Section 6

Particulate Matter Controls

Chapter 1

Baghouses and Filters

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1.1 Introduction

Fabric filters are one of the most widely used devices for controlling particulate matter (PM) emissions and are used in many different industrial applications where high-efficiency particle collection is required. Their primary benefit is their ability to remove particles in a broad range of sizes, ranging from submicron (or submicrometers, 10^{-6} meter in diameter) to several hundred microns in diameter at control efficiencies generally in excess of 99%.

Fabric filters are available in a wide range of sizes and configurations to suit all types of applications. However, all fabric filters operate in the same way. Waste gas is passed through a fabric media and the particulate is collected on the fabric surface. The fabric media is typically made of a tightly woven or felted fabric and can be in the form of sheets, cartridges, or bags. Two types of fabric filters are available: single use and continuous use designs. In the single use design, filters are used until they are dirty and then replaced with a new filter. Common furnace filters, high efficiency particulate air (HEPA) filters, high-efficiency air filters (HEAFs), and automotive induction air filters are examples of filters that must be discarded after use. These filters are typically made of matted fibers, mounted in supporting frames, and used where dust concentrations are relatively low. In the continuous use design, the fabric filters are periodically cleaned and reused until the fabric becomes worn or damaged, at which time the fabric is replaced. Continuous-use fabric filters are recommended for dusty applications that generate large quantities of particulate. Long cylindrical bags are commonly used in continuous-use fabric filters and are the reason fabric filters are frequently referred to as baghouses.

The first fabric filters used natural fibers, such as cotton or wool, which proved extremely effective at controlling particulate emissions but were limited in the types of applications they could be used. For example, cotton and wool fabric are combustible, cannot be used at temperatures above 180^{o}F, have little resistance to acids and oxidizing agents, and are subject to bacteria, mold and mildew when used in moist conditions. Over the last 40 years, however, significant advances in fabric media were achieved that allow fabric filters to be used in more challenging conditions. Today, fabric filters made from fiberglass, polyester, aramid (Nomex®), polyamide (P-84®) and polytetrafluoroethylene (Teflon®) are widely available. If the correct media is selected, fabric filters can be used in applications where the waste gas stream contains acids, alkalis, oxidizing agents and organic solvents. Since they are not affected by mold or bacteria, they can be used in applications where some moisture is present. They can also tolerate high temperatures better. In the power sector, the use of membrane[1] and polyamide felted bags has become more widespread since 2011. [1] Applications with temperatures up to 500^{o}F can be accommodated by fiberglass and polybenzimidazole fabric filters. In addition to the fabric filters discussed above, solid ceramic filters are also available that can accommodate very high temperatures of up to 1,640^{o}F.

Fabric filters are not recommended for wet gas streams or where the particulate is moist or sticky, such as those from wood product dryers, which tend to clog filter pores and make the fabric filters difficult to clean. They are best suited to applications where the temperature of

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[1] Membrane fabrics consist of an expanded, semi-porous layer of polytetrafluoroethylene (PTFE) that is bonded to one side of a conventional filter fabric, such as fiberglass or polyester, to provide improved performance of the fabric filter. For additional information, see section 1.2.4.5.

waste gas is above the dew point and are commonly used to control filterable particulate emissions from coal-fired boilers, cement kilns, lime kilns, metalworking, woodworking, sandblasting, and various grinding and milling operations (e.g., flour milling, mineral crushing).[2] In addition to particulate control, they are also used for product recovery (e.g., recovery of useful metals) and material conveyance. They can be used alone or in combination with other emissions controls, such as cyclones, electrostatic precipitator (ESP), and SO_2 controls, such as dry sorbent injection (DSI), and activated carbon injection (ACI) to reduce mercury. The direct variable costs of fabric filters installed after an ESP or cyclone cost less than a full-burden (i.e., a fabric filter that is the primary or only PM control device) baghouse because a higher air-to-cloth ratio (A/C) [3] is possible with this arrangement. The A/C ratio is defined as the amount of gas in ft^3/min that penetrates one square foot of fabric. Hence, the lower the A/C ratio the higher the cost because more square feet of fabric filter media are required. A full-sized fabric filter with an A/C ratio of 4.0 or lower is recommended where the fabric filter will be the primary particulate collection device for ACI or DSI. Where the fabric filter is installed following another particulate collection device (e.g., ESP), the fabric filter is sometimes referred to as a 'polishing baghouse' and can have a higher A/C ratio of up to 6.0. [2] One example of this type of fabric filter is a COHPAC^{TM} (Compact Hybrid Particulate Collector), which is designed to provide both improved PM and mercury control at a lower pressure drop. [3] Fabric filters used in combination with ACI and/or DSI generally achieve higher removal rates for the target pollutants (i.e., SO_2 or mercury) at lower operating costs than can be achieved with an ESP that is used in combination with ACI and/or DSI. This is because the fabric filter provides both high particulate capture efficiency and increased opportunity for the pollutant to come into contact with sorbent as the waste gas passes through the filter media. Adding a fabric filter after an existing ACI/ESP system can reduce the amount of activated carbon required for any given removal rate by increasing the activated carbon interactions with mercury. Similarly, a fabric filter will also make collection of acid gases with dry sorbent injection (DSI) more effective than using an ESP after DSI. Thus, additional control of pollutants other than PM is possible through the addition of a fabric filter. [1, 2]

For some processes, the dust collected is reused either at the industrial site or sold for use in another application. For example, fly ash collected from coal-fired utility boilers can be sold as an extender for concrete paving mixes. In some cases, the dust collected contains materials that can be reclaimed or recovered for other uses. For example, one facility operating electric arc furnaces sends dust collected to a recycler for the purposes of recovering zinc at a cost of $3.25 per one hundred pounds (2015$) of baghouse dust. [4] However, in many applications the dust collected cannot be reused and must be disposed at a landfill.

In the following sections, we present more detailed information on the design and costs of fabric filters. Section 1.2 describes the various fabric filter designs, the various types of fabric filters available and explains the mechanisms that make fabric filters such an effective control technology. In section 1.3, we discuss the level of particulate control that can be achieved by a correctly sized and well-maintained fabric filter and describe the various factors that can impact

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[2] Unless otherwise stated, control or removal efficiencies in this chapter are in terms of filterable PM.

[3] The air-to-cloth (A/C) ratio is also sometimes called the gas-to-cloth (G/C) ratio or superficial velocity. The term superficial velocity comes from the units of flow rate (cubic feet per minute) and fabric surface area (square feet), which reduce to feet per minute.

control (or removal) efficiency. We also provide information on the typical equipment life for filter media and structural housing, discuss best practices in monitoring, inspection, and maintenance, and describe methods for improving the control efficiency of existing fabric filters. Section 1.4 focuses on the design parameters critical for determining the appropriate size of a fabric filter based on the characteristics of the waste gas and the mode of operation of the processes generating the emissions. In sections 1.5 and 1.6, we provide several approaches for preparing study-level estimates of capital and operating costs, where study-level estimates are those with a +-30% level of accuracy as described in the cost estimation methodology chapter (Section 1, Chapter 2) of this Control Cost Manual. The approaches presented in section 1.5 are based on correlations developed using data previously collected from vendors, while those presented in section 1.6 are based on cost data collected for fabric filters installed on utility boilers. Finally, section 1.7 reviews methodologies for estimating the costs of upgrades to existing fabric filters used on coal-fired combustion units.

1.2 Process Description

In this section, we describe the different types of fabric filters and explain how they work. Section 1.2.1 describes the mechanisms by which particulate is collected. Section 1.2.2 provides a general description of a typical industrial baghouse. Section 1.2.3 presents the different types of cleaning methods used to remove dust buildup on the fabric media. Section 1.2.4 identifies the different types of fabric media available and outlines their physical and chemical characteristics. Section 1.2.5 describes the different types of fabric filters and section 1.2.6 discusses the auxiliary equipment necessary to operate a typical fabric filter.

1.2.1 Particulate Matter and Theory of Particulate Collection Mechanisms

PM are small particles of solid or liquid suspended in air. They are emitted by mobile sources (e.g., ships, trucks) and many industrial processes (e.g., fossil-fuel combustion, woodworking, smelting furnaces) in a range of different sizes and compositions. Many toxins, such as heavy metals, are emitted as particulates. For example, arsenic, copper, lead, mercury, and zinc are emitted as particulate from coal-fired boilers, smelters and incinerators. Others are formed in the atmosphere through reaction of pollutants with atmospheric molecules (e.g., sulfates and nitrates). The size of PM can be defined as the physical diameter of the particle or by the aerodynamic diameter. The aerodynamic diameter is the diameter of a spherical particle with density of 1 g/cm^3 that behaves with the same aerodynamic characteristics (i.e., with the same momentum, drag, and terminal settling velocity) as the subject particle.

PM range from large particles with physical diameters larger than 10 micrometers (μm) to fine particulates with physical diameters of less than 1 μm. Particulates emitted from metallurgical processes range in size from about 0.001 to 100 μm. Fly ash from coal-combustion units range from 1 to over 100 μm. Fine particulate with diameters between about 0.7 to 7 μm are considered more hazardous to human health due to their tendency to become lodged in the lungs causing asthma, chronic respiratory illnesses, cardiovascular diseases, birth defects, and neurodegenerative disorders. For this reason, EPA sets National Ambient Air Quality Standards (NAAQS) for PM_{10} (inhalable particles with aerodynamic diameter of 10 μm or less) and $PM_{2.5}$ (fine inhalable particles with aerodynamic diameters of 2.5 μm or less) emissions. [5]

Fabric filters are effective at capturing solid particulate from waste streams and the particulates captured are sometimes referred to as filterable PM. There are three primary mechanisms by which fabric filters collect particulate: impaction, interception and diffusion. Figure 1-1 illustrates how the three mechanisms work. The impaction mechanism applies to large particles that have diameters typically greater than 1 micrometer. These particles are carried toward the filter in the air stream. As they approach the fiber of the filter, the air stream is diverted around the fabric fiber, but the momentum of the particle causes it to continue in a straight line, striking and adhering to the surface of filter fiber. The greater the mass and higher the velocity of the particle the more likely it will be collected by impaction.

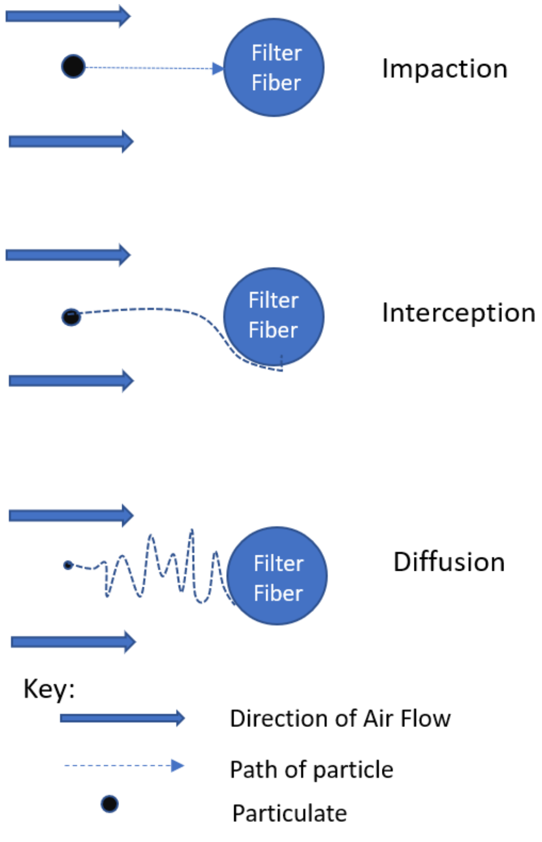

Figure 1-1: Particulate Collection Mechanisms [5]

Smaller particles of 0.1 to 1 µm diameter are diverted around the fabric fiber as they have insufficient mass and velocity to continue in a straight line. If the particle is carried by the air stream close enough for the particle sides to touch the filter fiber, then the particle will be intercepted and adhere to the fiber. This mechanism is called interception and is a much less common mechanism for particulate collection because the path of the particle must bring it close to the fiber in order for the particulate to be captured on the surface. For this reason, particles in the 0.1 to 1 µm diameter range are more difficult to collect than other sizes of particles.

Particles less than 0.1 µm diameter exhibit Brownian motion caused by random collisions with air molecules. These submicron particles move randomly within the air stream and are collected when they strike a filter fiber. As dust accumulates on the fabric surface, the dust particles in the dust cake become targets for dust collection in the same way as the filter fibers. After the dust cake has been established, the space between particles is small and the probability that particles will pass through the filter is reduced and the probability that particles will be collected through impaction, interception, and diffusion is increased. For this reason, particulate emissions from new bags are typically higher than for used bags. [5]

1.2.2 Conventional Baghouse Design

The typical industrial fabric filter is shown in Figure 1-2 and consists of an enclosed metal housing containing multiple cylindrical fabric bags connected to a tube sheet. The tube sheet is a metal sheet that contains uniformly spaced openings to which the open end of the filter bag can be secured. The filter bags are generally mounted vertically and arranged in rows above one or more hoppers, as shown in Figure 1-3. The bags may be supported from the top, as shown in Figure 1-3, or from the bottom. Particle-laden gas enters the compartment through an inlet in the housing and passes through the fabric bags. As the gas passes through the fabric, particles are retained on the surface of the bags. The clean gas exits the housing through the outlet and is typically vented to the atmosphere through a stack, as shown in Figure 1-2). However, the clean gas from the fabric filter may be directed to another air pollution control device, to other downstream units (e.g., heat recovery unit), or vented inside the building for some small applications where other air pollutants are not present in the exhaust gas. Where the fabric filter exhausts inside a building, a second filter is sometimes installed after the fabric filter to ensure emissions are controlled if leaks in the primary fabric filter occur. [6]

The gas stream may be either pushed through the fabric filter housing by a blower (referred to as a positive pressure system) or pulled through by a fan (referred to as a negative pressure system). Positive pressure fabric filters can be used where the waste gas stream has a low moisture content, low dust concentration and the dust is nonabrasive. The lower air infiltration makes the positive pressure fabric filters a good choice for applications where the dust is easily ignited. Negative pressure fabric filters are used for waste gas streams that have high moisture content, contain corrosive gases, or have high concentrations of abrasive dust. The particulate concentrations of the inlet waste gas are typically between 1 to 23 grams per cubic meter (g/m^3) (0.5 to 10 grains per cubic foot (gr/ft^3)). [5, 7, 8, 9, 10]

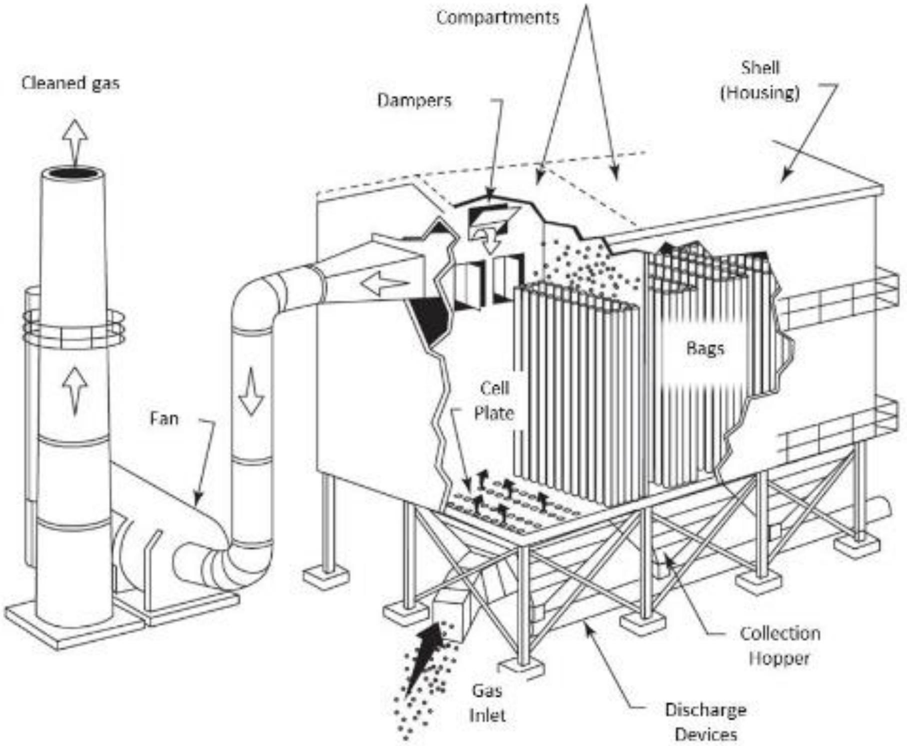

Figure 1-2: Schematic of a Typical Industrial Filter [10]

Figure 1-3: Filter Bags Installed Inside a Typical Fabric Filter Housing [11]

The waste gas inlet can be located at the top or bottom of the unit depending on the baghouse design. The location and design of the waste gas inlet is selected to ensure the waste gas is distributed evenly between the filter bags without disturbing particles collected in the hopper. As the dust-laden gas stream enters the baghouse, gas velocities typically decrease and the larger particles may drop out of the gas stream due to gravitational settling into the hopper below. Smaller particles are carried in the air stream, strike and become attached to fibers in the fabric filter and remain on the surface of filter until the filter is cleaned. The clean air passes through the pores in the filter fabric and is exhausted through the baghouse outlet. Small particles can also agglomerate forming larger particles that are removed either by falling out of the air stream or by impaction.

During operation, a layer of particulate (called a dust cake) builds up on the fabric surface. This dust cake consists of particles of various sizes and is usually less than 1/16th inch thick. [11] The dust cake which forms on the filter contributes significantly to collection efficiency. In fact, for most fabric media, the fabric is able to collect only the largest particles. The dust cake is the reason the fabric filter can collect very small particles of micrometer and sub-micrometer diameter. Over time, the dust cake layer becomes so thick that it begins to impede the air flow through the bags, increasing the pressure drop across the fabric filter. The fabric media must be replaced or cleaned before the pressure drop becomes so high that the air stream velocity in the ductwork leading to the fabric filter is reduced to a level at which the collection system no longer functions correctly. In most industrial applications, the unit is fitted with a cleaning mechanism that is activated periodically to remove dust from the fabric surface (see section 1.2.3 for a discussion of filter media cleaning methods). A spike in particulate emissions normally occurs immediately following cleaning due to the loss of some of the dust cake. [3, 5, 9, 11, 12,]

The frequency of cleaning depends on the particulate loading of the waste gas stream. For waste streams with low concentrations of particulate, the bags may be cleaned and the hopper emptied at the end of each shift. For most applications, bag cleaning is more frequent and is often automated. In applications where the particle loading remains consistent over time, cleaning may be initiated at regular timed intervals. Where the particle loading is variable, vendors recommend cleaning be initiated when the pressure drop reaches a set value. During cleaning the dust falls downwards and is collected in a hopper, which must be regularly emptied. Section 1.2.6.3 describes mechanisms for dust handling. Depending on the cleaning mechanism used, bag cleaning may take place while the unit is online or offline. The cleaning method used should not be so frequent or overly vigorous that all the dust cake is removed. It is also important that the cleaning mechanism remove dust as uniformly as possible throughout the entire length of the filter bag. The dust cake should be kept as uniform as possible throughout the fabric filter in order that the air flow through the bag be evenly distributed. [3, 5, 9, 10, 11]

In some designs, groups of bags are placed in two or more separate compartments. This arrangement allows a compartment to be taken off-line for bag cleaning, inspection, and maintenance (e.g., bag replacement), thereby avoiding shutdowns of continuously operating processes. Each compartment is operated cyclically, alternating between relatively long periods of filtering and short periods of cleaning. Single compartment systems are generally used for smaller processes or for processes that are not operated continuously. Depending on the design, bags can be accessed for purposes of replacement from the top, side, or bottom of the unit. [7, 13]

The metal housing is typically made of steel with an epoxy coating to prevent corrosion. Carbon steel is recommended for applications where the waste gas stream is corrosive. In applications where the waste gas stream is above the ambient temperatures, the housing is insulated to prevent moisture or acids contained in the gas stream from condensing inside the baghouse, causing damage to the fabric bags and corrosion of the walls, flanges, and other structures. For applications where the dust is flammable or explosive, a combination of spark arresters, explosion vents, abort gates, grounded and/or conductive filter bags, sprinklers, and inert gas injection systems should be used. Examples of materials that require special handling due to fire and explosion hazards are dusts from coal, woodworking, grain processing, flour mills, fertilizer plants, plastics/resin handling, charcoal, metalworking, food processing (e.g., sugar, milk powder), and cellulose. [13, 14, 15, 16]

In some baghouse designs, a baffle or other gas diffusion device is placed near the baghouse inlet to direct the high velocity inlet gas stream away from the bags. These devices reduce bag abrasion from high velocity dust particles and help increase bag life. They also help larger particles to drop out of the air stream into the hopper and prevent dust from the hopper becoming re-entrained in the gas flow by reducing turbulence in the vicinity of the hopper. [5, 15]

Important process variables include particle characteristics, gas characteristics, and fabric properties. The most important design parameter is the A/C ratio, which is defined as the amount of gas in ft^3/min that penetrates one ft^2 of fabric. The most important operating parameter is the pressure drop across the filter system. Typical values of pressure drop depend on several factors, including the chemical and physical properties of the particulate (e.g., size distribution, dust cohesivity), permeability of the filter media, and the cleaning method employed. The appropriate pressure drop range must be determined for the fabric filter based these site-specific characteristics, and this pressure drop range must be consistent with compliance with a variety of regulatory requirements. Inspection by regulatory agencies will often include examination of the pressure drop for fabric filter operations. Operators should measure the pressure drop across the fabric filter to establish a baseline differential pressure profile and determine a normal operating range. [5]

The major operating feature of fabric filters that distinguishes them from other gas filters is the ability to renew the filtering surface periodically by cleaning. The various methods used to clean the filters are discussed in section 1.2.3.

1.2.3 Filter Media Cleaning Methods

In this section we describe the cleaning methods used to remove dust from the fabric filters. These methods include mechanical shaker, reverse-air, reverse-jet, pulse-jet, rotating mechanical cages and sonic horns. Where baghouses larger than typical pulse-jet baghouses are required, they are often custom-built, reverse-air units. Table 1-1 shows a comparison of the mechanical shaker, reverse-air and pulse-jet cleaning systems and lists their typical applications.

The cleaning cycle for baghouses may be controlled by a timer that initiates cleaning at set intervals or by a monitoring device that triggers when bag cleaning is needed. The latter system is usually referred to as an “on-demand cleaning system” and triggers cleaning only when the differential pressure reaches a set value. [11]

Most new baghouses use the pulse jet cleaning method (described in section 1.2.3.4). The pulse-jet baghouses have become popular because they can operate continuously (i.e., they do not have to shut down a compartment for cleaning) and are typically smaller than the equivalent mechanical shaker and reverse-air baghouses. Pulse-jet baghouses are often less expensive to build and can handle a higher gas flowrate per square foot of filter fabric. However, they require stronger, more durable filter bags than the other designs. Reverse-air fabric filters were first used in coal-fired utility boilers in the 1970s and remained the most common baghouses used by utilities throughout the 1970s and 1980s in part due to their low air-to-cloth ratio and longer average bag life (5 to 10 years). Beginning in the early 1990s, there was a gradual shift away from reverse-air baghouses as developments in the pulse-jet technology and experience operating on smaller industrial boilers showed that pulse jet fabric filters could successfully operate on larger coal-fired boilers. A 1979 study found that most utilities (over 75% of respondents) were using reverse-air baghouses. By 2021, pulse-jet fabric filters had become the most common type of fabric filter used at U.S. power plants. Table 1-2 shows the number of pulse-jet, reverse-air and mechanical shaker fabric filters used at power plants for 2011 and 2021 based on data collected by the Department of Energy’s Energy Information Administration. In 2021, 466 pulse-jet units and only 168 reverse-air units were operating at U.S. power plants. As of the end of 2021, 71 percent of all such fabric filters used at power plants were pulse-jet designs compared to 65% in 2011. [1, 21, 22, 23, 24]

Table 1-1: Comparison of Shaker, Reverse-Air and Pulse-Jet Fabric Filter Systems [5, 7, 8, 10, 17, 18, 19, 20]

Fabric Filter Type	Advantages	Disadvantages	Common Applications
Mechanical Shaker	High collection efficiency Easy to operate	Operate at low air-to-cloth ratios (2 to 2.5 cfm/ft^2) Not recommended for high temperature applications Not recommended for applications where the dust particles are sticky. Large footprint No online cleaning - additional compartments needed for cleaning cycle if	Coal-fired boilers Metalworking Mining Woodworking Food processing Chemical industry Textiles industry Coal cleaning Asphalt plants

Fabric Filter Type	Advantages	Disadvantages	Common Applications
		used for continuously operating processes. Require higher pressure drop than reverse-air baghouses (more energy required; higher operating costs)	
Reverse-Air	High collection efficiency Recommended for high temperature applications. Can use very large bags of greater than 12 inches wide and up to 40 feet long. Longer bag life possible due to more gentle cleaning	Operate at low air-to-cloth ratio (2 to 2.5 cfm/ft^2) Less effective at removing dust cake. No online cleaning - additional compartments needed for cleaning cycle if used for continuously operating processes.	Coal-fired boilers Biomass-fired boilers Municipal solid waste incinerators Sintering Ore smelting/roasting. Gray iron foundries Steel furnaces Ferroalloy production Cement kilns Lime kilns Gypsum calcining Grain milling Rock dryers Carbon black production PVC spray dryer

Fabric Filter Type	Advantages	Disadvantages	Common Applications
Pulsejet	High collection efficiency Operate at higher air-to-cloth ratio (3 to 10 cfm/ft^2) Online cleaning (separate compartments not needed) Smaller, more compact units Very effective dust cake removal	Requires dry compressed air tank, valves, venturis, a control system and cages for gas support. Not recommended for high temperature and high humidity applications Require higher pressure drop than reverse-air baghouses (more energy required; higher operating costs)	Coal-fired boilers Metal working Foundries Cement plants (e.g., crusher, rotary dryer, packing machines) Woodworking Asphalt plants Food industry (e.g., grain milling)

Table 1-2: Type and Number of Fabric Filters Installed at U.S. Power Plants in 2021[4]

Fabric Filter Type	Number of Units (% of total)	
	2011	2021
Mechanical Shaker	30 (5%)	26 (4%)
Reverse Air	180 (30%)	168 (25%)
Pulse-Jet	392 (65%)	466 (71%)
Total	602	660

1.2.3.1 Mechanical Shaker Cleaning

The mechanical shaker cleaning system was initially developed in the 1920s and because of its simple design, it is easy to operate and generally very effective. They typically consist of a series of filter bags with the closed end of each bag hung from the top of the baghouse enclosure and the open ends attached to a fixed plate or tube sheet at the bottom. Unlike the pulse-jet systems (described in section 1.2.3.3), the bags are not mounted on metal cages. The waste gas stream enters from below the plate and is drawn up through the filter bags. Particulates from the waste gas stream are deposited on the inside surface of the bags and the clean air passes through the filter bags and exits the baghouse enclosure through an outlet duct at the top of the baghouse.

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[4] Based on data published by the Department of Energy, Energy Information Administration (EIA), 2021 survey Form EIA-860. Form EIA-860 collects generator-level information about existing and planned generators and associated environmental equipment at plants with 1 megawatt (MW) or greater of combined nameplate capacity. (https://www.eia.gov/electricity/data/eia860/). Data from the 2022 survey form was not available as of June 2023.

