case, the PM can be either bipolar or unipolar. Figure 5.4-12 is a schematic of a charged wet scrubber.[2]

### 5.4.2.9 Fiber-Bed Scrubbers

In a fiber-bed scrubbers, the moisture-laden gas stream passes through mats of packing fibers, such as spun glass, fiberglass, and steel. The fiber mats are often also spray wetted with the scrubbing liquid. Depending on the scrubber requirements, there may be several fiber mats and an impingement device for PM removal included in the design. The final fiber mat is typically dry for the removal of any droplets that are still entrained in the stream. Fiber-bed scrubbers are best suited for the collection of soluble PM, i.e. PM that dissolves in the scrubber liquid, since large amounts of insoluble PM will clog the fiber mats with time. For this reason, fiber-bed scrubbers are more often used as mist eliminators, i.e., for the collection of liquids, rather than for PM control.[2]

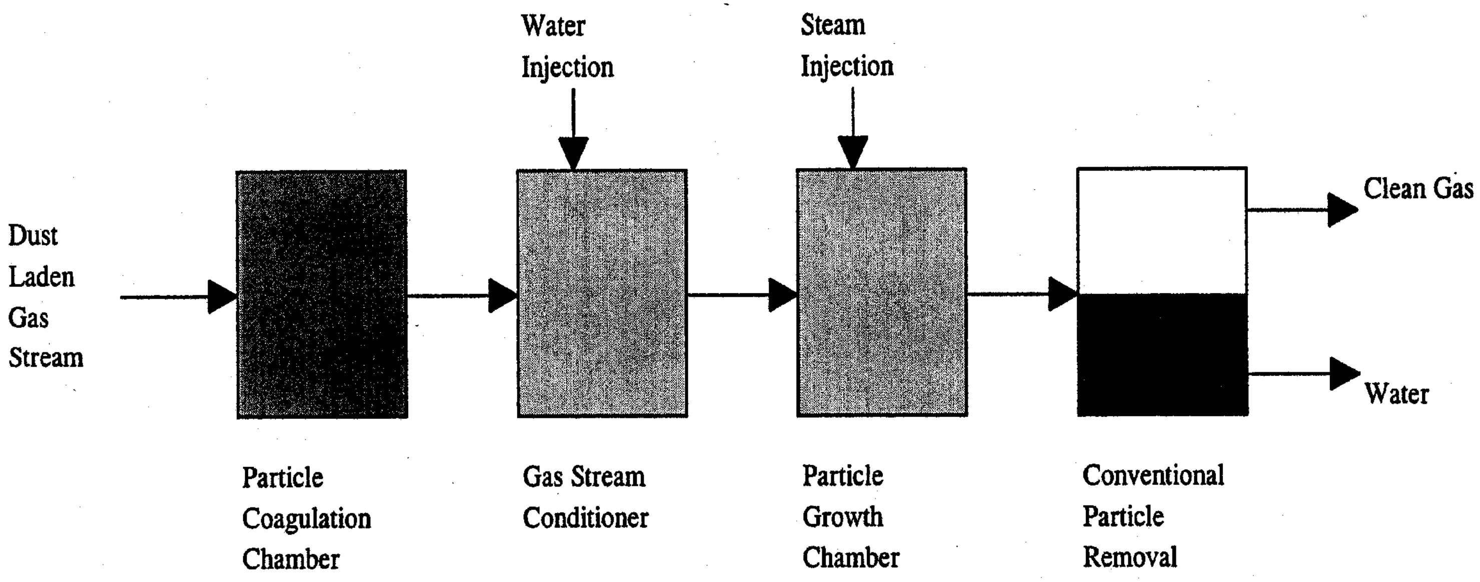


Figure 5.4-11. Schematic Diagram of a Condensation "Growth" Scrubber (adapted from Reference 4).

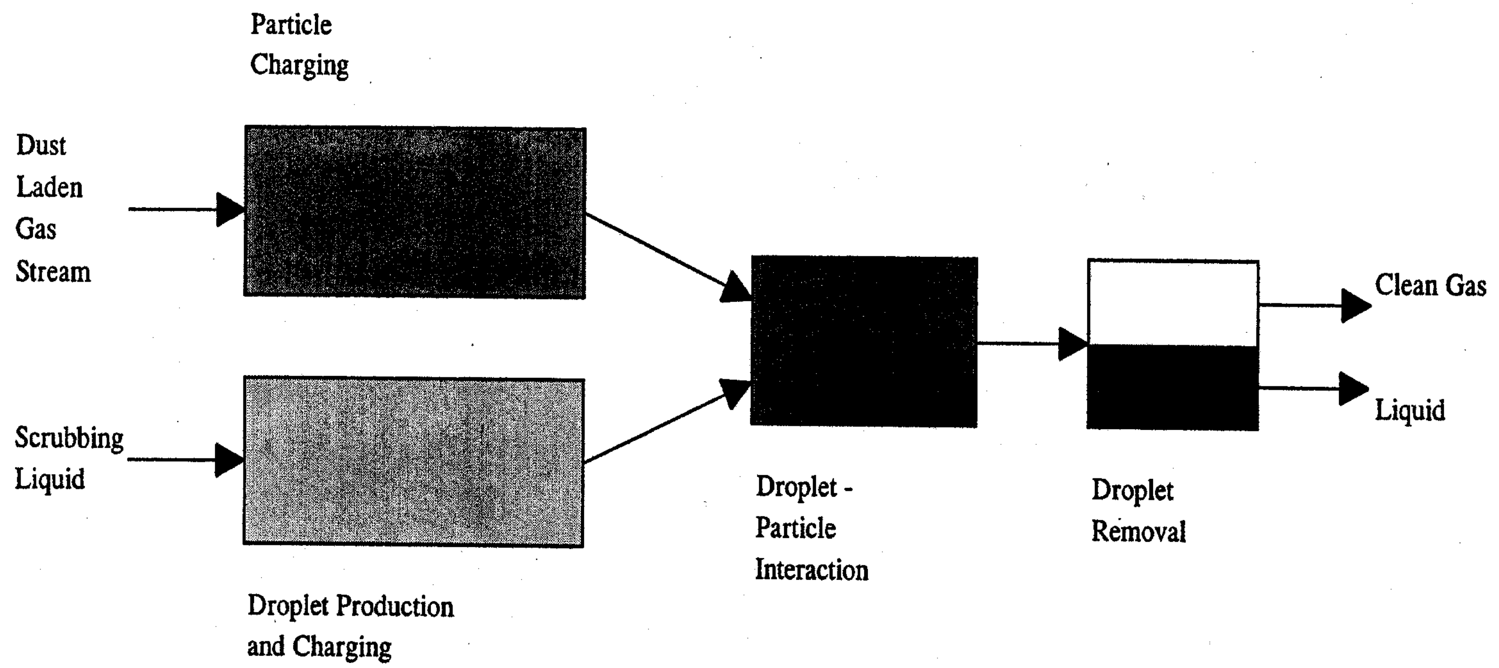


Figure 5.4-12. Schematic Diagram of Charged Wet Scrubber (adapted from Reference 2).

### 5.4.3 Collection Efficiency

Collection efficiencies for wet scrubbers are highly variable. Most conventional scrubbers can achieve high collection efficiencies for particles greater than 1.0 µm in diameter, however they are generally ineffective collection devices for submicrometer (<1 $\mu$m) particles. Some unconventional scrubbers, such as condensation and charged, are capable of high collection efficiencies, even for submicrometer particles. Collection efficiencies for conventional scrubbers depend on operating factors such as particle size distribution, inlet dust loading, and energy input. Figure 5.4-13 provides scrubber efficiency curves for coal and oil combustion, wood combustion, and coke production. Table 5.4-1 presents the PM-10 and PM-2.5 collection efficiencies.[6]

Conventional scrubbers rely almost exclusively on inertial impaction for PM collection. As discussed above, scrubber efficiency that relies on inertial impaction collection mechanisms will increase as particle size increases. Therefore, collection efficiency for small particles (<1 $\mu$m) are expected to be low for these scrubbers. The efficiency of scrubbers that rely on inertial impaction can be improved, however, by increasing the relative velocity between the PM and the liquid droplets. Increasing velocity will result in more momentum for all PM, enabling smaller particles to be collected by impaction. This can be accomplished in most scrubbers by increasing the gas stream velocity. Unfortunately, increasing the gas velocity will also increase the pressure drop, energy demand, and operating costs for the scrubber.[1,2,5]

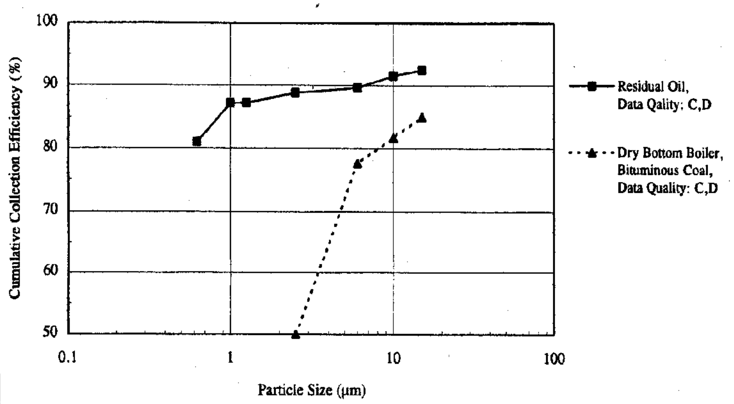
Another factor which contributes to low scrubber efficiency for small particles is short residence times. Typically, a particle is in the contact zone of a scrubber for only a few seconds. This is sufficient time to collect large particles that are affected by impaction mechanisms. However, since submicrometer particles are most effectively collected by diffusion mechanisms that depend on the random motion of the particles, sufficient time in the contact zone is needed for this mechanism to be effective. Consequently, increasing the gas residence time should also increase the particle/liquid contact time and the collection efficiency for small particles.[2]

An important relationship between inlet dust concentration (loading) and collection efficiency for fine PM in scrubbers has been recently found.[7] Collection efficiency for scrubbers has been found to be directly proportional to the inlet dust concentration. That is, efficiency will increase with increasing dust loading. This suggests that scrubber removal efficiency is not constant for a given scrubber design unless it is referenced to a specific inlet dust loading. In contrast, it has been shown that scrubber outlet dust concentration is a constant, independent of inlet concentration.[7]

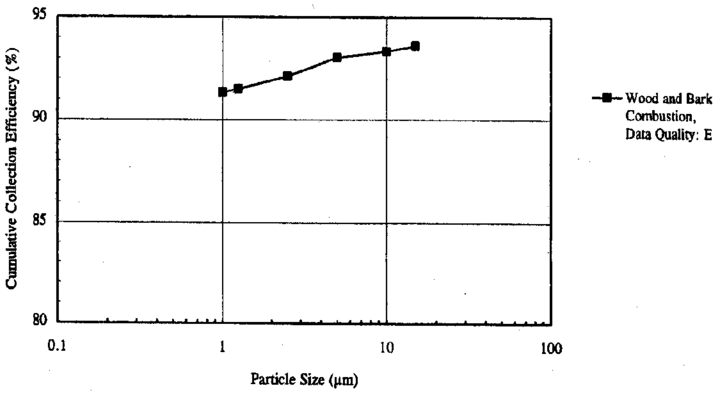
### 5.4.4 Applicability

Wet scrubbers have numerous industrial applications and few limitations. They are capable of collecting basically any type of dust, including flammable, explosive, moist, or sticky dusts. In addition, they can collect suspended liquids (i.e. mists) or gases alone or with PM simultaneously.[1] However, while scrubbers have many potential applications, there are some

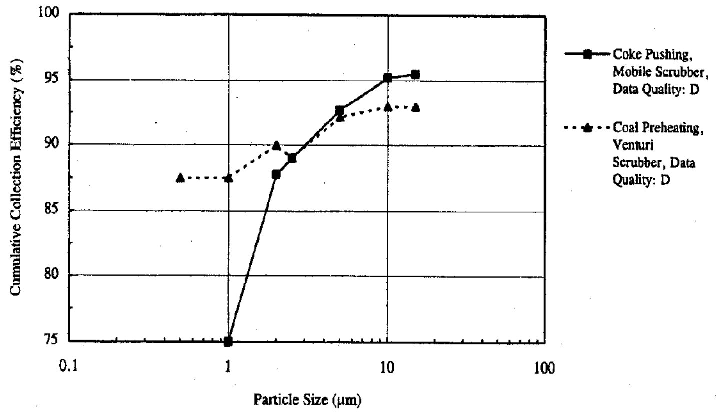
COAL AND OIL COMBUSTION



WOOD AND BARK COMBUSTION



COKE PRODUCTION



Note: Data quality refers to the data quality ratings assigned to the emission factors from which the efficiencies were calculated (Reference 6), as follows:

A = excellent
B = above average
C = average
D = below average
E = poor.

Figure 5.4-13. Cumulative Collection Efficiency Data for PM Wet Scrubbers at Coal, Oil, Wood, and Bark Combustion Sources, and Coke Production Operations (Reference 6)

Table 5.4-1. PM-10 and PM-2.5 Cumulative Collection Efficiencies for Wet Scrubbers at Coal, Oil, Wood, and Bark Combustors; and Coke Production Units (Reference 6).

| | Collection Efficiency (percent) | |
|---|---|---|
| Application | PM-10 | PM-2.5 |
| Combustion Sources | | |
| Bituminous coal (dry bottom) | 81.7 | 50.0 |
| Residual oil | 91.5 | 88.8 |
| Wood and bark | 93.3 | 92.1 |
| Bark only | 85.1 | 83.8 |
| Coke Production | | |
| Coal preheating (venturi scrubber) | 92.9 | 89.0 |
| Coke pushing (mobile-bed scrubber) | 95.2 | 89.0 |

characteristics that limit their use. The most significant consideration is the relatively low collection efficiency for fine PM, especially those less than 1.0 µm in diameter. Therefore, conventional scrubbers may not be suitable for processes which emit many submicrometer particles. As discussed above venturi, condensation, and charged scrubbers are capable of collecting submicrometer particles at higher efficiencies than other scrubbers and, therefore, can be used effectively in applications where there are a large percentage of fine PM in the gas stream.[2]

Gas stream composition may also be a limiting factor in scrubber application for a specific industry, since wet scrubbers are very susceptible to corrosion.[1] The use of wet scrubbers also may not be desirable when collecting valuable dust which can be recycled or sold. Since scrubbers discharge collected dust in the form of a wet slurry, reclaiming clean dry dust from this slurry is often inconvenient and expensive.[1] Because of design constraints, particulate scrubbers are generally not used in very large installations, such as utilities where gas flowrates exceed 250,000 ACFM, since multiple scrubbers are needed once flowrates exceed 60,000-75,000 ACFM.

Table 5.4-2 lists current applications of wet scrubbers.[1,2,8] It should be noted that the level of PM control supplied by each of the scrubber types listed in Table 5.4-2 will vary according to the level of control currently required by each industry and/or facility. The driving

Table 5.4-2. Current Industrial Applications
of Wet Scrubbers (References 1, 2, and 8)

| Application | Source Category Code | Typical Scrubber Type |
|---|---|---|
| Utility Boilers<br>(Coal, Oil) | 1-01-002...004 | Venturi |
| Industrial Boilers<br>(Coal, Oil, Wood, Liquid Waste) | 1-02-001...005,<br>-009, -011, -013 | Venturi, impingement plate (baffle) |
| Commercial/Institutional Boilers<br>(Coal, Oil, Wood) | 1-03-001...005<br>1-03-009 | Venturi |
| Chemical Manufacture | 3-01-001...999 | Packed-bed, venturi, fiber-bed |
| Non-Ferrous Metals Processing<br>(Primary and Secondary) | | |
| Copper | 3-03-005<br>3-04-002 | Spray chamber |
| Lead | 3-03-010<br>3-04-004 | Venturi, (cyclonic) spray chamber, fiber-bed, charged |
| Aluminum | 3-03-000...002<br>3-04-001 | Spray chamber, packed-bed, venturi, charged |
| Other | 3-03-011...014<br>3-04-005...006<br>3-04-010...022 | (Cyclonic) spray chamber |
| Ferrous Metals Processing | | |
| Coke Production | 3-03-003...004 | Charged, venturi, packed-bed (mobile) |
| Ferroalloy Production | 3-03-006...007 | Packed-bed, fiber-bed |
| Iron and Steel Production | 3-03-008...009 | Venturi |
| Gray Iron Foundries | 3-04-003 | Venturi, impingement plate (baffle) |
| Steel Foundries | 3-04-007, -009 | Venturi |
| Asphalt Manufacture | 3-05-001...002 | Venturi |
| Mineral Products | | |
| Coal Cleaning | 3-05-010 | Venturi, fiber-bed |
| Other | 3-05-003...999 | Venturi |
| Wood, Pulp, and Paper | 3-07-001 | Venturi, (cyclonic) spray chamber |
| Food and Agriculture | 3-02-001...999 | Impingement, fiber-bed, packed-bed |

| Application | Source Category Code | Typical Scrubber Type |
|---|---|---|
| Incineration | 5-01-001,<br>5-02-001, -005<br>5-03-001, -005 | Venturi, packed-bed, condensation |

force for PM control in many industries and/or facilities is the Federal, State, and local air pollution regulations. As more stringent PM regulations are put into place, a shift toward the use of higher efficiency scrubbers is likely to occur. Table 5.4-3 rates the various scrubber types according to their potential for controlling fine particles.

Table 5.4-3. $PM_{10}/PM_{2.5}$ Control Potential for Various Scrubber Designs

| Scrubber Type | $PM_{10}/PM_{2.5}$ Control Potential | Comments |
|---|---|---|
| Spray Chamber | Fair | Cyclonic are better than conventional spray |
| Packed-Bed | Poor | Useful for low dust loadings only |
| Impingement Plate | Good | Not as good for PM <1 $\mu$m |
| Mechanically-aided | Good | High energy consumption to achieve $PM_{10}/PM_{2.5}$ control |
| Venturi | Good | High energy consumption to achieve $PM_{10}/PM_{2.5}$ control |
| Orifice | Good | Not as good for PM <2 $\mu$m |
| Condensation | Good | Excellent control possible with condensation "growth" scrubbers |
| Charged | Excellent | Electric power costs add to overall scrubber costs |
| Fiber-Bed | Fair | Useful for soluble PM only |

### 5.4.5 Costs of PM Wet Scrubbers

The costs of installing and operating a scrubber include both capital and annual costs. Capital costs are all of the initial costs related to scrubber equipment and installation. Annual costs are the direct yearly costs of operating the scrubber, plus indirect costs such as overhead, capital recovery, taxes, insurance, and administrative charges. The following sections discuss capital and annual costs for scrubbers, referenced to the third quarter of 1995 unless otherwise noted.

#### 5.4.5.1 Capital Costs

The total capital investment (TCI) for scrubbers includes all of the initial capital costs, both direct and indirect. Direct capital costs are the purchased equipment costs (PEC), and the costs of installation (foundations, electrical, piping, etc.). Indirect costs are related to the installation and include engineering, construction, contractors, start-up, testing, and contingencies. The PEC is calculated based on the scrubber specifications. The direct and indirect installation costs are calculated as factors of the PEC. Table 5.4-4 provides the TCI factors for a typical scrubber.[9,10]

Wet scrubber costs are dependent upon the type of scrubber selected, the required size of the scrubber, and the materials of construction. Scrubber sizing incorporates several design parameters, including gas velocity, liquid-to-gas ratio, and pressure drop. Gas velocity is the primary sizing factor. Increasing the gas velocity will decrease the required size and cost of a scrubber. However, pressure drop will increase with increasing gas velocity. This will also result in increased electricity consumption and, therefore, higher operating costs. Determining the optimum gas velocity involves balancing the capital and annual costs. In most cases, scrubbers are designed to operate within recommended ranges of gas velocity, liquid-to-gas ratio, and pressure drop. These ranges are provided in Table 5.4-5.[11]

Another important scrubber parameter that affects costs is the temperature of the gas stream at saturation once it has been cooled by the scrubber liquid. This temperature affects the volumetric flowrate of the outlet gas and, consequently, the size of the scrubber. In addition, the saturation temperature impacts the scrubbing liquid makeup and the wastewater flowrate. The saturation temperature is a complex function of essentially three variables: the temperature of the inlet gas stream, the absolute humidity of the inlet gas stream, and the absolute humidity at saturation. Typically, the saturation temperature is determined graphically from a psychometric chart once these three variables are known. For this document, the sizing and costing of wet scrubbers were aided by the use of the CO$T-AIR Control Cost Spreadsheets,[12] that employ an iterative procedure for estimating the saturation temperature.

Table 5.4-4. Capital Cost Factors for a Typical Scrubber (Reference 10).

| Cost Item | Factor |
|---|---|
| Direct Costs | |
| Purchased equipment costs | |
| Scrubber + auxiliary equipment | As estimated (A) |
| Instrumentation | 0.10 A |
| Sales taxes | 0.03 A |
| Freight | 0.05 A |
| Total Purchased Equipment Cost (PEC) | B = 1.18 A |
| Direct installation costs | |
| Foundations and supports | 0.06 B |
| Handling and erection | 0.40 B |
| Electrical | 0.01 B |
| Piping | 0.05 B |
| Insulation for ductwork | 0.03 B |
| Painting | 0.01 B |
| Total direct installation cost | 0.56 B |
| Site Preparation and Buildings (Site) | As required |
| Total Direct Cost (DC) | 1.56 B + Site |
| Indirect Costs (installation) | |
| Engineering | 0.10 B |
| Construction and field expense | 0.10 B |
| Contractor fees | 0.10 B |
| Start-up | 0.01 B |
| Performance test | 0.01 B |
| Model study | Model |
| Contingencies | 0.03 B |
| Total Indirect Cost (IC) | 0.35 B |
| Total Capital Investment = DC + IC | 1.91 B + Site + Model |

Table 5.4-5. Recommended Gas Velocities, Liquid/Gas Ratios, and Pressure Drops for Particulate Wet Scrubbers (Reference 9).

| Scrubber Type | Velocity (ft/sec) | Liquid/Gas Ratio (gal/1000 ACFM) | Pressure Drop (inches $H_2O$) |
|---|---|---|---|
| Venturi | 90-400[a] | 4-100 | <100 |
| Impingement plate | <14 | 2-10 | 2-3[c] |
| Spray chamber | 10 | --- | 2-4 |
| Cyclonic spray chamber | 105-140[b] | 7 | 4-6 |
| Packed tower | | | |
| Vertical | 2-6 | --- | --- |
| Horizontal | 4-8 | --- | --- |

[a] Venturi throat velocity varies with pressure drop, volumetric flowrate, gas density, and liquid/gas ratio as follows: $v_t$ = throat velocity (ft/sec) = $C(\Delta P/r_g)^{0.5}$, $\Delta P$ = pressure drop (inches $H_2O$), $r_g$ = gas density (lb/ft$^3$), L/G = liquid/gas ratio (gal/1000 ACFM), C = 1,060 exp(-0.0279 L/G).

[b] Varies with pressure drop and gas density.

[c] Pressure drop per plate.

Once a scrubber has been properly designed and sized, the costs can generally be expressed as a function of the inlet or total gas flowrate.[9] Cost curves are shown below for the following types of scrubbers: venturi, impingement plate, and packed tower.

All the estimates for scrubber capital costs have been escalated to third quarter 1995 dollars. However, the capital costs presented in this section can be escalated further to reflect more current values through the use of the Vatavuk Air Pollution Cost Control Indexes (VAPCCI), which are updated quarterly, available on the OAQPS Technology Transfer Network (TTN), and published monthly in *Chemical Engineering* magazine. The VAPCCI updates the PEC and, since capital costs are based only on the PEC, capital costs can be easily adjusted using the VAPCCI. To escalate capital costs from one year ($Cost_{old}$) to another more recent year ($Cost_{new}$), a simple proportion can be used, as follows:[13]

$$Cost_{new} = Cost_{old}(VAPCCI_{new}/VAPCCI_{old})$$

The VAPCCI for wet scrubbers for third quarter 1995 was 114.7.

Venturi Scrubbers: Venturi scrubber costs are based on data for two ranges of gas flowrates. Cost curves for scrubbers treating less than 19,000 ACFM are provided in Figure 5.4-14. Cost curves for venturi scrubbers capable of handling greater than 19,000 ACFM but less than 59,000 ACFM are shown in Figure 5.4-15. For total flowrates greater than 59,000 ACFM, the gas stream should be divided evenly and treated by two or more identical scrubbers (with inlet flowrates of <59,000 ACFM) operating in parallel.

The most common construction material for venturi scrubbers is carbon steel. Special applications may require other materials, such as rubber-lined steel, epoxy-coated steel, fiber-reinforced plastic (FRP), that will increase the cost of the unit.[9] Separate cost curves for carbon steel and other specialized materials are included in Figures 5.4-14 and 5.4-15.[12]

Impingement Plate Scrubbers: Impingement plate scrubber costs are dependent on the number of plates and the total gas flowrate. The costs for impingement scrubbers are based on data that corresponds to a total gas flowrate between 900 and 77,000 ACFM or above. For total gas flowrates above 77,000 ACFM, multiple scrubbers are required. Figure 5.4-16 presents cost curves for impingement plate scrubbers with total gas flowrates between 900 and 77,000 ACFM. Cost curves for scrubbers with total flowrates above 77,000 ACFM are shown in Figure 5.4-17[12] and require the use of 2, 3, or 4 identical scrubber units. All the cost correlations shown here are for sieve plate scrubbers with three plates. Impingement plate scrubbers are usually constructed with carbon steel. Some applications may require more expensive materials, such as coated carbon steel, FRP, or polyvinyl chloride (PVC).[9]

Packed-bed Scrubbers: The costs for packed-bed scrubbers depend on the inlet gas velocity/column diameter, orientation of the column (vertical vs. horizontal), height of packing material, and the presence of any auxiliary equipment. Figures 5.4-18 and 5.4-19 present costs curves for two types of packed-bed scrubbers. Figure 5.4-18 presents a cost curve for a small vertical column packed-bed scrubber. The costs for this unit vary with the column diameter, which can range from 1 to 2.5 feet. Gas flowrates range from 200 to 1200 ACFM.[9] For Figure 5.4-18, the scrubber is assumed to be constructed of FRP with 6 feet of polypropylene packing. Costs also include the costs for a spray nozzle, liquid distributor, and mist eliminator. Figure 5.4-19 provides a cost curve for a large packed-bed scrubber with horizontal gas flow from 800 to 80,000 ACFM. Costs for this unit are based on the use of PVC or FRP construction materials and a design that includes a spray section, a 1-foot packed bed, and a mist eliminator.[9] Capital and annual costs are also available from Chapter 9 of the *OAQPS Control Cost Manual* (Reference 14).

### 5.4.5.2 Annual Costs

The total annual cost of a wet scrubber consists of both direct and indirect costs. Direct annual costs are those associated with the operation and maintenance of the scrubber. These include labor (operating, supervisory, coordinating, and maintenance), maintenance materials, operating materials, electricity, sludge disposal, wastewater treatment, and conditioning agents.[12]

Heating and cooling may be required in some climates to prevent freezing or excessive vaporation loss of the scrubbing liquid.[2]

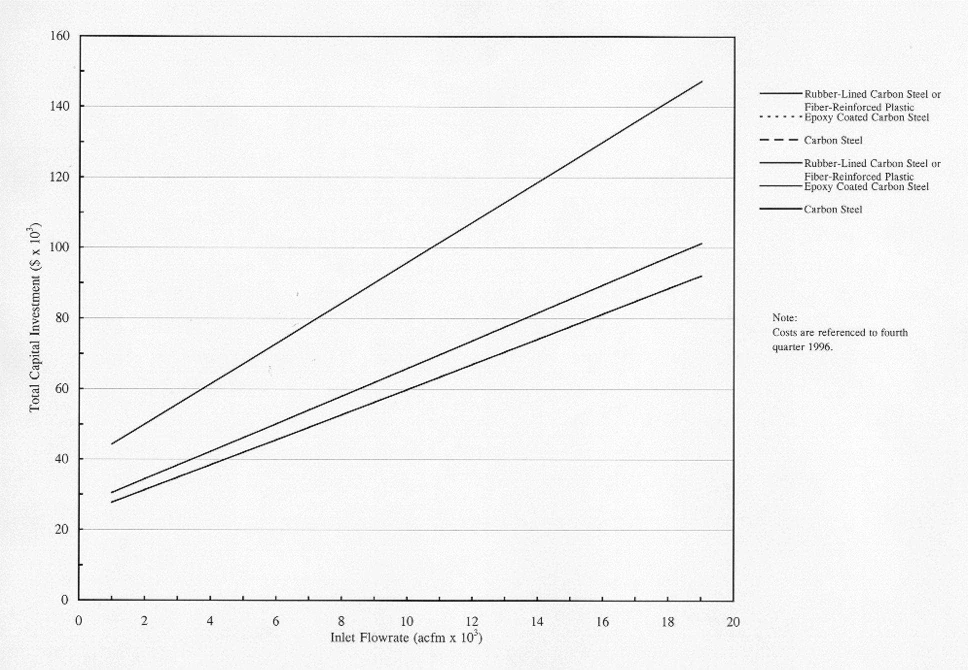


Figure 5.4-14. Venturi Scrubber Capital Costs, Inlet Flowrate < 19,000 ACFM (Reference 11)

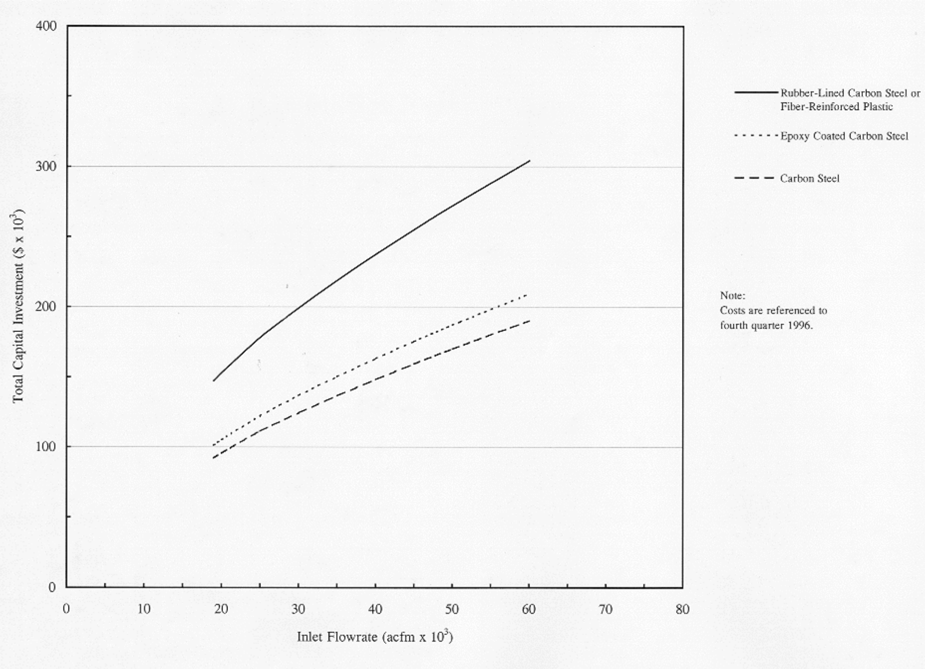


Figure 5.4-15. Venturi Scrubber Capital Costs, Inlet Flowrate >19,000 ACFM, <59,000 ACFM (Reference 11).

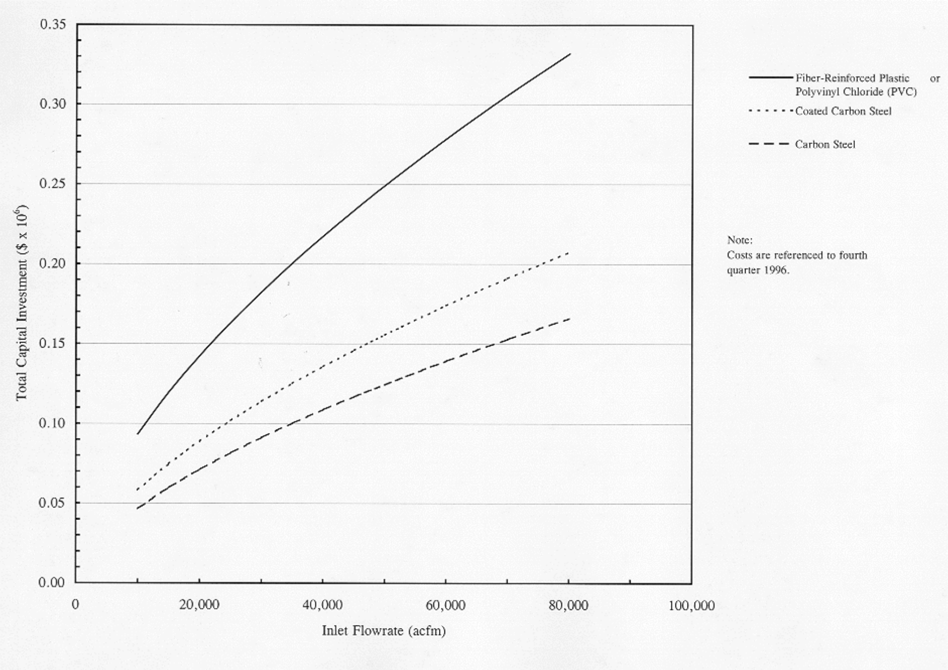


Figure 5.4-16. Impingement Scrubber Capital Costs, Inlet Flowrate <77,000 ACFM (Reference 11).

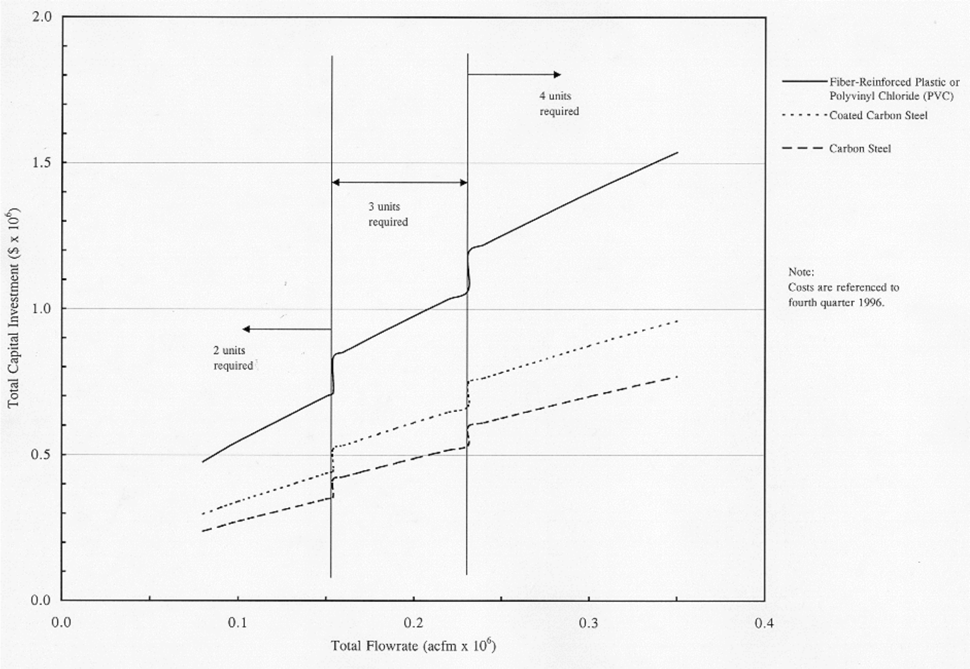


Figure 5.4-17. Impingement Scrubber Capital Costs, Inlet Flowrate >77,000 ACFM (Reference 11).

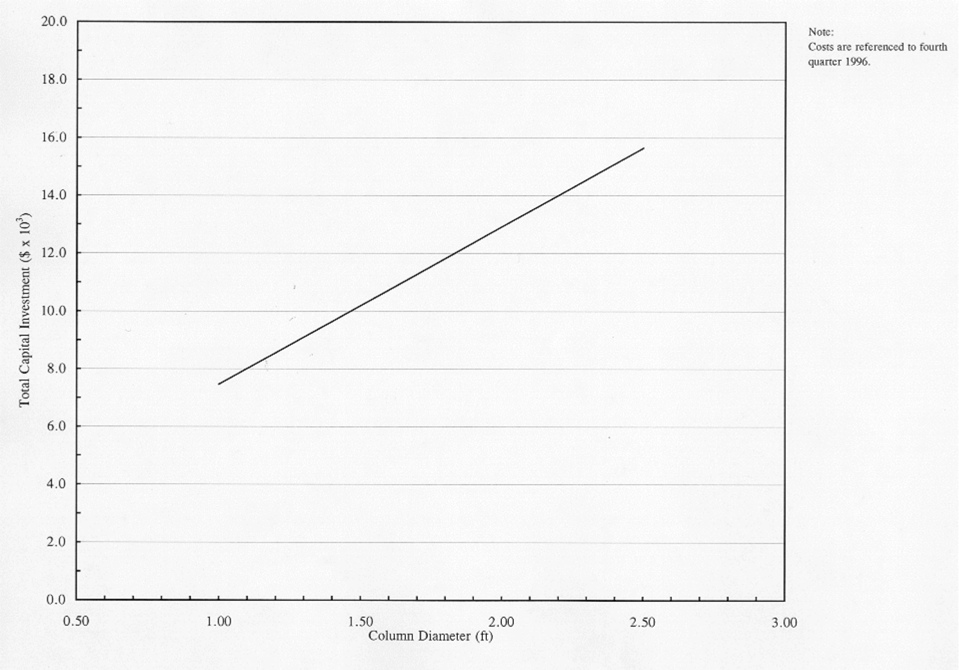


Figure 5.4-18. Vertical Packed-bed Scrubber Capital Costs (Reference 9).