The tops of the bags are attached to a shaker bar that can moved rapidly to vigorously shake or oscillate each bag. The shaker bar can be motor-driven or hand operated. The duration of cleaning varies from 30 seconds to a few minutes. The motion may be imparted to the bag in several ways, but the general effect is to create a sine wave along the fabric. As the fabric moves outward from the bag centerline during portions of the wave action, accumulated dust on the surface moves with the fabric. When the fabric reaches the limit of its extension, the patches of dust have enough inertia to tear away from the fabric and drop to the hopper. The waste gas flow to the baghouse is temporarily shut down during the cleaning cycle to allow the bags to deflate. Hence, shaker baghouses used to control a continuously operating process generally have two or more separate, parallel baghouse compartments that allow one compartment to be isolated from the production process for cleaning when needed, while the other compartments continue to remove particulate from the waste gas stream. [5, 7, 9, 19] For small, single-compartment baghouses, usually operated intermittently, a lever attached to the shaker mechanism may be operated manually at appropriate intervals, typically at the end of a shift. In multi-compartment baghouses, usually operated continuously, a timer or a pressure sensor responding to system pressure drop initiates bag shaking automatically. The compartments operate in sequence so that one compartment at a time is cleaned. During cleaning, the waste gas flow to a compartment is stopped, dust is allowed to settle, and the shaker mechanism is switched on for several seconds to a minute or more. The settling and shaking periods may be repeated, then the compartment is brought back on-line. Since the waste gas flow through a compartment must be turned off during the cleaning cycle, the baghouse collecting area must be increased to compensate for the compartment that is out of service during cleaning. During cleaning, the dust falls downwards into hoppers located below the suspended bags. Figure 1-4 shows a diagram of a typical shaker baghouse and Figure 1-5 shows two shaker methods. [5, 7, 19]

Parameters that affect cleaning include the amplitude and frequency of the shaking motion and the tension of the mounted bag. The first two parameters are part of the baghouse design and generally are not changed easily. The tension is set when bags are installed. Typical frequencies are about 4 Hertz (Hz), and amplitude (half-stroke) may be a fraction of an inch to a few inches. [5, 25] Some installations allow easy adjustment of bag tension, while others require that the bag be loosened and re-clamped to its attaching thimble.

Compared with reverse-air cleaned bags (described in section 1.2.3.2), the vigorous action of shaker systems tends to stress the bags more, which requires heavier and more durable fabrics. They generally use woven filter bags. [7, 19] Woven fabrics and felted fabrics may be used in shaker baghouses. Shaker baghouses can be useful where compressed air is not available, in batch applications, or where the user prefers the simplicity of the shaker baghouse system. [5, 7] Mechanical shaker cleaning is not recommended for applications where the dust is moist and sticky because the force required for cleaning results in greater wear and can cause tears in filter bags. [10]

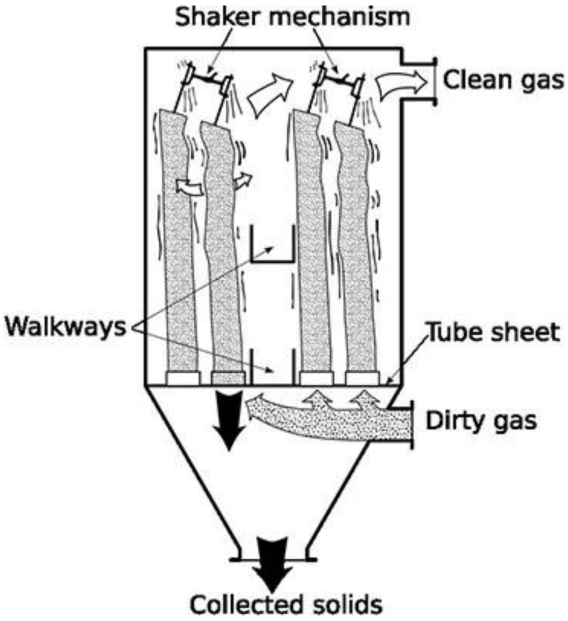

Figure 1-4: Typical Mechanical Shaker Baghouse [18]

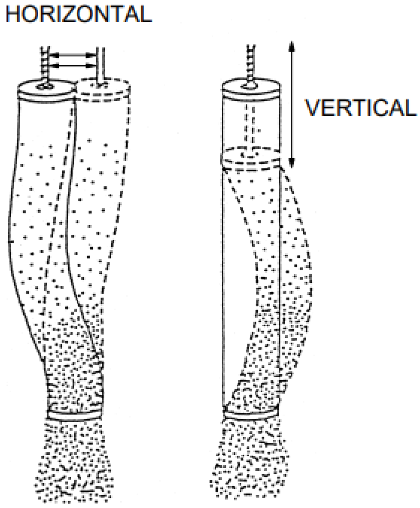

Figure 1-5: Typical Shaker Cleaning Mechanisms [9]

1.2.3.2 Reverse-air Cleaning

When glass fiber fabrics were introduced, a gentler means of cleaning the bags was needed to prevent premature degradation. Reverse-air cleaning was developed in the 1950s as a less intensive way to impart energy to the bags and has been used extensively over the years. [17] Most reverse-air baghouses operate in a manner similar to shaker baghouses. Typically, the bags are suspended vertically with the open end at the bottom connected to a tube sheet. The closed tops of the bags are attached to a support at the top of the baghouse so the bags are held taut. The waste gas flows upward inside the bag and passes from the inside to the outside of the bags with dust being captured on the inside. To clean the bags, waste gas flow to the baghouse compartment is stopped, dust is allowed to settle, and then low-pressure clean air is blown gently through the bag fabric in the reverse direction (i.e., outside-in) to the direction of waste gas flow. The reverse-air fan typically operates for 10 to 30 seconds and produces only a small pressure drop across the baghouse. The reversal of gas flow gently collapses the bags toward their centerlines, which causes the cake to detach from the fabric surface and fall into hoppers located below the bags. The particulate becomes detached from the fabric surface due to the shear forces developed between the dust and fabric as the latter changes its shape. To prevent the bags from completely collapsing, metal caps to support the bag tops are an integral part of the bag as are several sewn-in rings that encircle the bags to prevent their complete collapse during cleaning. Without these rings, falling collected dust tends to choke the bag as the fabric collapses in on itself while cleaning. The support rings are usually spaced from 3 to 4 feet apart. The cleaning cycle typically lasts about three minutes per compartment. [3, 5, 9, 17] As with shaker baghouses, extra filtering capacity must be added to reverse-air baghouses to compensate for the compartments that are out of service for cleaning. [3, 5]

Reverse-air cleaning is gentler and sometimes less effective cleaning mechanism than mechanical shaking. For this reason, some reverse-air baghouses employ a supplemental shaker system or sonic horns to assist cleaning by increasing the amount of energy delivered to the bag. In general, reverse-air cleaning without supplemental cleaning methods should be used only where the particulates are easily released from the fabric. Felt fabrics are generally not used in reverse-air baghouses because they retain dust more than woven fabrics and are consequently more difficult to clean. Woven fiberglass fabric coated with Teflon® or expanded polytetrafluoroethylene are often used for applications where high temperatures and acidic conditions prevail, such as for coal-fired boilers. [3, 17, 24]

The clean air is generally taken from the stream being discharged by other compartments of the reverse-air baghouse currently operating in filtering mode. Figures 1-6 and 1-7 show two reverse-air cleaned baghouse designs.

Because reverse-air cleaning is gentle, reverse-air baghouses typically require a low air-to-cloth ratio of 2 ft/min. [3] The operating costs of reverse-air baghouses may be lower than the other types of baghouses as the gentler cleaning process reduces wear and tear on the bags, thereby increasing the time between bag replacement. However, if the particulate material is more difficult to remove from the fabric, cake may build up on the fabric and shorten bag life. [5]

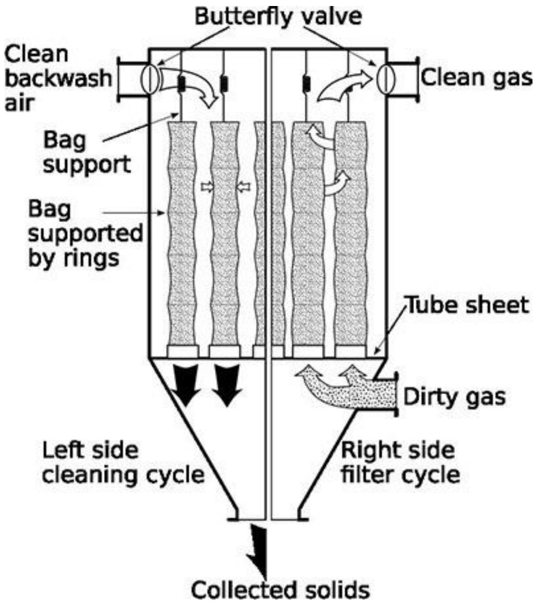

Figure 1-6: Typical Reverse-Air Baghouse [18]

In some reverse-air baghouses, the open end of each bag is attached to a tube sheet at the top and particulates collect on the outside of the bags as the waste gas passes through the bags from the outside to the inside. The clean air exits through the top of each bag. In this design, reverse-air cleaning is performed by blowing clean air into each bag from the top, forcing the clean air through the filters in the opposite direction of the waste gas flow and dislodging particulates from the outside of the bag. The particulates are collected in a hopper below the bags. [17]

Although most reverse-air baghouses have a rectangular housing some have a round housing with bags arranged in concentric rings around the center of the baghouse and a single collection hopper located below the bags. These baghouses typically include a tangential inlet to impart a cyclonic flow to remove larger particles prior to the filter bags. The dust is collected on the exterior of the bags and a mechanical arm rotates above the bags delivering clean air to each row of bags via a manifold with multiple cleaning heads. Each bag is cleaned once during a single revolution of the cleaning air. One advantage of this systems is that the baghouse remains online. The baghouses are prefabricated in a series of different sizes ranging from a cloth area of about 1,175 square feet units (7 feet diameter containing 112 bags of 8 feet in length) up to 17, 640 square feet (22 feet diameter baghouse containing over 1,800 bags of 12 feet in length). Figure 1-7 shows cross-sectional schematics of the side and top of a typical round reverse-air baghouse with rotating cleaning arm. [25, 26]

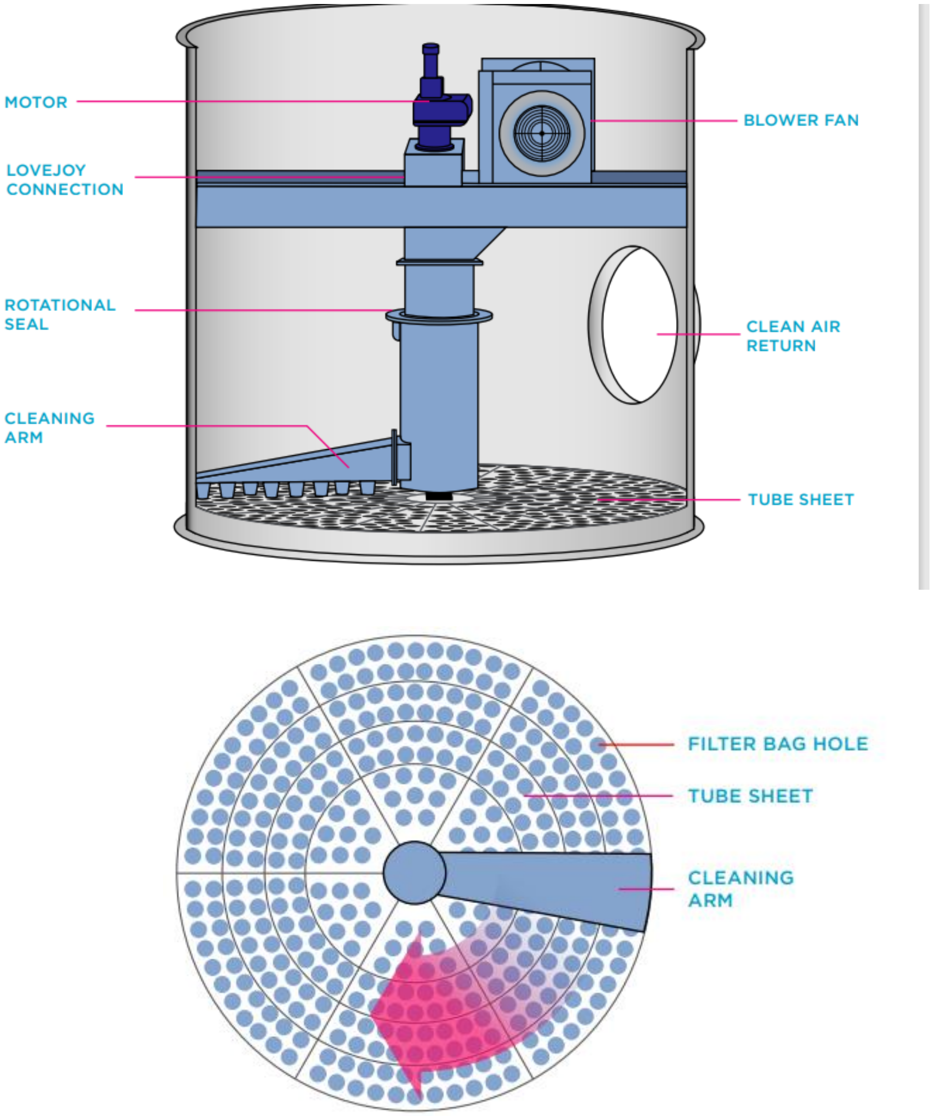

Figure 1-7: Rotating Reverse-air Baghouse [26]

1.2.3.3 Reverse-jet cleaning

Reverse-jet baghouses were developed in the 1950s to improve removal of particulates over the reverse-air cleaning method. The baghouse design is similar to the reverse-air baghouse described above in which the bags are suspended from the top with the open ends of each bag secured to a tube sheet. In the reverse-jet cleaning system, the clean air is piped to a ring with a narrow slot that is positioned around the bag. The clean air is constricted by the slot size, creating a high velocity air stream that flexes the bag. The ring is mounted on a carriage system and is moved up and down the bag. Due to its complexity, the number of reverse-jet baghouses has declined in favor of pulse-jet baghouses. The principal advantage of the reverse-jet baghouse was its improved cleaning capability compared with the reverse-air baghouse. Re-circulation and redeposit of dust are reduced and the continuous-cleaning allows the baghouse to operate at higher air-to-cloth ratios, which decreases the size of the unit and lowers costs. The disadvantages include higher maintenance requirements and increased bag wear. [17, 27]

1.2.3.4 Pulse-jet Cleaning

Pulse-jet cleaning of fabric filters was developed in 1960s and has grown in popularity over the years to be the most popular form of baghouse on the market today as mentioned above in section 1.2. Pulse-jet cleaning uses compressed air to force a burst of air down through the bag dislodging the dust cake that forms on the outside of the bag. Pulse-jet baghouses may be categorized as high pressure, medium pressure, and low pressure depending on the pressure of the compressed air used. [5, 8, 11, 12] Figure 1-8 shows a diagram of a typical pulse-jet baghouse.

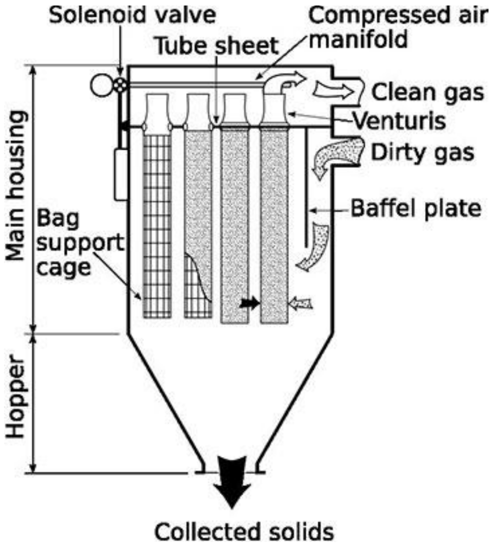

Figure 1-8: Diagram of a Typical Pulse-Jet Baghouse [18]

The bags are hung vertically with the open end attached at the top to the tube sheet. The bottom end of the assembly may move in the turbulent waste gas flow during operation, which may cause abrasion damage to bags. An internal cage inside each bag holds the bag open as the waste gas flows from the outside to the inside of the bag. Particulate cake forms on the outside of the bag and clean air exits through the top. [5]

The cages are typically made from stainless steel (304 or 316) and carbon steel. They are also available with special coating, including Teflon, epoxy, power coating or plating. The cages may be round or oval and can have between 6 and 24 vertical wires, with cage diameters ranging 4 to about 6.25 inches. Cage lengths vary from about 18 inches up to 30 feet with evenly spaced horizontal support rings spaced at either 3, 4, 6 or 8 inches apart. The wire gauge ranges from about 0.125 to 0.25 inches. The number of vertical wires and horizontal rings. and the gauge of the wire used in the construction of the cage depends on the characteristics of the fabric media. Filter cages with 10 vertical wires are used for heavier weight felts. Cages with 12 vertical wires are used for lighter to medium weight felt fabrics. Cages with 20 to 24 vertical wires are used for filter fabrics that require more support to reduce fabric flexing (e.g., fiberglass). The greater the number of vertical wires and the smaller the space between the horizontal support rings the more rigid the cage and the support the cage provides to the filter bag. Cages with more vertical and horizontal wires are more expensive. However, by minimizing bag flexing, they can lengthen bag life by reducing wear and tear. Figure 1-9 shows several different types of cages. Cages with a built-in venturi are also available from some vendors. [5, 27, 28, 29, 30, 31]

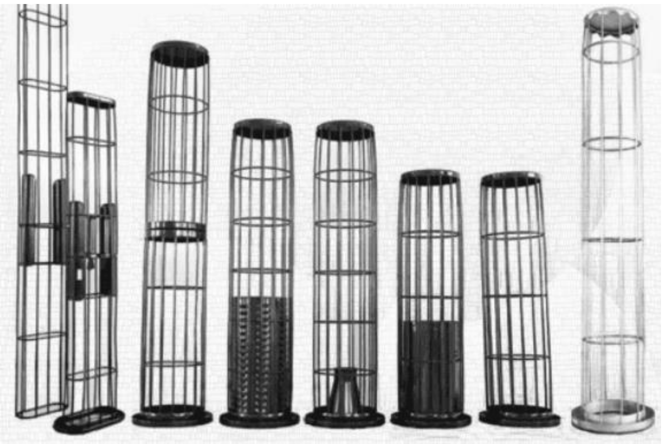

Figure 1-9: Typical Cages [29]

The pulse-jet cleaning system consists of a pressure tank equipped with a pressure gauge and solenoid valve with control system. The pressure tank is connected to a manifold system equipped with nozzles. Each nozzle must be located directly above the bag opening for cleaning to be effective. During the cleaning cycle, the solenoid valve is opened, and compressed air is blown down the center of each bag from above. The compressed air creates a shock wave that continues from the top down to the bottom of each bag. The wave flexes the fabric and pushes it away from the cage as shown in Figure 1-10. After the wave of compressed air passes, the bag snaps back against the cage, further dislodging the dust cake. [3, 5, 8, 11, 13, 27]

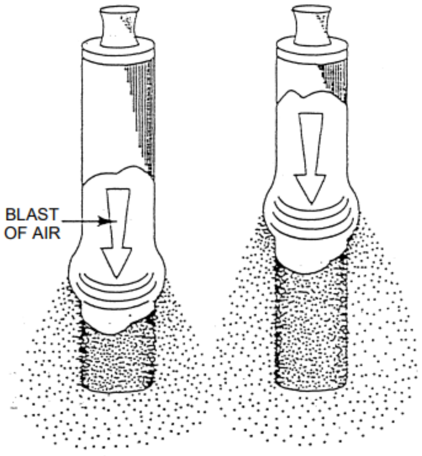

Figure 1-10: Diagram Illustrating the Pulse-Jet Cleaning Mechanism [9]

In the high-pressure pulse-jet baghouse, the pressure of the clean air jet is typically between 60 and 100 pounds per square inch (psi) and the air is often injected through venturi nozzles that accelerate the air flow. The duration of the pulse is typically between 0.03 and 0.1 seconds. Pressures of 60 to 70 psi are generally preferred as they cause less wear and tear on bags and allow particulate to remain agglomerated allowing particulate to avoid being re-entrained in the waste gas stream and instead fall into the hopper. Pressures above 90 psi can damage bags by causing abrasion at the tops and potentially rip seams. Best practice is to use the lowest pressure that effectively dislodges the particulate. One manufacturer recommends the operator find the lowest effective pressure by adjusting pressure downward until the cleaning effort begins to be ineffective and then increase the pressure by about 5 psi. This procedure should be performed when the facility is running at the highest production rate so that the cleaning system is adjusted for the highest expected loading rate. [5, 11, 13, 28]

In low-pressure pulse-jet baghouses, the pressure of the clean air jet is generally between 7 and 14 psi. Medium-pressure pulse-jet baghouses use pressures of about 15 to 40 psi. The duration of the pulse jet is generally longer and the volume of compressed air greater than in the high-pressure pulse-jet system. Medium and low-pressure pulse-jet baghouses are more widely used in Canada, Australia and Europe. High-pressure pulse-jet baghouses are common in the U.S. [5, 13] Such baghouses can often generate noise that needs to be mitigated. Silencers, noise barriers, and air inlet filter houses are among the ways to mitigate noise generated by baghouses.

Bags are cleaned one row at a time either when a timer initiates cleaning or when monitors indicate cleaning is necessary. Ideally, the cleaning frequency should be adjustable. For example, a pulse-jet baghouse with three adjustable speeds can shift from one speed to another based upon baghouse differential pressure. This can avoid over cleaning bags. If the pulse interval is too large, the waste gas stream will rush through the recently cleaned row of bags, taking the path of least resistance. This rush of waste gas may pull particles through the bag fabric resulting in higher emissions and more particles entrained in the fabric. Vendors recommend the compressed air pressure and frequency of the cleaning cycle be adjusted such that the pressure drop across the baghouse is maintained between 3 and 5 inches of water in order to maintain a correct amount of dust cake. Felted (i.e., non-woven) fabrics are generally used because they achieve high collection efficiencies with less dust cake. In high temperature acidic applications, such as coal-fired boilers, woven fiberglass, polyphenylene sulfide (PPS) felt, acrylic felt, polyamide felt, aramid felt or fiber blends are commonly used in combination with surface treatments (e.g., surface singe, Teflon coatings, and expanded polytetrafluoroethylene membrane). [3, 5, 8, 11, 13, 24, 28]

The pulsed clean air opposes and interrupts forward gas flow for only a few tenths of a second. However, the quick resumption of forward flow can redeposit particulate back on the clean bag or on adjacent bags. This action has the disadvantage of inhibiting dust from dropping into the hopper, but the advantage of quickly reforming the dust cake that provides efficient particle collection. Ideally, the particulate must have some capacity to combine into larger pieces in order to fall into the hopper and avoid re-entrainment in the counter current of the rising waste gas stream. For this reason, pulse-jet baghouses work best when used in applications where the fine particulate easily clump together to form larger agglomerates. [8, 11]

Pulse-jet baghouses using cartridge filters instead of the traditional filter bags and cages are also available from some vendors and are appropriate for applications where the waste gas stream is dry. The cartridges are generally arranged vertically, similar to the typical pulse-jet baghouse. However, an alternate configuration is also available in which the cartridges are arranged horizontally with one or more collection hoppers located below the cartridges. Figure 1-11 shows a schematic of a typical horizontal pulse-jet cartridge unit. Horizontal units can be purchased with as few as 2 cartridges up to 128 cartridges. [32]

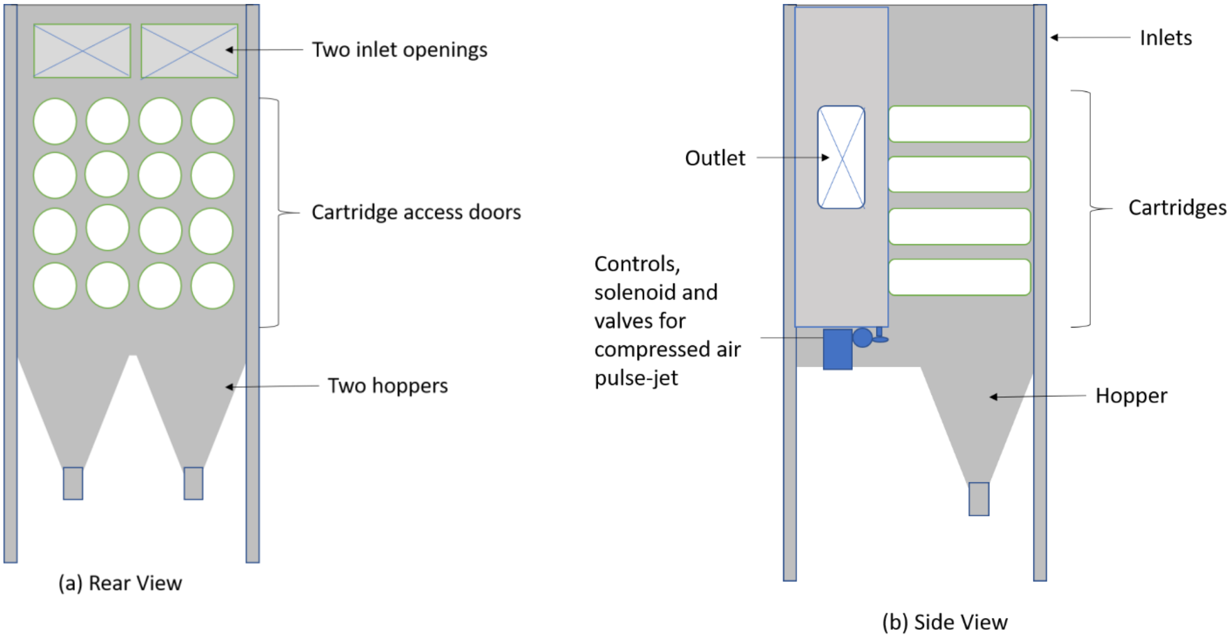

Figure 1-11: Cross-Section of a Typical Horizontal Pulse-Jet Cartridge Filter [32]

Although most pulse-jet baghouses have a rectangular housing as shown in Figure 1-11, some are manufactured with a round housing. The arrangement is similar to the rotating reverse-air design described in section 1.2.3.2 in which the bags are arranged in concentric rings around the center of the baghouse, with a single collection hopper located below the bags, and a rotating mechanical arm located above the bags that delivers the pulsed jet to each section of bags. A compressed air tank is located above the rotating arm. Each section of bags is cleaned once during a single revolution of the rotating arm as illustrated in Figure 1-12. Round pulse-jet baghouses are marketed in a series of different sizes similar to those available for the round reverse-air baghouses. [26]

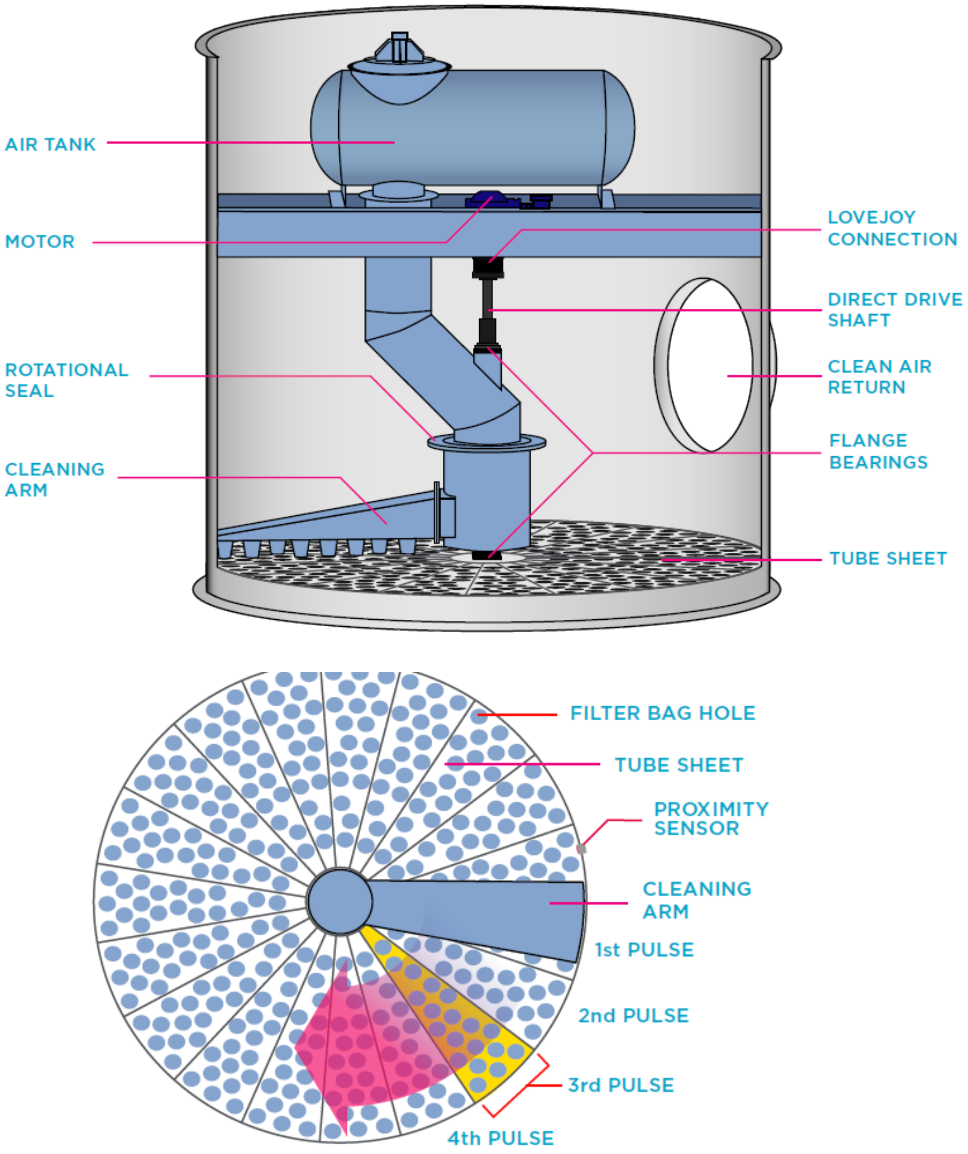

Figure 1-12: Rotating Pulse-Jet Baghouse [26]

There are two primary advantages of the pulse-jet baghouse: smaller size and lower capital cost. Since no bags are removed from service for cleaning, pulse-jet baghouses can operate on a continuous basis, which makes it unnecessary to have separate compartments with additional fabric filter media available for off-line cleaning. Due to the intensity and frequency of cleaning, pulse-jet baghouses can treat higher gas flow rates with higher dust loadings. For these reasons, pulse-jet baghouses can be smaller and have higher A/C ratios than other types of baghouses used to treat the same amount of gas and dust. Pulse-jet baghouses can have lower capital costs than a similar capacity mechanical shaker and traditional reverse-air baghouse because they have less fabric media and are not separated into compartments. [3, 8, 11]

1.2.3.5 Rotating Mechanical Cage

The system consists of a helix-shaped rotating cage that rotates around a fixed cage. The air passes through the bag and dust forms on the outside. As the rotating cage moves it dislodging particulates by beating the bag from the inside. The rotation can occur at set intervals or can be continuous and the baghouse can remain online during cleaning. No current applications of this cleaning technology are known. [33]

1.2.3.6 Sonic Cleaning

Sonic horns (sometimes called acoustic horns) were first used in the 1950s to clean filter bags in reverse-air baghouses in the carbon black and cement industries. In the 1980s, utilities started using sonic horns to improve cleaning and reduce the pressure drop in large baghouses used on coal-fired generators. [4] Sonic horns clean using low frequency sound waves to induce vibrations that break bonds between particulates and between particulates and other structures thereby dislodging particulate from filter bags.[5] They provide efficient removal of particulate build-up on baghouses and prevent bridging and plugging of hoppers and ductwork. They can reduce system downtime and maintenance costs by preventing plugged hoppers and fouled fan systems. Compared to the other cleaning methods, sonic cleaning is gentler and does not cause abrasion or flexing of fibers that can shorten bag life and cause premature failure of bags. [34]

Sonic horns can be used as the sole cleaning method in applications where the particulate is easily removed. However, sonic horns are generally used in combination with other cleaning methods to provide enhanced cleaning, where they are a cost-effective method of reducing operation and maintenance costs. [35] They are frequently used in reverse-air and mechanical shaker baghouses, where they are operated during the cleaning cycle. In reverse-air baghouses, the additional energy is helpful to obtain adequate dust removal in some applications. Sonic horns are used in mechanical shaker baghouses for applications where dense particulates are handled, such as particulate from utility boilers, metal processing, and mineral products. In mechanical shaker baghouses, sonic horns are reported to decrease the pressure drop across the filter fabric by up to 60 percent thereby reducing energy costs. Some sources state that sonic horns can decrease operation and maintenance costs by up to 3 percent. They are also said to increase bag life by reducing the frequency and duration the mechanical shaker operates. In pulse-jet baghouses, they are said to reduce the amount of compressed air used, reduce the frequency of reverse pulsing, and increase the bag life by up to 80 percent. However, they are generally used in pulse-jet baghouses to prevent buildup of material in the hopper [5, 7, 15, 17, 34, 35, 36] When properly applied, sonic horns can reduce the mass of dust on bags considerably. However, they may also lead to increased dust penetration through the fabric, which reduces the efficiency of the baghouse.