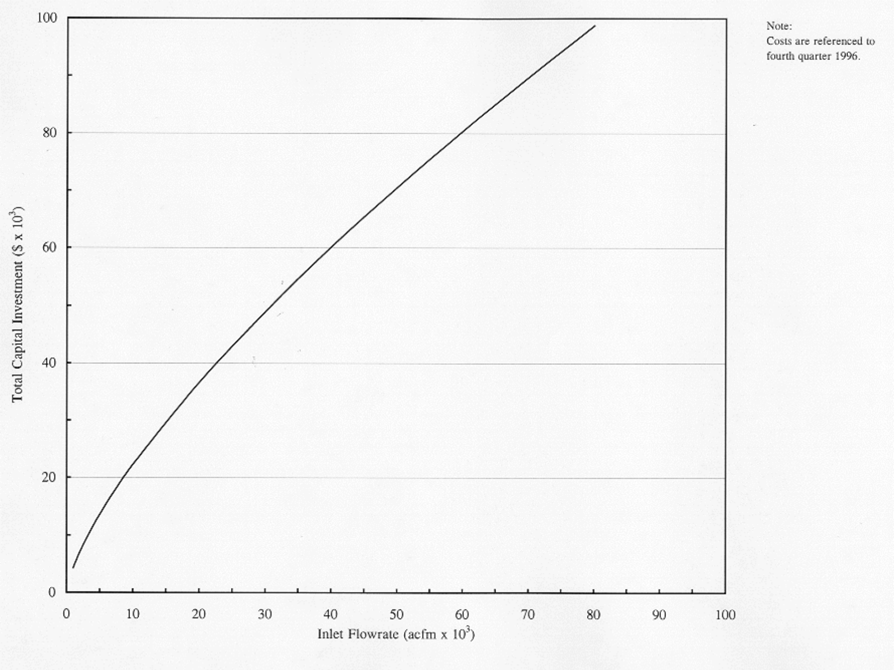


Figure 5.4-19. Horizontal Packed-bed Scrubber Capital Costs (Reference 9).

Indirect annual costs include taxes, insurance, administrative costs, overhead, and capital recovery. All of these costs except overhead are dependent on the TCI. Table 5.4-6 lists the parameters that impact wet scrubber annual costs with typical values provided for each parameter. Table 5.4.7 provides the annual cost factors for scrubbers. Annual costs for scrubbers are difficult to generalize because these costs are very site-specific.

### 5.4.6 Energy and Other Secondary Environmental Impacts

The secondary environmental impacts of wet scrubber operation are related to energy consumption, solid waste generation, and water pollution. The energy demands for wet scrubbers generally consist of the electricity requirements for fan operation, pump operation, and wastewater treatment. Charged scrubbers have additional energy demands for charging the water droplets and/or PM. Energy demands for wastewater treatment and charged scrubbers are very site specific and, therefore, are not estimated here.[2]

The fan power needed for a scrubber can be estimated by the following equation:[14]

$$\text{Fan Power (kW-hr/yr)} = 1.81 \times 10^{-4}(V)(\Delta P)(t) \qquad \text{(Eq. 5.4-1)}$$

where $V$ is the gas flowrate (ACFM), $\Delta P$ is the pressure drop (in. $H_2O$), $t$ is the operating hours per year, and $1.81 \times 10^{-4}$ is a unit conversion factor. Electricity costs for fan operation can be determined by multiplying the cost of electricity (in $/kW-hr) by the fan power. Pump power requirements for wet scrubbers can be determined as follows:[14]

$$\text{Pump Power (kW-hr/yr)} = (0.746(Q_l)(Z)(S_g)(t)) \,/\, (3{,}960\ \eta) \quad \text{(Eq. 5.4-2)}$$

where $Q_l$ is the liquid flowrate (gal/min), $Z$ is the fluid head (ft), $S_g$ is the specific gravity of the liquid, $t$ is the annual operating time (hr/yr), $\eta$ is the pump-motor efficiency, and 0.746 and 3,960 are unit conversion factors.

Wet scrubbers generate waste in the form of a slurry. This creates a need for both wastewater treatment and solid waste disposal operations. Initially, the slurry should be treated to remove and clean the water. This water can then be reused or discharged. Once the water is removed, the remaining waste will be in the form of a solid or sludge. If the solid waste is inert and nontoxic, it can generally be landfilled. Hazardous wastes will have more stringent procedures for disposal. In some cases, the solid waste may have value and can be sold or recycled.[2]

Table 5.4-6. Annual Cost Parameters for Particulate Scrubbers (Reference 12).

| Parameter | Description | Typical Values |
|---|---|---|
| Direct Cost Parameters | | |
| Operating factor (OF) | Hours of scrubber operation per year | 8,640 hr/yr |
| Operator labor rate (OR) | Operator labor pay rate | $12.50/hr[a] |
| Operator shift factor (OS) | Fraction of operator shift on scrubber | 0.25[b] |
| Supervisor labor factor (SF) | Fraction of operator labor cost | 0.15[b] |
| Maintenance labor rate (MR) | Maintenance labor pay rate | 1.1 x OR[b] |
| Maintenance shift (MS) factor | Fraction of maintenance shift on scrubber | 0.25[b] |
| Maintenance materials factor (MF) | Fraction of maintenance labor cost | 1.0[b] |
| Electricity rate (ER) | Cost of electricity | $0.07/kW-hr[a] |
| Chemical cost (CC) | Cost of chemical conditioning agents | $/lb (Site specific) |
| Chemical rate (CR) | Rate of chemical use | lb/hr (Site specific) |
| Wastewater treatment (WT) | Cost of treating scrubber effluent | $/gal (Site specific) |
| Throughput (T) | Rate of liquid throughput | gal/hr (Site specific) |
| Waste fraction (WF) | Fraction of throughput that is wast | Site specific |
| Indirect Cost Parameters | | |
| Overhead factor (OV) | Fraction of total labor and (MM) costs | 0.60[b] |
| Annual interest rate (I) | Opportunity cost of the capital | 7 percent[b] |
| Operating life (n) | Expected operating life of scrubber | 10 years[b] |
| Capital recovery factor (CRF) | Function of (n) and (I) | 0.1424[c] |
| Taxes (TAX) | Fraction of the TCI[d] | 0.01[b] |
| Insurance (INS) | Fraction of the TCI[d] | 0.01[b] |
| Administrative costs (AC) | Fraction of the TCI[d] | 0.02[b] |

[a] Estimated for 1996 from currently available information.

[b] Estimates from "CO$T-AIR" Control Cost Spreadsheets (Reference 12).

[c] Capital Recovery Factor is calculated from the following formula: $CRF = \{I(1 + I)^n\} \div \{(1 + I)^n - 1\}$, where $I$ = interest rate (fraction) and $n$ = operating life (years).

[d] The total capital investment (TCI) can be escalated to current values by using the Vatavuk Air Pollution Control Cost Indexes (VAPCCI), described in Section 5.4.5.

Table 5.4-7. Annual Cost Factors for Particulate Scrubbers (Reference 11).

| Cost Item | Formula[a] | Factor |
|---|---|---|
| Direct Costs | | |
| Labor | | |
| Operator (OL) | (OF)×(OR)×(OS) | A |
| Supervisor (SL) | (SF)×(OL) | 0.15 A |
| Maintenance (ML) | (OF)×(MR)×(MS) | 1.1 A |
| Maintenance materials (MM) | (MF)×(ML) | 1.1 A |
| Electricity (E) | Power[b] × (ER) | E |
| Chemicals (C) | (OF)×(CR)×(CC) | C |
| Wastewater treatment (W) | (OF)×(T)×(WF)×(WT) | W |
| Total Direct Cost (DC) | | 3.35 A + E + C + W + D |
| Indirect Costs | | |
| Overhead | (OV)×(OL+SL+ML+MM) | 2.01 A |
| Capital Recovery | (CRF)×(TCI) | 0.1424 TCI |
| Taxes | (TAX)×(TCI) | 0.01 TCI |
| Insurance | (INS)×(TCI) | 0.01 TCI |
| Administrative Costs | (AC)×(TCI) | 0.02 TCI |
| Total Indirect Cost (IC) | | 2.01 A + 0.1824 TCI |
| Total Annual Cost (DC + IC) | | 5.36 A + 0.1824 TCI + E + C + W + D |

[a] Includes values also described in Table 5.4-6.

[b] Equal to total power requirements, e.g. fan, pump, etc.

### 5.4.7 References for Section 5.4

1. Cooper, C.D and F.C. Alley. *Air Pollution Control: A Design Approach.* 2nd ed. Waveland Press, Prospect Heights, Illinois. 1994.

2. The Scrubber Manual (Revised). The McIlvaine Company, Northbrook, Illinois. January 1995.

3. Perry, R.H. and D.W. Green. Perry's Chemical Engineers' Handbook (6th Edition). McGraw-Hill Publishing Company, Inc. New York, New York. 1984.

4. Sun, J., B.Y.H Liu, P.H. McMurry, and S. Greenwood. A Method to Increase Control Efficiencies of Wet Scrubbers for Submicron Particles and Particulate Metals. J. Air & Waste Management Association. 44:2. February 1994.

5. Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-81-005a, NTIS PB83-127498). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. September 1982.

6. Compilation of Air Pollutant Emission Factors (AP-42). Volume I (Fifth Edition). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. January 1995.

7. Lerner, B.J. "Particulate Wet Scrubbing: The Efficiency Scam" in the Proceedings of the A&WMA Specialty Conference on "Particulate Matter; Health and Regulatory Issues (VIP-49)" held on April 4-6, 1995, in Pittsburgh, Pennsylvania. A&WMA, Pittsburgh, Pennsylvania. 1995.

8. Source Category Emission Reductions with Particulate Matter and Precursor Control Techniques. Prepared for K. Woodard, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina (AQSSD/IPSG), under Work Assignment II-16 (EPA Contract No. 68-03-0034), "Evaluation of Fine Particulate Matter Control." *September 30, 1996.*

9. Vatavuk, W.M. *Estimating Costs of Air Pollution Control.* Lewis Publishers, Chelsea, Michigan. 1990.

10. Vatavuk, W.M. and Neveril, R.B., Factors for Estimating Capital and Operating Costs, *Chemical Engineering,* November 3, 1980, pp. 157-162.

11. Schifftner, K.C. and H.E. Hesketh. *Wet Scrubbers: A Practical Handbook.* Lewis Publishers, Chelsea, Michigan. 1986.

12. Vatavuk, W.M. "CO$T-AIR" Control Cost Spreadsheets. Innovative Strategies and Economics Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. February 1996.

13. Vatavuk, W.M. Escalate Equipment Costs. Chemical Engineering. December 1995. pp. 88-95.

14. OAQPS Control Cost Manual (Fourth Edition, EPA 450/3-90-006). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. January 1990.

## 5.5 INCINERATORS

This section presents the basic operating principles, typical designs, industrial application, and costs of incinerators used as control devices. An incinerator is the only PM control device that does not concentrate the PM for subsequent disposal. An incinerator utilizes the principles of combustion to control pollutants. Incinerators used as add-on control devices are however, seldom used to remove only particulate matter (PM); PM control is usually desirable as a secondary treatment of a gas stream with a high volatile organic compounds (VOC) content.[1] The type of PM that is usually controlled by an incinerator is commonly composed of soot (particles formed as a result of incomplete combustion of hydrocarbons (HCs)), coke, or carbon residue. There are two basic types of incinerators used as add-on control devices: thermal and catalytic. For purposes of PM control, the use of a catalytic incinerator is limited because catalysts are subject to blinding from the PM.[2]

There are several advantages to using incinerators for waste air streams that contain VOC and PM. These advantages are: simplicity of operation; capability of steam generation or heat recovery in other forms; and capability for virtually complete destruction of organic contaminants. Disadvantages include: relatively high operating costs (particularly associated with fuel requirements); potential for flashback and subsequent explosion hazard; and incomplete combustion possibly creating potentially worse pollution problems.[3] High gas velocities are usually required for incinerators used for PM control to prevent settling of PM.[5] This may increase the incinerator size necessary to achieve the minimum required gas residence time.

### 5.5.1 Incinerator Control Mechanisms

Incinerator control is based on the principle that at a sufficiently high temperature and adequate residence time, any HC can be oxidized to carbon dioxide ($CO_2$) and water. In an incinerator, PM containing HCs is first vaporized to a gas and then oxidized.[1]

To achieve complete combustion, i.e. convert all the HC to $CO_2$ and water, sufficient space, time, turbulence and temperature high enough to ignite the constituents must be provided by the incinerator. The "three T's" of combustion: time, temperature, and turbulence, govern the speed and completeness of the combustion reaction. For complete combustion, oxygen must come into close contact with the combustible molecule at sufficient temperature and for a sufficient length of time for the reaction to be complete.[2]

The combustion time required for PM control is dependent on particle size and composition, oxygen content of the furnace, atmosphere, furnace temperature, gas velocity, and extent of mixing of the combustibles. For PM less than 100 $\mu$m in diameter, the combustion rate is controlled by chemical kinetics; for PM greater than 100 $\mu$m, diffusion controls the combustion rate.[1] In collection devices (ESP's, fabric filters, scrubbers) diffusion controls the collection rate of particles less than 1 $\mu$m in diameter.

For particles smaller than 100 μm the time required for complete combustion can be calculated using the following equation:[1]

$$t_c = (\rho\ d_p)/(2\ K_s\ p_g) \qquad \text{Eq. 5.5-1}$$

where for coke and carbon residue,

$$K_s = 8{,}710\ \exp(-35{,}700/RT_s) \qquad \text{Eq. 5.5-2}$$

and for soot,

$$K_s = (1.085 \times 10^4\ T_s^{-½})\ (\exp(-39{,}300/RT_s)) \qquad \text{Eq. 5.5-3}$$

where $t_c$ is the combustion time for a chemical kinetics controlled reaction (sec), $\rho$ is the density of particle (g/cm$^3$), $d_p$ is the diameter of particle (cm), $K_s$ is the surface reaction rate coefficient (g/cm$^2$-sec-atm), $p_g$ is the partial pressure of oxygen in combustion air (atm), R is the universal gas law constant (82.06 atm-cm$^3$/mole-°K), $T_s$ is the surface temperature of the particle (assumed to be the incinerator temperature) (°K).

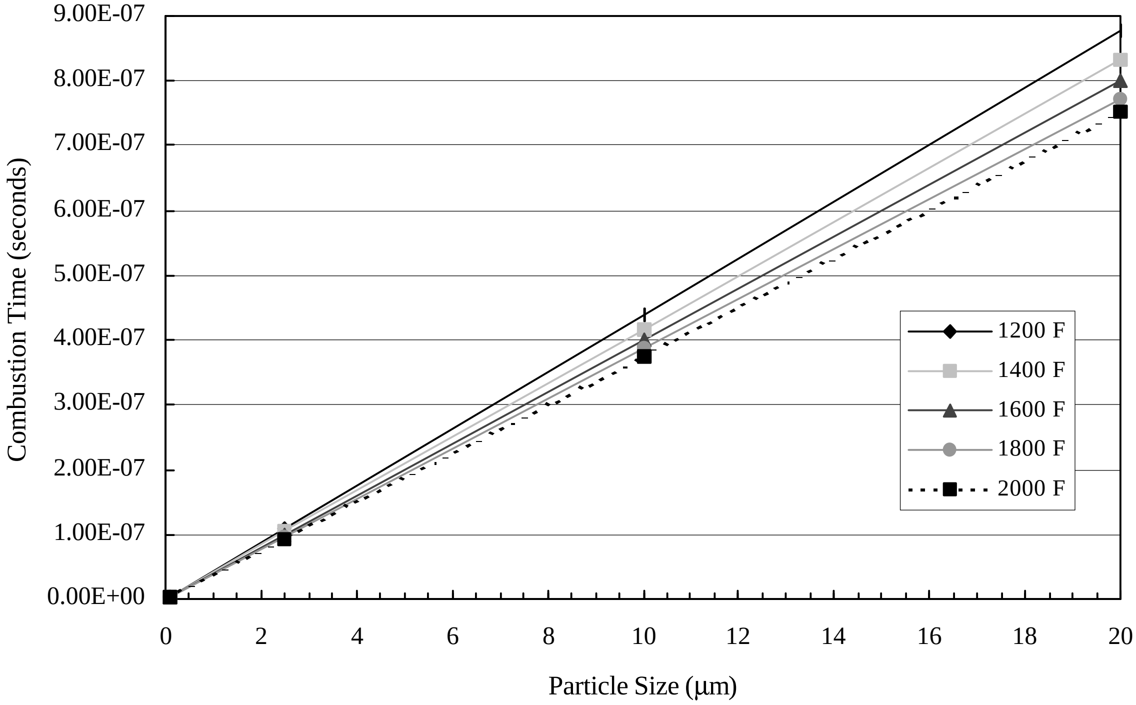


Figure 5.5-1. Calculated Theoretical Residence Times for Various-sized Coke PM in an Incinerator at Various Temperatures

With the proper residence time, complete combustion should result in >99 percent control of particles containing HCs. Figure 5.5-1 shows the theoretical residence time needed for >99 percent control of various sized coke PM in an incinerator operated from 1200-2000°F calculated using the above equations.[1]

Although residence time and incinerator temperature are the primary incinerator parameters affecting incinerator performance, other important parameters are the heat content and water content of the gas stream, and the amount of excess combustion air (i.e. amount above the stoichiometric amount needed for combustion). Combustion of gas streams with heat contents less than 50 Btu per standard cubic foot of air (SCF) usually will require supplemental fuel to maintain the desired combustion temperature. Supplemental fuel may also be needed for flame stability, regardless of the heat content of the gas.[4]

For incinerators operated above 1400°F, the oxidation reaction rates become much faster than the gas diffusion mixing rate. As a result, the combustion reaction may be hindered because sufficient oxygen molecules are not in proximity to the HCs. To ensure that this does not occur, mixing must be enhanced via vanes or other physical methods.[5]

## 5.5.2 Types of Incinerators

As discussed above, there are two basic types of incinerators, thermal and catalytic. Both types of incinerator may use heat exchangers to recover some of the heat energy from the incinerator. Therefore, this section discusses both types of incinerators as well as heat exchangers.