Each manufacturer's sonic horns are different in design, size and shape. Figures 1-13 and 1-14 show a photograph and cross-sectional diagram of a typical sonic horn. Horn construction includes a horn-shaped outlet (known as the bell) attached to an inlet chamber containing a diaphragm. The bell and drivers are typically constructed of cast iron, stainless steel, or carbon

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[5] In addition to fabric filters, sonic horns are used to prevent dust buildup in electrostatic precipitators, selective catalytic reduction reactors, spray dryers, heat exchangers, air preheaters, bins, hoppers and silos.

steel. Compressed air at 40 to 90 pounds per square inch gauge (psig) enters the chamber, vibrates the diaphragm, and the horn amplifies the sound. Compressed air consumption varies from 45 to 80 standard ft^3 per minute (scfm) depending on the size of the horn. [34, 35, 37]

The sound level and the fundamental frequency are the two main characteristics of the sonic horn's acoustic energy. Each sonic horn operates in a frequency range rather than at a specific frequency. The optimal frequencies for sonic cleaning are in the range of 63 to 250 Hz. Frequencies above 300 Hz are less effective for cleaning and are more audible to humans. The fabric filter media and metal surfaces and structures are not affected by the sound waves at frequencies above 20 Hz. Frequencies below 20 Hz can be close to the natural harmonic frequency of plant equipment, which can potentially cause damage by inducing vibration in solid structures. The intensity or sound pressure level (measured in decibels) is also important and sonic horns capable of producing sound pressures of 120 to 149 decibels are more effective. Most sonic horns operate in this range. The interval between activation bursts and the duration of the sonic horn burst are usually adjustable. The interval between sonic bursts should be sufficiently short so that the layer of particles on the bags does not become too thick and particles in the hopper and on other surfaces is minimized. In a typical mechanical shaker and reverse-air baghouse, the sonic horn is activated for approximately 10 seconds during each cleaning cycle. A brief pause should occur after sounding the sonic horn to allow the dust to settle before returning the compartment to service. In other applications (such as in the hopper of a pulse-jet baghouse), the sonic horn is typically operated 10 seconds every 10 minutes. [7, 15, 34, 35, 36, 37]

Figure 1-15 shows typical mounting locations for sonic horns in various types of baghouses. In pulse-jet baghouses, sonic horns are generally mounted in the hopper section below the filter bags where they can also help to clean frame works and keep the hopper sections free from build-up. Horns can be flange mounted through the baghouse siding with the flange at either the outlet end of the horn or at the inlet chamber. The horns also can be suspended inside the baghouse structure as shown in Figure 1-1.13(a) and (b) for the mechanical shaker and reverse-air baghouses. Sonic horns require only a small amount of space, although curved designs are available for locations with limited space. [34, 37, 38] Sonic horns work best in low moisture conditions of below 20 percent. [35] They are not recommended for applications where the material is sticky. [36]

Figure 1-13: Typical Sonic Horn [34]

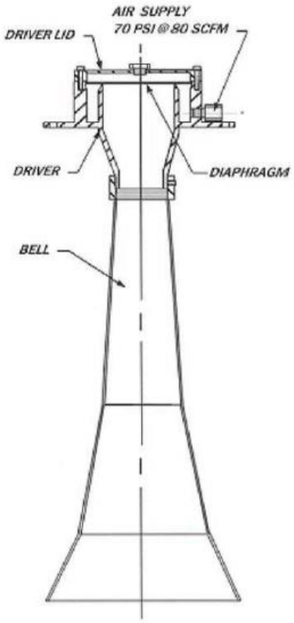

Figure 1-14: Cross-section of a Typical Sonic Horn [34]

The number of horns required is determined by the size, fabric area and the number of baghouse compartments. Typically, 1 to 4 horns are used in each baghouse compartment. [17, 36]

Typical costs for sonic horns cost range between $1,450 and $3,500 (in 2022$) depending on size and the material used in their construction. Costs for ancillary equipment are typically less than 50 percent of the costs of the sonic horn and include solenoid valves, ball valves, hoses, and mounting hardware). [36] In a 2002 project, the system investment for horns was reported to be $13,500 (in 2002$) for a 6-compartment baghouse requiring 1 horn per compartment.[6] The installed horns operated at 125 Hz and used 75 scfm of compressed air at 75 psig and each horn cleaned 8,500 ft^2 of fabric. The same size horn can clean up to 15,000 ft^2 of fabric. [38]

The bells have an equipment life of over 20 years but the diaphragm and sound generators typically last 3 to 5 years depending on the application. A replacement diaphragm costs between $325 and $1,950 (in 2022$).[7] For most applications, the sonic horns and their ancillary equipment should be checked about once every two years. Hearing protection should be used when in close proximity to horns. [36, 37]

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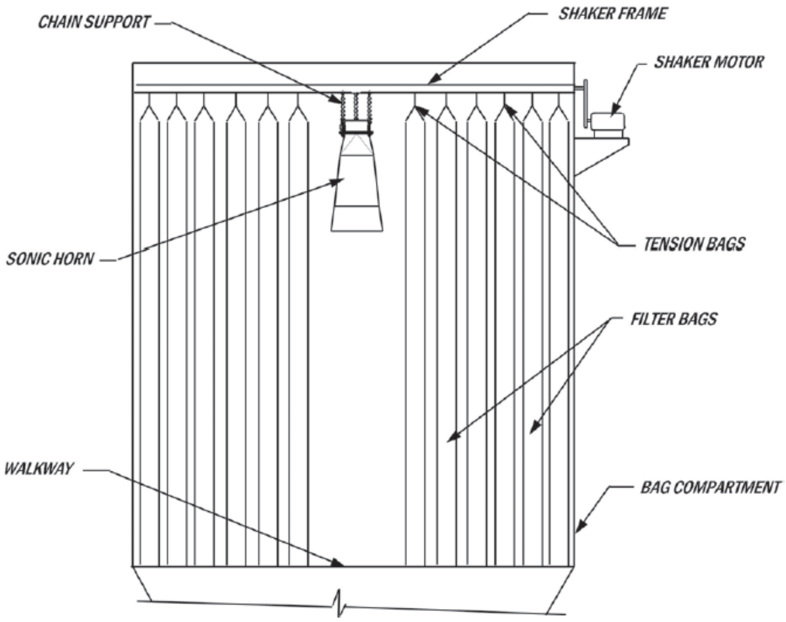
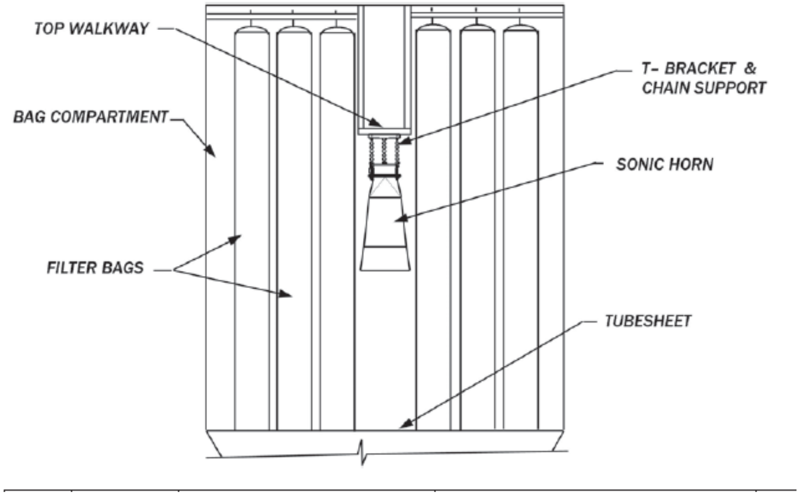
[6] Based on information provided by a vendor in 2023, the costs quoted here in 2002$ remain representative of the typical cost for a six-horn system.

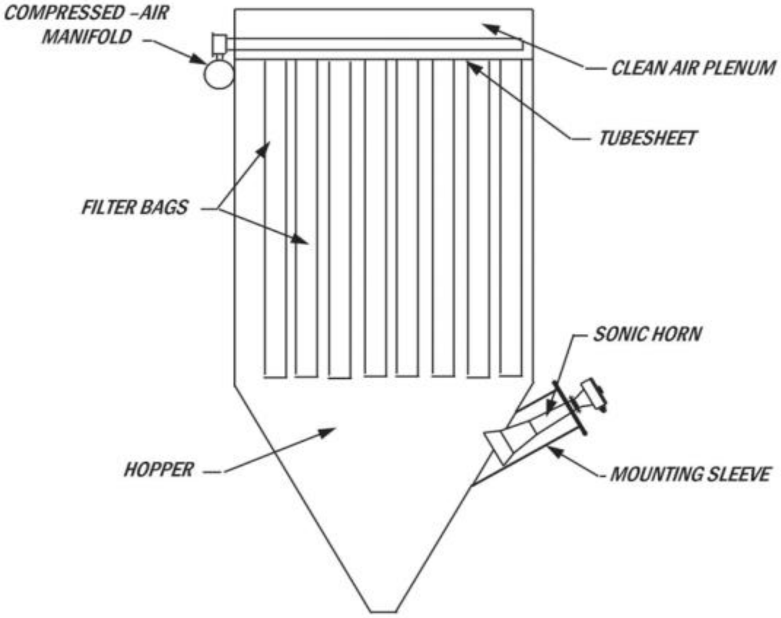
[7] Obtaining site-specific cost estimates will be useful in order to accurately estimate the costs of replacement, especially given the wide range of costs included in this Cost Manual chapter.



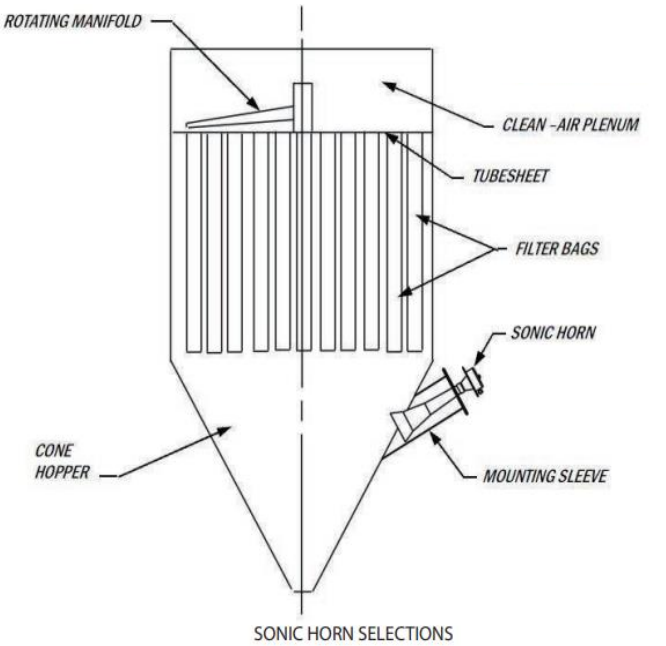
(a) Mechanical Shaker Baghouse



(b) Reverse-air Baghouse



(c) Pulse-jet Baghouse



(d) Rotating Pulse Baghouse

Figure 1-15: Typical Mounting Positions for Sonic Horns [34]

1.2.4 Fabric Media

The first baghouses used bags made from natural fibers, such as cotton and wool. Over the last 40 years, however, many synthetic fibers have been developed that can withstand higher temperatures and have better chemical resistance. The synthetic fabrics commonly used today include polyester (e.g., Dacron®), acrylic homopolymer, PPS, aramid (sometimes known by its tradename Nomex®), PTFE, P84®, and fiberglass. [37, 38] Fiberglass was once the most widely used material for higher-temperature applications, such as coal-fired combustion units, but has largely been replaced by aramid, PPS, P84 and Teflon-coated bags that are more durable. In addition to durability, the new synthetic fabrics are also easier to clean, which can enable the operator to use less frequent and less vigorous cleaning and thereby increase bag life. [1] Ceramic filters, sometimes called candles, are also available for high temperature applications where other filter media cannot be used. [5, 40, 41]

The fabric media may be woven, felted (sometimes referred to as nonwoven media), spun-bonded, or knit. Woven fabrics are stronger and generally last longer than felted fabrics. They come in several different weave patterns, including plain, twill, and sateen. In the plain weave, the threads are woven in an alternating over and under or checkerboard pattern that forms the tightest weave with the smallest pore size. In the twill weave, the threads are woven in a repeating pattern of over two threads under one thread for a 2 to 1 pattern or an over three threads under one thread for a 3 to 1 pattern. In the sateen weave, the threads are woven in a repeating pattern of over thread under four. The sateen fabric has the largest pore size, does not retain particles as well as the plain twill weave and is not as resistant to abrasion as the other fabrics. However, the sateen fabric releases cake easier during cleaning and have a lower pressure drop. The plain weave is better able to capture small particles but operates at a higher pressure drop and is more likely to become blinded. The plain weave is less commonly used for filter bags because of the higher pressure drop. Twill fabric is a good compromise as it has pore sizes between the plain and sateen fabrics, operates at medium pressure drops, is less likely to become blinded than plain weave fabric and has good resistance to abrasion. (See section 1.3.4 for discussion of bag blinding). [5, 10]

Felted fabrics generally consist of a woven base (called scrim) sandwiched between needle-punched felt fibers. A typical felted medium with scrim is shown in Figure 1-16. The scrim provides structure to the cloth and should be no more than 15 percent of the fabric weight. The felt fibers are generally randomly arranged and attached to the scrim by chemical, heat, resin or stich-bonding methods. The individual felt fibers provide the target for particle collection through impaction and interception. For this reason, bags with a higher weight of scrim per square foot have less felt for filtration and lower particulate collection efficiency. Felted media are typically two to three times thicker than woven media. The felt fabric is sometimes passed through heated rollers in a process called calendaring, which increases the density of the felt. Felted fabric without scrim is also available and these fabrics use interlocking directional layers of fiber to provide support to the fabric. For fabrics of the same weight, felt fabrics without a scrim provide better filtering performance than those supported by scrim because the greater number of fibers in the scrim-less fabric increase the incidence of particulate impaction and interception. [5, 10, 11]

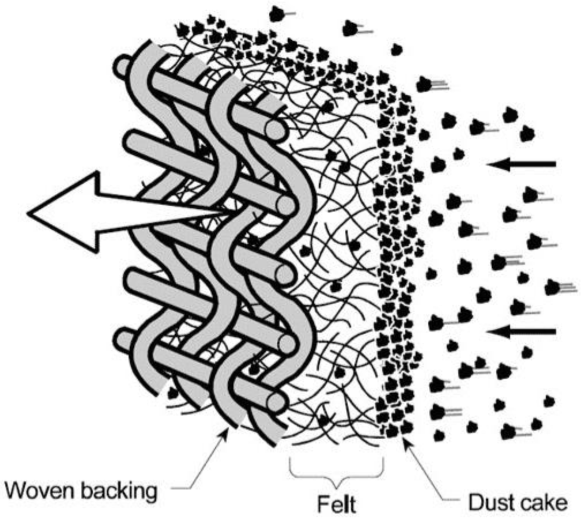


Figure 1-16: Diagram showing the Construction of a Typical Felted Medium [10]

Because of their strength, woven bags are typically used in the mechanical shaker and reverse air baghouses. Although both woven and felted bags are used in pulse-jet baghouses, felted bags are more common. Pulse-jet cleaning of woven bags can cause bags to stretch thereby opening the weave slightly and allowing more particulate to pass through the fabric. Initially a new felted bag provides better capture efficiency than a new woven bag, however, the collection efficiency of woven bags gradually improves as the dust cake forms on the fabric surface. [5, 11]

Fabric media is available in different weights and denier. The fabric weight refers to the weight of one square yard of fabric, while the denier is the grams of material it takes to make a certain length of the fiber. Typical fabric weights range from 5 to 26 ounces per square yard. The heavier weight fabrics provide more area for particulate collection, but they are more expensive and operate at a higher pressure drop. [5, 11]

Properties of some commonly used media are presented in section 1.2.4.1. Table 1-3 lists some of the applications in which the media can be used and Table 1-4 shows typical costs for some fabric filters.

1.2.4.1 Common Fabric Media

Cotton

Cotton fabric filters are available in a woven fabric and are often used in mechanical shaker type collectors due to their strength and durability. The maximum continuous operating temperature for cotton filters is 180°F; however, they can tolerate temperatures up to 200°F for short periods. Cotton filters are resistant to alkalis and organic solvents, but they are not recommended for applications where acids and oxidizing agents are present. They are recommended for use in dry and ambient temperature conditions due to their poor resistance to bacteria and mildew. Cotton fabric filters are also available with a flame-retardant finish. Since cotton fabric readily combusts, untreated cotton bags are not a good choice for applications where the waste stream is combustible. They are often used for applications such as cleanrooms, woodworking, cement manufacturing, and movement or drying of aggregate products (e.g., sand). Cotton is also one of the lower cost options at a cost of about $8 for one 8-foot bag (2016$). [5, 13, 43, 44]

Wool

Wool fabric filters are available in felted fabric. The maximum continuous operating temperature for wool filter is 200°F; however, they can tolerate temperatures up to 250°F for short periods. Wool filters have good resistant to acids and can withstand moisture better than cotton. However, they have low abrasion resistance and are not recommended for applications where alkalis conditions are present. Wool fabric is best suited for low temperature applications, such as woodworking and aggregate processing. Wool is one of the lower cost options but is more expensive than cotton. [5]

Polyester

Polyester is available in woven, felted, spun-bonded and knit fabrics. It is the most common type of filter media for applications where temperatures are below 275°F because it provides durability, good filtration properties, lower price, and can be used in all types of baghouses. [44] It provides good resistance to chemicals and abrasion and is not affected by bacteria and mildew. The maximum continuous operating temperature is 275°F, but the fabric can withstand short term temperature excursions up to 300°F. Polyester is good for applications where the waste gas is dry. Polyester is not a good choice for waste gas that has a high moisture content as it is subject to hydrolytic degradation under certain circumstances. Polyester is resistant to oxidizing agents, organic solvents, weak alkalis, most mineral and organic acids. It is not resistant to strong alkalis or high concentrations of nitric acid, sulfuric acid, and carbolic acid. It is only moderately resistance to strong alkalis at low temperature and is not recommended for some phenolic compounds or for use in high moisture and temperature applications. Polyester is not recommended for waste streams containing ammonia or glycol, or for processes where sparks or other sources of ignition might result in fires. Polyester bags are relatively inexpensive option at about $15 for an 8-foot bag and $16 for a 10-foot bag (in 2023$). Polyester bags can be coated or glazed with finishes that help protect the fabric from moisture and high temperatures (see section 1.2.4.2). Some polyester bags are available with a PTFE membrane (see section 1.2.4.4). [5, 13, 43, 44, 45, 46]

Polypropylene

Polypropylene is available in both woven and felt fabrics and provides excellent resistance to most chemicals and high durability. It has excellent resistance to organic solvents, reducing agents, acids, and alkalis. The smooth surface of the fibers allows dust particles to be easily removed during cleaning. The maximum continuous operating temperature is 170°F, but the fabric can withstand short term temperature excursions up to 200°F. The polypropylene fibers do not absorb moisture and are not affected by bacteria or mildew. However, polypropylene fabric will support combustion, has poor resistance to sodium and potassium hydroxide above 200°F, and poor resistance to some organic solvents, including ketones, esters, and chlorinated hydrocarbons. Polypropylene is not recommended for processes where sparks or other sources of ignition are possible. Polypropylene is a good choice for applications where chemical and moisture is present. Polypropylene bags typically cost about $8 for an 8-foot bag (in 2016$). [5, 13, 43, 45]

Fiberglass

Fiberglass is available in either a woven or felted fabric and is an excellent choice for high temperature applications such as cement kilns, high temperature dryers, carbon black reactors, power plants, and electric furnaces. The maximum continuous operating temperature for fiberglass is 500°F and the fabric can withstand short term temperature excursions as high as 550°F. Fiberglass is resistant to most acids, alkalis, oxidizing agents and organic solvents. Fiberglass is not recommended for applications where hydrofluoric acid, chlorides, bromides, and cyanides are present in the waste gas. Fiberglass is also less resilient to abrasion and some vendors recommend support cages with 20 or more vertical wires be used to reduce wear from bag flexing (see Section 1.2.3.4 for additional information on selection of cages for pulse-jet fabric filters). Fiberglass bags are more expensive than many of the other filter media available, costing about twice that of acrylic and three times more than cotton, polyester and polypropylene for comparably sized bags. A typical 8-foot fiberglass bag costs about $24 (in 2016$). [5, 13, 38, 43, 44, 45, 46]

Acrylic

Acrylic provides good resistance to acids, most organic solvents, hydrolysis and temperature. Acrylic is often used to control emissions from dryers, electric furnaces, aluminum reduction, and other primary or secondary smelting. The recommended maximum continuous operating temperature is 260°F, but acrylic fabric can tolerate short-term temperatures of 285°F. Resistance to minerals and organic acids is higher than polyamides and polyesters. Acrylic has a moderate level of resistance to alkalis and most oxidizing agents, but its resistance is superior to polyamide (P84). Acrylic is not available in all fabric forms and is more expensive than polyester or polypropylene. The typical cost for an 8-foot bag is $13 (in 2016$). [5, 13]

Nylon

Nylon has good resistance to alkalis and most organic solvents and is a strong, resilient fabric that withstands abrasion well. Nylon can be used for temperatures up to 250°F. Nylon is not recommended for most mineral oxides (e.g., iron oxides) because they can cause degradation and in some cases decomposition, particularly at high concentrations and high temperatures. [5, 13]

Aramid

Aramid (sometimes known by its trade name Nomex®) is a strong, resilient fabric that has good resistance to alkalis and organic solvent, moderate resistance mineral and organic acids, and can tolerate high temperatures. The normal maximum continuous operating temperature is 375°F but aramid can withstand temperatures of up to 425°F. It is available in either a woven or felted fabric. It has good resistance to abrasion and wear and is recommended for applications with highly abrasive dust and/or high temperatures, such as electric arc furnaces, high temperature dryers, and cupolas. Aramid is not recommended for applications where mineral oxides (e.g., chromium trioxide), phenolic compounds (e.g., phenol), hydrofluoric acid, and oxalic acid are present in the waste gas stream. Most mineral oxides cause degradation and partial decomposition, while some phenolic compounds can have solubility issues. Aramid is one of the more expensive fabrics. The typical cost for an 8-foot aramid bag is $39 and a 10-foot bag is $44 (in 2023$). [5, 13, 43, 44, 45, 46]

Polyamide (P-84®)

Polyamide is more commonly known by its trade name P-84® and is available as a felted fabric. It is nonflammable and not hydroscopic and is resistant to acids, oxidizing agents, and organic solvents. It is good choice for high temperature applications. The recommended normal maximum continuous operating temperature is 475°F with temperatures as high as 500°F tolerated for short-term process upsets. P-84 is also a very strong, resilient fabric that provides longer bag life than fiberglass. P-84 bags are commonly used in baghouses controlling particulate emissions from smelters, dryers, coal-fired boilers, incinerators, kilns, and calciners. P-84 is not recommended for use in high temperature applications where the waste gas contains sodium hydroxide, sodium bromide, zinc chloride, formic acid, acetone, ethyl ether, methanol, toluene, xylenes, or butane. Polyamide is sometimes used in a composite fabric consisting of a polyamide felt mounted on a less expensive substrate (e.g., fiberglass). In these composite fabrics, the interlocking fibers of the polyamide provides improved filtration at a lower cost. The typical cost of a 33 ft long P-84 felt bag is approximately $150 (in 2013$). [1, 13, 43, 46, 47]

Polyphenylene sulfide (PPS)

Polyphenylene Sulfide (PPS) (commonly known by its brand names of Ryton® and Procon®) is resistant to alkalis, mineral acids, organic acids and organic solvents. It is available as either a woven or felted fabric and works well in high moisture applications and situations where the temperature of the waste gas stream is near the dew point. PPS has a maximum continuous operating temperature of 375°F but it can tolerate temperature surges of up to 425°F. PPS is not recommended for applications where oxidizing agents are present in the waste stream. PPS bags are commonly used for coal-fired boilers, incinerators, fluidized bed combustion units, cement mills, and asphalt plants. A study in 2010, found that PPS felt was the most common fabric used by power plants for pulse-jet fabric filters. [1] PPS is a good choice for applications subject to low emissions standards. The typical cost of a 33 ft long PPS felt bag is approximately $90 (in 2013$). [13, 42, 47]