### 5.5.2.1 Thermal Incinerators

A typical thermal incinerator is a refractory-lined chamber containing a burner (or set of burners) at one end. Thermal incinerators typically use natural gas to supplement the caloric content of the waste gas stream. In a thermal incinerator, the combustible waste gases pass over or around a burner flame into a residence chamber where oxidation of the waste gases is then completed. The most recent guidelines for incinerators to promote more complete destruction of VOC are:[5]

- A chamber temperature high enough to enable the oxidation reaction to proceed rapidly to completion (1200-2000 °F or greater);
- Flow velocities of 20-40 feet per second, to promote turbulent mixing between the hot combustion products from the burner, combustion air, and waste stream components; and
- Sufficient residence time (approximately 0.75 seconds or more) at the chosen

temperature for the oxidation reaction to reach completion.

The following sections discuss the two types of thermal incinerators: discrete burner and distributed burner. Both types may also use heat recovery equipment. This equipment is discussed in Section 5.5.2.3 below.

**5.5.2.1.1 Discrete Burner Thermal Incinerator**. In a discrete dual burner incinerator, shown in Figure 5.5-2, the waste gas stream and combustion air feed into a

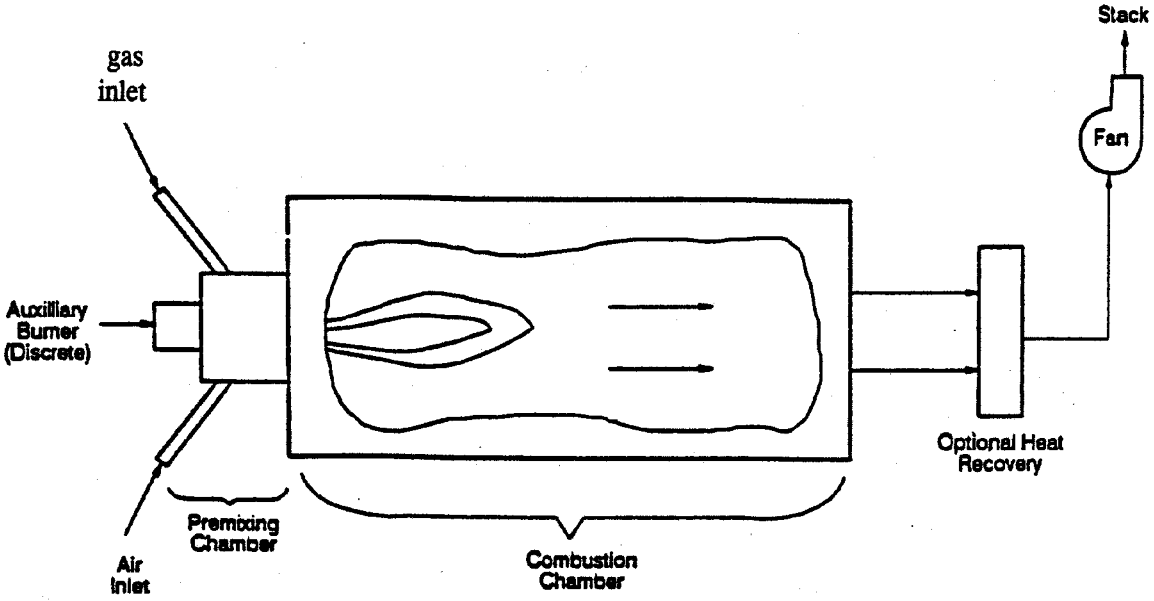


Figure 5.5-2. Schematic Diagram of a Discrete Burner Thermal Incinerator (Reference 4).

premixing chamber fitted with a (auxiliary) discrete fuel burner. In this chamber, both gases are thoroughly mixed and pre-heated by the auxiliary burner. The mixture of hot reacting gases then passes into the main combustion chamber where another (primary) burner is located. This chamber is sized to allow the mixture enough time at the elevated temperature for the oxidation reaction to reach completion. Energy can the be recovered from the hot flue gases in a heat recovery section.[6]

**5.5.2.1.2 Distributed Burner Thermal Incinerator**. Thermal incinerators (that use natural gas as the supplemental fuel) may also use a grid-type, or distributed, gas burner. This gas burner configuration is shown in Figure 5.5-3. In a distributed thermal incinerator, small gas flame jets on a grid surface ignite the vapors in the gas as it passes through the grid. The grid acts as a baffle to promote mixing before the gases enters the second part of the incinerator chamber. Because there are many small flames distributed on the entire cross-section of the combustion chamber and the vapors are well-mixed, this arrangement enables the gas vapors to burn at a lower chamber temperature and allows for the use of less fuel than the discrete burner configuration, described above.[4] In the discrete burner, vapors and particles are more likely to survive the single large flame initially, so the chamber must be maintained at a higher temperature to ensure complete combustion.

### 5.5.2.2 Catalytic Incinerators

A catalytic incinerator is not usually recommended as a control device for PM since the PM, unless removed prior to incineration, will often coat the catalyst so that the catalyst active sites are prevented from aiding in the oxidation of pollutants in the gas stream. This effect of PM on the catalyst is called blinding.[2] Despite this drawback, catalytic incinerators are sometimes used for PM control in the chemical manufacturing and textile industries, and for combustion sources such as IC engines, boilers, and dryers.[7] Therefore, a brief description of this type of incinerator is included here.

Catalytic incinerators are very similar to thermal oxidation, with the primary difference that the gas, after passing through the flame area, passes through a catalyst bed.[5] The catalyst has the effect of increasing the oxidation reaction rate, enabling conversion at lower reaction temperatures than in thermal incinerator units. Catalysts, therefore, also reduce the incinerator volume/size.[5] Catalysts typically used for VOC incineration include platinum and palladium. Other formulations include metal oxides, which are used for gas streams containing chlorinated compounds.[4]

A schematic of a catalytic incinerator is presented in Figure 5.5-4.[4] in a catalytic incinerator, the gas stream is introduced into a mixing chamber where it is also heated. The waste gas usually passes through a recuperative heat exchanger (discussed below), where it is preheated by post-combustion gas.[11] The heated gas then passes through the catalyst bed. Oxygen and VOCs migrate to the catalyst surface by gas diffusion and are adsorbed onto the catalyst active sites on the surface of the catalyst where oxidation then occurs. The oxidation reaction products are then desorbed from the active sites by the gas and transferred by diffusion back into the gas stream.[8]

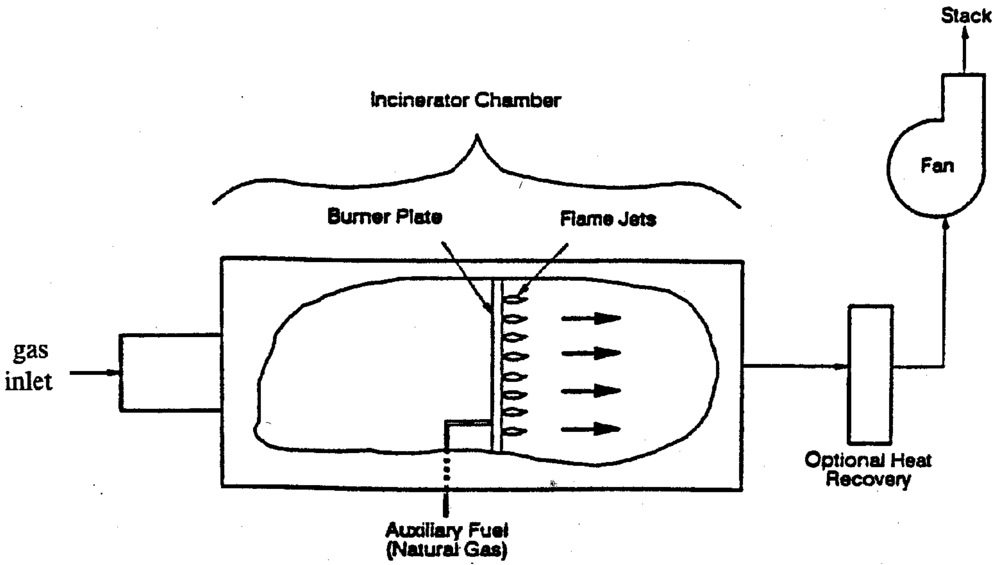


Figure 5.5-3. Schematic Diagram of a Distributed Burner Thermal Incinerator (Reference 6).

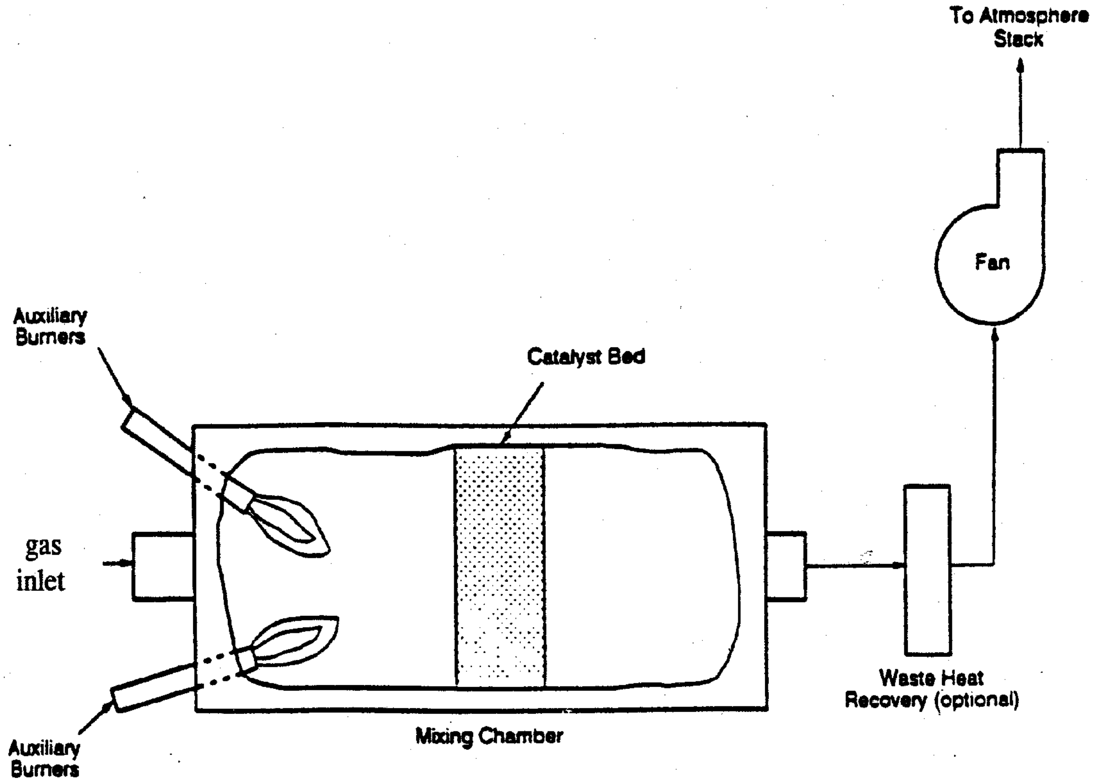


Figure 5.5-4. Schematic Diagram of a Catalytic Incinerator (Reference 4).

As discussed above, PM can rapidly blind the pores of the catalysts and deactivate the catalyst over time. Because essentially all the active surface of the catalyst is contained in relatively small pores, the PM need not be large to blind the catalyst. No general guidelines exist as to the PM concentration and size that can be tolerated by catalysts because the pore size and volume of catalysts vary greatly.[9] This information is likely to be available from the catalyst manufacturers.

The advantages of catalytic combustion reactors over thermal incinerators, therefore, include:[5]

- Lower fuel requirements,
- Lower operating temperatures,
- Little or no insulation requirements,
- Reduced fire hazards, and
- Reduced flashback problems.

The disadvantages include:[5]

- Higher capital costs,
- Catalyst blinding causes operational problems and/or higher maintenance requirements (annual costs),
- PM may need to be precollected, and
- Spent catalyst that cannot be regenerated may need to be disposed.

#### 5.5.2.3 Heat Recovery Equipment

Since the flue gas that is still hot after exiting the incinerator, heat may be recovered with the proper auxiliary incinerator equipment. Heat recovery equipment for an incinerator can be either recuperative or regenerative. Recuperative heat exchangers, that recover heat on a continuous basis, include crosscurrent-, countercurrent-, and cocurrent-flow heat exchangers. For a given heat flow and temperature drop, recuperative heat exchanger surface requirements will be the lowest in a countercurrent flow configuration.

Regenerative heat exchangers recover heat by intermittent heat exchange through alternate heating and cooling of a solid. Heat flows alternately into and out of the same exchanger as air and flue gas flows are periodically reversed. The heat sink and heat transfer area for regenerative heat exchangers can be either a fixed bed, a moving bed or a rotary cylinder.[1]

### 5.5.3 Control Efficiency

#### 5.5.3.1 Control Efficiency for Volatile Organic Compounds

Theoretically, all organic material, including VOC, are combustible with combustion efficiency limited only by cost. On the basis of studies of thermal incinerator efficiency, it has been concluded that at least 98 percent VOC destruction (or a 20 part per million by volume (ppmv) VOC exit concentration) is achievable by all well-designed incinerators. An estimate of 98 percent efficiency is predicted for thermal incinerators operating at 1,400°F or higher, with at least 0.75 seconds residence time.[5] If a thermal incinerator is properly designed and operated to produce the optimum conditions in the combustion chamber, it should be capable of higher than 99 percent destruction efficiencies for nonhalogenated VOC, when the VOC concentration in the gas stream is above approximately 2,000 ppmv.[6]

### 5.5.3.2 Control Efficiency for Particulate Matter

Controlled emissions and/or efficiency test data for PM in incinerators are not generally available in the literature. Emission factors for PM in phthalic anhydride processes with incinerators were available, however.[10] The PM control efficiencies for these processes were calculated from the reported emission factors and are shown in Table 5.5-1. The PM control efficiencies ranged from 79 to 96 percent control for total PM.

In EPA's 1990 National Inventory,[7] incinerators were used as control devices for PM to achieve from 25 to 99.9 percent control of $PM_{10}$ at point source facilities. The VOC control reported for these devices ranged from 0 to 99.9 percent. These ranges of control efficiencies are large because they include facilities that do not have VOC emissions and control only PM (these facilities would report 0 percent efficiency for VOC control), as well as facilities which have low PM emissions and are primarily concerned with controlling VOC.

## 5.5.4 Applicability

Although incinerators can be used to any organic material, their application is limited to a range of gas vapor concentration. To prevent explosions, the vapor concentration must be substantially below the gas lower flammable level (lower explosive limit [LEL]). As a rule, a factor of 4 is employed to give a margin of for safety.[2] Therefore, incinerators are not likely to be used for processes with very high VOC content. The presence of halogens also requires additional equipment such as scrubbers for acid gas removal.[4]

Thermal incinerators can be designed to handle minor fluctuations in flow rate. However, processes with the potential for excessive fluctuations in flow rate (i.e., process upsets) may not be suitable for incinerator use, since control efficiency could decrease outside the acceptable range.[4] Flares may be an appropriate control for processes with excessive fluctuation potential. Table 5.5-2 presents the operating conditions required for satisfactory incinerator performance in various industrial applications.[3] Note that the residence time and incinerator temperature required for PM control is much higher than for non-PM sources.

An examination of the EPA's 1990 National Inventory,[7] presented in showed that the primary source categories in which incinerators were used for PM control were:

- Petroleum and Coal Production

Table 5.5-1 PM Control Efficiencies for Thermal Incinerators in Phthalic Anhydride Manufacturing Processes (Reference 10)

| | PM Emission Factor (lb PM/ton product) | | Calculated Control Efficiency (percent) |
|---|---|---|---|
| Process Unit | Uncontrolled | Controlled | |
| O-xylene Processing | | | |
| Oxidation | 138 | 7 | 95 |
| Pretreatment | 13 | 0.7 | 95 |
| Distillation | 89 | 4 | 96 |
| Naphthalene Processing | | | |
| Oxidation | 56 | 11 | 80 |
| Pretreatment | 5 | 1 | 80 |
| Distillation | 38 | 8 | 79 |

- Chemical and Allied Product Manufacturing
- Primary Metal Industries
- Electronic and Other Electric Equipment.

These source categories were identified from the reported data in the 1990 National Inventory,[7] and correspond to facilities that reported $PM_{10}$ control efficiencies for incinerators likely to have been used as primary control devices.

### 5.5.5 Costs of Incinerators

The costs of installing and operating an incinerator include both capital and annual costs. Capital costs are all of the initial equipment-related costs of the incinerator. Annual costs are the direct costs of operating and maintaining the incinerator for one year, plus such indirect costs as overhead; capital recovery; and taxes, insurance, and administrative charges. The following sections discuss capital and annual costs for incinerators, referenced to the fourth quarter of 1996, unless otherwise noted.

Incinerators designed for PM control are likely to have higher costs than incinerators designed for VOC control, because of the higher temperatures and longer gas residence times are needed for PM destruction (see Table 5.5-2). Incinerators designed for PM control are also likely to need more supplemental fuel to maintain the higher temperatures and larger combustion chambers to achieve the longer residence times. Since the incinerator cost data presented below were probably derived for incinerators designed for VOC control only, the actual costs for incinerators designed for PM control are likely to be higher.

Table 5.5-2 Operational Requirements for Satisfactory Incinerator Performance for Various Industrial Applications and Control Levels (Reference 3)

| Application | Control Level (percent) | Residence Time (sec) | Temperature (°F) |
|---|---|---|---|
| HC Control | >90 | 0.3-0.5 | 1100-1250[a] |
| HC + CO | >90 | 0.3-0.5 | 1250-1500 |
| Odor | | | |
| Low control | 50-90 | 0.3-0.5 | 1000-1200 |
| Medium control | 90-99 | 0.3-0.5 | 1100-1300 |
| High control | >99 | 0.3-0.5 | 1200-1500 |
| Smokes/Plumes | | | |
| White smoke (liquid mist) | >99 | 0.3-0.5 | 800-1000[b] |
| HC and CO | >90 | 0.3-0.5 | 1250-1500 |
| Black smoke (soot and other combustible PM) | >99 | 0.7-1.0 | 1400-2000 |

[a] Temperatures of 1400 to 1500°F may be required if there is a significant amount of any of the following: methane, cellosolve, and substituted aromatics (e.g., toluene and xylenes).

[b] Operation for plume abatement only is not recommended, since this merely converts a visible hydrocarbon emission into an invisible one and frequently creates a new odor problem because of partial oxidation in the incinerator.

The use of a catalytic incinerator for PM control is limited because catalysts are subject to poisoning/blinding from PM;[2] consequently, only thermal incinerator costs are discussed in this section. For information on the costs of catalytic incinerators, consult *Estimating Costs of Air Pollution Control*[11] and EPA's *"CO$T-AIR" Control Cost Spreadsheets*.[12]

### 5.5.5.1 Capital Costs

The total capital investment (TCI) for incinerators includes all of the initial capital costs, both direct and indirect. Direct capital costs are the purchased equipment costs (PEC), and the costs of installation (foundations, electrical, piping, etc.). Indirect costs are related to the installation and include engineering, construction, contractors, start-up, testing, and contingencies. The PEC is calculated based on the incinerator specifications. The direct and indirect installation costs are calculated as factors of the PEC.[11] The equipment cost presented in Table 5.5-3 are the TCI cost factors for custom incinerators (as opposed to packaged units).

The flue gas flow rate and auxiliary fuel requirement are the most important sizing parameters for a thermal incinerator. The former determines the equipment size and cost, while the latter comprises most of annual operating and maintenance costs. These parameters are interdependent, based on material and energy balances taken around the incinerator.[9]

Figure 5.5-5 shows total capital investment vs. flow rate (size) for a thermal incinerator with recuperative heat recovery equipment.[12] Three levels of heat recovery are shown in Figure 5.5-5: 0 percent, 35 percent, and 50 percent. For the purposes of the figure, the thermal incinerator was assumed to operate at a combustion temperature of 1600°F and the waste gas was assumed to have a heat content of 4 Btu/SCF. The curves illustrate two phenomena: 1) the direct proportionality of capital cost to flow rate (size), and 2) the proportionality of capital cost to heat recovery efficiency. That is, capital costs increase with both increasing flow rate (size) and increasing heat recovery efficiency.

Figure 5.5-6 shows total capital investment vs. flow rate (size) for thermal incinerators with 85 percent and 95 percent regenerative heat recovery systems.[12] As in the previous figure, the thermal incinerator was assumed to operate at a combustion temperature of 1700°F and the waste gas was assumed to have a heat content of 4 Btu/SCF. Also, as in the previous figure, capital costs for incinerators with regenerative heat recovery systems increase with increasing flow rate (size) and decrease with increasing heat recovery efficiency.

A comparison between the capital cost of incinerators with recuperative vs. regenerative heat recovery systems shows that for the same size incinerator, the capital investment of a regenerative heat recovery system is over twice the capital investment required for an incinerator with a recuperative heat recovery system.

### 5.5.5.2 Annual Costs

The total annual cost of an incinerator consists of both direct and indirect costs. Direct annual costs are those associated with the operation and maintenance of the incinerator. These include labor (operating, supervisory, coordinating, and maintenance); maintenance materials; operating materials; electricity; and supplemental fuel, if applicable.

Table 5.5-3 Capital Cost Factors for Thermal Incinerators (from Reference 11)

| Cost Item | Factor |
|---|---|
| Direct Costs | |
| Purchased equipment costs | |
| Incinerator + auxiliary equipment | As estimated (A) |
| Instrumentation | 0.10 A |
| Sales taxes | 0.03 A |
| Freight | 0.05 A |
| Total Purchased Equipment Cost (PEC) | B = 1.18 A |
| Direct installation costs | |
| Foundations and supports | 0.08 B |
| Handling and erection | 0.14 B |
| Electrical | 0.04 B |
| Piping | 0.02 B |
| Insulation for ductwork | 0.01 B |
| Painting | 0.01 B |
| Total direct installation cost | 0.30 B |
| Site Preparation and Buildings | As required (Site) |
| Total Direct Cost, DC | 1.30 B + Site |
| Indirect Costs (installation) | |
| Engineering | 0.10 B |
| Construction and field expense | 0.05 B |
| Contractor fees | 0.10 B |
| Start-up | 0.02 B |
| Performance test | 0.01 B |
| Contingencies | 0.03 B |
| Total Indirect Cost (IC) | 0.31 B |
| Total Capital Investment = DC + IC | 1.61 B + Site |

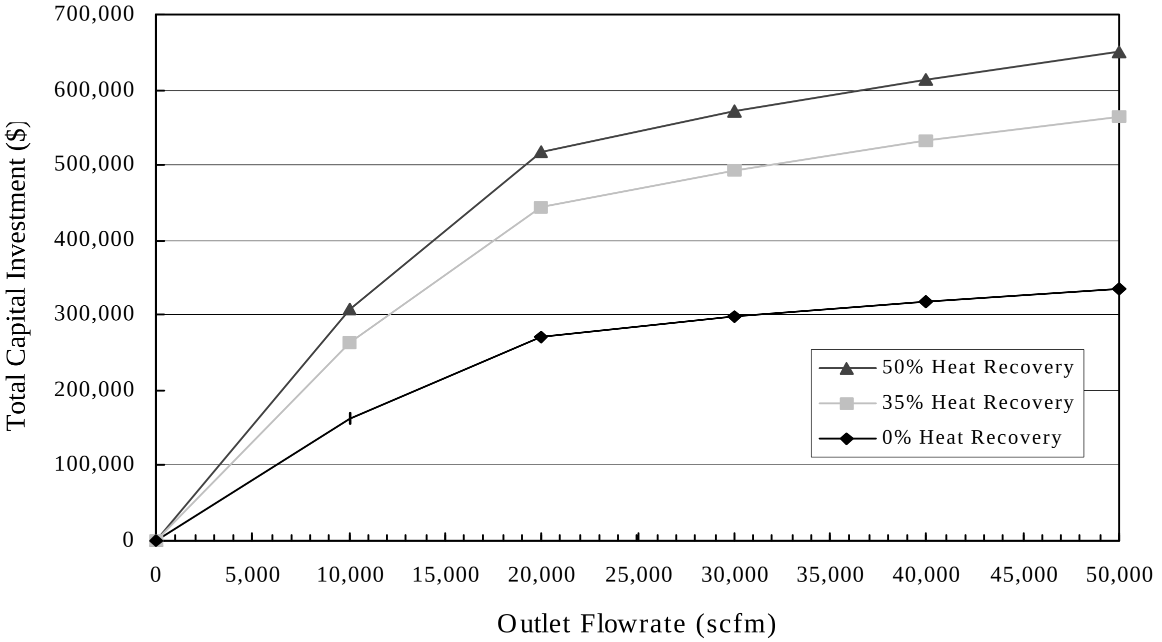


Figure 5.5-5. Total Capital Investment vs. Flow Rate for a Thermal Incinerator with 0, 35, and 50 Percent Recuperative Heat Recovery (Reference 12).

Indirect annual costs include taxes, insurance, administrative costs, overhead, and capital

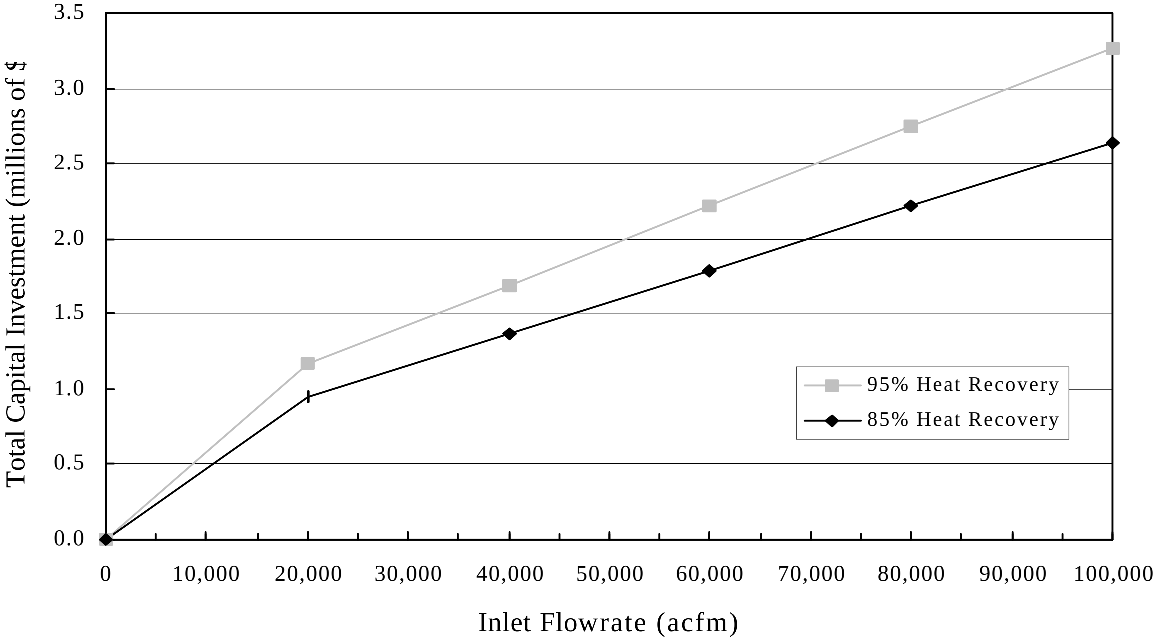


Figure 5.5-6. Total Capital Investment vs. Flow Rate for a Regenerative Thermal Oxidizer with 85 and 95 Percent Heat Recovery (Reference 12).

recovery. All of these costs except overhead are dependent on the TCI. Table 5.5-4 lists the annual cost parameters that impact incinerator costs, with typical values provided for each parameter. Table 5.5-5 provides the annual cost factors for incinerators. It is difficult to generalize these costs for all incinerators, since annual costs are very site-specific.[11]

The supplemental fuel and electricity requirements for an incinerator are likely to have a large impact on incinerator annual costs. The requirements for each can be estimated from incinerator design values. The auxiliary heat requirement to be supplied by the fuel, usually natural gas, can be calculated using the incinerator design equations described below.

An incinerator is designed to handle a total volumetric gas flow rate ($Q_f$) equal to the waste gas inlet flow rate ($Q_i$), which is known, and auxiliary fuel gas flow rate ($Q_a$):

$$Q_f = Q_i + Q_a \qquad \text{(Eq. 5.5-4)}$$

and where the requirements for auxiliary fuel gas are determined with the following equation:

$$Q_a = (x/y)(Q_i) \qquad \text{(Eq. 5.5-5)}$$

for $$x = (1.1\, C_{pf}\, (T_f - T_r)) - (C_{pi}\, (T_i - T_r)) - h_1 \qquad \text{(Eq. 5.5-6)}$$

$$y = h_a - 1.1 C_{pf}\, (T_f - T_r) \qquad \text{(Eq. 5.5-7)}$$

where $Q_f$ is the flue gas flow rate (SCFM), $Q_i$ is the inlet waste gas flow rate (SCFM),$Q^a$ is the auxiliary fuel gas (heat) requirement (SCFM), $C_{pf}$ is the mean heat capacity of gas leaving the combustion chamber (Btu/SCF-°F), $C_{pi}$ is the mean heat capacity of gas entering the combustion chamber (Btu/SCF-°F), $T_f$ is the combustion chamber temperature (°F), $T_i$ is the waste gas inlet temperatures (°F), $T_r$ is the reference temperature, equal to the inlet fuel temperature (typically 70°F), $h_1$ is the waste gas heat content (Btu/SCF), and $h_a$ is the fuel heating value (Btu/SCF).

Electricity to run the incinerator exhaust fan is calculated with the following equation:

$$\text{Fan Power (kW)} = (1.575\text{x}10^{-4})\, \Delta P\, Q / n \qquad \text{(Eq. 5.5-8)}$$

where $\Delta P$ is the system pressure drop (inches of water), Q is the waste gas volumetric flow rate through system (ACFM), and n is the efficiency of fan and motor (generally 0.50-0.70).

Figure 5.5-7 shows annual operating cost curves for an example thermal incinerator with recuperative heat recovery systems at three levels of heat recovery efficiency: 0, 35, and 50 percent, and 85 percent regenerative heat recovery. For these curves, the example incinerator was assumed to operate 8,000 hours per year, at a combustion temperature of 1700°F, with a waste gas heat content of 4 Btu/SCF. Figure 5.5-7 shows that annual operating costs for incinerators with recuperative heat recovery decrease with increasing heat recovery system efficiency, and increase with increasing inlet flow rates (size).

Table 5.5-4.  Incinerator Annual Cost Parameters (from Reference 11)

| Parameter | Description | Typical Values |
|---|---|---|
| Direct Cost Parameters | | |
| Operating factor (OF) | Yearly incinerator (INC) operation hours | 8,000 |
| Operator labor rate (OR) | Cost of operator labor | \$12.50/hr[a] |
| Maintenance Labor Rate (ML) | Cost of maintenance labor | 1.1 (OR)[a] |
| Operator shift factor (OS) | Fraction of operator's shift spent on INC | 0.5 |
| Maintenance shift factor (MS) | Fraction of maintenance shift spent on INC | 0.5 |
| Electricity rate (ER) | Cost of electricity | \$0.07/kW-hr[a] |
| Fuel (F) | Cost of fuel (natural gas) | \$2.30/$10^3$ SCF[a] |
| Indirect Costs | | |
| Annual Interest Rate (I) | Opportunity cost of the capital | 7 percent[c] |
| Operating Life (n) | Expected operating life of INC | 10 years[c]? |
| Capital Recovery Factor (CRF) | Function of (n) and (I) | 0.0944[d] |
| Taxes (TAX) | Fraction of TCI[d] | 0.01[c] |
| Insurance (INS) | Fraction of TCI[d] | 0.01[c] |
| Administrative Costs (AC) | Fraction of TCI[d] | 0.02[c] |

[a] Estimated for 1996 from currently available information.

[b] Estimates from "CO$T-AIR" Control Cost Spreadsheets (Reference 12).

[c] Capital recovery factor is calculated from the following formula:

$$CRF = \{I(1+I)^n\} \div \{(1+I)^n - 1\},$$

where $I$ = interest rate (fraction) and $n$ = operating life (years).

[d] The total capital investment (TCI) can be escalated to current values by using the Vatavuk Air Pollution Control Cost Indicies (VAPCCI), described in Section 5.4.5.

Table 5.5-5. Annual Cost Factors for Incinerators (Reference 12).

| Cost Item | Formula[a] | Factor |
|---|---|---|
| Direct Costs | | |
| Labor | | |
| Operator (OL) | (OF)×(OR)×(OS) | A |
| Supervisor (SL) | (SF)×(OL) | 0.15 A |
| Maintenance (ML) | (OF)×(MR)×(MS) | 1.1 A |
| Maintenance materials (MM) | (MF)×(ML) | 1.1 A |
| Electricity (E) | Power[b] × (ER) | E |
| Fuel (F) | Fuel[c] X (FR) | F |
| Total Direct Cost (DC) | | 3.35 A + E + F |
| Indirect Costs | | |
| Overhead | (OV)×(OL+SL+ML+MM) | 2.01 A |
| Capital Recovery | (CRF)×(TCI) | 0.1424 TCI |
| Taxes | (TAX)×(TCI) | 0.01 TCI |
| Insurance | (INS)×(TCI) | 0.01 TCI |
| Administrative Costs | (AC)×(TCI) | 0.02 TCI |
| Total Indirect Cost (IC) | | 2.01 A + 0.1824 TCI |
| Total Annual Cost (DC + IC) | | 5.36 A + 0.1824 TCI + E + F |

[a] Includes values also described in Table 5.5-5.

[b] Equal to the total power requirements, i.e. electricity and fan.

[c] Equal to the auxiliary fuel requirements.

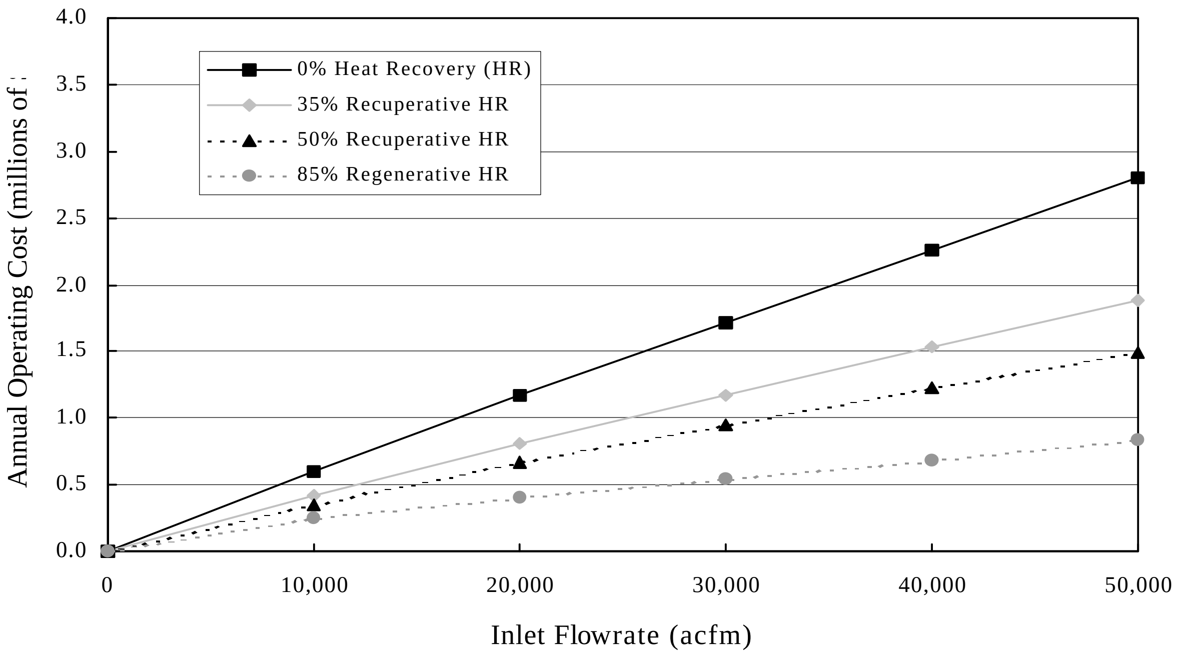


Figure 5.5-7. Annual Costs for Incinerators with Recuperative and Regenerative Heat Recovery (Reference 12).

Figure 5.5-7 also shows that annual costs for the example incinerator with regenerative heat recovery increase with inlet flow rate. Regenerative thermal incinerators achieve higher heat recovery (≥85 percent vs. ≤50 percent) at lower annual costs than recuperative systems. However, the higher capital costs of regenerative systems (see Figure 5.5-6) compared trecuperative systems (see Figure 5.5-5), present a trade-off in the choice incinerator type.

### 5.5.6 Energy and Other Secondary Environmental Impacts

No liquid, solid or hazardous wastes are generated from the use of thermal incinerators. As discussed above, the energy impacts of incinerator operation include that associated with the energy required to run the fan and are proportional to the gas flow rate and the system pressure drop.

Nitrogen oxides are also generated as air pollution during incineration. Because of the lower operating temperatures of catalytic incinerators, less $NO_x$ is generated with this type of incinerator. Based on the combustion of natural gas only, thermal incinerators have the potential to generate 100 pounds (lb) of $NO_x$ per $10^6$ SCF of natural gas combusted, and catalytic incinerators have the potential to generate 50 lb of $NO_x$ per $10^6$ SCF of natural gas.[13]

## 5.5.7 References for Section 5.5

1. Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-81-005a, NTIS PB83-127498). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. September 1982.