Polytetrafluoroethylene (PTFE or Teflon®)

Generally known by its trade name, Teflon® consists of fluorocarbon fibers that are hydrophobic, oleophobic and capable of withstanding temperatures up to 500°F. The normal maximum continuous operating temperature is 450°F. Teflon® is available in both a woven and a felted fabric. Manufacturers recommend Teflon® be used with cages with 20 or more vertical wires to provide sufficient support to reduce flexing. Teflon® is one of the more expensive fabric media. The typical cost for an 8-foot bag is $26 (in 2016$). Because of its high cost, Teflon® is generally used only for applications where other fabric media cannot be used or would quicky degrade resulting in premature failure and frequent bag replacement. Common applications include coal-fired power plants, cement production, and steel foundries. [5, 13, 28, 45]

Polybenzimidazole (PBI)

PBI is another chemical resistant polymer with similar in properties to Teflon®. PBI is capable of withstanding extreme environments, including high temperatures and acidic conditions. Like Teflon®, PBI has good resistance to alkalis, mineral acids, organic acids, and organic solvents. PBI has some resistance to oxidizing agents, however, its resistance is not as good as Teflon®. However, the temperatures at which PBI can be used is higher than Teflon®. While the recommended maximum operating temperature for Teflon® is 500°F, PBI can tolerate temperatures as high as 650°F. PBI's excellent resistance to both acids and high temperatures make it a good choice for controlling particulate emissions from coal-fired boilers. PBI fabric also very durable with good abrasion resistance properties. [42]

Ceramic

Ceramic filters were developed in the 1980s and consist of a rigid, porous and lightweight medium formed from fine fibers of silicon carbide, silicon nitride or aluminum oxide in a clay binding agent. They are typically formed into long cylinders similar in shape to a test tube with a round closed end at the bottom and an open end with a flange at the top. Because of their shape, they are often called ceramic candles. The walls of the ceramic candle are typically 0.6 to 0.75 inches thick. The filtering mechanism is the same as for traditional fabric media, where dust cake formed on the surface of the ceramic candle improves the collection efficiency. To prevent fine particulates from entering the porous ceramic media and causing irreversible blinding of the filter, some manufactures use a thin outer layer over the main body of the filter. The removal efficiency (≥99.9% for most applications) is the same as for other media. The ceramic candles are inert, resistant to alkali and acidic conditions and can operate in high-temperature and high-pressure applications. Although ceramic filters are a rigid medium, they may be cleaned using the pulse-jet mechanism (discussed in section 1.2.3.4), where the dust accumulated on the outside of the ceramic candles is periodically removed by a pulsed jet of clean compressed air into the candle interior. The compressed air flows outward through the wall of the candle, in the reverse direction to the normal flow of the waste gas steam. Ceramic filters are available in various sizes; however, 10-foot-long ceramic candles with 6-inch diameter are the most commonly used size. They are the most expensive medium available, with the typical cost for a 5-foot-long candle with a 2.4-inch diameter being about $1,000 (in 2020$). [5, 40, 41, 48, 49]

They are well suited for high temperature applications, such as pressurized fluid bed combustion units, incinerators, and metal refining (e.g., nickel, secondary aluminum). Based on pilot-scale installation studies, ceramic filters may be useful for combustion units burning biomass where temperatures of 400 to 600^{o}C are recommended. The waste gas temperature for biomass combustion units must be maintained above 350^{o}C to avoid tar deposition on the filter media, which makes the filter media difficult to clean and decreases control efficiency. The recommended maximum operating temperature is 1650°F and ceramics can tolerate temperatures as high as 1830°F. Unlike other fabric media, their ability to operate at high temperatures enables them to be positioned before heat recovery devices to prevent plugging and fouling. Although they can withstand high temperatures, ceramic media are prone to cracks if exposed to thermal shocks. For this reason, ceramics are not suitable for applications where rapid temperature swings may occur. Some ceramic media are made with continuous fibers that provide additional structural support. [5, 50, 51]

In addition to standard ceramic candles, ceramic media containing catalysts are also available that help to remove nitrogen oxides (NO_x). Removal of NOx requires ammonia injection upstream from the filter. The gas-phase reaction of the ammonia with NOx is catalyzed by the small particles of catalyst embedded in the ceramic media. The reaction occurs at temperatures between 350 to 950°F. NOx removal is reported to be approximately 70% at 350°F and 90% at 400°F. Optimal removal of 95% is reported at temperatures around 450°F. Unlike conventional Selective Catalytic Reduction (SCR) systems, this approach helps prevent catalyst blinding by protecting the catalyst surface from particulates. [5, 40, 41, 48]

Ceramic candles can also be used with dry sorbent injection (DSI) systems to remove acidic gases (e.g., hydrogen chloride (HCl), hydrogen fluoride (HF), sulfur dioxide (SO_2), sulfur trioxide (SO_3)) and mercury. However, pollutant removed is temperature dependent with the optimum PM, SO_2, NO_x, HCl and other acidic gases removal occurring at operating temperatures between 450 and 750°F. [5, 40, 41]

Table 1-3: Fabric Media Properties and Common Applications [5, 40, 41]

Fabric Media	Properties			Examples of Typical Applications
	Normal Operating Temperatures (°F)	Chemical Resistance	Relative Abrasion Resistance	
Cotton	<180	Resistant to alkalis and organic solvents	Good	Cleanrooms, woodworking, cement, and aggregate processing
Wool	<200	Resistant to acids.	Average	Cleanrooms, woodworking, cement, and aggregate processing
Nylon	<200	Resistant to alkalis and most organic solvents	Excellent	Cleanrooms, woodworking, cement, and aggregate processing
Polypropylene	<200	Resistant to organic solvents (except ketones,	Excellent	Coal-fired boilers, Incinerators, fluidized bed

Fabric Media	Properties			Examples of Typical Applications
	Normal Operating Temperatures (°F)	Chemical Resistance	Relative Abrasion Resistance	
		esters and chlorinated hydrocarbons), reducing agents, acids, and most alkalis (except sodium and potassium hydroxides).		combustion units, cement mills, asphalt plants, and aluminum smelting
Acrylic	<260	Resistant to acids	Average	Dryers, aluminum reduction furnaces, and other primary and secondary metal smelting.
Polyester	<275	Resistant to oxidizing agents, organic solvents, weak alkalis, and weak mineral and organic acids.	Excellent	Woodworking, coal processing, foundry sand casting
Polyphenylene Sulfide (PPS) (Ryton®, Procon®)	<375	Resistant to alkalis, mineral acids, organic acids and organic solvents. Not recommended for oxidizing agents	Good	Coal-fired boilers, incinerators, fluidized bed combustion units, cement mills, and asphalt plants.
Aramid (Nomex®)	<375	Resistant to alkalis and organic solvents. Some resistance to mineral and organic acids. Not recommended for mineral oxides, phenolic compounds, hydrofluoric acid, and oxalic acid.	Excellent	Electric arc furnaces, asphalt plants, high temperature dryers, and cupolas

Fabric Media	Properties			Examples of Typical Applications
	Normal Operating Temperatures (°F)	Chemical Resistance	Relative Abrasion Resistance	
Polytetrafluoroethylene (PTFE or Teflon®)	<450	Resistant to alkalis, mineral and organic acids, and organic solvents.	Fair	Coal-fired boilers, cement production, and steel foundries.
Polyamide (P-84®)	<475	Resistant to acids, oxidizing agents and organic solvents. No recommended for sodium hydroxide, sodium bromide, zinc chloride, formic acid, acetone, ethyl ether, methanol, toluene, xylenes or butane.	Excellent	Smelters, dryers, coal-fired boilers, incinerators, kilns, calciners, and soil remediation plants
Polybenzimidazole (PBI)	<500	Resistant to alkalis, mineral and organic acids, and organic solvents. Some resistance to oxidizing agents.	Excellent	Coal-fired boilers
Fiberglass	<500	Resistant to alkalis, oxidizing agents, organic solvents and acids (except hydrofluoric acid)	Fair	Cement kilns, dryers
Ceramics with embedded catalyst	<750	Resistant to alkalis and acids.	Not applicable	Pressurized fluid bed combustion units, incinerators, combined cycle combustion units, glass furnaces, and cement kilns.
Ceramics without embedded catalysts	<1650	Resistant to alkalis and acids.	Not applicable	Pressurized fluid bed combustion units, incinerators,

Fabric Media	Properties			Examples of Typical Applications
	Normal Operating Temperatures (°F)	Chemical Resistance	Relative Abrasion Resistance	
				combined cycle combustion units, coal gasification, glass manufacturing, aluminum powder production, nickel refining, zirconia production, and secondary aluminum production

Table 1-4: Typical Costs of Common Filter Bags [44, 52]

Type	Diameter (inches)	Length (feet)	Surface Treatment	Typical Cost (2023$)
Cotton Sateen Bag	5	4	None	$26
Cotton Sateen Bag	5	4	Napped	$30
Cotton Sateen Bag	5	8	None	$36
Cotton Sateen Bag	5	8	Napped	$41
Polyester felt	4	4.25	Singed	$15
Polyester felt (16 oz.)	4	8.4	Singed	$17
Polyester felt (16 oz.) Bottom load bag with raw top	4.75	12	Singed	$11
Polyester felt (16 oz.) Top Load bag	5	10	Singed	$16
Polyester felt (16 oz) Top load bag	5	12	Singed	$18
Polyester felt (16 oz) Top load bag	6	10	Singed	$20
Polyester felt with PTFE Membrane. Top load bag	6.25	10	Singed	$28
Aramid felt (16 oz.) Top load bag	6	8	Singed	$39
Aramid felt (14 oz.) Top load bag	6	10	Singed	$44

1.2.4.2 Fabric Treatments

Several types of fabric treatments can be used to improve durability, collection efficiency and/or cleaning. The most common treatments are calendaring, napping, singeing, and glazing. In calendaring, the fabric is passed through rollers that flatten or smooth the material by applying high pressure. Calendaring increases density of the fabric and improves the stability of the fabric.

It also produces a more uniform surface. In napping, the fabric surface is scraped by passing the fabric across a metal comb. This process raises or fluffs the surface fibers, thereby increasing the collection efficiency of the fabric by providing more opportunity for particle collection by interception and diffusion. Singeing involves passing the fabric over an open flame. This process removes any loose surface fibers to produce a more uniform surface that allows dust cake fall off more easily. In glazing, the fabric is exposed to high pressure at high temperatures, which fuse filter media together. Glazing improves the mechanical strength of the fabric. Natural fabrics such as cotton and wool are generally preshrunk to eliminate bag shrinkage during operation. [5]

1.2.4.3 Surface Coatings

Surface coatings are sometimes applied to fabric media to improve the properties of the fabric. Coatings of silicone, graphite, and fluorocarbons (e.g., polytetrafluoroethylene) provide protection from acid attack and improve abrasion resistance. Coatings of silica fibers can provide woven fabrics protection from high temperatures. Bags coated with polytetrafluoroethylene are resistant to chemicals, high temperatures and moisture. They are commonly used in applications where the waste gas contains corrosive chemicals or high moisture. Oleophobic and hydrophobic coatings of fluorocarbon resins provide water and oil resistance. Fabrics can also be treated with a flame retardant to help reduce the potential for fires in applications where the dust is combustible. [3, 5, 7, 38, 45, 54]

1.2.4.4 PTFE Membrane

Membrane fabrics consist of an expanded, semi-porous layer of polytetrafluoroethylene (PTFE) that is bonded to the surface of a conventional filter fabric, including fiberglass, polyester, and aramid (Nomex). The PTFE membrane is applied to one side of the fabric and is thin enough that the pressure drop across the fabric is low. The PTFE membrane consists of very fine fibers that are packed closely together to produce a very high control efficiency. The PTFE membrane bags do not need pre-conditioning as is the case for traditional filter bags because the membrane functions in the same manner as the dust cake. The PTFE membrane releases dust more easily than other fabrics, which minimizes dust cake build up. The PTFE membrane can handle sticky, difficult to clean dust and helps prevent fine particulates from penetrating the filter fabric causing filter blinding. For these reasons, PTFE membrane bags operate at high particulate collection efficiency, generally last longer, and operate at a lower and more consistent pressure drop when compared with traditional fabrics. PTFE membrane bags are not recommended for applications in which the waste gas stream contains oils or hydrocarbons as these chemicals tend to block membrane pores. It can be used with pleated filters or cartridges. The properties of the fabric to which the PTFE membrane is bonded must be considered when determining whether the PTFE membrane bag is appropriate for a particular application. PTFE membranes can be applied to both woven and felted media. PTFE membranes used on PPS bags on coal-fired utility boilers have been shown to provide lower pressure drops than bags without membranes. The PTFE membranes also resulted in less frequent and lower pressure cleaning cycles in pulse-jet fabric filters, which resulted in longer bag life. Costs of bags with a PTFE membrane are higher than standard bags and vary based on size and type filter bag. The typical cost of a 33 ft long woven fiberglass bag with PTFE membrane is $80, compared to standard woven fiberglass bag cost of about $70 (in 2013$) [5, 25, 43, 47, 54]

1.2.4.5 High Efficiency Particulate Air and Ultra-Low Particulate Air Filters

High efficiency particulate air (HEPA) filters and ultra-low particulate air (ULPA) filters are high efficiency filters that are able to achieve extremely low concentration of airborne particulates. They are commonly used in cleanrooms in pharmaceutical, medical device, and electronics manufacturing (e.g., semiconductor production). In the US, HEPA filters must meet a minimum standard that require the filter to remove 99.97 percent of particles of diameter 0.3 µm. ULPA filters must remove at least 99.99 percent of ultrafine particles of 0.12 µm. HEPA and ULPA filters have similar structures. They typically consist of a square or rectangular casing containing multiple layers of randomly arranged and densely packed PTFE, polypropylene, fiberglass or polyester felts. As air is drawn through the filter, particulates are trapped within the filter layers and clean air exits at the rear of the filter. In the ULPA filters, the fibers are more densely packed, air flow rate is lower, and pressure drop higher than in HEPA filters. ULPA filters cost about 35% more than a comparably sized HEPA filter. ULPA filters are generally only necessary for a limited number of specialized applications, such as microelectronics manufacturing. HEPA filters are more common and are used in a broad range of applications. HEPA and ULPA filters must be periodically replaced. The frequency of replacement varies with the type of application. [55]

1.2.5 Filter Designs

Standard filter bags, cartridges, or pleated filters are the three common filter designs used in industrial baghouses. The traditional design for industrial baghouses was the standard cylindrical filter bag (described in section 1.2.5.1); however, cartridges (described in section 1.2.5.2) and pleated filters (described in section 1.2.5.3) are also popular due to the filter area they provide in a small, compact filter. Other filter designs include panel filters, box filters, and pocket filters (described in section 1.2.5.4).

1.2.5.1 Filter Bags

Standard filter bags consist of cylindrical bags that are open on one end. They are available in many different sizes and fabric and can be used with all types of filter cleaning methods. Typical bag sizes vary from a few feet to up to 32 ft long and 4 to 12 inches in diameter. Some bags are equipped with a built-in grounding wire to prevent build-up of static electric charge. Costs vary depending on the bag size, type of fabric, and surface treatment. Standard bags are significantly less than cartridges and pleated filters. A typical 5-inch diameter, 10-foot polyester bag costs about $15 and $24 with a copper ground wire (2022$). [52]

1.2.5.2 Cartridges

In addition to the standard filter bags, filter cartridges are also available that provide increased filter area per unit of baghouse volume. Cartridge filters are round cylinders or tubes consisting of a finely pleated filter medium supported on a wire framework. The typical cartridge contains an inner supporting core surrounded by the pleated filter medium and outer supporting mesh. One end of the cartridge is open, which allows gas passing through the filter from the outside to exit to a clean air plenum. The other end of the cartridge is closed by an end cap. The manufacturing process requires strong, rigid joints where the end caps attach to the filter medium and cores. Epoxy or polyurethane plastics are used to seal the medium against the end caps. The cartridge is held tightly in place against a mounting plate surrounding the hole that connects it to the clean air plenum. They are available in a single use and continuous use designs. In the single use design, the dirty cartridges are replaced and the collected dust removed when the fabric filter is offline. In the continuous use design, the cartridges are cleaned using the pulse-jet cleaning system discussed in section 1.2.3.4. Figure 1-16 shows a typical cartridge filter and Figure 1-17 illustrates a typical cartridge collector. Cartridges are good choice for applications with very fine dust, lower dust loading and moderate temperatures, such as powder coating, metalworking, sanding/blasting, and welding. [15, 55, 56]

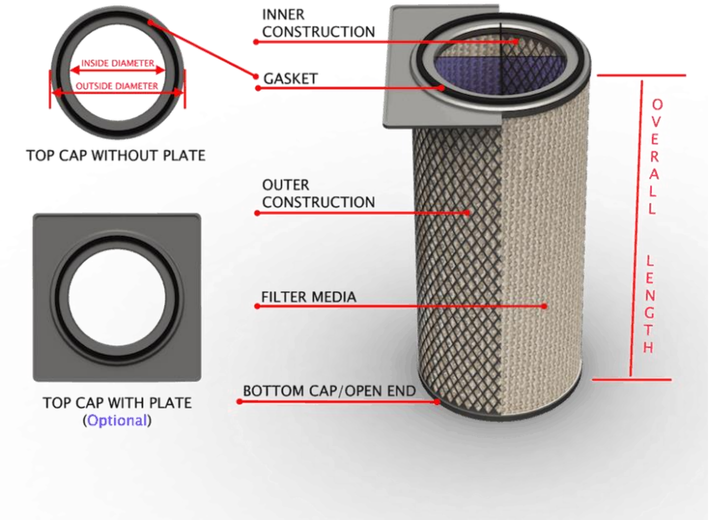


Figure 1-16: Typical Cartridge Filter [15]

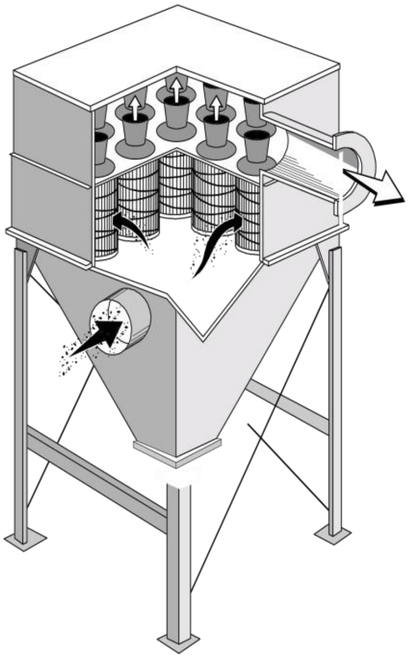


Figure 1-17: Typical Vertical-Mount Cartridge Baghouse
(Courtesy of North Carolina State University)

Cartridges are available in various sizes and shapes ranging from about 6 to 14 inches in diameter and about 10 inches to 30 inches in length. Although cartridges are generally round cylinders, oval and conical shaped cartridges are also available. [56]

Cartridge filters were initially available in cellulose and paper, but today are available in a wider range of fabrics. Filter media for cartridges may be paper, spunbonded monofilament plastics (e.g., polyester), aramid, P84, and PTFE membranes. For most applications cartridges with an 80/20 cellulose and polyester blend provides good filtration efficiency and releases dust easily but is not resistant to moisture and not as durable as other types of media. For applications where higher efficiency and greater durability is required, nonofiber cartridges are often used. Cartridges are also available with flame resistant and oleophobic surface coatings. Cartridges made from aramid or PPS with stainless steel inner cores, end caps, and gaskets are available for higher temperature applications up to 375°F. However, these cartridges cost up to 3 times more than nanofiber and spunbond cartridges. [15]

The filtering surface is from about 25 ft^2 to 317 ft^2. The more pleats the filter has the greater the filter area for a specific cartridge volume. However, filters with a high number of pleats have smaller spaces between each pleat, which increases the likelihood of dust permanently bridging the bottoms of the pleats and reducing the available filtering area. For non-agglomerating dusts of small particle size (up to a few micrometers), a paper or cellulose filter with 12 pleats/in. to 16 pleats/in. may be used for waste streams that have ambient temperature and low moisture content. Nonwoven fabrics that have 4 pleats/in. to 8 pleats/in. may be used for waste streams that have higher temperature and moisture content. Pleat depth is typically from 1 to 3 inches. [56]

Cartridges can be mounted vertically or horizontally. The horizontal design typically has the filters mounted in tandem with a gasket seal between them. If not properly mounted or if the gasket material is not of high quality, leakage will occur after repeated cleaning pulses. [56] They can also be used as replacements for traditional bags and cages in existing pulse-jet fabric filters. Retrofit costs for one case were 70% of the cost of building a new baghouse. [57] No changes to the cleaning equipment are generally required to accommodate the cartridges. Cartridges cost about three to three-and-a-half times more than traditional bags and cages. The costs vary based on the size and type of media. A typical cost for a 13-inch diameter, 26-inch-long cartridge can vary from $120 for a cellulose filter media able to tolerate temperatures up to 180°F to over $1,000 for a high-temperature, stainless steel cartridge able to withstand temperatures up to 350°F in 2023$. A cartridge of the same size with cellulose filter media treated with a flame-retardant coating costs about $160 in 2023$. Table 1-5 shows the typical costs for cartridge filters. [44, 62]

Table 1-5: Example Costs for Typical Cartridge Filters [44]

Size (diameter x length, inches)	Number of Pleats	Maximum Temperature (degrees F)	Filter Area (ft2)	Media	Typical Costs (2023$)
12.75 x 26	325	180	226	80/20 Cellulose/Polyester Blend	$94
12.75 x 26	190	180	112	100% Spun-Bond Polyester	$140
6.25 x 39	70	180	39	100 % Spun-Bond Polyester with Polytetrafluoroethylene (PTFE) Membrane	$174
12.75 x 26	148	180	100	100 % Spun-Bond Polyester with Polytetrafluoroethylene (PTFE) Membrane	$200

1.2.5.3 Pleated Filters

Pleated filters consist of a long, tubular filter assembly that looks very similar to a cartridge filter and offer many of the same benefits. They are available in a variety of fabric media, including spunbonded polyester, aramid, and PTFE membranes. Some pleated bag designs have curved openings at their top to increase cleaning energy, similar to the venturi used in some baghouse filters. Figure 1-18 shows a typical pleated filter. They are available in a wide range of sizes from diameters of 4.4 to 6.02 inches, lengths of 16 to 84 inches and media areas of 4 to 58 ft^2. Some come with a built-in grounding wire to prevent build-up of static electricity. Table 1-6 shows the typical costs for pleated filters. [55, 58]

Table 1-6: Example Costs for Typical Pleated Filters [62, 63]

Size (diameter x length, inches)	Number of Pleats	Filter Area (ft^2)	Media	Typical Costs (2023$)
6 x 21	54	14.5	Spunbonded polyester	$100
5 x 41	54	23.6	Spunbonded polyester	$120
5 x 56	54	41.3	Spunbonded polyester with conductive grid & PTFE membrane	$260

Pleated bags are used in pulse-jet fabric filter units, where they replace both the bag and the cage. In recent years, they have become very popular both for new pulse-jet fabric filters and for retrofitting in existing pulse-jet fabric filters that used traditional bags. They can be used in wide range of applications, including food, agricultural products, and pharmaceutical processing; metals fabrication; woodworking; and mineral processing. [13, 55, 58]

Figure 1-18: Examples of Pleated Filters Used in a Pulse-jet Fabric Filter [15, 60]

Pleated filters provide several advantages over traditional filter bags. Table 1-7 summarizes the advantages and disadvantages of pleated filters compared with traditional filter bags used in pulse-jet units. Like cartridges, their principal advantage over traditional bags is their large filter area. They provide significantly more filter cloth area than a standard bag and are generally shorter than typical filter bags. The typical pleated filter has from 30 to 60 pleats and can provide double the filtration area per foot of filter length than a traditional filter bag. For example, a typical traditional 10-foot-long filter bag has about 16 ft^2 of filter area, while a typical 6-foot-long pleated filter of the same diameter has about 44 ft^2 of filter area. For this reason, pleated filters have a much smaller footprint than a traditional unit of the same size. Fabric filters equipped with pleated filters are a good choice for situations where space is limited. Fabric filters with pleated filters are often designed to operate with a higher air-cloth ratio than traditional baghouses, which results in a lower pressure drop across the fabric filter and lower energy costs. The high air-to-cloth ratio can also reduce the number of cleaning cycles needed, which further lowers operating costs by reducing the amount of compressed air used and extends the service life of the filters. One vendor claims that pleated filters can reduce compressed air usage in pulse-jet fabric filters by 30 to 50%. Pleated filters are best suited for dry, free-flowing dust and are not recommended for high moisture applications or for handling hydroscopic materials (e.g., salts, sugars, and cellulose particles) because the water makes it harder to remove the dust cake during cleaning. Their shorter length allows the fabric filter housing to be more compact. [5, 13, 15, 27, 58, 60]

Existing traditional filter bag and cage configurations in pulse cleaning dust collection systems can be replaced with pleated filters. This type of retrofit can provide some reductions in capital and annual costs. First, the pleated filters can provide increased filter area, which can increase the capacity of an existing baghouse and thereby avoid the cost of replacing the existing unit or adding another fabric filter. Second, the higher the air-to-cloth ratio lowers the pressure drop across the collector, which results in lower energy usage. Third, pleated bags can reduce labor costs for filter replacement significantly as the pleated filters are easier and more quickly replaced because their shorter length makes them easier to handle and they do not have the separate bags and cages that must be replaced with tradition bags. Lastly, in baghouses where traditional bags are failing prematurely due to abrasion from the waste gas stream inlet, replacing traditional bags with shorter pleated bags can increase filter bag life. The shorter bags create a large empty space below the bags that can function as a knockout box to slow the velocity of the inlet gas stream to a level at which larger particles drop down into the hopper. [60]

Table 1-7: Advantages and Disadvantages of Pleated Filters Compared to Traditional Bags in Pulse-Jet Fabric Filters [45, 59, 59]

Filter Type	Advantages	Disadvantages
Pleated Filters	Smaller footprint. Can use fewer filters than traditional bags due to the higher air-to-cloth ratio. Filters are shorter than traditional bags. Easier to clean; use less compressed air. Operate with lower can velocity. Operate with lower pressure drop. Filters easier to install, lower labor costs for filter replacement. Longer service life. Smaller fabric filter housing results lower capital costs.	Material can collect in pleats causing filter to clog. Pleats can be damaged by high air pressures. Pulse-jet cleaning less effective; difficult to clean in moist conditions or with hydroscopic dust. More expensive than conventional filter bags. Most not suitable for very high temperature applications. Most not suitable for use where corrosive gases are present.

Filter Type	Advantages	Disadvantages
Traditional Filter Bags	Available in a wide range of fabric media. Pulse-jet cleaning more effective. With selection of the right fabric media, filter bags can be used for high temperature (up to 500°F), corrosive and high moisture applications. Filter bags are less expensive than cartridge filters.	Larger footprint. Higher capital costs for larger fabric filter housing. More difficult to install bags, particularly in pulse-jet units where each bag must be fitted on to cage, higher labor costs for filter replacement. More compressed air needed for cleaning; more frequent cleaning required.

1.2.5.4 Other Filter Designs

Fabric filters in panels, box, and pocket designs are also available. Panel filters are square or rectangular flat or pleated mats of filter fabric with a plastic, aluminum or steel frame and grill for support and are typically about 3 inches deep. Box filters are square or rectangular filters housed in an aluminum or galvanized steel frame. They vary in depth from about 6 to 12 inches. Both panel and box filters are commonly used for HEPA and ULPA filters for applications such as cleanrooms for pharmaceuticals, food, biotechnology, and electronics manufacturing. Figure 1-19(a) shows a typical rectangular box HEPA filter.