2. Theodore, L., and A.J. Buonicore. *Air Pollution Control Equipment. Volume II: Gases.* CRC Press, Inc., Boca Raton, Florida. 1988.

3. *Perry's Chemical Engineers' Handbook.* Sixth Edition. R.H. Perry and D.W. Green, Eds. McGraw-Hill, Inc., New York, New York. 1984.

4. Hazardous Air Pollutant Emissions from Process Units in the Synthetic Organic Chemical Manufacturing Industry--Background Information for Proposed Standards. Volume 1B: Control Technologies. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. November 1992.

5. Buonicore, A.J. "Incineration" in the *Air Pollution Engineering Manual*. A.J. Buonicore, and W.T. Davis, Eds. Air & Waste Management Association, Pittsburgh, Pennsylvania; and Van Nostrand Reinhold, New York, New York. 1992.

6. Reed, R.J. *North American Combustion Handbook.* North American Manufacturing Company, Cleveland, Ohio. 1978.

7. 1990 National Inventory. (Available at earth1.epa.gov/pub/gopher/Emis.Inventory). U.S. Environmental Protection Agency, Research Triangle Park, NC. January 1996.

8. Control Techniques for Volatile Organic Emissions from Stationary Sources (EPA-450/2-78-002). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. May 1978.

9. OAQPS Control Cost Manual (Fourth Edition, EPA 450/3-90-006). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. January 1990.

10. Compilation of Air Pollutant Emission Factors (AP-42). Volume I (Fifth Edition). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. January 1995.

11. Vatavuk, W.M. *Estimating Costs of Air Pollution Control.* Lewis Publishers, Chelsea, Michigan. 1990.

12. Vatavuk, W.M. "CO$T-AIR" Control Cost Spreadsheets. Innovative Strategies and Economics Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. February 1996.

13. Organic Chemical Manufacturing, Volume 4: Combustion Control Devices (EPA-450/3-80-026). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. December 1980.

# 6. INDUSTRIAL FUGITIVE EMISSION CONTROLS

This section describes measures used to control fugitive PM emissions from industrial sources. Fugitive PM emission sources can be divided into two broad categories--process fugitive emission sources and fugitive dust emission sources. Process fugitive emissions sources include emissions from mechanical and metallurgical operations that receive and/or generate dusty material. Fugitive dust emission sources relate to the transfer, storage, and handling of dusty materials and include those sources from which particles are entrained by the forces of nature acting on exposed dusty surfaces or from vehicle motion on dusty roads.

The most widely used methods of controlling process fugitives are local ventilation and building enclosure/evacuation. Both types of systems have their advantages and drawbacks, but local ventilation is generally more cost effective. Process optimization, good operation and maintenance (O&M), and other industry-specific practices can also be quite effective in reducing process fugitive emissions. However, both the selection of the system and the ultimate performance of the system are related to industry and facility-specific design and operating characteristics.

For most industrial plants, paved and unpaved roads are the primary sources of fugitive dust emissions. Fugitive dust emissions from handling operations for storage pile materials are usually less significant in comparison to road sources, unless the moisture content of the storage pile materials is extremely low. Emissions due to wind erosion of storage piles are likewise less significant unless wind speeds are unusually high.[1] Low wind speeds can result in significant emissions if storage pile materials are fines (e.g. cement kiln dust or materials collected by fabric filters or ESPs)

The control of road dust from both paved and unpaved roads, therefore, can achieve a significant reduction in fugitive dust emissions. Paving of unpaved roads; eliminating, reducing, or managing truck transportation; and street cleaning are the most effective techniques to reduce fugitive dust emissions from roads.

More information about fugitive dust emission sources and controls can be found in the EPA publications *Fugitive Dust Background Document and Technical Information Document for Best Available Control Measures,*[2] and *Compilation of Air Pollutant Emission Factors (AP-42), Volume I: Stationary Point and Area Sources*.[3]

## 6.1 ENCLOSURES AND VENTILATION

Partial or full enclosures, windbreaks, hoods and other ventilation systems, and complete building evacuation are widely used methods to capture and control fugitive PM emissions. These methods are usually used with traditional stack PM control devices (e.g. fabric filters or scrubbers) to collect the captured PM. Processes amenable to this type of control include materials handling devices such as conveyors, elevators, feeders, loading and unloading operations, and bagging; solids benefication, such as crushing, screening, and other classifying operations; mining, i.e. drilling and crushing; and furnaces, ovens, and dryers.[7]

### 6.1.1 Local Ventilation Systems

Local ventilation systems can consist of a "secondary" hood at a localized source of PM emissions or large canopy-type hood suspended over the entire source. An example of a secondary local hood is a mobile hood that is used to collect emissions from pots or other containers that are set aside for cooling. Ventilation systems are usually uniquely designed to conform with the facility configuration and need for process access; these factors, however, can limit their performance as well as their design. Ventilation hooding and its ductwork may be difficult to retrofit in some facilities due to space limitations. In addition, local ventilation systems may limit personnel and equipment access. For these reasons, a local ventilation system may not be a feasible method of process fugitive emissions control for some operations. Design information about local ventilation systems in general and for specific applications can be found in the most recent edition of the American Conference of Governmental Industrial Hygienists (ACGIH) publication: *Industrial Ventilation: A Manual of Recommended Practice*.

Most ventilation systems are designed to meet several objectives.[1] First, the hood must enclose the source to the degree possible without excessively interfering with the access needed for normal operations. Second, the hood should be configured in such a way that natural buoyancy or mechanical forces direct the plume into, rather than away from, the hood. Finally, the system must be designed with sufficient exhaust ventilation to maintain recommended face velocities at all hood faces. Typically, these velocities are in the range of 75 to 150 meters per minute. Additionally, for buoyant plumes that generate a natural draft, the ventilation rate must exceed the plume generation rate, or "spillage" from the hood will occur.[1]

Metal operations, both primary and secondary, generate a large quantity of fugitive PM emissions. One of the major sources of metallurgical process fugitive emissions that can be controlled by local ventilation are stationary-type furnaces such as blast furnaces, reverberatory furnaces, and cupolas. Hoods may be designed to collect gas perpendicular to the buoyant gas flow, in which high face velocities are required; other designs may be such that the buoyant gas plume is directed into the hood. Figure 6-1 shows a local ventilation system at a blast furnace slag tapping area.[1,4] A very different local ventilation design would be needed for nonstationary electric arc and rotary furnaces that rotate during operation. A key feature of these systems is that charging and tapping occur in the same general area. Hence, hooding must be designed in such a way that it does not interfere with either operation.

Material handling operations can also be equipped with local ventilation to control fugitive PM emissions. Figure 6-2 shows a local ventilation system at "skip hoist" loading station that is part of a metallurgical operation.

An air curtain capture system is a specially designed local ventilation system that can capture fugitive emissions from a process without interfering in normal operations, such as the use of an overhead crane.  With an air curtain, air is blown across the space above the PM-generating operation using a plenum or row of nozzles designed to form an air sheet which causes as little turbulence as possible.  The curtain air, entrained air (from above and below the curtain) and PM, including fine PM fumes, are captured by the exhaust system.  Capture of

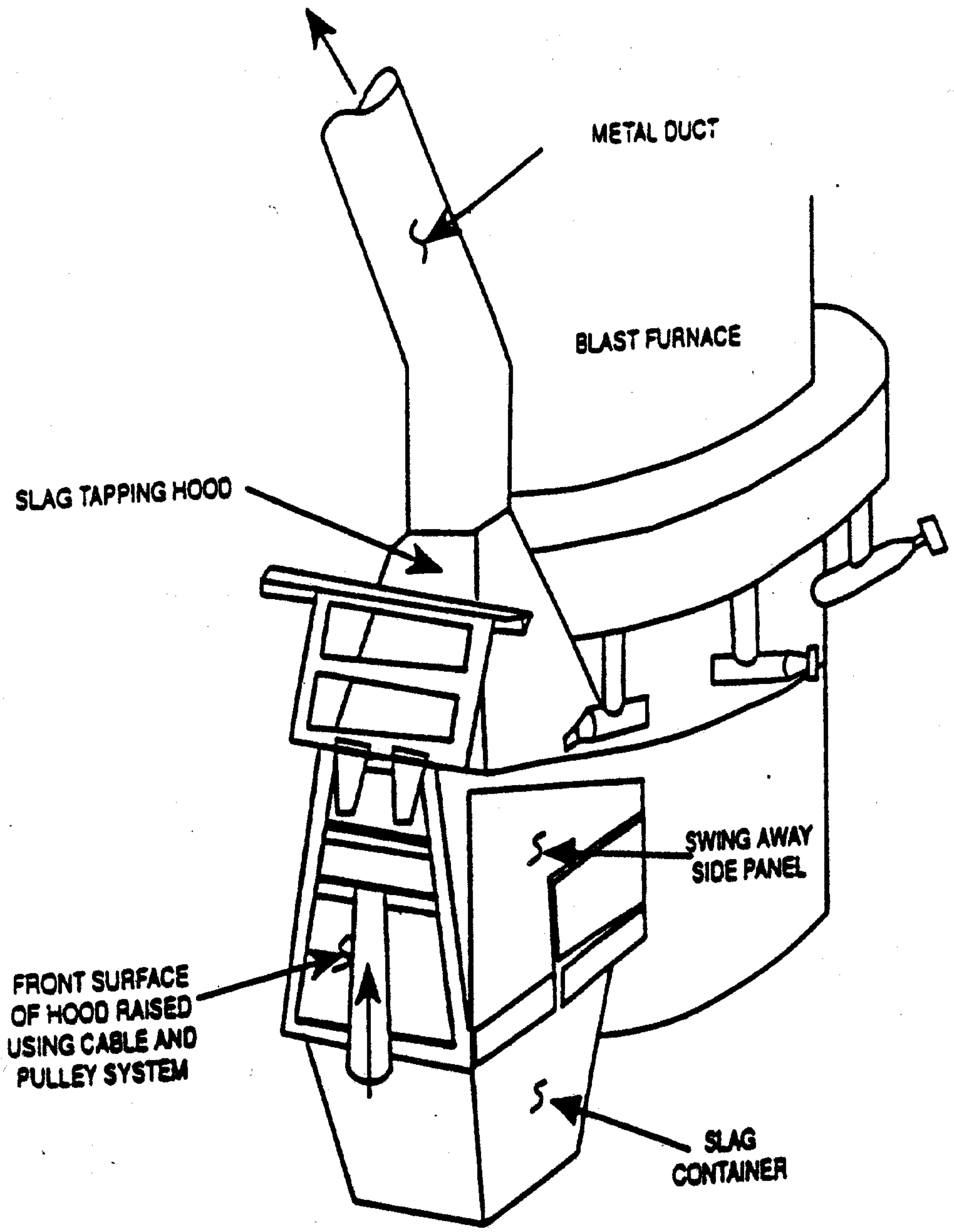


Figure 6-1. Schematic of a Slag-tapping Hood at a Blast Furnace (from Reference 4).

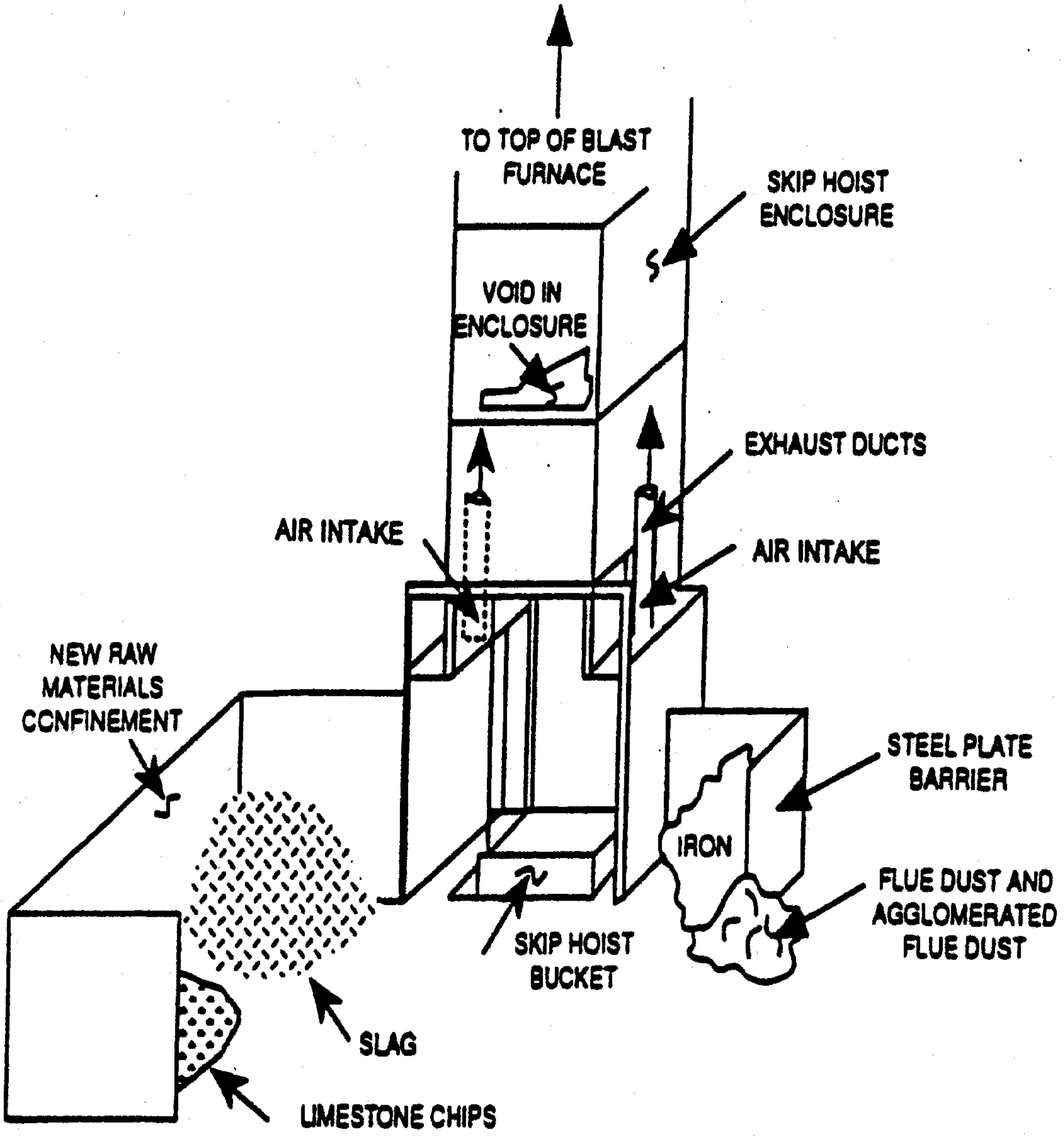


Figure 6-2. Schematic of a Local Ventilation System at a "Skip Hoist" Loading Station

fugitive PM is greater than 90 percent. This type of system has been used successfully in primary copper production.[1]

### 6.1.2 Building Enclosure/Evacuation

Enclosing and ventilating an entire building may be the only feasible control method when the process operation is characterized by a number of small fugitive emissions sources. A typical building evacuation system might consist of opposing wall-mounted ventilators that force air across process equipment and out through an overhead plenum to a fabric filter.[5] In order to limit worker exposure to emissions and expel the heat generated by process operations, large airflow rates are required. Thus, operational costs for this type of system can be prohibitive. In addition, the need to keep the building enclosed during operation of the ventilation system may be too restrictive on process operations, such as the movement of forklifts and other equipment into and out of the building.[1]

## 6.2 OPTIMIZATION OF EQUIPMENT AND OPERATION

Optimization of equipment and operation includes: 1) limiting the amount of dust available for emissions; 2) improving the arrangement of materials that generate dust; 3) optimizing the process so that less dusty material is used, generated, or made vulnerable to air contact; 4) preventing or minimizing leaks; and 5) other good O&M procedures that reduce PM emissions. In some industries, optimizing equipment and operation to reduce PM emissions can also reduce operating costs if valuable products and/or raw materials can be recovered and used.

### 6.2.1 Source Extent Reduction and Improvement

Source extent reduction measures are largely a function of good work practices and include measures designed to reduce the volume and/or area of PM-generating materials disturbed or reduce the frequency of disturbances and spills.[1,7] These goals can generally be achieved through good work practices and without a large investment in a control program.[1]

Examples of source extent reductions/improvements include:[1]

- Drop height reduction through the use of hinged-boom conveyors, rock ladders, lower wells, etc.[7] Table 6-1 lists estimated control efficiencies for improvements through drop height reduction techniques;[6]
- Use of less dusty raw materials;
- Choke-feed or telescopic chutes to confine the material being transferred;[7]
- Increasing moisture retention in dusty areas;[1]

Table 6-1. Estimated Control Efficiencies for Drop Height Reduction Techniques (from Reference 6)

| Technique | Control Efficiency (percent) |
|---|---|
| Lowering well or perforated pipe | 80 |
| Telescoping chute | 75 |
| Rock ladder | 50 |
| Hinged-boom conveyor | 25 |

- Washing down or scraping conveyor belts regularly;[1]

- Performing PM-generating activities only as needed, e.g. in secondary lead production, breaking of batteries only as needed to keep pace with the furnace;[1]

- Monitoring of feed materials to identify high PM-generating conditions;[1]

- Use of clean scrap in metal-melting furnaces;[7] and

- Removing crankcase oil prior to automobile salvage.[7]

### 6.2.2 Process Optimization/Modification

Process optimization and/or modification can be an effective preventive measure for process fugitive emission control. Also included in this category is the optimization of the primary PM control devices and their capture systems. Some general techniques are:

- Mass transfer frequency reduction,
- Improved operational efficiency, and
- Use and proper operation of point-of-generation dust collection devices.

Some process-specific optimization techniques are:

- Designing a sulfuric acid plant at a primary lead smelter with sufficient capacity to preclude the creation of back pressure and excess venting of the sinter machine.[1]

- Changing from a cupola to an electric arc furnace.[7]

- Changing from an (open) bucket elevator to more efficient (closed) pneumatic conveyor.[7]

- Screening out undersized coke (<1 inch) to reduce blast furnace fugitive emissions in primary lead smelting.[1]

- Improving blast furnace combustion efficiency during primary lead smelting by improving the furnace water cooling system.[1]

- Injecting molten sodium in primary lead smelting kettle drossing to form liquid matte rather than dross.[1]

- Eliminating fugitive PM from transporting, pouring, and stirring molten lead by the use of continuous kettle drossing rather than manual in primary lead smelting (as is currently done in only foreign facilities).[1]

- Improving raw material quality, e.g. improve the quality of coke and sinter concentrate used in primary lead production.[1]

- Cooling lead pots to reduce fume generation during kettle drossing in primary lead production.[1]

- Pumping (primary) lead directly to dross kettles using an electromagnetic pump.[1]

- Agglomerating blast furnace flue dust in an agglomerating furnace to reduce the load on the baghouse to improve its performance. This process completely eliminates handling of the dust and the associated fugitive emissions, and eliminates fugitive emissions from flue dust storage piles.[1]

- Using permanent mold castings in gray iron foundries instead of green sand. This is reported to reduce PM emissions by 99 percent.[1]

- Pre-treating glass manufacturing raw materials to reduce the amount of fine particles. Pretreatments include: presintering, briquetting, pelletizing, or liquid alkali treatment.