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(a) HEPA Box Filter

(b) Fiberglass Pocket Filter

Figure 1-19: Examples of Typical Box and Pocket Fabric Filters [61, 62]

Pocket filters consists of felted or woven fabric media formed into a pocket that is supported by a galvanized steel or plastic frame depending on the application. Figure 1-19(b) shows a typical 6-pocket filter. However, pocket filters are available with 3, 6, 8 and 12 pockets. The air flows from the inside to the outside of the pocket filter and the dust collects on the inside of the pocket. They are available in a range of different fabric media and sizes, including different pocket depths and a different number of pockets. Pocket filters are sometimes used to remove larger particles as a pre-treatment for HEPA filters and are useful for collecting toxic dusts. Panel, box, and pocket fabric filters are disposable filters that must be replaced when the fabric media become loaded with particulates. Costs vary depending on the size and type of filter fabric. Table 1-8 shows some typical costs for box and pocket filters. [10, 61]

Table 1-8: Typical Costs for Panel, Box and Pocket Filters [44, 61, 62, 63]

Filter Size (Length, width, depth in inches)	Media Type	Maximum Air Flow	Control Efficiency (%)	Approx. Cost (in 2023$)
Pocket Filters				
24 x 24 x 22 with 6 pockets	Fiberglass	NA	90 – 95	$80 - $94
24 x 24 x 22 with 8 pockets	Fiberglass	NA	90 – 95	$90 - $110
24 x 24 x 22 with 10 pockets	Fiberglass	NA	90 – 95	$110 - $125
24 x 24 x 22 with 6 pockets	Synthetic	NA	90 – 95	$70 - $80
24 x 24 x 22 with 8 pockets	Synthetic	NA	90 – 95	$70 - $80
24 x 24 x 22 with 10 pockets	Synthetic	NA	90 – 95	$90 - $105
Box Filter				
12 x 24 x 6	Microfiber	625 fpm	90 – 95	$130
24 x 24 x 6	Microfiber	625 fpm	90 – 95	$200–
12 x 24 x 12	Microfiber	625 fpm	90 – 95	$160
24 x 24 x 12	Microfiber	625 fpm	90 – 95	$190 - $215
12 x 12 x 6	HEPA	NA	99.97	$250
12 x 12 x 11.5	HEPA	300cfm	99.97	$310 - $410
12 x 24 x 11.5	HEPA	600 cfm	99.97	$400 - $630
24 x 24 x 11.5	HEPA	1,200 cfm	99.97	$565 - $900
24 x 24 x 11.5	HEPA	2,000 cfm	99.97	$330
12 x 12 x 11.5	ULPA	300 cfm	99.99	$390 - $450
12 x 24 x 11.5	ULPA	600 cfm	99.99	$500 – $800
24 x 24 x 11.5	ULPA	1,200 cfm	99.99	$565 - $1,120
Panel Filter				
12 x 12 x 3	HEPA	300 cfm	99.99+	$350 - $410
24 x 48 x 3	ULPA	2,400 cfm	99.99+	$670

NA – Data not available.

1.2.6 Auxiliary Equipment

The typical auxiliary equipment associated with fabric filter systems is shown in Figure 1-20. The auxiliary equipment necessary for operating a fabric filter typically includes: a capture device (i.e., hood or direct exhaust connection); ductwork; dust removal equipment (screw conveyor, etc.); fans, motors, and starters; monitoring equipment and an exhaust stack. In addition, spray chambers, mechanical collectors, and dilution air ports may be needed to pretreat the gas before it reaches the fabric filter.

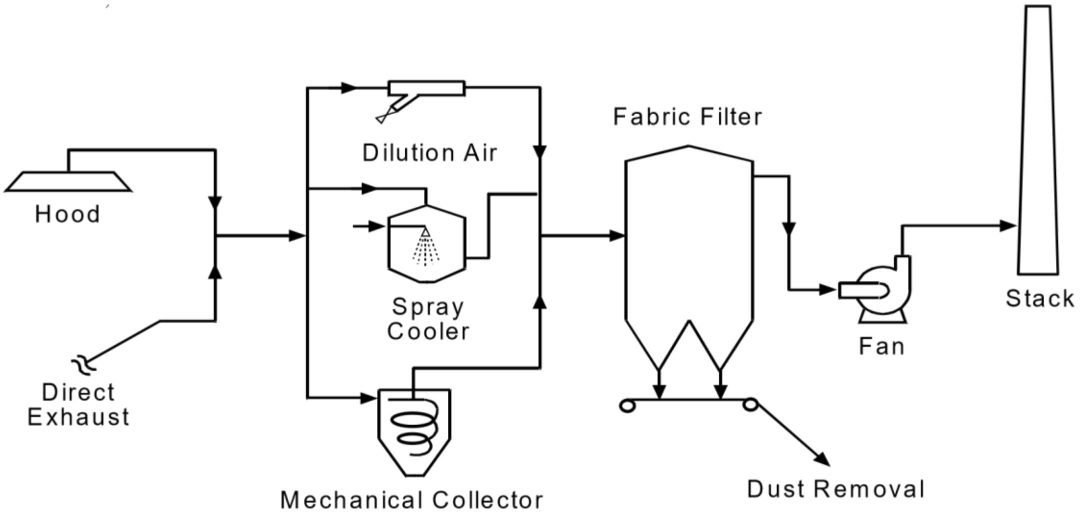

Figure 1-20: Typical auxiliary equipment used with fabric filter control systems.

1.2.6.1 Particulate Capture and Transfer

Particulate capture devices are usually attached to a process vessel by a hoods or direct exhaust couplings. Direct exhaust couplings are less common, requiring sweep air to be drawn through the process vessel, and may not be feasible in some processes. Ductwork (including dampers) is used to contain and regulate the flow of the exhaust stream as it moves from the emission source to the fabric filter. An exhaust fan is used to move the waste gas stream from the point of pickup (e.g., hood) through the ductwork and baghouse filter media to the exhaust stack. The fan can be mounted before the fabric filter (referred to as a positive pressure system) or after the fabric filter (referred to as a negative pressure system). The fan selected must be correctly sized to accommodate the volume of air and pressure drop across the system. For proper conveyance in the air stream, most materials require air flow velocities between 3,500 ft/min to 5,000 ft/min. The velocity of the air flow is important. For dust suspended in air to be transported, the velocity of the air must be at or above the minimum conveying velocity. If the air velocity falls below the minimum conveying velocity, dust will drop out of the airstream and accumulate in the ductwork causing blockages and even collapse of the ductwork. If the air flow velocity is too high, abrasive particles (e.g., metals, silica, cement, asphalt) can wear holes in the ductwork. The minimum conveying velocity for the dust should be determined to ensure the system works correctly. Some vendors recommend a variable frequency drive fans be selected for applications where air volumes and dust loads are variable, as they provide the operator with greater control over the system. [10, 53]

1.2.6.2 Waste Gas Stream Pretreatment

In some applications it is necessary to pretreat the waste gas stream before it enters the fabric filter. Spray chambers and dilution air ports can be used to decrease the temperature of the waste gas stream to protect the filter fabric from excessive temperatures. When a substantial portion of the pollutant loading consists of relatively large particles (more than about 20 µm), a mechanical collector can be used to remove the larger particles and prevent excessive wear and damage to the fabric filters. Knockout boxes and cyclones can be used for this purpose. Pretreatment using a mechanical collector is recommended for some applications. For example, exhaust from a dryer at a typical hot mix asphalt plant contains relatively large particles. If not removed from the waste gas stream, these particles can abrade the bags and cause premature failure. They also form a more porous dust cake that reduces the performance of the baghouse. Cyclones are generally preferred over the knockout box as they are more efficient and can be used to selectively collect particles above a certain size, allowing the smaller particles to pass through the cyclone to the baghouse. Knockout boxes tend to be less effective than cyclones, particularly in applications where the volume of gas is variable. They also take up more space than a cyclone. However, cyclones can add a large pressure drop across the control system. For example, a cyclone used as a pre-cleaning device on a hot mix asphalt dryer is reported to have a pressure drop of about 3 to 4 inches of water. [7, 11]

1.2.6.3 Dust Handling Systems

The dust that accumulates in the hopper below the filter bags must be emptied and moved to storage for either use onsite or more often for transfer to a landfill. There are several types of mechanism can be used to discharge dust from the hopper. The simplest and lowest cost approach is the manual slide gate that can be opened periodically by plant personnel. This option works well where the dust loading is light and dust accumulates slowly in the hopper. Where the dust loads are high, vendors recommend a rotary airlock or double tipping valve be used. A rotary airlock consists of blades or vanes welded to a shaft that rotates during operation. As the valve is rotated, the pockets between the blades are filled with dust from the hopper at the inlet port. The dust is then rotated inside the valve until it reaches the discharge port at the bottom of the valve and falls out by gravity into the dust container. Figure 1-21 shows a typical rotary valve. They are available in different diameters from 8 to 12-inch inlet diameter with 6 vanes. The double tipping valve consists of two flaps attached to counterweights or springs. Particulate builds up on the flap until the weight exceeds that of the counterweight and flap is opened, allowing material to pass through the separate chambers in batches. Both the rotary airlock and double tipping valve prevent air from flowing between the hopper and the dust container. Rotary airlocks are more expensive than slide gates, costing between \$2,000 – \$3,000 per valve (in 2020 dollars). [55, 65]

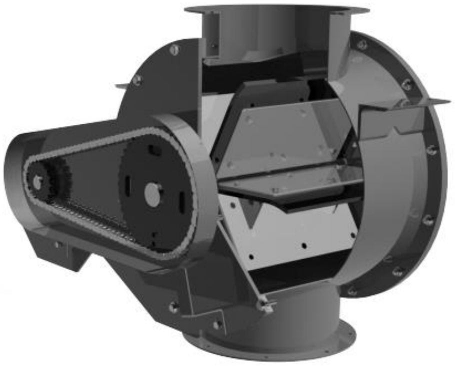

Figure 1-21: Typical Rotary Valve [65]

The dust from the hopper can be discharged directly to portable storage containers, covered boxes or drums, or a conveyor system. Portable storage containers are drums or bags that placed under the hopper discharge. When full they can be moved either by hand or forklift to trucks for shipping offsite. Covered boxes and drums are connected to the hopper discharge and have vents that are either equipped with a vent filter or are ducted to the baghouse housing to prevent dust from escaping when the hopper is emptied. The containers must be carefully monitored to avoid the dust overflowing or backing up and clogging the hopper gate. For large baghouses with heavy dust loads, the preferred method is a discharge conveyance system that moves the dust to a central dust storage facility. The most common system is the screw conveyor, but pneumatic conveyors or sluices may also be used for this purpose. Conveyance systems are more expensive than the other methods described above and are more expensive to maintain. [52, 55]

1.2.6.4 Monitoring Systems

The performance of the fabric filter can be monitored in several ways. The most common method is a differential pressure gauge that measures the pressure drop across the fabric filter. A decrease in pressure drop can be caused when holes or tears have occurred in the fabric. Increases in pressure, can indicate that the bags need to be cleaned. If high pressure drop persist after cleaning, blinding may have occurred. Operators may also use monitors to check the temperature, exhaust flow rate, and fan current. The pressure drop across the fabric filter is typically measured in units of inches of water column and can be measured using a Magnehelic® pressure gauge or a Photohelic® pressure gauge. The Magnehelic® gauge is the most common type of differential pressure gauge and costs range from $80 to $380 (2023$). [66, 67, 68] Photohelic® gauges are similar to the Magnehelic® differential pressure gauge but include a switch that activates the cleaning cycle when the pressure drop reaches a previously set pressure drop target. Photohelic® gauges cost about $600 (2023$). [66] Digital pressure gauges are also available that measure differential pressure and gas flow rates. Costs for digital gauges are between $230 and 300. [69]

Performance can also be monitored using a PM continuous emissions monitoring system (PM CEMS) or a triboelectric bag leak detector, both of which are placed in the exhaust vent or stack. Use of CEMS and bag leak detectors enable operators to quickly identify and fix problems. One study of fabric filters operated by power plants found that the best-performing units commonly use PM CEMS. [1] Because the type and characteristics of PM vary from source to source, PM CEMS must be calibrated after installation in accordance with EPA's Performance Specification 11 (PS-11): *Specifications and Test Procedures for Particulate Matter Continuous Emission Monitoring Systems at Stationary Sources*. PS-11 provides the calibration procedures for developing a site-specific correlation of the PM CEMS measurements against manual gravimetric reference method measurements made using EPA Methods 5, 5I, or 17.[8]

Bag leak detectors detect particles in the gas stream exiting the baghouse. Figure 1-22 shows a typical bag leak detector system. They measure changes in particulate emissions relative to baseline or normal emissions. They consist of a stainless-steel probe inserted into the exhaust

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[8] Additional information on Performance Specification 11 is available on EPA's Air Emission Measurement Center website at https://www.epa.gov/emc/performance-specification-11-particulate-matter.

duct connected to an electronic controller that is connected to a new or existing monitoring management system with an alarm and recording equipment. The probe measures small changes in current caused by particles striking the probe (called the triboelectricity) or by particles passing near the probe (called electrostatic induction). The monitors can detect very small changes in current of about 0.1 picoampere (pA) or 0.5 pA, depending on the resolution of the monitor purchased. They help operators track baghouse performance and provide early notification of imminent bag failures before they occur, allowing operators to take necessary corrective actions. They can help operators determine when to replace bags and when to conduct other preventive maintenance. They can be used in all types of fabric filter designs and in a wide range of operating conditions. Typical operating conditions are shown in Table 1-9. Temperature does not affect the signal directly, however, if the temperature drops below the dew point, small droplets of condensation are seen as particulate, causing higher signal levels that can incorrectly trigger the bag leak alarm. [70, 72]

Table 1-9: Typical Operating Ranges for Bag Leak Detectors [70]

Parameter	Typical Operating Range
Temperature	-40 to 1650^{o}F (-40 to 898^{o}C)
Moisture	0 to 95 percent relative humidity (non-condensing)
Gas flow rate	400 to 6,000 ft/min[1]
PM concentration	0.01 to 10,000 mg/m^3

1- Flow rates outside this range may be possible in some situations.

After installation, vendors recommend the operator observe signals from the monitor during the first month of operation to collect information on the normal operation of the fabric filter and emissions source. During this initial operation, the operator should:

- Review process variables and determine the appropriate scaling.
- Monitor the particulate real-time trend throughout each process event, including filter cleaning, and adjust the real-time signal smoothing so the baseline signal is relatively smooth while response to peaks is dynamic and fast.
- Adjust the averaging period to achieve the desired response for long-term trend analysis or to meet regulatory leak detection requirements, and
- Establish alarm levels, delays, and logic for all monitored variables.

System changes (e.g., new type of filter media, changes in ductwork or fans, process changes that increase or decrease the load into the baghouse) may require range and/or alarm levels to be adjusted. If the alarm activation level is set too low, the alarm may be triggered following bag cleaning cycles. [1, 70, 71] The system should be checked annually by checking the outputs, performing verification checks of the electronics, and visual checks of the probe and insulator for particulate buildup and/or moisture. Some systems include automated periodic checks to confirm calibration. If required for quality programs or by regulations, the system or the electronics controller may be returned to the manufacturer for National Institute of Standards and Technology (NIST) traceable calibration certification. [70]

Bag leak detection system are less expensive than PM CEMS and can be more effective than a PM CEMS at identifying problems as the PM CEMS measure PM in the total gas flow, whereas bag leak detectors can be used on each compartment. [1] The monitoring hardware consisting of probe, electronic controller and coaxial wiring costs between $7,000 and $8,500 per monitoring point (2023$). A complete bag leak detection system including a new data management system cost between $23,000 and $27,500 per system (2023$). Typical replacement cost for the remote sensor is between $2,500 and $3,000 (in 2023$). The typical installation takes one to two days to complete. Additional equipment needed for the installation include a mounting for the monitor and sensor and enclosure for the electronic controller. Costs for installation are typically higher where new wiring and conduit is needed. [70] PM CEMS are reported to cost between $125,000 to $350,000 (2023$), including equipment and installation costs. [72] The expected life of a bag leak detection system varies depending on the application. Lifetime is affected by site conditions and care and maintenance of equipment. Many systems have operated for over a decade. The most common replacement is for remote sensors as these are installed within the exhaust duct. The expected life expectancy of the sensor is 8 to 10 years, with a factory service interval of 2-3 years, depending on the application. [70]

Continuous opacity monitoring systems (COMS) are also used on some baghouses to monitor performance. However, COMS are less reliable indicator for PM performance than PM CEMS or bag leak detectors. [1] COMS measure the light transmittance passing through a flue gas or optical density of the flue gas. COMS converts the optical density to an opacity reading expressed as a percentage, where 100 percent opacity means no light can be transmitted through the flue gas. Performance and design specifications for COMS are provided in EPA's *Performance Specification 1: Specifications and Test Procedures for Continuous Opacity Monitoring Systems in Stationary Sources* (PS-1).[9]

Visual observations of opacity can also be used to monitor fabric filter performance and are commonly included in operating permits. EPA Method 9 quantifies the percentage of light blocked by the particulate matter in the stack plume by observing the stack plume from the ground and is conducted by personnel that are trained and certified to Method 9 observations.[10] Method 22 is similar to the Method 9 but is used to determine the presence of opacity in a stack plume and does not require the personnel to be certified.[11] Methods 9 and 22 are typically conducted at regular intervals (e.g., once per shift) and are not as accurate as the continuous measurements made using COMS.

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[9] A copy of PS-1 is available on EPA's Air Emission Measurement Center website at https://www.epa.gov/emc/performance-specification-1-opacity.

[10] Copies of EPA Method 9, Visual Emissions Field Manual, and other guidelines and manuals are available on EPA's Air Emission Measurement Center (EMC) website at https://www.epa.gov/emc/method-9-visual-opacity.

[11] A copy of EPA Method 22 is available on EPA's Air Emissions Measurement Center website at https://www.epa.gov/emc/method-22-visual-determination-fugitive-emissions.

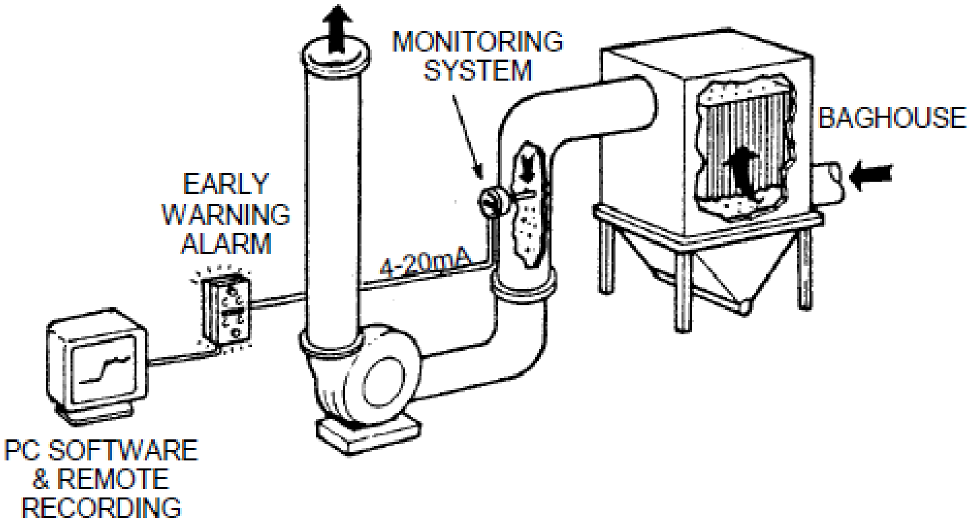

Figure 1-22: Typical Bag Leak Detection System [9, 72]

1.3 Performance

1.3.1 Typical Removal Efficiencies for PM_{10} and $PM_{2.5}$

The collection efficiency is affected by the gas filtration velocity, particle characteristics, fabric characteristics, and cleaning mechanism. A properly designed and well maintained and operated baghouse will generally have an extremely high PM collection efficiency over 99% across a range of particle sizes.

Fabric filters are particularly effective for collecting small particles. For example, tests of baghouses on two utility boilers showed efficiencies of 99.8 percent for particles 10 µm in diameter and 99.6 to 99.9 percent for particles 2.5 µm in diameter. [74, 77] For combustion units, emissions as low as 0.0015 lbs/MMBTU have been reported for well-functioning and well-maintained baghouses. [1] PTFE membrane filters provide the highest collection efficiency available today. They can collect $PM_{2.5}$ at over 99.99% efficiency. [52] For pulse jet fabric filters used on coal-fired utility boilers, suppliers have provided PM control guarantees of 0.010 lb/MMBtu. However, new fiberglass bags with PTFE membrane coatings have been reported to achieve filterable PM emission rates of 0.005 lb/MMBtu. [75] Typically, filter cartridges can achieve higher removal efficiencies than standard fabric filters for smaller particles. [10]

Ceramic candles typically achieve outlet grain loadings of less than 0.001 gr/dscf, although levels as low as 0.0007 gr/dscf have been reported for some applications. As with other types of media, removal efficiencies for ceramic candles are typically greater than or equal to 99.9%. NO_x removal for ceramic candles embedded with catalyst is reported to be 95% at temperatures of 450°F. [41] One study of PM removal for a biomass gasification process controlled using ceramic candles achieved a control efficiency of over 99%. [51]

1.3.2 Typical Removal Efficiencies for Mercury and Acid Gases

Fabric filters have also been used to control mercury and acid gases (e.g., sulfur dioxide, sulfur trioxide, hydrochloric acid) from coal-fired combustion units. Fabric filters are often used in combination with ACI for mercury control and DSI for acid gas control using an alkali sorbent. The activated carbon converts elemental mercury to its oxidized form and then captures and retains the mercury in the carbon. A fabric filter installed downstream from the ACI system collects the carbon and mercury. Conversion of the mercury is more efficient when a halogen is present in the exhaust gas or on the carbon surface. If the halogen content of the coal is too low, halogen is added either to the coal, the exhaust gas or to the activated carbon before injection. Using ACI in combination with a fabric filter can achieve mercury removal above 90 percent. DSI in combination with a fabric filter can remove greater than 90 percent of hydrogen chloride and between 50 and 90 percent of sulfur dioxide depending on the type of sorbent used. The required injection rate for alkali sorbents varies depending on the required removal efficiency, normalized stoichiometric ratio, the type of alkali used, and control efficiency of the particulate control device. Fabric filter media that are resistant to acid gases should be used with DSI systems and with ACI systems that inject brominated activated carbon. A full-sized fabric filter with an A/C ratio of 4.0 or lower is recommended where the fabric filter will be the primary particulate collection device for ACI and/or DSI. [1, 2]

Where the fabric filter is installed following another particulate collection device (e.g., ESP), the fabric filter is sometimes referred to as a ‘polishing baghouse’. A polishing baghouse typically has a higher A/C ratio of up to 6.0 and is therefore has lower capital and operating costs than a fabric filter used as the primary particulate collection device for an ACI or DSI system. Systems that use fabric filters either instead of or in combination with an ESP have higher control efficiency due to the increased opportunity for the pollutant to come into contact with sorbent as the waste gas passes through the filter media. Adding a fabric filter after an existing ACI/ESP system can reduce the amount of activated carbon required for any given removal rate by increasing the activated carbon interactions with mercury. Similarly, a fabric filter will also make collection of acid gases with DSI more effective than using a DSI/ESP system. [2]

In cases where ACI or DSI is added to an existing baghouse, the design specifications of the exiting fabric filter must be assessed to determine whether the additional PM loading can be accommodated. Where an existing fabric filter can be used, operating costs will increase due to increased costs associated with more frequent cleaning cycles and waste disposal. [2]

1.3.3 Approaches to Improving Control Efficiency

Several methods can be used to improve control efficiency and achieve a lower emission rate:

Decrease the Air-to-cloth Ratio

The A/C ratio is the gas flow rate divided by the fabric collection area. A baghouse with a high A/C ratio provides a smaller collection area and potentially higher pressure drops, particularly if the A/C ratio is too high for the particle loading and the cleaning mechanism is ineffective. A baghouse with a low A/C ratio provides a larger collection area and pressure drop increases more slowly and bag cleaning can be performed less frequently. A lower A/C ratio can be achieved by increasing the cloth area.[12] This can be accomplished by (1) replacing the existing bags with longer bags; (2) replacing an existing baghouse with a larger baghouse that can accommodate more and/or longer bags; or (3) adding additional compartments to an existing baghouse. Most baghouses are designed for a particular length of bag and generally do not have sufficient additional space to accommodate longer bags. Adding longer bags to an existing baghouse typically requires significant modification to the existing baghouse. [75]

Upgrade the Fabric Media

Replacing the type of fabric filter media can improve the achievable PM emissions reductions. For example, lower PM emissions rates have been achieved by replacing standard fiberglass bags with fiberglass bags that have a PTFE membrane coating. Section 1.7.0 presents a methodology for calculating the costs of replacing existing filter bags with upgraded bags that can achieve a higher control efficiency. [75]

Replace Fabric Media More Frequently

Data from electric generating units (EGUs) has shown that the emission rate for new fabric filter bags is approximately 50-70% lower in the first six months compared to the emission rate of older bags. Although the typical bag life for filter bags used in a pulse-jet fabric filter on an EGU is 3 to 5 years, the collection efficiency of filter bags can be impaired by excessive wear, high temperatures, acidic conditions, aggressive cleaning cycles, and other factors. Replacing filter bags more frequently may achieve significant reductions in emissions. While replacing bags more frequently would achieve the maximum reduction in emissions, this may not be practical or economic for many applications. Nevertheless, replacing fabric filters at more frequent intervals (e.g., 1.5- or 2.5-year intervals instead of 3- and 5- year intervals) can have significant impacts on emissions. Section 1.7.0 presents a methodology for calculating the increased costs of replacing filter bags on a more frequent basis. [75]

1.3.4 Factors Impacting Performance

The following factors can impact the performance of a fabric filter and result in increased emissions and baghouse shutdown:

Blinding – Caused by fine particles becoming entrained in the fabric media or by sticky particles (e.g., condensed hydrocarbon vapors, hydroscopic particles) adhering to the fabric surface. In both cases, the particles are not removed during the cleaning cycle and impede the air flow through the fabric resulting in high pressure drops. Blinding puts additional stress on bags and reduces filter bag life by causing more air to be forced through the unblinded portions of the bags. Filter bags with permeability of less than 2 cfm are considered blinded and should be replaced.

Abrasion – Caused by physical rubbing of filter bags with each other, the cage, or the housing, and by poor alignment of air-jets in pulse cleaning systems. Poor inlet design

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[12] Reducing the air flow would also lower the A/C ratio. However, this may not be an option for applications where lowering the air flow would result in larger particles being deposited in the ductwork upstream from the fabric filter.

can also result in abrasions where high velocity inlet gas laden with dust strikes filters in the same spot. Abrasion problems cause premature failure of filter bags. Abrasion problems may be fixed by replacing bent or corroded cages, correcting the alignment of air-jets, and by adding baffles or diffusers in front of the air inlet.

Condensation – Caused when moisture in the waste gas stream condenses as temperatures drop below the dew point. Condensation can result in corrosion of the housing and premature failure filter media, particularly where corrosive chemicals, such as acids, are present in the gas stream. Depending on the characteristics of the dust, condensation can cause the dust to become sticky resulting in blinding or to agglomerate and clog the hopper. Vendors recommend temperatures be maintained above 220^{o}F to avoid condensation.

Temperature – Caused by process upsets. Temperature excursions above the recommended maximum operating temperature of the fabric media will result premature failure of the filter bags.

Leaks – Caused by poorly fitted ductwork and tube sheets. can also occur due to failure of tube-sheet seals due to corrosion, exposure to chemicals in the exhaust stream, or due to high temperature excursions. Leaks allow dust laden air to bypass the bag filters, resulting in higher emissions. In a negative pressure fabric filter, leaks in the duct work and baghouse housing draws in moisture from outside, which may result in condensation forming inside fabric filter housing. As noted above, condensation can cause corrosion, blinding of fabric filters, and clogging of hoppers.

Hopper Discharge Bridging – Caused by particulate build-up in the hopper. Bridging is sometimes caused by a leaking rotary airlock allowing moist air to enter the housing, causing the dust to clump together and block the hopper valve. As dust gradually accumulates in the hopper, the dust particles can become re-entrained in the air flow.

Fabric filter performance can also be impacted by upstream control devices. Control systems, such as flue gas desulfurization (FGD), selective catalytic reduction (SCR), and electrostatic precipitators (ESPs), are frequently used on coal-fired utility boilers and their operation can result in operational issues for fabric filters. For example, spray dry FGD and dry sorbent injection (SDI) control systems located upstream from a fabric filter can increase moisture content in fly ash making it harder to clean bags and increasing the pressure drop. These systems can also decrease the temperature of the waste gas resulting in condensation in a downstream fabric filter. Ammonia used in SCR systems can form ammonia bisulfate, which makes the dust sticky and more difficult to remove during cleaning. ESPs tend to remove larger particles from the waste gas stream but let finer particles pass through. The finer dust reaching the fabric filter is more difficult to collect and more likely to penetrate the fabric causing blinding. Carbon injection used to control mercury emissions can increase the potential for fires in the fabric filter. [24]

1.3.5 Methods for Evaluating Fabric Media Performance

Several tests have been developed by the American Society of Testing and Materials (ASTM) for evaluating the characteristics and performance of filter media. The tests focus on the following five characteristics:

Abrasion Resistance

Abrasion resistance measure the relative ability of the fabric to withstand physical stress without tearing. Abrasion resistance can be determined for new and used filter media. Measurements on used filter media can provide information on whether the abrasion resistance of filter bags is degraded to an extent that bag failure is likely.

Tensile Strength

Tensile strength is a measure of the fabric media’s ability to stretch without tearing. Tensile strength depends on the fabric type and weight. Synthetic fabrics typically have greater tensile strength than those made from natural fibers.

Burst Strength

Burst strength is a measure of the fabric media’s ability to withstand pressure from pulsing of air during pulse-jet cleaning.

Permeability

Permeability measures the amount of air that can flow through the fabric media at a specified pressure drop (typically 125 Pascals). Woven fabric media typically have higher permeability than felted media. The permeability of felted media typically ranges between 15 and 35 ft/minute (8 to 18 cm/s). The permeability of woven fabrics is typically greater than 50 ft/minute (25 cm/s).

Flexibility

Flexibility measures the ability of the fabric media to bend without breaking. Flexibility tests are used to assess the potential for self-abrasion of the fabric media.

Table 1-10 lists the several test methods used to measure the performance of fabric media. The methods can be used on new and used filter media. For used media, they can be used to assess the condition of the fabric media over time. Permeability measurements on used filter bags can be compared to the permeability of the filter bags when new. Where the permeability has decreased, the test helps determine the extent to which filter bags have become blinded. Where the permeability has increased, the test helps to identify bags where aggressive cleaning has caused the fabric pores to grow wider. Abrasive resistance, tensile strength, burst strength and flexibility tests provide information necessary to evaluate the extent of filter media degradation and to assess the potential for bag failure. [10]

When used on new media, test methods can be used to evaluate the relative performance characteristics of different types of fabric media, which can help industry identify a fabric media with optimal performance characteristics for a specific application. In addition to aiding in selection of fabric media, test methods also provide valuable information on the operating parameters for a specific filter media. For example, ASTM D6830 – 02 measures the pressure drop, airflow resistance, drag, cleaning requirements, and particulate filtration performance for filter media operating at specific air flow, dust concentration, temperature, humidity, and cleaning cycle settings that simulate fabric filter operation. This information can be used to identify recommended operating parameters for the fabric media and is helpful for designing of the fabric filter system.[13]

Table 1-10: Test Methods Used to Evaluate Fabric Media Performance [10]

Filter Fabric Media Performance Characteristic	Test Method
Abrasion Resistance	ASTM D4966-12 – Standard Test Method for Abrasion Resistance of Textile Fabrics (Martindale Abrasion Tester Method) and ASTM D3885-07A (2019): Standard Test Method for Abrasion Resistance of Textile Fabrics (Flexing and Abrasion Method).
Tensile Strength	ASTM D6614/D6614M-20 – Standard Test Method for Stretch Properties of Textile Fabrics – CRE Method ASTM D1424-21 – Standard Test Method for Tearing Strength of Fabrics by Falling Pendulum (Elmendorf Type) Apparatus ASTM D5034-21 – Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test) ASTM D5035-11 – Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method)
Burst Strength	ASTM D6797-15 – Standard Test Method for Bursting Strength of Fabrics Constant Rate of Extension (CRE) Ball Burst Test ASTM D3787-16 – Standard Test Method for Bursting Strength of Textiles Constant Rate of Traverse (CRT) Ball Burst Test ASTM D3786/D3786M-18 – Standard Test Method for Bursting Strength of Textile Fabrics – Diaphragm Bursting Strength Tester Method

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[13] Methods listed in this table are available for a fee from the American Society for Testing and Materials (ASTM) at https://webstore.ansi.org.

Filter Fabric Media Performance Characteristic	Test Method
Flexibility	ASTM D2176-16 – Standard Test Method for Folding Endurance of Paper and Plastics Film by the M.I.T. Tester
Permeability	ASTM D737-18 – Standard Test Method for Air Permeability of Textile Fabrics
Pressure Drop and Filtration	ASTM D6830-02 – Standard Test Method for Characterizing the Pressure Drop and Filtration Performance of Cleanable Filter Media

1.3.6 Operating, Monitoring, Inspection and Maintenance Procedures

Proper operation and maintenance of the fabric filter is essential for ensuring the system is operating efficiently enough for the source demonstrate compliance with applicable regulations. Operators should carefully follow the operating and maintenance procedures and performance monitoring recommended by the fabric filter vendor for startup, shutdown and operation. Initial and periodic training for supervisors, operators and maintenance staff is also important for ensuring fabric filters achieve optimal performance. Training sessions should cover all aspects of the fabric filter system, including:

- system design,
- system controls,
- critical limits of equipment,
- function of each baghouse component,
- operating parameters that should be monitored,
- good operating practices,
- preventive maintenance,
- startup and shutdown procedures,
- emergency shutdown procedures, and
- safety considerations.

The length of the training varies depending on the complexity and design. Initial training for maintenance staff typically takes about 40 hours. [10]

Performance monitoring is necessary to confirm the fabric filter is operating properly and to help identify and diagnose problems when they occur. At a minimum, the pressure drop and opacity should be monitored at least once per shift when the fabric filter is operating. Increases in pressure drop indicate that either (1) the cleaning is insufficient and the frequency or duration of the cleaning cycle should be adjusted, or (2) the fabric media is becoming blinded and should be replaced. A decrease in pressure drop may indicate the fabric media has become compromised or the seal between a filter bag and the tube sheet has failed. Maintaining an appropriate pressure drop across the fabric filter can also minimize energy consumption and reduce operating costs.

The typical pressure drop range across a fabric filter differs depending the permeability of the fabric media, size distribution of the particulate, cohesivity of the dust cake, and the frequency and effectiveness of the cleaning cycles (see section 1.4.5 for information on how to estimate pressure drop). For pulse-jet fabric filters, vendors recommend cleaning cycles be adjusted so that the pressure drop across the baghouse is maintained between 3 and 5 inches of water. [5, 24, 53]

Temperature is another key parameter to monitor for systems handling gases that contain moisture or acidic gases. Temperature spikes can damage the fabric media and cause premature failure of filter bags. If the temperature drops below the dew point, condensation will form inside the fabric filter housing causing premature bag failure and corrosion. Operators should establish a normal operating temperature range and should monitor the temperature of the gases entering the fabric filter to ensure the temperature remains within the appropriate operating range. Special precautions should be taken during startup and shutdown of a fabric filter, especially where the fabric filter is handling hot exhaust gases that contain high levels of moisture which make condensation a concern. Fabric filters should be preheated to the raise the temperature of the fabric filter above the dew point. The system should be heated using clean, hot air before introducing the exhaust gas. Typical startup procedures include:

- Check all collector components are in working order and in proper mode,
- Check air flow is within design specifications,
- Preheat the system to a temperature above the dew point,
- Operate the emergency by-pass system to confirm the system is operational in case of an emergency, and
- Check all monitoring devices for proper operation.

To shut down the fabric filter, operators should purge the unit with clean, dry air and gradually decrease the temperature. Operators should run one or two cleaning cycles to clean the filter bags and empty and clean the dust hoppers. Some types of dust left in the hopper can agglomerate overtime and become difficult to remove. [10] Some facilities use bag leak detectors installed downstream from the fabric filter to detect malfunctions, such holes in bags and leaks in tube sheets. In applications where the temperature of the waste gas stream can fluctuate, the temperature should be monitored and filter media replaced if temperatures exceed the recommended maximum temperature.

In addition to regular monitoring, periodic inspections and maintenance are also required. Table 1-11 lists some recommended inspections for fabric filters and auxiliary equipment. In most applications, the hopper should be checked at least once per shift. The other inspections should be completed at least annually, although more frequent inspections may be appropriate for some applications.

Table 1-11: Recommended Inspection Practices

What to Inspect	Check for . . .	Recommended Actions
Hopper	Dust build-up, bridging and clogging	Clean out any blockages promptly, fix any leaks and replace any leaking airlock valves.
Air flow rate	Air flow velocity is above the minimum conveying velocity	Replace fan, reduce particulate loading.
Filter media	Wear and damage	Replace filter bags/cartridges.
Cages (pulse-jet systems)	Bent cages, failed welding, and corrosion	Replace cages
Fan	Loose or worn belts	Tighten or replace belts.
Hopper discharge valve and dust storage containers	Wear and corrosion	Replace worn valves. Paint storage containers when needed.
Ductwork	Dust build-up and leaks	Remove any accumulated dust and fix leaks. Consider replacing fan.
Media cleaning system	Varies depending on cleaning system. For pulse-jet and reverse-air systems: Wear and tear, air nozzles position directly above bag openings, valves are working correctly, leaks in compressed air system (pulse-jet systems), hoses between the solenoid valves and deterioration in blow pipes.	Replace failed solenoid valves, degraded hoses, and fix any air nozzle alignment problems and leaks in air/compressed air supply system.
Clean air plenum	Checked for corrosion and dust accumulation	Replace corroded parts; conduct leak testing to identify leaks.
Housing	Structural integrity, signs of corrosion and wear, leaks in joints and flanges.	Fix any holes, repaint surfaces, and replace seals.

1.3.7 Equipment Life

The fabric filter housing and hopper are manufactured from steel generally with epoxy coating. In applications where the waste gas stream contains corrosive gases, stainless steel is often used. The equipment life of the fabric filter housing is typically at least 20 years.

Bag life varies depending on the filter type, fabric media, cleaning method, frequency of cleaning and properties of the gas stream. Conventional filter bags have a service life of between 2 and 10 years, with 3 years considered typical for most applications. Pleated filters generally last longer than conventional filter bags because they are cleaned less frequently and therefore experience less wear. In some applications, pleated filters can last up to three times longer than conventional bags. [5, 19, 51, 58] Ceramic candles have a service life of up to 10 years. Ceramic candles embedded with catalysts are reported to have a service life of between 5 and 10 years. [5, 41, 50]. For the power sector, one source reported typical bag life of 5 to 10 years for woven fabric filter bags used in reverse-air fabric filters, while another study reported an expected equipment life of 10-15 years. For pulse-jet systems, the average bag life is reported to be between 3 and 6 years. For combustion units using a pulse-jet baghouse, the typical bag life is reported to be 3 to 5 years for a fiberglass bags and 2 to 3 years for a PTFE bag. For a pulse-jet fabric used as a polishing baghouse after another particulate control device, filter bags are expected to have a longer lifespan of up to 6 to 8 years [24, 75, 76]

There are several ways in which filters can fail prematurely [64, 73]. These include:

1. Filter blinding by particles that become embedded in the fabric and are not removed during the cleaning cycle.
2. Filter blinding by sticky particles that adhere to the fabric media and to themselves and are not removed by the cleaning cycle.
3. Filter blinding caused by high moisture levels that change the adhesion characteristics of the dust, creating a coating of mud that cannot be removed by cleaning.
4. Holes from abrasive particles in the high-velocity inlet gas stream striking the lower portion of the bags.
5. Holes caused by abrasion from filter bags rubbing against each other or the sides of the housing during normal operation or cleaning.
6. Decomposition and/or wear of the fabric media caused by chemical attack by gases present in the waste gas.
7. Decomposition and/or wear of the fabric media caused by high temperature excursions.
8. Holes, tears, and broken seems due to overly aggressive cleaning (e.g., excessively high or poorly directed air jets in a pulse-jet fabric filter).
9. Excessive wear and failed seams caused by too frequent cleaning.
10. Holes or tears resulting from improperly installing filter bags (e.g., incorrect placement and tightening of the clamp securing the bag to the cage in a pulse-jet fabric filter).
11. Tears and worn spots caused by corroded, broken, or bent cages in a pulse-jet fabric filter.
12. Burn holes caused by sparks from upstream processes.

13. Acid burns caused by high moisture levels and/or poor insulation in applications where acidic gases are present.

Many of these problems can be solved or the severity of their impact reduced by using baffles near the inlet, selecting fabric media better suited to the conditions, pre-treating the waste gas stream, inspecting and replacing older cages in pulse-jet units, replacing standard bags with pleated bags to increase the air-to-cloth ratio, and providing additional training for operators and maintenance staff. Experts recommend operators optimize bag-cleaning frequency to reduce or prevent blinding but avoid too much stress from over-cleaning. Operators should avoid over-cleaning bags as each cleaning cycle puts additional stress on the bags and gradually degrades the fabric. Fabric filters are designed to withstand a certain number of cleaning cycles and the longer the time between cleaning cycles, the longer the filter bag will last. [1, 24] To improve bag life, vendors recommend new bags should be seasoned by gradually developing a dust cake. Manufacturers recommended low air filtering velocities be maintained until the dust cake has developed sufficiently to protect the new bags. Exposure of new fabric media to high velocity particles causes some fine particles to become embed deeply in the fabric, which impedes air flow (a condition known as blinding) and results in premature bag failure. Some vendors recommend new bags be seasoned using a conditioning agent that contains large diameter particles. Conditioning helps prevent fine particles from penetrating deeply into the fabric by creating an initial dust layer that provides good permeability for air but prevents fine particles from penetrating the fabric. Examples of pre-conditioning agents and their recommended usage amounts is provided in Table 1-12. [5, 12, 13]

Table 1-12: Typical Conditioning Agents and Recommended Usage [13]

Pre-Conditioning Agent	Recommended Usage
PreKote	1 lb/40 square feet of filter media
Diatomaceous earth	1 lb/20 square feet of filter media
Agricultural limestone	1 lb/5 square feet of filter media

1.4 Design Factors

The key to designing a baghouse is to determine the face velocity that produces the optimum balance between pressure drop (operating costs increase as pressure drop increases) and baghouse size (capital costs decrease as the baghouse size is reduced). Baghouse size is reduced as the face velocity or A/C ratio is increased. However, higher A/C ratios cause higher pressure drops. Major factors that affect the design A/C ratio are discussed in section 1.4.1. These factors include particle and fabric characteristics and gas temperature. Because high efficiency is assumed, the design process focuses on the pressure drop.

Pressure drop occurs from the flow through inlet and outlet ducts, from flow through the hopper regions, and from flow through the bags. The pressure drop through the baghouse compartment (excluding the pressure drop across the bags) depends largely on the baghouse design and ranges from 1 to 2 inches of H_2O [77] in conventional designs and up to about 3 inches of H_2O in designs having complicated gas flow paths. This loss can be kept to a minimum (i.e., 1 inch of H_2O or less) by investing in a flow modeling study of the proposed design and modifying the design in accordance with the study results. A study of this sort would cost on the order of $130,000 (2021$).

The pressure drop across the bags (also called the tube-sheet pressure drop) can be as high as 10 inches of H_2O or more. The tube-sheet pressure drop is a complex function of the physical properties of the dust and the fabric and the manner in which the baghouse is designed and operated. The duct and hopper losses for a specific configuration are constant and can be minimized effectively by changing the configuration through proper design based on a knowledge of the flow through the baghouse.[14]

Fabric filtration is a batch process that has been adapted to continuous operation. One requirement for a continuously operating baghouse is that the dust collected on the bags must be removed periodically. Shaker and reverse-air baghouses normally use woven fabric bags, run at relatively low face velocities, and have cake filtration as the major particle removal mechanism. That is, the fabric merely serves as a substrate for the formation of a dust cake that is the actual filtration medium. Pulse-jet baghouses generally use felt fabric and run with a high A/C ratio (about double that of shaker or reverse-air baghouses). The felt fabric may play a much more active role in the filtration process. This distinction between cake filtration and fabric filtration has important implications for the rate of pressure loss across the filter bags. The theoretical description and design process for cake filtration is quite different from that for fabric filtration. Fabric selection is aided by bench-scale filtration tests to investigate fabric effects on pressure drop, cake release during cleaning, and collection efficiency. These tests cost less than one-tenth the cost of flow modeling. Electrical properties of the fabric, such as resistivity and triboelectric order (the fabric’s position in a series from highly electropositive to highly electronegative as determined from its charge under a specific triboelectrification procedure), may be measured to aid in fabric selection. Although their effects are generally poorly understood, electrical/electrostatic effects influence cake porosity and particle adhesion to fabrics or other particles. [78, 79, 80] Knowledge of the effects can lead to selection of fabrics that interact favorably regarding dust collection and cleaning.

The following sections show the general equations used to size a baghouse, beginning with the reverse air/shake deflate type of baghouse.

1.4.1 Reverse Air/Shake Deflate Baghouses

The construction of a baghouse begins with a set of specifications including average pressure drop, total gas flow, and other requirements; a maximum pressure drop may also be specified. Given these specifications, the designer must determine the maximum face velocity that can meet these requirements. The standard way to relate baghouse pressure drop to face velocity is given by the relation:

$$\Delta P(\theta) = S_{sys}(\theta) V_{f(avg.)} \tag{1.1}$$

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[14] A procedure for estimating duct pressure losses is given in Section 2 (“Hoods, Ductwork, and Stacks”) of this Manual.

where:

$\Delta P(\theta)$ = the pressure drop across the filter, a function of time, θ (inches H_2O)
$S_{sys}(\theta)$ = system drag, a function of time (inches H_2O/(ft/min))
$V_{f(avg.)}$ = average (i.e., design) face velocity or A/C, constant (ft/min)

For a multi-compartment baghouse, the system drag, which accounts for most of the drag from the inlet flange to the outlet flange of the baghouse, is determined as a combination of resistances representative of several compartments. For the typical case where the pressure drop through each compartment is the same, and where the filtering area per compartment is equal, it can be shown that:[80]

$$S_{sys}(\theta) = \left\lfloor \frac{1}{M} \sum_{i=1}^{M} \frac{1}{S_i(\theta)} \right\rfloor^{-1} = \frac{M}{\sum_{i=i}^{M} \frac{1}{S_i(\theta)}} \tag{1.2}$$

where:

M = number of compartments in the baghouse
$S_i(\theta)$ = drag across compartment i

The compartment drag is a function of the amount of dust collected on the bags in that compartment. Dust load varies nonuniformly from one bag to the next, and within a given bag there will also be a variation of dust load from one area to another. For a sufficiently small area, *j*, within compartment *i*, it can be assumed that the drag is a linear function of dust load:

$$S_{i,j}(\theta) = S_e + K_2 W_{i,j}(\theta) \tag{1.3}$$

where:

K_2 = dust cake flow resistance (inches H_2O/(ft/min)/(lb/ft^2))
$W_{i,j}(\theta)$ = dust mass per unit area of area *j* in compartment *i*, areal density (lb/ft^2)

If there are N different areas of equal size within compartment *i*, each with a different drag $S_{i,j}$, then the total drag for compartment *i* can be computed in a manner analogous to Equation 1.2:

$$S_i(\theta) = \frac{N}{\sum \frac{1}{S_{i,j}(\theta)}} \tag{1.4}$$

The constants S_e and K_2 depend upon the fabric and the nature and size of the dust. The relationships between these constants and the dust and fabric properties are not understood well enough to permit accurate predictions and so must be determined empirically, either from prior experience with the dust/fabric combination or from laboratory measurements. The dust mass as a function of time is defined as:

$$W_{i,j}(\theta) = W_r + \int_0^{\theta} C_{in} V_{i,j}(\theta) d\theta \tag{1.5}$$

where:

W_r = dust mass per unit area remaining on a “clean” bag (lb/ft^2)
C_{in} = dust concentration in the inlet gas (lb/ft^3)
$V_{i,j}(\theta)$ = face velocity through area *j* of compartment *i* (ft/min)

The inlet dust concentration and the filter area are assumed constant. The face velocity, (A/C ratio) through each filter area *j* and compartment *i* changes with time, starting at a maximum value just after clearing and steadily decreasing as dust builds up on the bags. The individual compartment face velocities are related to the average face velocity by the expression:

$$V_{f(avg)} = \frac{\sum_i \sum_j V_{i,j}(\theta) A_{i,j}}{\sum_i \sum_j A_{i,j}} = \frac{\sum_i \sum_j V_{i,j}(\theta)}{M} \tag{1.6}$$

(for M compartments with equal area)

Equations 1.1 through 1.6 reveal that there is no explicit relationship between the design face velocity and the tube-sheet pressure drop. The pressure drop for a given design can only be determined by the simultaneous solution of Equations 1.1 through 1.5, with Equation 1.6 as a constraint on that solution. Solving the equations requires an iterative procedure: begin with a known target for the average pressure drop, propose a baghouse design (number of compartments, length of filtration period, etc.), assume a face velocity that will yield that pressure drop, and solve the system of Equations 1.1 through 1.6 to verify that the calculated pressure drop equals the target pressure drop. If not, repeat the procedure with new parameters until the specified face velocity yields an average pressure drop (and maximum pressure drop, if applicable) that is sufficiently close to the design specification. Examples of the iteration procedure’s use are given in reference [81].

1.4.2 Pulse-Jet Baghouses

The distinction between pulse-jet baghouses using felts and reverse-air and shaker baghouses using woven fabrics is basically the difference between cake filtration and composite dust/fabric filtration (noncake filtration). This distinction is more a matter of convenience than physics, as either type of baghouse can be designed for a specific application. However, costs for the two types will differ depending on application- and size-specific factors. Some pulse jets remain on-line at all times and are cleaned frequently. Others are taken off-line for cleaning at relatively long intervals. The longer a compartment remains on-line without cleaning, the more its composite dust/fabric filtration mechanism changes to cake filtration. Therefore, a complete model of pulse-jet filtration must account for the depth filtration occurring on a relatively clean pulse-jet filter, the cake filtration that inevitably results from prolonged periods on-line, and the transition period between the two regimes. When membrane fabrics are used, filtration takes place primarily at the surface of the membrane, which acts similarly to a cake. The following analysis has not been tested against membrane fabrics.

Besides the question of filtration mechanism, there is also the question of cleaning method. If the conditions of an application require that a compartment be taken off-line for cleaning, the dust removed falls into the dust hopper before forward gas flow resumes. If conditions allow a compartment to be cleaned while on-line, only a small fraction of the dust removed from the bag falls into the hopper. The remainder of the dislodged dust will be redeposited (i.e., “recycled”) on the bag by the forward gas flow. The redeposited dust layer has different pressure drop characteristics than the freshly deposited dust. The modeling work that has been done to date focuses on the on-line cleaning method. Dennis and Klemm [82] proposed the following model of drag across a pulse-jet filter:

$$S = S_e + (K_2)_c W_c + K_2 W_o \tag{1.7}$$

where:

S = drag across the filter
S_e = drag of a just-cleaned filter
$(K_2)_c$ = specific dust resistance of the recycling dust
W_c = areal density of the recycling dust
K_2 = specific dust resistance of the freshly deposited dust
W_o = areal density of the freshly deposited dust

This model has the advantage that it can easily account for all three regimes of filtration in a pulse-jet baghouse. As in Equations 1.1 to 1.6, the drag, filtration velocity and areal densities are functions of time. For given operating conditions, however, the values of S_e, $(K_2)_c$, and W_c may be assumed to be constant, so that they can be grouped together [82]:

$$\Delta P = (PE)_{\Delta w} + K_2 W_o V_f \tag{1.8}$$

where:

ΔP = pressure drop (in. H_2O)
V_f = filtration velocity (ft/min)
$(PE)_{\Delta w}$ = $[S_e + (K_2)_c W_c] V_f$

Equation 1.8 describes the pressure drop behavior of an individual bag. To extend this single bag result to a multiple-bag compartment, Equation 1.7 would be used to determine the individual bag drag and total baghouse drag would then be computed as the sum of the parallel resistances. Pressure drop would be calculated as in Equation 1.1. It seems reasonable to extend this analysis to the case when the dust is distributed unevenly on the bag and then apply Equation 1.7 to each area on the bag, followed by an equation analogous to 1.4 to compute the overall bag drag. The difficulty in following this procedure is that one must assume values for W_c for each different area to be modeled.

The disadvantage of the model represented by Equations 1.7 and 1.8 is that the constants, S_e, $(K_2)_c$, and W_c, cannot be predicted currently. Consequently, correlations of laboratory data must be used to determine the value of $(PE)_w$. For the fabric-dust combination of Dacron felt and coal fly ash, Dennis and Klemm [83] developed an empirical relationship between $(PE)_{\Delta w}$, the face velocity, and the cleaning pulse pressure. This relationship (converted from metric to English units) is as follows:

$$(PE)_{\Delta w} = 6.08 V_f P_j^{-0.66} \tag{1.9}$$

where:

V_f = face velocity, (ft/min)
P_j = pressure of the cleaning pulse (usually 60 to 100 psig)

This equation is essentially a regression fit to a limited amount of laboratory data and should not be applied to other dust/fabric combinations. The power law form of Equation 1.9 may not be valid for other dusts or fabrics. Consequently, more data should be collected and analyzed before the model represented by Equation 1.9 can be used for rigorous fabric filter sizing purposes.

Another model that developed to predict noncake filtration pressure drop is that of Leith and Ellenbecker [84] as modified by Koehler and Leith.[85] In this model, the tube-sheet pressure drop is a function of the clean fabric drag, the system hardware, and the cleaning energy. Specifically:

$$\Delta P = \frac{1}{2}\left[P_s + K_1 V_f - \sqrt{\left(P_s - K_1 V_f\right)^2 - 4W_o\frac{K_2}{K_3}}\right] + K_v V_f^2 \tag{1.10}$$

where:

P_s = maximum static pressure achieved in the bag during cleaning
K_1 = clean fabric resistance
V_f = face velocity
K_2 = dust deposit flow resistance
K_3 = bag cleaning efficiency coefficient
K_v = loss coefficient for the venturi at the inlet to the bag

Comparisons of laboratory data with pressure drops computed from Equation 1.10 [84, 85] are in close agreement for a variety of dust/fabric combinations. The disadvantage of Equation 1.10 is that the constants K_1, K_2, and K_3 must be determined from laboratory measurements. The most difficult one to mine is the K_3 value, which can only be found by making measurements in a pilot-scale pulse-jet baghouse. A limitation of laboratory measurements is that actual filtration conditions cannot always be adequately simulated. For example, a redispersed dust may not have the same size distribution or charge characteristics as the original dust, thereby yielding different values of K_1, K_2, and K_3 than would be measured in an operating baghouse.

1.4.3 Baghouse Sizing Parameters

The design procedure requires estimating an A/C ratio that is compatible with fabric selection and cleaning type. Fabric selection for composition depends on gas and dust characteristics; fabric selection for construction (woven or felt) largely depends on type of cleaning. Systems with high air-to-cloth ratios generally use felted fabric media because they have better dimensional stability and tensile strength than woven fabrics. [10] Estimating an A/C ratio that is too high, compared to a correctly estimated A/C ratio, leads to higher pressure drops, higher particle penetration (lower collection efficiency), and more frequent cleaning that leads to reduced fabric life. Estimating an A/C ratio that is too low increases the size and cost of the baghouse unnecessarily. Each of the parameters for design is discussed below.

1.4.4 Air-to-Cloth Ratio

The A/C ratio is difficult to estimate from first principles. However, shortcut methods of varying complexity allow rapid estimation. Three methods of increasing difficulty follow. For shaker and reverse-air baghouses, the third method is best performed with publicly available computer programs. Although pulse-jet baghouses have taken a large share of the market, they are not necessarily the least costly type for a specific application. Costing should be done for pulse-jet baghouses at their application-specific A/C ratios and for reverse-air or shaker baghouses at their application-specific A/C ratios.

The methods outlined below pertain to conventional baghouses. Use of electrostatic stimulation may allow a higher A/C ratio at a given pressure drop; thus a smaller baghouse structure and fewer bags are needed. Viner and Locke [86] discuss cost and performance models for electrostatically stimulated fabric filters; however, no data are available for full-scale installations. Use of extended area bag configurations (star-shaped bags or pleated media cartridges) do not allow significant changes in A/C ratios but do allow installation of more fabric in a given volume.