- Replacing grease and oil lubricants (e.g. in glass manufacturing) with silicone emulsions and water-soluble oils that eliminate the smoke generated from flash vaporization of hydrocarbons from greases and oils that come into contact with process materials.[1]

### 6.2.3 Leak Prevention and Detection and Other Good O&M Practices

Good O&M practices can help to reduce fugitive PM emissions significantly. A key aspect of a good O&M program to reduce PM emissions is a formalized leak prevention and detection program. Examples of items that may be included in a program are: 1) adequate design and prompt repairs of exhaust hood leaks; 2) maintenance of door and window seals;[1] and 3) repair and/or prevention of warpage of oven doors to maintain proper seal.[7]

Good housekeeping practices and/or prompt response to process upsets, accidents, and spills are also key elements in the control of fugitive dust. This prevents the build-up of dusty material that can be resuspended into localized drafts. Good housekeeping practices include the following procedures:[1]

- Washing down of building interiors regularly,
- Wetting floors during high dust periods,
- Use of oil-based sweeping compounds,
- Wet-wiping drums after the packaging of products,

A central vacuum system may be cost-effective for especially dusty operations.[1] A full-time clean-up crew may be required for some facilities to regularly implement the above procedures.[1,7]

The proper operation of equipment is a good industrial practice to prevent fugitive dust emissions. One example that may be applicable to a number of industries, especially in metallurgy, is the operation of furnaces so that they are not overloaded to eliminate the possibility of back pressure from the primary PM control system as well as "puffing" during opening of the charging door.[7] Employee incentive programs to limit fugitive dust emissions also have been used successfully in some industries.[1]

## 6.3 COSTS OF HOODS

Chapter 10 of the *OAQPS Cost Manual* provides information on estimating costs for circular canopy, rectangular canopy, push-pull, slide-draft, and back-draft (slotted) hoods.[8] Hood costs are estimated by using parameters from Table 6.2 in the following equation:

$$C_h = aA_f^b \qquad (6.1)$$

where $C_h$ = hood cost ($)
$A_f$ = hood inlet (face) area (ft$^2$)
a,b = equation regression parameters

## 6.4 FUGITIVE DUST CONTROL

For information on the control of fugitive dust, please refer to *Fugitive Dust Background Document and Technical Information Document for Best Available Control Measures* (EPA-450/2-92-004) and *Control of Open Fugitive Dust Sources* (EPA-450/3-88-008).

## Table 6.2. Parameters for Hood Cost Equation (Reference 8)

| Type of Hood | Fabrication Material[a] | Equation Material | | Equation Range ($A_f$, $ft^2$) [b] |
|---|---|---|---|---|
| | | a | b | |
| Canopy, circular | FRP | 123 | 0.575 | 2 - 200 |
| Canopy, rectangular | FRP | 294 | 0.505 | 2 - 200 |
| Push-pull | FRP | 595 | 0.318 | 2 - 200 |
| Side-draft | FRP | 476 | 0.332 | 2 - 200 |
| Back-draft, slotted[c] | PVC | 303 | 1.43 | 0.6 - 2.0 |
| Back-draft, slotted[d] | PVC | 789 | 0.503 | 1. 1- 2.1 |
| Back-draft, slotted | PP | 645 | 0.714 | 1. 1- 2.1 |
| Back-draft, slotted | FRP | 928 | 0.516 | 1. 1- 2.1 |
| Back-draft, slotted | Galvanized Steel | 688 | 0.687 | 0.5 - 1.3 |

[a] FRP = fiberglass reinforced plastic, PVC = polyvinyl chloride, PP = polypropylene

[b] For slotted hoods, equation range indicates the range in the area of the slot openings, which is much less than the total face area.

[c] Hoods with two rows of slots and no dampers.

[d] Hoods with four rows of slots and manual slot dampers.

## 6.5 REFERENCES FOR SECTION 6

1. Estimating and Controlling Fugitive Lead Emissions from Industrial Sources (EPA-452/R-96-006). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. May 1996.

2. Fugitive Dust Background Document and Technical information Document for Best Available Control Measures (EPA-450/2-92-004). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 1992.

3. Compilation of Air Pollutant Emission Factors (AP-42). Volume I (Fifth Edition). U.S. Environmental Protection Agency, Research Triangle Park, NC. January 1995.

4. Coleman, R., Jr. and R. Vandervort. Demonstration of Fugitive Emission Controls at a Secondary Lead Smelter in *Lead-Zinc-Tin 1980*, J.M. Cigan, T.S. Mackey, and T.J. O'Keefe (eds.). Proceedings of TMS-AIME World Symposium on Metallurgy and Environmental Control in Las Vegas, Nevada, February 24-28, 1980. 1981.

5. Smith, R.D., O.A. Kiehn, D.R. Wilburn, and R.C. Bowyer. Lead Reduction in Ambient Air: Technical Feasibility and Cost Analysis of Domestic Primary Lead Smelters and Refineries. Bureau of Mines, U.S. Department of the Interior, Washington, D.C. 1987.

6. Bohn, R., T. Cuscino, Jr., and C. Cowherd, Jr. Fugitive Emissions from Integrated Iron and Steel Plants (EPA-600/2-78-050). U.S. Environmental Protection Agency, Washington, DC. March 1978.

7. Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-81-005a, NTIS PB83-127498). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. September 1982.

8. OAQPS Control Cost Manual (Fourth Edition, EPA 450/3-90-006). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. January 1990.

# 7. EMERGING TECHNOLOGIES

This section discusses the technologies that are currently being developed to enhance the operation and/or collection efficiency of particulate control devices. In many cases, the increase in collection efficiency is achieved through increase in collection of fine particles.
The sections below present emerging technologies for fabric filters, ESP's, scrubbers, and mechanical control devices. Control techniques that allow for simultaneous control of PM along with other pollutants are discussed here, despite the fact the PM collection efficiencies of the devices may not be substantially higher than that in traditional devices; these devices are included here because of the large savings in efficiency that are offered by the methods. Table 7-1 summarizes the technologies presented in this section.

## 7.1 EMERGING FABRIC FILTER TECHNOLOGIES

Emerging technologies for fabric filters include 1) ceramic filter elements and ceramic fiber enhancement, 2) fine 1.1 dtex fibers, and 3) electrostatically stimulated fabric filtration (ESFF). These technologies are discussed below.

### 7.1.1 Ceramics: Ceramic Filter Elements and Ceramic Fiber Enhancement

Ceramic filters have become available (Altair, Ltd., UK; Didier, GmbH, FRG) that can be used for high temperature PM filtration applications. Ceramic material is formed into stiff cylindrical filter elements, called "candles." The tubes are generally 1 to 1.5 meters in length, with outside diameters of 60 mm and a wall thickness of 10 to 20 mm. One end of the tube is closed, and the other is open. The open ends of the tubes are mounted either vertically or horizontally on a tubesheet, as with fabric bags. Tubes are generally cleaned by pulse jets.[1]

Ceramic fibers have been successfully processed into synthetic yarns and woven into fabric filter bag material by 3M Inc. These ceramic-enhanced bags, called Nextel®, are capable of high efficiency filtration (>99 percent) of gas streams at temperatures up to 1400°F. High temperature operation saves the expense of gas cooling, reduces maintenance due to condensation of corrosive gases, allows for energy recovery, and allows for PM removal from the hot gas before other catalyst processes are performed. The Electric Power Research Institute (EPRI) is currently testing the performance of these bags.[2]

### 7.1.2 Fine 1.1 dtex Fibers

New fine fibers, of 1.1 dtex (textile density - grams fiber per 10,000 meters of fiber ) have been developed by Dupont, GmbH (FRG), for high-efficiency fabric filtration. The fine fibers are available in Nomex® and Teflon® materials. The fine fibers are half the weight of standard Nomex fibers. The advantage of the new fibers is that while two (1.1 dtex) fine fibers will weigh the same as one standard (2.2 dtex) fiber, the fine fibers have 40 percent

Table 7-1.  Summary of Emerging PM Control Technologies

| Device | Technology | Benefit |
|---|---|---|
| Fabric Filter | | |
| | 1) Ceramics<br>ceramic filter elements and ceramic fiber bag enhancement | 1) High temperature capabilities |
| | 2) Fine 1.1 dtex Fibers | 2) Higher fine PM control efficiency |
| | 3) Electrostatically-Stimulated Fabric Filtration (ESFF) | 3) Higher PM control efficiency and lower pressure drop |
| ESP | | |
| | 1) Sonic Horn Rappers | 1) Better plate cleaning efficiency, lower capital costs, lower energy requirements, less maintenance, and less downtime |
| | 2) Cold-pipe Precharger ESP | 2) Higher PM control efficiency, especially for high resistivity PM |
| | 3) SUPER ESP | 3) Higher PM control efficiency, especially for high resistivity PM; smaller ESP; and eliminates need for flue gas conditioning |
| | 4) Advanced Computer-Based Control System | 4) Higher PM control efficiency |

(continued)

Table 7-1. (continued)

| Device | Technology | Benefit |
|---|---|---|
| Combination Devices | COHPAC Hybrid ESP/FF | Higher PM control efficiency, especially for $PM_{10}$; smaller size, and less downtime than an ESP |
| Scrubber | 1) Annular Orifice Venturi Scrubber | 1) Higher PM control efficiency, especially for $PM_{2.5}$ |
| | 2) Waterweb Mesh | 2) Higher PM control efficiency, less clogging |
| Mechanical Collector | Core Separator | Higher PM control efficiency |
| Fugitive Dust | 1) High-Voltage PM Ionizer | 1) Higher PM control efficiency ($\leq$100 percent control) for PM $\geq$0.005 $\mu$m, as well as $\geq$99 percent $SO_2$ and $NO_x$, and $\geq$95 percent VOCs |
| | 2) Dry Fog | 2) 10 percent of the water requirements for conventional spray techniques |
| Simultaneous Control | 1) SOx-NOx-Rox Box (SNRB) Catalytic Fabric Filter | 1) Controls SOx and NOx as well as PM (Rox) |
| | 2) Catalyst-Coated Fabric Filters | 2) Controls NOx and PM |

more filter surface area. This enables the construction of denser and less porous filter media. Potential improvements in fabric filter operation include higher efficiency at the same weight of media, or lighter media with the same or better efficiency. These fine fibers are suitable for operation in pulse jet fabric filters.[3]

### 7.1.3 Electrostatically-Stimulated Fabric Filtration (ESFF)

Electrostatically-stimulated fabric filters (ESFF) have been developed that reduce fabric filter pressure drop and significantly reduce particle penetration. Electrically-charged particles have been found to form highly porous dust layers in fabric filters.[4] One type of ESFF involves the placement of discharge electrodes (wires) axially inside reverse air filter bags with conductive fibers woven into the bags. This generates an electric field between the wire and the surface of the bag. A second type of ESFF uses external placement of discharge wires within an array of pulse-jet bags.[17] Another variation of ESFF includes the placement of a pulse-jet ESFF module within an existing ESP, discussed in section 7.3.[5]

## 7.2 EMERGING ESP TECHNOLOGIES

Emerging technologies for ESP's include 1) sonic horn rappers, 2) cold pipe precharger ESP, 3) alternating charging and short ESP collector sections (SUPER ESP), and 4) advanced computer-based ESP control systems. These technologies are discussed below.

### 7.2.1 Sonic Horn Rappers

Sonic horn rappers for ESP cleaning have been developed by Atlantic Electric, Ltd. (UK) for application in the electric utility industry to improve cleaning of ESP plates. The sonic horns, used with magnetic impulse gravity impact (MIGI) rappers, were found to be superior to tumbling hammers in terms of lower capital costs, lower energy requirements, less maintenance, and less downtime.[6]

### 7.2.2 Cold-Pipe ESP Precharger

A cold-pipe ESP precharger has been developed by Denver Research Institute. This device circulates cool water through the pipe of a wire-pipe ESP precharger section. This configuration reduces the resistivity of the dust layer collected on the outside surface of the cold pipe and achieves a very high level of charge on the entrained dust particles in a very short flow distance. Retrofit of existing ESPs with cold-pipe prechargers showed that the effect of the addition of a cold pipe section exceeded the negative effects of back corona, and significantly improved the collection efficiency with high resistivity dusts.[7,8]

One potential application of this technology entails placing a cold-pipe precharger in-line downstream from a conventional ESP that has at least one main electrical section. The cold-pipe precharger can have collection pipes substantially shorter than in the main ESP, and can be operated with a current density 75 percent or lower than pipes in the main ESP section.[9] Another application involves placing a cold-pipe precharger in front of each collection section of a wire-plate ESP. This second application is referred to as a "multistage" ESP.[17] A new concept of multi-stage ESP uses smaller sections preceded by cold-pipe prechargers, discussed in the next section.

### 7.2.3 Alternating Charging and Short ESP Collector Sections (SUPER ESP)

By separating the charging and collecting sections and optimizing each separately, a new concept called SUPER ESP has evolved. Instead of long, wire-plate ESP sections, the SUPER ESP uses a wire-pipe (cold-pipe) precharger previously described followed by an abbreviated wire-plate collector section.[10] Research has shown the collection efficiency of a SUPER ESP section of 3-4 wires to be equivalent to a conventional ESP section of 7-8 wires for lower resistivity dust, and a 12-14 wire section for high resistivity dust. Therefore a new ESP using this concept may be only one-half to one-fourth the length of a conventional ESP; or an existing ESP can be upgraded by replacing one section with two or more SUPER ESP sections in the same space.[11]

### 7.2.4 Advanced Computer-Based ESP Control Systems

The operation of an ESP can be optimized with the use of a computerized control systems. The computer can be programmed to monitor and control the ESP parameters that influence efficiency, and do so in a way that exceeds the capability of manual techniques. For example, the computer can identify the existence of back corona and then change the ESP current or voltage settings so as to avoid or minimize the influence of the back corona. Another example of advanced computer-based ESP control is a method used by The Mitsubishi Company in Japan, where computer-controlled intermittent energization[12] is accomplished within an ESP, as needed to avoid back corona.[17]

## 7.3 EMERGING COMBINATION DEVICES

A combination fabric filter/ESP hybrid has been developed by EPRI and is called the Compact Hybrid Particulate Collector (COHPAC). This device involves using pulse jet fabric filtration to capture PM that escape an ESP. The device has two designs called COHPAC I and II. COHPAC I involves placing a (pulse jet) fabric filter downstream from an ESP. COHPAC II utilizes a fabric filter in place of the last field(s) of an ESP.[13,14, 15,16] COHPAC has been successfully tested in pilot facilities at utility boilers.[17] In a similar configuration to COHPAC II, an EPA-developed innovation is to replace the last section of an ESP with pulse-jet ESFF and maintain a high-voltage charging and collection field with the existing ESP power supply. This results in an order of magnitude lower emissions and significantly lower pressure loss than for an uncharged fabric filter.[5]

The COHPAC merges the advantages of an ESP and fabric filter. Advantages due to the fabric filter component of the COHPAC are:[17]

- Less sensitive to changes in fuel composition, than an ESP, since a fabric filter at steady state has constant outlet emissions.
- Better collection efficiency of $PM_{10}$, as typical of fabric filtration.
- On-line maintenance can be utilized for the fabric filter section of the COHPAC, resulting in less downtime.

Advantages due to an upstream ESP collector are:[17]

- The PM loading to the fabric filter is low enough to allow the fabric filter to operate at a very high gas-to-cloth ratio (10-18 ft/min), without excessive pressure drop or penetration.
- The collection efficiency of fabric filtration is enhanced because the PM has a residual charge from the ESP.

## 7.4 EMERGING SCRUBBER TECHNOLOGIES

The emerging technologies for scrubbers include: 1) annular orifice venturi scrubber and 2) waterweb mesh scrubber. These technologies are described below.

### 7.4.1 Annular Orifice Venturi Scrubber

The annular orifice venturi scrubber has been developed (Leisegang QTV-Process, N.A.) that is an alkaline scrubbing process for the removal of PM and gaseous pollutants. Flue gases are first cooled by injection of a lime liquor and then scrubbed in an annular orifice venturi. The unit generates no wastewater and uses the heat from the flue gases to concentrate residue into a paste with 50 percent solids. This device has been successfully used in MSW incineration where, with a pressure drop of 16 in. water, 99 percent control efficiency of PM $\geq$ 2.5 µm was achieved. At 24 in. water pressure drop, >99 percent control efficiency was achieved for PM $\geq$ 1.0 $\mu$m and 97.5 percent for 0.5 µm PM.[18]

### 7.4.2 Waterweb Mesh Scrubber

A waterweb mesh scrubber has been developed by Mystaire Air Pollution Control Systems, of Misonix Inc. of Farmingdale, New York, that is suitable for many types of PM, gases, vapors, odors, and mists. Waterweb mesh is an extremely effective scrubber packing that consists of sections of layered PVC-coated fiberglass that is compressed and bonded to create thousands of microventuri passages where gas is forcibly dispersed through scrubbing liquid. The mesh is nonclogging and thoroughly mixes the gas and scrubbing liquid. This scrubber is reported to be able to handle up to 50,000 CFM.[19]

## 7.5 EMERGING MECHANICAL COLLECTOR TECHNOLOGIES

An emerging technology for mechanical collectors is the "Core Separator" that has been developed by LSR Technologies, Inc. for use with PM from coal combustion. The core separator consists of a centrifugal separator and a conventional cyclone. The centrifugal separator is a cylindrical chamber with a tangential inlet at the bottom and two outlets, which generates a circular motion and centrifugal force. In the Core Separator, dust-laden gas enters the centrifugal separator, where solid PM is forced to the wall outwards from the center of the centrifugal separator leaving clean gas. This clean gas in the center of the separator is exhausted to the atmosphere and the remaining dust-laden portion of the gas is sent to a cyclone for additional PM removal. The cleaned gas from the cyclone is then recirculated back to the centrifugal separator. The Core Separator system costs about three times more than an equivalent-sized cyclone, but removes 80 percent of what usually penetrates the conventional cyclone, to give 95 to 98 percent overall PM control.[20,21]

## 7.6 EMERGING FUGITIVE DUST CONTROL TECHNOLOGIES

Emerging technologies that may be applicable for PM control from fugitive PM sources are 1) high-voltage PM ionizer and 2) dry fog. These technologies are discussed below.