1.4.4.1 Air-to-Cloth Ratio From Similar Applications

After a fabric has been selected, an initial A/C ratio can be determined using Table 1-13. Column 1 shows the type of dust; column 2 shows the A/C ratios for woven fabric; and column 3 shows A/C ratios for felted fabrics. Notice that these values are all “net” A/C ratios, equal to the total actual volumetric flow rate in cubic feet per minute divided by the net cloth area in square feet. This ratio, in units of feet per minute, affects pressure drop and bag life as discussed in section 1.2. The net cloth area is determined by dividing the exhaust gas flow rate in actual cubic feet per minute (acfm) by the design A/C ratio. For an intermittent-type baghouse that is shut down for cleaning, the net cloth area is also the total, or gross, cloth area. However, for continuously operated shaker and reverse-air filters, the area must be increased to allow the shutting down of one or more compartments for cleaning. Continuously operated, compartmented pulse-jet filters that are cleaned off-line also require additional cloth to maintain the required net area when cleaning. Table 1-14 provides a guide for adjusting the net area to the gross area, which determines the size of a filter requiring off-line cleaning.

Table 1-13: Air-to-Cloth Ratios for Baghouse/Fabric Combinations (actual ft^3/min)/(ft^2 of net cloth area)[(a), (b)]

Dust	Shaker/Woven Fabric Reverse-Air/Woven Fabric	Pulse-Jet/Felt Fabric Reverse-Air/Felt Fabric
Alumina	2.5	8
Asbestos	3.0	10
Bauxite	2.5	8
Carbon Black	1.5	5

Dust	Shaker/Woven Fabric Reverse-Air/Woven Fabric	Pulse-Jet/Felt Fabric Reverse-Air/Felt Fabric
Coal	2.5	8
Cocoa, Chocolate	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 Pigments	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 (wood)	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	13
Talc	2.5	5
Tobacco	3.5	
Zinc Oxide	2.0	

(a) See reference [87].

(b) Generally safe design values; application requires consideration of particle size and grain loading.

Table 1-14: Approximate Guide to Estimate Gross Cloth Area From Net Cloth Area[(a)]

Net Cloth Area (ft^2)	Multiplier to Obtain Gross Cloth Area (ft^2)
1 – 4,000	2
4,001 – 12,000	1.5
12,001 – 24,000	1.25
24,001 – 36,000	1.17
36,001 – 48,000	1.125
48,001 – 60,000	1.11
60,001 – 72,000	1.10
72,001 – 84,000	1.09
84,001 – 96,000	1.08
96,001 – 108,000	1.07
108,001 – 132,000	1.06
132,001 – 180,000	1.05
Above 180,001	1.04

(a) See reference [88].

1.4.4.2 Air-to-Cloth Ratio From Manufacturer's Methods

Manufacturers have developed nomographs and charts that allow rapid estimation of the A/C ratio. Two examples are given below, one for shaker-cleaned baghouses and the other for pulse-jet baghouses.

For shaker baghouses, Table 1-15 gives a factor method for estimating the ratio. Ratios for several materials in different operations are presented but are modified by factors for particle size and dust load. Directions and an example are included. A/C ratios for reverse-air baghouses would be about the same or a little lower compared to the Table 1-15 values.

For pulse-jet baghouses, which normally operate at two or more times the A/C ratio of reverse-air baghouses, another factor method [89] has been modified with equations to represent temperature, particle size, and dust load:

$$V = 2.878A \times B \times T^{-0.2335} L^{-0.06021} (0.7471 + 0.0853 lnD) \tag{1.11}$$

where:

V = A/C ratio (ft/min)
A = material factor, from Table 1-16
B = application factor, from Table 1-16
T = temperature, (°F, between 50 and 275)
L = inlet dust loading (gr/ft^3, between 0.05 and 100)
D = mass mean diameter of particle (μm, between 3 and 100)

For temperatures below 50°F, use $T = 50$ but expect decreased accuracy; for temperatures above 275°F, use $T = 275$. For particle mass mean diameters less than 3 μm, the value of D is

0.8, and for diameters greater than 100 μm, $D$is 1.2. For dust loading less than 0.05 gr/ft^3, use L = 0.05; for dust loading above 100 gr/ft^3, use L = 100. For horizontal cartridge baghouses, a similar factor method can be used. Table 1-17 provides the factors.

Table 1-15: Manufacturer's Factor Method for Estimating Air-to-cloth Ratios for Shaker Baghouses

A 4/1 RATIO		3/1 RATIO		2.5/1 RATIO		2/1 RATIO		1.5/1 RATIO	
Material	**Operation**	**Material**	**Operation**	**Material**	**Operation**	**Material**	**Operation**	**Material**	**Operation**
Cardboard Feeds Flour Grain Leather Dust Tobacco Supply Air Wood, Dust, Chips	1 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 1, 7, 8 1, 4, 6, 7 13 1, 6, 7	Asbestos Aluminum Dust Fibrous Mat'l Cellulose Mat'l Gypsum Lime (Hydrated) Perlite Rubber Chem. Salt Sand* Iron Scale Soda Ash Talc Machining Operation	1, 7, 8 1, 7, 8 1, 4, 7, 8 1, 4, 7, 8 1, 3, 5, 6, 7 2, 4, 6, 7 2, 4, 5, 6 4, 5, 6, 7, 8 2, 3, 4, 5, 6, 7 4, 5, 6, 7, 9, 15 1, 7, 8 4, 6, 7 3, 4, 5, 6, 7 1, 8	Alumina Carbon Black Cement Coke Ceramic Pigm. Clay and Brick Dust Coal Kaolin Limestone Rock, Ore Dust Silica Sugar	2, 3, 4, 5, 6 4, 5, 6, 7 3, 4, 5, 6, 7 2, 3, 5, 6 4, 5, 6, 7 2, 4, 6, 12 2, 3, 6, 7, 12 4, 5, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 3, 4, 5, 6, 7	Ammonium Phosphate Fertilizer Diatomaceous Earth Dry Petrochem. Dyes Fly Ash Metal Powders Plastics Resins Silicates Starch Soaps	2, 3, 4, 5, 6, 7 4, 5, 6, 7 2, 3, 4, 5, 6, 7, 14 2, 3, 4, 5, 6, 7 10 2, 3, 4, 5, 6, 7, 14 2, 3, 4, 5, 6, 7, 14 2, 3, 4, 5, 6, 7, 14 2, 3, 4, 5, 6, 7, 14 6, 7 3, 4, 5, 6, 7	Activated Carbon Carbon Black Detergents Metal Fumes, Oxides and other Solid Dispersed Products	2, 4, 5, 6, 7 11, 14 2, 4, 5, 6, 7 10, 11

CUTTING - 1
CRUSHING - 2
PULVERIZING - 3
MIXING - 4
SCREENING - 5
STORAGE - 6
CONVEYING - 7
GRINDING - 8
SHAKEOUT - 9
FURNACE FUME - 10
REACTION FUME - 11
DUMPING - 12
INTAKE CLEANING–- 13
PROCESS - 14
BLASTING - 15

B FINENESS FACTOR		**C** DUST LOAD FACTOR	
Micron Size	Factor	Loading gr/cu ft	Factor
> 100	1.2	1 -3	1.2
50–- 100	1.1	4–- 8	1.0
10 -5 0	1.0	9–- 17	0.95
3 -1 0	0.9	18–- 40	0.90
1 -3	0.8	> 40	0.85
< 1	0.7		

This information constitutes a guide for commonly encountered situations and should not be considered a "hard-and-fast" rule. Air-to-cloth ratios are dependent on dust loading, size distribution, particle shape and "cohesiveness" of the deposited dust. These conditions must be evaluated for each application. The larger the interval between bag cleaning the lower the air-to-cloth ratio must be. Finely-divided, uniformly sized particles generally form more dense filter cakes and require lower air-to-cloth ratios than when larger particles are interspersed with the fines. Sticky, oily particles, regardless of shape and size, form dense filter cakes and require lower air-to-cloth ratios.

Example: Foundry shakeout unit handling 26,000 CFM and collecting 3,500 lb/hr of sand. The particle distribution shows 90% greater than 10 microns. The air is to exhaust to room in winter, to atmosphere in summer.

lb m in *ft* ^{3} *gr* *gr*
3 , 500 ÷ 60 ÷ 26 000, × 7 000, = 15. 7 $_3$ *hr hr m in lb ft*

*Chart A = 3/1 ratio, Chart B = Factor 1.0, Chart C = 0.95; 3 x 1 x 0.95 = 2.9 air-to-cloth ratio. 26,000 / 2.9 = 9,000 sq. ft.

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Table 1-16: Factors for Pulse-Jet Air-to-Cloth Ratios(a)

A. Material Factor				
15(b)	**12**	**10**	**9.0**	**6.0(c)**
Cake mix Cardboard dust Cocoa Feeds Flour Grain Leather dust Sawdust Tobacco	Asbestos Buffing dust Fibrous and Cellulosic Material Foundry Shakeout Gypsum Lime (hydrated) Perlite Rubber Chemicals Salt Sand Sandblast dust Soda ash Talc	Alumina Aspirin Carbon black Cement Ceramic Pigments Clay and Brick dusts Coal Fluorspar Gum, natural Kaolin Limestone Perchlorates Rock dust Ores Minerals Silica Sorbic acid Sugar	Ammonium Phosphate fertilizer Cake Diatomaceous earth Dry petrochemicals Dyes Fly ash Metal powder Metal oxides Pigments metallic end synthetic Plastics Resins Silicates Starch Stearates Tannic acid	Activated carbon Carbon black Detergents Fumes and other dispersed products from reactions Powdered milk Soap

B. Application Factor	
Nuisance Venting Relief of transfer points, conveyors, packing stations, etc.	1.0
Product Collection Air conveying-venting, mills, flash driers, classifiers, etc.	0.9
Process Gas Filtration Spray driers, kilns, reactors, etc.	0.8

(a) See Reference [89].
(b) In general, physically and chemically stable material.
(c) Also includes those solids that are unstable in their physical or chemical state due to hygroscopic nature, sublimation, and/or polymerization.

1.4.4.3 Air-to-Cloth Ratio From Theoretical/Empirical Equations

Shaker and reverse-air baghouses

The system described by Equations 1.1 through 1.6 is complicated; however, numerical methods can be used to obtain an accurate solution. A critical weakness in baghouse modeling that has yet to be overcome is the lack of a fundamental description of the bag cleaning process. That is, to solve Equations 1.1 through 1.6, the value of W_r (the dust load after cleaning) must be known. Clearly, there must be a relationship between the amount and type of cleaning energy and the degree of dust removal from a bag. Dennis et. al.[82] have developed correlations for the removal of coal fly ash from woven fiberglass bags by shaker cleaning and by reverse-air cleaning. These correlations have been incorporated into a computer program that generates the solution to the above system of equations. [83, 90, 91] If one were to apply the correlations developed with coal ash and woven glass fabrics to other dust/fabric combinations, the accuracy of the results would depend on how closely that dust/fabric combination mimicked the coal ash/woven glass fabric system.

Physical factors that affect the correlation include the particle size distribution, adhesion and electrostatic properties of the dust and fabric, and fabric weave, as well as cleaning energy. More research is needed in this area of fabric filtration.

The rigorous design of a baghouse thus involves several steps. First, the design goal for average pressure drop (and maximum pressure drop, if necessary) must be specified along with total gas flow rate and other parameters, such as S_e and K_2 (obtained either from field or laboratory measurements). Second, a face velocity is assumed and the number of compartments in the baghouse is computed based on the total gas flow, face velocity, bag size, and number of bags per compartment. (Typical compartments in the U.S. electric utility industry use bags 1 ft in diameter by 30 ft in length with 400 bags per compartment.) Standard practice is to design a baghouse to meet the specified pressure drop when one compartment is off-line for maintenance. The third step is to specify the operating characteristics of the baghouse (i.e., filtration period, cleaning period, and cleaning mechanism). Fourth, the designer must specify the cleaning efficiency so that the residual dust load can be estimated. Finally, the specified baghouse design is used to establish the details for Equations 1.1 through 1.6, which are then solved numerically to establish the pressure drop as a function of time. The average pressure drop is then computed by integrating the instantaneous pressure drop over the filtration cycle and dividing by the cycle time. If the computed average is higher than the design specification, the face velocity must be reduced and the procedure repeated. If the computed average pressure drop is significantly lower than the design specification, the proposed baghouse was oversized and should be made smaller by increasing the face velocity and repeating the procedure. When the computed average pressure drop comes sufficiently close to the assumed specified value, the design has been determined. A complete description of the modeling process can be found in the reports by Dennis et al. [82, 91] A critique on the accuracy of the model is presented by Viner et al. [92]

Pulse-jet baghouses

The overall process of designing a pulse jet baghouse is actually simpler than that required for a reverse-air or shaker baghouse if the baghouse remains on-line for cleaning. The first step is to specify the desired average tube-sheet pressure drop. Second, the operating characteristics of the baghouse must be established (e.g., on-line time, cleaning energy). Third, the designer must obtain values for the coefficients in either Equation 1.9 or Equation 1.10 from field, pilot plant, or laboratory measurements. Fourth, a value is estimated for the face velocity and the appropriate equation (Equation 1.8 or 1.10) is solved for the pressure drop as a function of time for the duration of the filtration cycle. This information is used to calculate the cycle average pressure drop. If the calculated pressure drop matches the specified pressure drop, the procedure is finished. If not, the designer must adjust the face velocity and repeat the procedure.

Table 1-17: Manufacturer’s Factor Method for Estimating Air-to-Cloth Ratio for Horizontal Cartridge Baghouses [100]

Factor A Table for Selected Materials				
2.5	**2.1**	**1.9**	**1.3**	**Dust Sample Required**
Rock dust and ores Salt, Mineral* Sand (Not foundry)	Activated carbon Alumina (transfer) Cake Mix* Carbon black (finished) Ceramic pigment Coal Coke Diatomaceous earth Flour Fluorspar Fly ash Foundry shakeout Gypsum Lime, hydrated Limestone Paint, electrstatic spray (powder coating) Petrochemicals (dry) Pigments, metallic, synthetic Plaster Rubber additives Silicates Soda ash Starch Sugar* Welding fumes	Fertilizers* Talc	Alumina (air lift) Dyes Fumes, metallurgical Pigments, paint Stearates	Detergents Feeds Grains Perlite Pharmaceuticals Powdered milk Resins Soap Tobacco

Table 1-17: (Cont.)

Factor A Table for Selected Materials		
1.7	**0.7**	**Excluded dusts**
Aspirin Cement Clay and brick dust Cocoa* Coffee* Graphite Kaolin Metal oxides Metal powder Perchlorates Selenium Silica (flour)	Silica (fume)	Asbestos Arc washing Fiberglass Fibrous and cellulosic materials Leather Metallizing Mineral Wool P.C. board grinding Paper dust Particle board Sawdust

* Under controlled humidity (40 %R.H.) and room temperature only.

The approximate A/C ratio for a Mikropul horizontal cartridge collector in acfm per square foot of filter area is obtained by multiplying the following five factors: A/C = A x B x C x D x E

For example, A/C for process gas filtration of 10 µm rock dust at 250 F and 2 gr/acf = 2.5 x 0.8 x 0.75 x 0.9 x 1.1 = 1.49.

Table 1-17: (Cont.)

Factor B Table for Applications

Application	Factor B
Nuisance Venting Relief of transfer points, conveyors, packing stations, etc.	1.0
Product Collection Air conveying-venting, mills, flash driers, classifiers, etc.	0.9
Process Gas Filtration Spray driers, kilns, reactors, etc	0.8

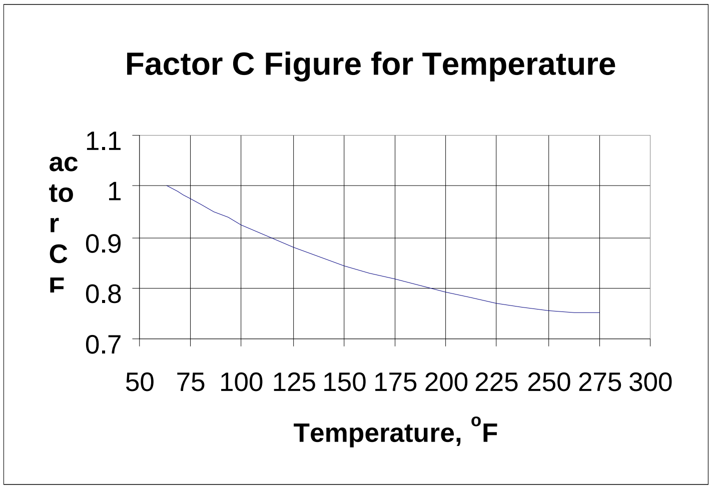
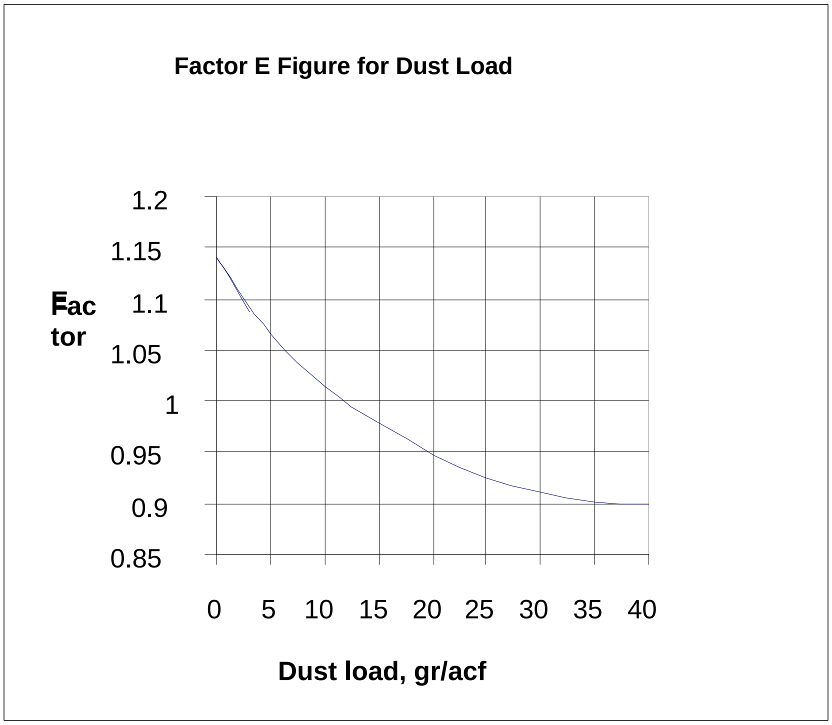


Table 1-17: (Cont.)

Factor D Table for Dust Fineness

Fineness	Factor D
Over 50 µm	1.1
20 - 50 µm	1.0
2-20 µm	0.9
Under 2 µm	0.85



1.4.5 Pressure Drop

Pressure drop depends on the permeability of the fabric media, the size distribution of the particles, cohesivity of the dust cake and the cleaning efficiency. [5] The pressure drop can be calculated from the equations given in the preceding section if values for the various parameters are known. Frequently they are not known, but a maximum pressure drop of 5 to 10 in. H_2O across the baghouse and 10 to 20 in. H_2O across the entire system can be assumed if it contains much ductwork.

A comparable form of Equations 1.1 and 1.3 that may be used for estimating the maximum pressure drop across the fabric in a shaker or reverse-air baghouse is:

$$\Delta P = S_e V + K_2 C_i V^2 \theta \qquad (1.12)$$

where:

ΔP = pressure drop (in. H_2O)
S_e = effective residual drag of the fabric [in. H_2O/(ft/min)]
V = superficial face velocity or A/C ratio (ft/min)
K_2 = specific resistance coefficient ((inches H_2O/(ft/min))/(lb/ft^2))
C_i = inlet dust concentration (lb/ft^3)
Θ = filtration time (min)

Although there is much variability, values for S_e may range from about 0.2 to 2 in. H_2O/(ft/ min) and for K_2 from 1.2 to 30–40 in. H_2O/(ft/min)]/(lb/ft^2). Typical values for coal fly ash are about 1 to 4. Inlet concentrations vary from less than 0.05 gr/ft^3 to more than 100 gr/ft^3, but a more nearly typical range is from about 0.5 to 10 gr/ft^3. Filtration times may range from about 20 to 90 minutes for continuous duty baghouses, but 30 to 60 minutes is more frequently found. For pulse-jet baghouses, use Equations 1.8 and 1.9 to estimate P, after substituting C_iV for W_o and for S_eV.

1.4.6 Particle Characteristics

Particle size distribution and adhesiveness are the most important particle properties that affect design procedures. Smaller particle sizes can form a denser cake, which increases pressure drop. As shown in Tables 1-11 and 1-13 and Equation 1.11, the effect of decreasing average particle size is a lower applicable A/C ratio.

Adhering particles, such as oily residues or electrostatically active plastics, may require installing equipment that injects a precoating material onto the bag surface, which acts as a buffer that traps the particles and prevents them from blinding or permanently plugging the fabric pores. Informed fabric selection may eliminate electrostatic problems.

1.4.7 Gas Stream Characteristics

Moisture and corrosives content are the major gas stream characteristics requiring design consideration. The baghouse and associated ductwork should be insulated and possibly heated if condensation may occur. Both the structural and fabric components must be considered, as either may be damaged. Where structural corrosion is likely, stainless-steel substitution for mild steel may be required, provided that chlorides are not present when using 300 series stainless. (Most austenitic stainless steels are susceptible to chloride corrosion.)

1.4.7.1 Temperature

The temperature of the pollutant stream must remain above the dew point of any condensable in the stream. If the temperature can be lowered without approaching the dew point, spray coolers or dilution air can be used to drop the temperature so that the temperature limits of the fabric will not be exceeded. However, the additional cost of a precooler will have to be weighed against the higher cost of bags with greater temperature resistance. The use of dilution air to cool the stream also involves a tradeoff between a less expensive fabric and a larger filter to accommodate the additional volume of the dilution air. Generally, pre-cooling is not necessary if temperature and chemical resistant fabrics are available. (Costs for spray chambers, quenchers, and other precoolers are found in the “Wet Scrubbers” chapter in the PM section of the Control Cost Manual). Table 1-3 lists several of the fabrics in current use and provides information on temperature limits and chemical resistance. The column labeled “Relative Abrasion Resistance” indicates the fabric’s suitability for cleaning by mechanical shakers.

1.4.7.2 Pressure

Standard fabric filters can be used in pressure or vacuum service but only within the range of about ± 25 inches of water. Because of the sheet metal construction of the house, they are not generally suited for more severe service. However, for special applications, high-pressure shells can be built.

1.4.8 Filter Media Selection Criteria

The following factors are considered when selecting the fabric media:

- Operating temperatures,
- Abrasion resistance,
- Type of cleaning method,
- Waste gas stream chemical characteristics,
- Air-to-cloth ratio, and
- Cost.

The type of filter material used in baghouses depends on the specific application and the associated chemical composition of the gas, operating temperature, dust loading, and the physical and chemical characteristics of the particulate. Selection of a specific material, weave, finish, or weight is based primarily on past experience. For woven fabrics, the type of yarn (filament, spun, or staple), the yarn diameter, and twist are also factors in the selection of suitable fabrics for a specific application. For some applications, the selection of fabric is difficult. For example, some applications generate small or smooth particles that readily penetrate the cake and fabric. Other applications generate dust particles that adhere strongly to the fabric and are difficult to remove. Other applications generate gas streams that degrade particle collection or cleaning. For some of these applications, a polytetrafluoroethylene (PTFE) membrane laminated to a fabric backing (felt or woven) may be used.

Because of the violent agitation of mechanical shakers, spun or heavy weight staple yarn fabrics are commonly used with this type of cleaning, while lighter weight filament yarn fabrics are used with the gentler reverse air cleaning. Needle-punched felts are typically used for pulse-jet baghouses. These heavier fabrics are more durable than woven fabrics when subjected to cleaning pulses. Woven fiberglass bags are an exception for high-temperature application, where they compete successfully, on a cost basis, against felted glass and other high temperature felts.

The type of material limits the maximum operating gas temperature for the baghouse. Cotton fabric has the least resistance to high temperatures (about 180^{o}F), while ceramic candles can tolerate the highest temperatures (about 1600 ^{o}F). If condensable particulate (i.e., gases or vapors in the liquid state that may condense to form particulate).[15] are contained in the gas stream, the temperature must be well above the dew point because liquid particles will usually quickly plug the fabric pores. However, the temperature must be below the maximum limit of the fabric media provided in Table 1-3.

1.4.9 Filter Drag

Filter drag measures the resistance across the fabric and dust cake and is defined as:

$$S = \frac{\Delta P}{V_f}$$

Where,

S = filter drag,
ΔP = pressure drop across the fabric and dust cake, and
V_f = filtration velocity.

The filter drag for a clean bag is called the residual drag. As shown in Figure 1-23, the filter drag increases exponentially initially as dust accumulates on the filter fabric surface. Once the dust cake is formed, the filter drag increases at a constant rate until the total pressure drop reaches a set value and cleaning is initiated. Effective filtration occurs after the filter cake has formed. To ensure the maximum removal efficiency in mechanical shaker and reverse-air baghouses using woven fabric media, the cleaning cycles must be designed and operated so that a dust layer remains on the surface of the fabric filters at the end of the cleaning cycle. Filter drag taken at normal operating conditions can be used to measure the efficiency of a baghouse. A small filter drag means that the pressure drop is small compared to the air-to-cloth ratio. A small filter drag typically equates to a more efficient fabric filter that is less expensive to operate. [10]

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[15] Condensable particulate matter is of great concern due to the inherently small size of condensation products. Condensable particulate can be classified as PM2.5.

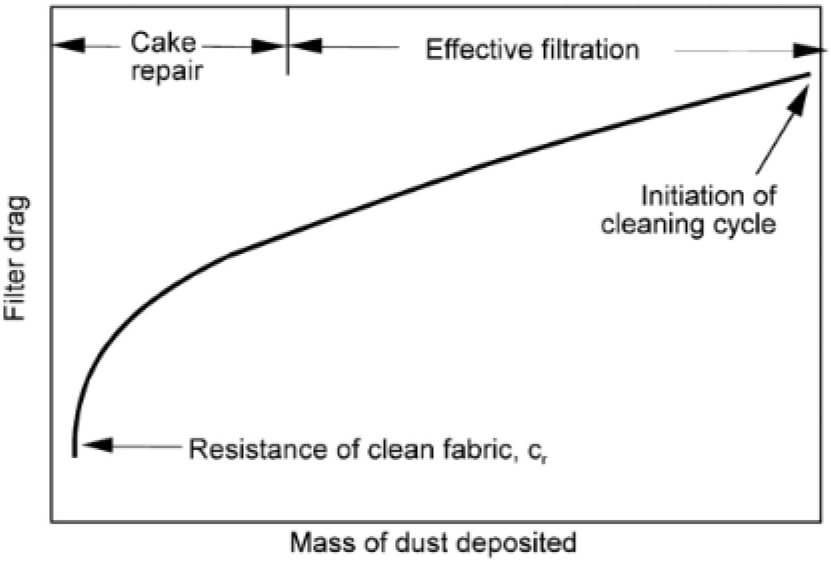

Figure 1-23: Relationship Between Filter Drag and Dust Deposition [10]

1.4.10 Other Design Considerations

1.4.10.1 Pressure or Suction Housings

The location of the baghouse with respect to the fan in the gas stream affects the capital cost. A suction-type baghouse, with the fan located on the downstream side of the unit, must withstand high negative pressures and therefore must be more heavily constructed and reinforced than a baghouse located downstream of the fan (pressure baghouse). The negative pressure in the suction baghouse can result in outside air infiltration, which can result in condensation, corrosion, or even explosions if combustible gases are being handled. In the case of toxic gases, this inward leakage can have an advantage over the pressure-type baghouse, where leakage is outward. The main advantage of the suction baghouse is that the fan handling the process stream is located at the clean-gas side of the baghouse. This reduces the wear and abrasion on the fan and permits the use of more efficient fans (backward curved blade design). However, because for some designs the exhaust gases from each compartment are combined in the outlet manifold to the fan, locating compartments with leaking bags may be difficult and adds to maintenance costs. Pressure-type baghouses are generally less expensive because the housing must only withstand the differential pressure across the fabric. In some designs the baghouse has no external housing. Maintenance also is reduced because the compartments can be entered and leaking bags can be observed while the compartment is in service. With a pressure baghouse, the housing acts as the stack to contain the fumes with subsequent discharge through long ridge vents (monitors) at the roof of the structure. This configuration makes leaking bags easier to locate when the plume exits the monitor above the bag. The main disadvantage of the pressure-type baghouse in that the fan is exposed to the dirty gases where abrasion and wear on the fan blades may become a problem.