### 7.6.1 High-Voltage PM Ionizer

A technique that utilizes high-voltage electrical pulses to control air pollutants has been developed by two companies. One device, called the Ion Blast, has been developed by Ion Blast, Inc. of Vantaa, Finland. In the Ion Blast, gas is blown into a chamber where a 150 kilovolt (kV) current charges the PM in the air. The PM is then attracted towards a collection surface where they become attached. The device is reported to have low energy requirements and no moving, wearing, or replaceable parts. The Ion Blast is reported to be able to remove nearly 100 percent of the PM, including biological matter such as viruses, as small as 0.005 µm. Only small quantities of gas, up to 5,000 SCFM, can be treated.[22]

A similar device, called the Pulsatech, has been developed by Pulsatron Technology, Ltd. of Los Angeles, California. This technology was acquired from a Russian government agency, which had implemented the device at four Russian industrial plants. The Pulsatech is reported to achieve 99 percent destruction of $SO_2$ and $NO_x$ and >95 percent destruction of VOCs, while ionizing the PM so that it collects on the chamber walls. The device uses a 22 kV charge and has a capacity of less than 1,500 SCFM.[23]

### 7.6.2 Dry Fog

A device to control fugitive coal dust emissions from transfer points has been developed and patented by Sonic Development Corp., Parsippany, New Jersey. In the "Dry Fog" device, a fog of micrometer-size water droplets is generated by nozzles. The water moistens the coal and triggers agglomeration of the dust particles to sizes large enough to settle. Once the dust drops reach the ground, the water evaporates leaving dry coal. A unit installed near the power plant of a grain processor uses water at a rate of 1 gal/min, about 10 percent of that used in conventional wetting techniques.[24]

## 7.7 EMERGING SIMULTANEOUS POLLUTION CONTROL TECHNOLOGIES

Emerging technologies that target the simultaneous control of PM and other pollutants include: 1) $SO_x$-$NO_x$-Rox Box (SNRB) catalytic fabric filter, and 2) catalyst-coated fabric filters. These technologies are discussed below.

### 7.7.1 SNRB ($SO_x$-$NO_x$-Rox Box) Catalytic Fabric Filter

A $SO_x$-$NO_x$-Rox Box (SNRB) has been developed by Babcock & Wilcox (Alliance, Ohio) for use in coal combustion, that controls PM ("Rox") as well as $SO_x$ and $NO_x$. The device consists of a pulse-jet fabric filter equipped with ceramic fiber filter bags for high temperature application, alkali (sodium or calcium based) sorbent injection used for $SO_2$ removal, and ammonia injection and selective catalytic reduction (SCR) used for catalytic reduction and control of $NO_x$. The catalyst is located inside the filter bags (see Section 7.7.2 below). The alkali sorbent and ammonia injection can be performed at the high temperatures of the fabric filter. Consolidating the removal of three pollutants into one device saves on capital and operating costs, and the need for flue gas cooling is eliminated. Efficiencies reported are 99.9 percent for PM, 85 percent for $SO_x$, and 90 to 95 percent for $NO_x$.[25,26]

### 7.7.2 Catalyst-Coated Fabric Filters

Catalyst-coated fabric filters have been developed by the Energy & Environmental Research Center of Grand Forks, North Dakota, and Owens Corning Fiberglass Corporation use with combustion sources. Using a sol-gel process, high temperature fabric filters are coated with a vanadium/titanium (V/Ti) catalyst. The catalyst-coated filters can then be used in utility or industrial hot-side fabric filter and are capable of simultaneous PM and $NO_x$ control.[27]

## 7.8 REFERENCES FOR SECTION 7

1. Butcher, C. Hot News in Ceramic Filters. Chemical Engineer. October 10, 1991.

2. Fischer, E.M. "Performance of Ceramic Fiber and Composite Filters at High Temperatures," in *Clean Air Technology News*, Institute of Clean Air Companies, Washington, DC. Summer 1995.

3. Dilger, F. Lowering Emissions - More Effective Air Pollution Control with Fine Fibre Filter Media. Filtration & Separation. March/April 1994.

4. Plaks, N. and B.E. Daniel. "Advances in Electrostatically Stimulated Fabric Filtration," in *Proceedings of the Seventh Symposium on the Transfer and Utilization of Particulate Control Technology* (EPA-600/9-89-046b). U.S. Environmental Protection Agency, Washington, DC. May 1989.

5. Plaks, N. and C.B. Sedman. Enhancement of Electrostatic Precipitation with Electrostatically Augmented Fabric Filtration. U.S. Patent No. 5,217,511. June 8, 1993.

6. ESP Newsletter. The McIlvaine Company, Northbrook, Illinois. March 1996.

7. Yamamoto, T., P.A. Lawless, and N. Plaks. Evaluation of the Cold Pipe Precharger. IEEE Transactions on Industry Applications. 26(4): 639-645. July/August 1990.

8. Rinard, et al. "Development of a Charging Device for High-resistivity Dust Using Heated and Cooled Electrodes," in *Proceedings of the Third Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. II* (EPA-600/9-2-005b). U.S. Environmental Protection Agency, Washington, DC. 1982

9. Mosley, R.B., L.E. Sparks, and N. Plaks. Electroprecipitator with Suppression of Rapping Reentrainment. U.S. Patent No. 4,822,381. April 18, 1989.

10. N. Plaks and L.E. Sparks. Electroprecipitator with Alternating Charging and Short Collector Sections (SUPER ESP). U.S. Patent No. 5,059,219. October 22, 1991.

11. Plaks, N. "The SUPER ESP - Ultimate Electrostatic Precipitation," in *Proceedings: 1991 Symposium on the Transfer and Utilization of Particulate Control Technology*. Electric Power Research Institute, Palo Alto, California. 1992.

12. Oglesby, S., Jr. Future Directions of Particulate Control Technology: A Perspective. J. Air Waste Management Assoc. 40(8): 1184-1185. August 1990.

13. Fabric Filter Newsletter. The McIlvaine Company, Northbrook, Illinois. April 1996.

14. Miller, R.L. "Combining ESPs and Fabric Filters for Particulate Collection," in *Clean Air Technology News*, Institute of Clean Air Companies, Washington, DC. Winter 1994.

15. Lamarre, L. COHPing with Particulates. EPRI Journal. July/August 1993.

16. Chang, R. Compact Hybrid Particulate Collector (COHPAC). U.S. Patent No. 5,158,580. October 27, 1992.

17. C. Sedman, N. Plaks, W. Marchant, and G. Nichols. Advances in Fine Particle Control Technology. Presented at the Ukraine Ministry of Energy and Electrification Conference on Power Plant Air Pollution Control Technology, in Kiev, The Ukraine, September 9 - 10, 1996.

18. The Scrubber Manual. The McIlvaine Company, Northbrook, Illinois. February 1987.

19. Personal communication. C. Thomas, Misonix Inc., Farmingdale, New York, with T. Stobert, EC/R Inc., Durham, North Carolina. Mystaire® Scrubbing Systems. August 6, 1996.

20. ESP Newsletter. The McIlvaine Company, Northbrook, Illinois. May 1996.

21. Wysk, S.R. and L.A. Smolensky. Novel Particulate Control Device for Industrial Gas Cleaning. Filtration & Separation. January/February 1993.

22. ESP Newsletter. The McIlvaine Company, Northbrook, Illinois. April 1996.

23. High-Power Pulses Blast Pollutants. Chemical Engineering. 103(9): 21-22. September 1996.

24. Reason, J. Dust Suppression System Doesn't Wet Coal. Power. March 1989.

25. Kudlac, G.A., et. al. SNRB Catalytic Baghouse Laboratory Pilot Testing. Environmental Progress. 11:1. February 1992.

26. Gennrich T. Filter Bags Help Meet Particulate Control Standards. Power Engineering. August 1993.

27. Ness, S.R., et al. SCR Catalyst-Coated Fabric Filters for Simultaneous $NO_x$ and High Temperature Particulate Control. Environmental Progress. 14:1. February 1995.

# APPENDIX A

## LIST OF RESOURCE DOCUMENTS FOR PM AND PM PRECURSOR CONTROL

The following is a list of documents that can be use as resources to identify control techniques for particulate matter ($PM_{10}$ and $PM_{2.5}$), as well as the PM precursors: sulfur oxides, ammonia, nitrogen oxides, and volatile organic compounds.

### PARTICULATE MATTER

Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (EPA-450/3-81-005a, PB83-127498). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1982. (change to 1996 update, when completed)

Guidance Document for Residential Wood Combustion Emission Control Measures (EPA-450/2-89-015). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 1989.

Technical Information Document for Residential Wood Combustion Best Available Control Measures (EPA-450/2-92-002). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 1992.

Control of Open Fugitive Dust Sources (EPA-450/3-88-008). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 1988.

Fugitive Dust Background Document and Technical Information Document for Best Available Control Measures (EPA-450/2-92-004). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. September 1992.

Agricultural Activities Influencing Fine Particulate Matter Emissions. Draft Final Report prepared for Mr. K. Woodard, U.S. Environmental Protection Agency, Air Quality Strategies and Standards Division, Research Triangle Park, North Carolina, under EPA Contract No. 68-D3-0031, Work Assignment II-19. March 25, 1996.

### SULFUR OXIDES

Control Techniques for Sulfur Oxide Emissions from Stationary Sources, Second Edition (EPA-450/3-81-004). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1981.

# APPENDIX B

## VATAVUK AIR POLLUTION CONTROL COST INDEXES

The Vatavuk Air Pollution Control Cost Indexes (VAPPCI) are updated quarterly and published monthly in *Chemical Engineering* magazine. For a detailed explanation of the development and use of the VAPPCI, see *Chemical Engineering*, December 1995, pp 88-95.

Vatavuk Air Pollution Control Cost Indexes
(1st Quarter 1994 = 100.0)[a]

| Control Device | 1995 (Avg.) | 1st Q. 1996 | 2nd Q. 1996 | 3rd Q. 1996 | 4th Q. 1996[b] | 1st Q. 1997[b] |
|---|---|---|---|---|---|---|
| Carbon adsorbers | 110.7 | 109.2 | 107.5 | 105.2 | 103.9 | 104.2 |
| Catalytic incinerators | 107.1 | 107.7 | 107.0 | 107.1 | 105.8 | 105.6 |
| Electrostatic precipitators | 108.2 | 107.0 | 107.6 | 108.9 | 108.3 | 108.8 |
| Fabric filters[c] | 102.7 | 104.0 | 104.2 | 104.8 | 105.0 | 105.3 |
| Flares | 107.5 | 104.5 | 104.9 | 105.1 | 105.7 | 105.5 |
| Gas absorbers | 105.6 | 108.6 | 108.2 | 107.1 | 106.9 | 108.7 |
| Mechanical collectors[c] | 103.0 | 103.3 | 103.3 | 103.3 | 103.3 | 103.5 |
| Refrigeration systems | 103.0 | 104.2 | 104.2 | 104.4 | 104.8 | 105.1 |
| Regenerative thermal oxidizers | 104.4 | 105.8 | 106.0 | 106.7 | 106.5 | 107.3 |
| Thermal incinerators | 105.9 | 108.0 | 108.0 | 108.3 | 108.2 | 109.1 |
| Wet scrubbers | 112.5 | 111.7 | 110.1 | 109.3 | 109.0 | 108.3 |

[a] Index values have been rounded to the nearest tenth.

[b] All fourth quarter 1996 and first quarter 1997 indexes are preliminary.

[c] For fabric filters and mechanical collectors, each quarterly value shown is the average of the Producer Price Indexes (PPIs) for the three months in question, divided by the average of the PPIs for January, February, and March 1994 (i.e., first quarter 1994)

## AMMONIA

ApSimon, H.M., D. Cowell, and S. Couling. Assessing the Potential for Abatement of Ammonia Emissions from Agriculture in Europe: the MARACCAS Model (Draft). International Conference on Atmospheric Ammonia Emissions, Deposition and Environmental Impacts, NETCEN, Culham, Oxford, England. October 2-4, 1995.

## NITROGEN OXIDES

Meeting the 15-Percent Rate-of-Progress Requirement Under the Clean Air Act: A Menu of Options. STAPPA/ALAPCO, Washington, D.C. September 1993.

Controlling Nitrogen Oxides Under Clean Air Act. STAPPA/ALAPCO and ESI International, Washington, D.C. July 1994.

## VOLATILE ORGANIC COMPOUNDS

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume I: Control Methods for Surface Coating Operations. EPA-450/2-76-028 (NTIS). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. November 1976.

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume II: Surface Coating of Cans, Coils, Paper, Fabrics, Automobiles, and Light-Duty Trucks. EPA-450/2-77-008. U.S. Environmental Protection Agency, Office of Air Quality Planning and standards, Research Triangle Park, North Carolina. May 1977.

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume III: Surface Coating of Metal Furniture. EPA-450-2-77-032. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1977.

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume IV: Surface Coating for Insulation of Magnet Wire. EPA-450/2-77-033. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1977.

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume V: Surface Coating of Large Appliances. EPA-450/2-77-034. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1977.

Control of Volatile Organic Emissions from Bulk Gasoline Plants.  EPA-450/2-77-035.  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.  December 1977.

Control of Volatile Organic Emissions from Storage of Petroleum Liquids in Fixed-Roof Tanks. EPA-450/2-77-036.  U.S. Environmental Protection Agency, Office of Air and Quality Planning and Standards, Research Triangle Park, North Carolina.  December 1977.

Control of Refinery Vacuum Producing Systems, Wastewater Separators, and Process Unit Turnarounds.  EPA-450/2-77-025.  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.  October 1977.

Control of Volatile Organic Compounds from Use of Cutback Asphalt.  EPA-450/2-77-037.  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.  December 1977.

Control of Hydrocarbons from Tank Truck Gasoline Loading Terminals.  EPA-450/2-77-026. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.  October 1977.

Design Criteria for Stage I Vapor Control Systems - Gasoline Service Stations, (no document number issued).  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. November 1975.

Control of Volatile Organic Emissions from Solvent Metal Cleaning.  EPA-450/2-77-022.  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.  November 1977.

Summary of Group I Control Technique Guideline Documents for Control of Volatile Organic Emissions from Existing Stationary Sources.  EPA-450/3-78-120.  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1978.

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume VI:  Surface Coating of Miscellaneous Metal Parts and Products.  EPA-450/2-78-015.  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.  June 1978.

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume VII:  Factory Surface Coating of Flat Wood Paneling.  EPA-450/2-78-032.  U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. June 1978.

Control of Volatile Organic Emissions from Existing Stationary Sources - Volume VIII: Graphic Arts - Rotogravure and Flexography. EPA-450/2-78-033. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1978.

Control of Volatile Organic Compound Leaks from Petroleum Refinery Equipment. EPA-450/2-78-036. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. June 1978.

Control of Volatile Organic Emissions from Petroleum Liquid Storage in External Floating Roof Tanks. EPA-450/2-78-047. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1978.

Control of Volatile Organic Compound Leaks from Gasoline Tank Trucks and Vapor Collection Systems. EPA-450/2-78-051. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1978.

Control of Volatile Organic Emissions from Manufacture of Synthesized Pharmaceutical Products. EPA-450/2-78-029. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1978.

Control of Volatile Organic Emissions from Manufacture of Pneumatic Rubber Tires. EPA-450/2-78-030. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1978.

Summary of Group II Control Technique Guideline Documents for Control of Volatile Organic Emissions from Existing Stationary Sources. EPA-450/2-80-001. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1979.

Control of Volatile Organic Compound Emissions from Large Petroleum Dry Cleaners. EPA-450/3-82-009. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. September 1982.

Control of Volatile Organic Compound Emissions from Manufacture of High-Density Polyethylene, Polypropylene, and Polystyrene Resins. EPA-450/3-83-008. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. November 1983.

Control of Volatile Organic Compound Equipment Leaks from Natural Gas/Gasoline Processing Plants. EPA-450/2-83-007. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1983.

Control of VOC Fugitive Emissions from Synthetic Organic Chemical, Polymer, and Resin Manufacturing Equipment. EPA-450/3-83-006. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. March 1984.

Control of Volatile Organic Compound Emissions from Air Oxidation Processes in Synthetic Organic Chemical Manufacturing Industry, EPA-450/3-84-015. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1984.

Control of Volatile Organic Compound Emissions from Reactor Processes and Distillation Operations Processes in the Synthetic Organic Chemical Manufacturing Industry, draft. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. November 15, 1993.

Control of Volatile Organic Compound Emissions from the Application of Agricultural Pesticides. EPA-453/R-92-011. U.S. Environmental Protection Agency, Office of Air Quality Planning and standards, Research Triangle Park, North Carolina. 1993.

Reduction of Volatile Organic Compound Emissions from Automobile Refinishing. EPA-450/3-88-009. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. October 1998.

Halogenated Solvent Cleaners. EPA-450/3-89-030. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. August 1989.

Organic Waste Process Vents. EPA-450/3-91-007. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. December 1990.

Reduction of Volatile Organic Compound Emissions from Application of Traffic Markings. EPA-450/3-88-007. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. August 1988.

VOC/HAP Emissions from Marine Vessel Loading Operations: Technical Support Document for Proposed Standards. EPA-450/3-93-001a. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. May 1992.

# TECHNICAL REPORT DATA

*(Please read Instructions on reverse before completing)*

1. REPORT NO.
EPA-452/R-97-001

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
Stationary Source Control Techniques Document for Fine Particulate Matter

5. REPORT DATE
October 1998

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-D-98-026

12. SPONSORING AGENCY NAME AND ADDRESS
Director
Office of Air Quality Planning and Standards
Office of Air and Radiation
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE
EPA/200/04

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Stationary Source Control Techniques Document for Fine Particulate Matter presents recent developments in the control of particulate matter which have become available since preparation of an earlier document entitled Control Techniques for Particulate Emissions from Stationary Sources - Volume 1 (1982).

This document focuses on fine particulate matter ($PM_{10}$ and $PM_{2.5}$ - particles with an aerodynamic diameter less than or equal to an nominal 10 microns and 2.5 microns, respectively). Information presented in this document includes background on particulate matter emissions; measurement methods for particulate matter; types of particulate control devices, their operating principles, design, operation, and control efficiencies; costs and environmental effects of particulate matter control systems; and emerging technologies for particulate matter control.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Air Pollution<br>Pollution Control<br>Fine Particulate Matter<br>Costs | Air Pollution Control<br>Fine Particulate Matter | |

| | | |
|---|---|---|
| 18. DISTRIBUTION STATEMENT<br>Release Unlimited | 19. SECURITY CLASS *(Report)*<br>Unclassified | 21. NO. OF PAGES<br>242 |
| | 20. SECURITY CLASS *(Page)*<br>Unclassified | 22. PRICE |

**EPA Form 2220-1 (Rev. 4-77)** PREVIOUS EDITION IS OBSOLETE