1.4.10.2 Standard or Custom Construction

The design and construction of baghouses are separated into two groups, standard and custom. [88] Standard baghouses are further separated into low, medium, and high-capacity size categories. Standard baghouses are pre-designed and factory built as complete off-the-shelf units that are shop-assembled and bagged for low-capacity units (hundreds to thousands of acfm throughput). Medium-capacity units (thousands to less than 100,000 acfm) have standard designs, are shop-assembled, may or may not be bagged, and have separate bag compartment and hopper sections. One form of high-capacity baghouses is the shippable module (50,000 to 100,000 acfm), which requires only moderate field assembly. These modules may have bags installed and can be shipped by truck or rail. Upon arrival, they can be operated singly or combined to form units for larger-capacity applications. Because they are preassembled, they require less field labor.

Custom baghouses, also considered high capacity, but generally 100,000 acfm or larger, are designed for specific applications and are usually built to specifications prescribed by the customer. Generally, these units are much larger than standard baghouses. For example, many are used on power plants. The cost of the custom baghouse is much higher per square foot of fabric because it is not an off-the-shelf item and requires special setups for manufacture and expensive field labor for assembly upon arrival. The advantages of the custom baghouse are many and are usually directed towards ease of maintenance, accessibility, and other customer preferences. In some standard baghouses, a complete set of bags must be replaced in a compartment at one time because of the difficulty in locating and replacing single leaking bags, whereas in custom baghouses, single bags are accessible and can be replaced one at a time as leaks develop.

1.5 Cost Methodology

1.5.1 Total Capital Investment

Total capital investment includes costs for the baghouse structure, the initial complement of bags, auxiliary equipment, and the usual direct and indirect costs associated with installing or erecting new structures as described in the Control Cost Manual’s cost estimation methodology chapter. These costs are described below.

1.5.1.1 Direct Capital Costs

Bare Baghouse Costs

Correlations of cost with fabric area for seven types of baghouses are presented. These seven types, six of which are preassembled and one, field-assembled, are listed in Table 1-18.

Table 1-18: List of cost curves for seven baghouse types

	Baghouse Type	**Figure No·**
	Preassembled Units	
Intermittent	Shaker (intermittent)	24
Continuous	Shaker (modular)	25
Continuous	Pulse-jet (common housing)	26
Continuous	Pulse-jet (modular)	27
Continuous	Pulse-jet (cartridge)	28
Continuous	Reverse-air Field-assembled Units	29
Continuous	Any method	30

Each figure displays costs for a baghouse type and for additional cost items.[16] All curves are based on vendor quotes. A regression line has been fitted to the quotes and its equation is given. In most cases these lines should not be extrapolated beyond the limits shown. If the reader obtains vendor quotes, they may differ from these curves by as much as ± 25%. All estimates include inlet and exhaust manifold supports, platforms, handrails, and hopper discharge devices. The indicated prices are flange to flange. The reader should note that the scale of each figure changes to accommodate the different gas flow ranges over which the various types of baghouses operate.

The 304 stainless steel add-on cost is used when such construction is necessary to prevent the exhaust gas stream from corroding the interior of the baghouse. Stainless steel is substituted for all metal surfaces that are in contact with the exhaust gas stream.

Insulation costs represent 3 inches of shop-installed glass fiber encased in a metal skin, except for custom baghouses, which have field-installed insulation. Costs for insulation include only the flange-to-flange baghouse structure on the outside of all areas in contact with the exhaust gas stream. Insulation for ductwork, fan casings, and stacks must be calculated separately as discussed later.

Figure 1-24 represents an intermittent service baghouse cleaned by a mechanical shaker. [93] This baghouse is suitable for operations that require infrequent cleaning. It can be shut down and cleaned at convenient times, such as the end of the shift or end of the day. Figure 1-24 presents the baghouse cost as a function of required fabric area. Because intermittent service baghouses do not require an extra compartment for cleaning, gross and net fabric areas are the same. The plot is linear because baghouses are made up of modular compartments and thus have little economy of scale.

Figure 1-25 presents costs for a continuously operated modular baghouse cleaned by mechanical shaker. [93] Again, price is plotted against the gross cloth area in square feet. Costs

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[16] Costs in Figures 24 to 30 are in second quarter 1998 dollars. For price escalation guidance, please refer to Section 1, Chapter 2 of the Cost Manual.

for these units, on a square foot basis, are higher than for intermittent shaker baghouses because of increased complexity and generally heavier construction.

Figures 1-26 and 1-27 show [93] common-housing and modular pulse-jet baghouses, respectively. Common housing units have all bags within one housing; modular units are constructed of separate modules that may be arranged for off-line cleaning. Note that in the single-unit (common-housing) pulse jet, for the range shown, the height and width of the unit are constant and the length increases; thus, for a different reason than that for the modular units discussed above, the cost increases linearly with size. Because the common housing is relatively inexpensive, the stainless-steel add-on is proportionately higher than for modular units. Added material costs and setup and labor charges associated with the less workable stainless-steel account for most of the added expense. Figure 1-28 shows costs for cartridge baghouses cleaned by pulse.

Figures 1-29 and 1-30 show costs for modular and custom-built reverse-air baghouses, respectively. [93] The latter units, because of their large size, must be field assembled. They are often used on power plants, steel mills, or other applications too large for the factory- assembled baghouses. Prices for custom-built shaker units are not shown but are expected to be similar to custom-built reverse-air units.

Figure 1-24: Equipment Costs for Shaker Filters (Intermittent)
Note: this graph should not be extrapolated; GCA = Gross Cloth Area in sqft
Source: ETS Inc.

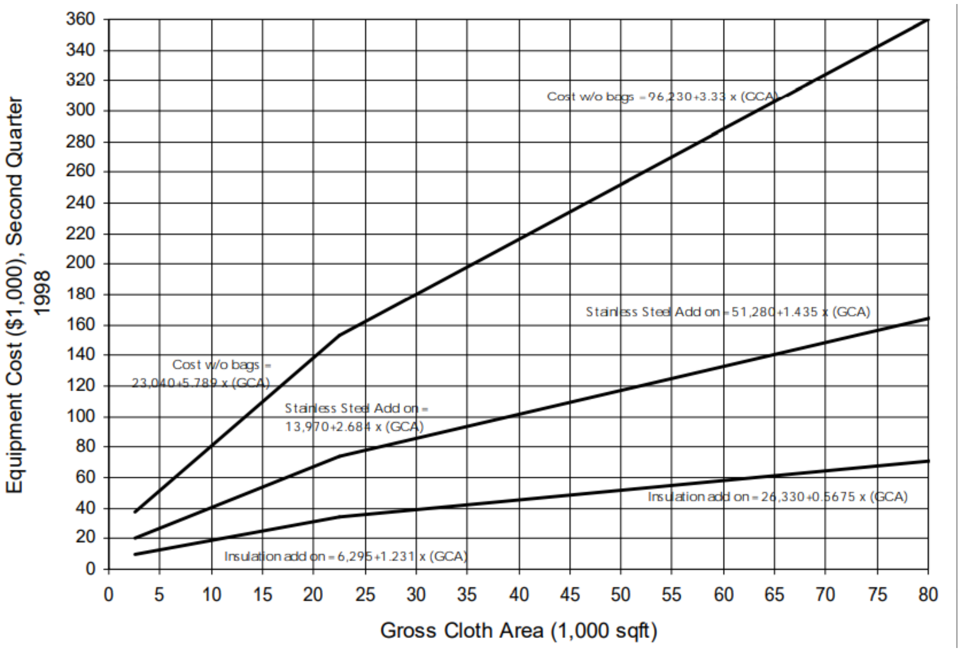

Figure 1-25: Equipment Costs for Shaker Filters (Continuous)

Note: this graph should not be extrapolated; GCA = Gross Cloth Area in sqft
Source: ETS Inc.

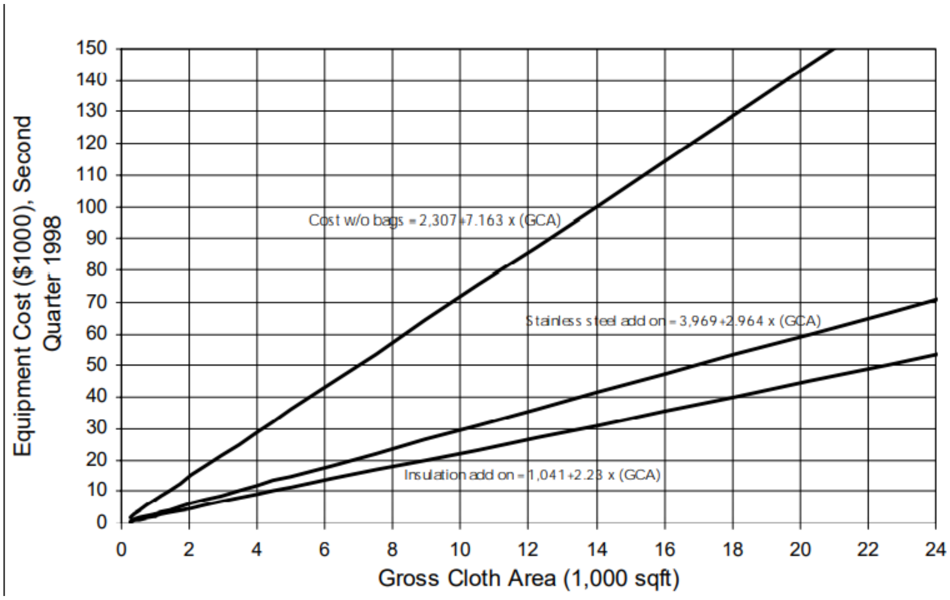

Figure 1-26: Equipment Costs for Pulse-Jet Filters (Common Housing)

Note: this graph should not be extrapolated Note: GCA= Gross Cloth Area in sqft
Source: ETS Inc.

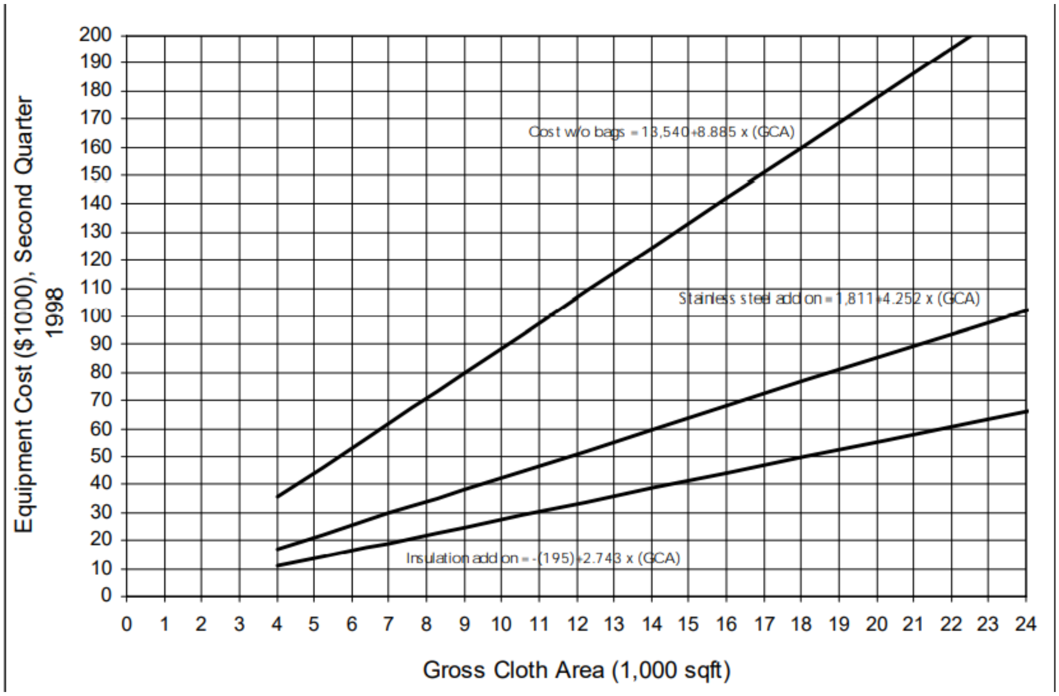

Figure 1-27: Equipment Costs for Pulse-Jet Filters (modular)

Note: this chart should not be extrapolated; GCA= Gross Cloth Area in sqft
Source: ETS Inc.

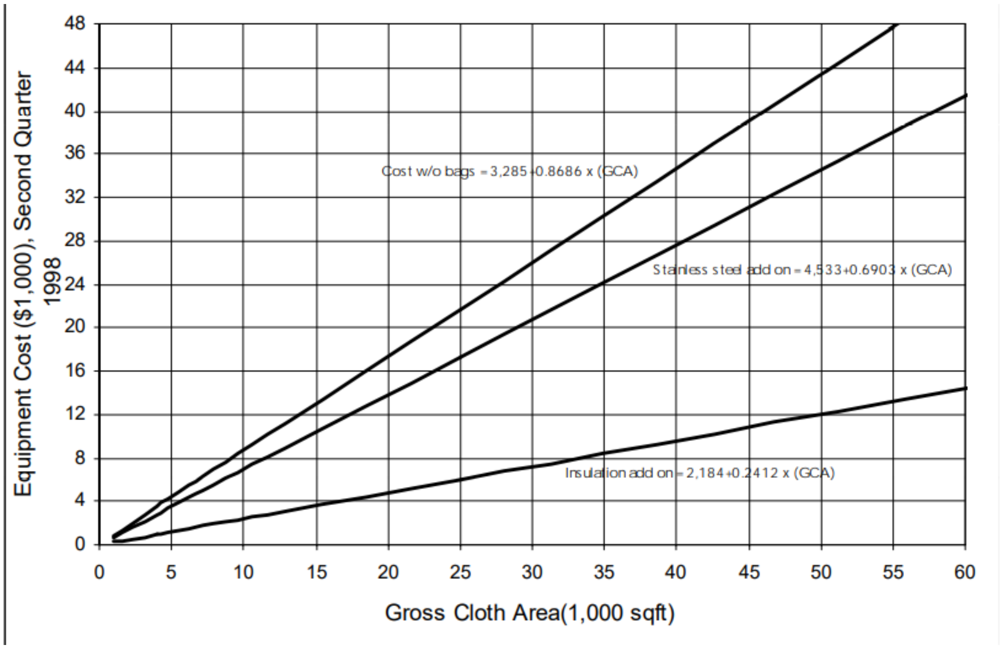

Figure 1-28: Equipment Costs for Cartridge Filters

Note: this graph should not be extrapolated; GCA= Gross Cloth Area in sqft

Source: ETS Inc.

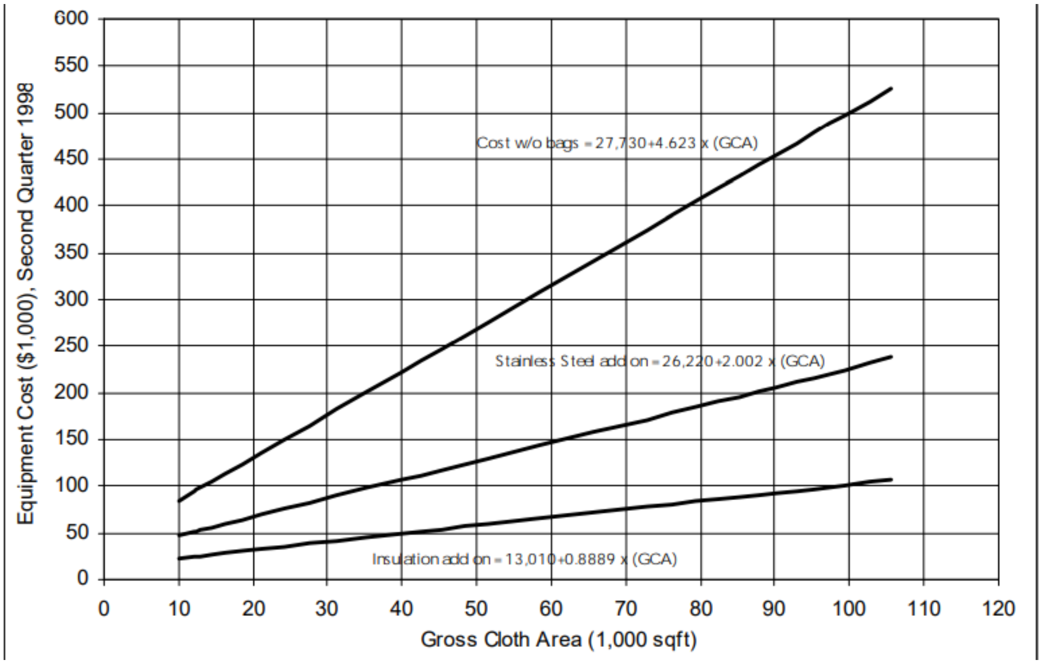

Figure 1-29: Equipment Costs for Reverse-Air Filters (Modular)

Note: this graph should not be extrapolated; GCA= Gross Cloth Area in sqft
Source: ETS Inc.

Figure 1-30: Equipment Costs for Reverse -Air filters (Custom Built)

Note: this graph should not be extrapolated; GCA= Gross Cloth Area in sqft
Source: ETS Inc.

Bag Costs

Table 1-19 give the 1998 price per square foot of bags by type of fabric and by type of cleaning system used. Table 1-20 gives costs for cages for pulse-jet baghouse. Actual quoted prices may vary by ± 10 % from the values in the table. When estimating bag costs for an entire baghouse, gross cloth area as determined from Table 1-14 should be used. Membrane PTFE fabric costs are a combination of the base fabric cost and a premium for the PTFE laminate and its application. As fiber market conditions change, the costs of fabrics relative to each other also change. Prices are based on typical fabric weights in ounces/ square yard. Sewn-in snap rings are included in the price, but other mounting hardware, such as clamps or cages, must be added, based on the type of baghouse.

Auxiliary Equipment Costs

Auxiliary equipment often used in conjunction with a fabric filter include hoods, ductwork, precoolers, cyclones, fans, motors, dust handling and storage equipment and stacks or vents. Since auxiliary equipment are common to many pollution control systems, they are (or will be) given extended treatment in separate chapters. For instance, Chapter 1 in section 2 (Hood, Ductwork, and Stacks) provides design, sizing and costing procedures and data for hoods, ductwork, and stacks. Chapter 2 in section 1 (Fans, Pumps, and Motors) provides sizing and costing for fans.

Total Purchased Cost

The total purchased cost of the fabric filter system is the sum of the costs of the baghouse, bags, and auxiliary equipment, instruments and controls, taxes, and freight. Instruments and controls, taxes, and freight are generally taken as percentages of the estimated total cost of the first three items. Typical values, from section 1, are 10% for instruments and controls, 3% for taxes, and 5% for freight.

Bag costs vary from less than 15% to more than 100% of the cost of the bare baghouse (baghouse without bags or auxiliaries), depending on the type of fabric required. This situation makes it inadvisable to estimate total purchased cost without separately estimating baghouse and bag costs and discourages the use of a single factor to estimate a cost for the combined baghouse and bags.

Table 1-19: Bag Prices (2nd quarter 1998 $\$/\text{ft}^2$)

		Type of Material[a]									
Type of Cleaning	**Bag Diameter (inches)**	**PE**	**PP**	**NO**	**HA**	**FG**	**CO**	**TF**	**P8**	**RT**	**NX**
Pulse jet, TR[b]	4-1/2 to 5-1/8 6 to 8	0.75 0.67	0.81 0.72	2.17 1.95	1.24 1.15	1.92 1.60	NA NA	12.21 9.70	4.06 3.85	2.87 2.62	20.66 NA
Pulse jet, BBR	4-1/2 to 5-1/8 6 to 8	0.53 0.50	0.53 0.60	1.84 1.77	0.95 0.98	1.69 1.55	NA NA	12.92 9.00	3.60 3.51	2.42 2.30	16.67 NA
Pulse jet, Cartridge[c]	4-7/8 6-1/ 8	2.95 1.53	NA NA	6.12 4.67	NA NA	NA NA	NA NA	NA NA	NA NA	NA NA	NA NA
Shaker, Strap top	5	0.63	0.88	1.61	1.03	NA	0.70	NA	NA	NA	NA
Shaker, Loop top	5	0.61	1.01	1.53	1.04	NA	0.59	NA	NA	NA	NA
Reverse air with rings	8 11-1/2	0.63 0.62	1.52 NA	1.35 1.43	NA NA	1.14 1.01	NA NA	NA NA	NA NA	NA NA	NA NA
Reverse air w/o rings	8 11-1/2	0.44 0.44	NA NA	1.39 1.17	NA NA	0.95 0.75	NA NA	NA NA	NA NA	NA NA	NA NA

NA = Not applicable.

[a] Materials:

PE = 16-oz polyester;
PP = 16-oz polypropylene
NO = 14-oz Nomex
HA = 16-oz homopolymer acrylic
FG = 16-oz fiberglass with 10% Teflon NX = 16-oz Nextel
CO = 9-oz cotton
TF = 22-oz Teflon felt
P8 = 16-oz P84
RT = 16-oz Ryton

[b] Bag removal methods: TR = Top bag removal (snap in) and BBR = Bottom bag removal

[c] Costs for 12.75-in. diameter by 26-in. length cartridges are \$59.72 for a polyester/cellulose blend ($\$0.26/\text{ft}^2$ for 226 ft^2) and \$126.00 for spunbonded polyester ($\$1.26/\text{ft}^2$ for 100 ft^2).

NOTE: For pulse-jet baghouses, all bags are felts except for the fiberglass, which is woven. For bottom access pulse jets, the mild steel cage price for one 4 1/2-in. diameter cage or one 5 5/8-in. diameter cage can be calculated from the single-bag fabric area using the following two sets of equations, respectively.

Source: ETS, Inc. [93]

Table 1-20: Cage Prices (2nd quarter 1998 $\$/ft^2$)

4-1/2 in. x 8 ft cages:	5-5/8 in x 10 ft cages:
$\$ = 7.8444 \exp(0.0355\ ft^2)$ *in 25 cage lots*	$\$ = 5.6542\ ft^{2\ (0.4018)}$ *in 25 cage lots*
$\$ = 6.0211 \exp(0.0423\ ft2)$ *in 50 cage lots*	$\$ = 4.3080\ ft^{2\ (0.4552)}$ *in 50 cage lots*
$\$ = 4.2635 \exp(0.0522\ ft^2)$ *in 100 cage lots*	$\$ = 3.0807\ ft^{2\ (0.5249)}$ *in 100 cage lots*
$\$ = 3.4217 \exp(0.0593\ ft^2)$ *in 500 cage lots*	$\$ = 2.5212\ ft^{2\ (0.5686)}$ *in 500 cage lots*

These costs apply to 8-foot and 10-foot cages made of 11-gauge mild steel and having 10 vertical wires and "Roll Band" tops. For snap-band collar with built-in venturi, add $6.00 per cage for mild steel and $13.00 per cage for stainless steel. For stainless steel cages use:

$\$ = 8.8486 + 1.5734\ ft^2$ *in 25 cage lots*	$\$ = 21.851 + 1.2284\ ft^2$ *in 25 cage lots*
$\$ = 6.8486 + 1.5734\ ft^2$ *in 50 cage lots*	$\$ = 8.8486 + 1.2284\ ft^2$ *in 50 cage lots*
$\$ = 4.8466 + 1.5734\ ft^2$ *in 100 cage lots*	$\$ = 8.8486 + 1.2284\ ft^2$ *in 100 cage lots*
$\$ = 3.8486 + 1.5734\ ft^2$ *in 500 cage lots*	$\$ = 8.8486 + 1.2284\ ft^2$ *in 500 cage lots*

For shaker and reverse air baghouses, all bags are woven. All prices are for finished bags, and prices can vary from one supplier to another. For membrane bag prices, multiply base fabric price by factors of 3 to 4.5.

Sources: ETS Inc. [93]

1.5.1.2 Total Capital Investment

The total capital investment (TCI) is the sum of three costs, purchased equipment cost, direct installation costs, and indirect installation costs. The factors needed to estimate the TCI using this methodology for estimating baghouse capital costs are given in Table 1-21. The Table 1-21 factors may be too large for "packaged" fabric filters—those pre-assembled baghouses built by modular construction off-site that consist of the compartments, bags, waste gas fan and motor, and instruments and controls. Because these packaged units require very little installation, their installation costs would be lower (20–25% of the purchased equipment cost). Because bag costs affect total purchased equipment cost, the cost factors in Table 1-21 may cause overestimation of total capital investment when expensive bags are used. Using stainless steel components can also cause overestimation. Because baghouses range in size, specific factors for site preparation or for buildings are not given. Costs for buildings may be obtained from such references as Gordian's RS Means Construction Cost Database. [94] Land, working capital, and off-site facilities are not normally required for building and installing a fabric filter and have been excluded from the table. When necessary, these costs can be estimated**.** The estimate of TCI in Table 1-21, including the estimate of contingency, applies the methodology in the cost estimation methodology chapter of the Control Cost Manual (Section 1, Chapter 2).

1.5.2 Total Annual Costs

Total annual cost for owning and operating a fabric filter system is the sum of the components:

$$TAC = DC + IC \tag{1.13}$$

where:

TAC = total annual cost ($)
DC = direct annual cost ($)
IC = indirect annual cost ($)

1.5.2.1 Direct Annual Cost

Direct annual costs include operating and supervisory labor, operating materials, replacement bags, maintenance (labor and materials), utilities, and dust disposal. Most of these costs are discussed individually below. They vary with location and time, and, for this reason, should be obtained to suit the specific baghouse system being costed. One example of useful labor rates can be found in such publications as the Monthly Labor Review, published by the U.S. Department of Labor, Bureau of Labor Statistics (BLS), or obtained from the BLS web site at: *http://stats.bls.gov*. This is only one example of labor rates that can be useful for estimating direct annual costs. Sales tax for fabric filters may be zero if the state that the device is in provides a full exemption. As one example, Michigan provides a 100% exemption on "facilities that are designed and operated primarily for the purpose of controlling or disposing of air pollution…"[17].

Operating and Supervisory Labor

Typical operating labor requirements are 2 to 4 hours per shift for a wide range of filter sizes.[95] Small or well-performing units may require less time, while very large or troublesome units may require more. Supervisory labor is taken as 15% of operating labor.

Operating Materials

Operating materials are generally not required for baghouses. An exception is the use of precoat materials injected on the inlet side of the baghouse to provide a protective dust layer on the bags when sticky or corrosive particles might harm them. Adsorbents may be similarly injected when the baghouse is used for simultaneous particle and gas removal. Costs for these materials should be included on a dollars-per-mass basis (e.g., dollars per ton).

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[17] This is mentioned at https://www.michigan.gov/taxes/property/exemptions/air/air-pollution-control-exemptions.

Maintenance

Maintenance labor varies from 1 to 2 hours per shift. As with operating labor, these values may be reduced or exceeded depending on the size and operating difficulty of a particular unit. Maintenance materials costs are assumed to be equal to maintenance labor costs. [95]

Table 1-21: Capital Cost Factors for Fabric Filters

Cost Item	Factor
Direct costs	
Fabric filter + insulation (EC) + bags + auxiliary equipment	As estimated, A
Instrumentation	0.10 A
Sales taxes	0.03 A
Freight	0.05 A
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(a)	0.07 B
Painting(b)	0.04 B
	0.74 B
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost (DC)	**1.74 B + SP + Bldg.**
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
Total Indirect Cost (IC)	**0.42 B**
Total Capital Investment (TCI) = DC + IC	**2.16 B + SP + Bldg.**
Contingency (C) c	0.1 x TCI
TCI with Contingency =	**1.1x (2.16B + SP + Bldg.)**

(a) - Ductwork and stack costs, including insulation costs, may be obtained from Chapter 10 of the manual. This installation factor pertains solely to insulation for fan housings and other auxiliaries, except for ductwork and stacks.

(b) - The increased use of special coatings may increase this factor to 0.06B or higher. [The factors provided are for average installation conditions. Considerable variation may be seen with other-than-average installation circumstances.]

(c) – Contingency value applied in this example is the midpoint of a range from 5-15% of the TCI. See Section 1, Chapter 2 of the Control Cost Manual for more information.

Replacement Parts

Replacement parts consist of filter bags and cages for pulse-jet baghouses. The operating life for filter bags varies based on the application, baghouse design, and type of fabric selected. Typical operating life for filter bags is between 2 to 10 years. Cages used on pulse-jet baghouses are more durable than filter bags and have an operating life that is typically two or three times longer than for filter bags. However, while not necessary for typical fabric filter use, many vendors recommend cages be replaced when the filter bags are replaced.

The following formula is used for computing the filter bag replacement cost for shaker and reverse air baghouses:

$$\mathrm{CRC}_{B} = \left(\mathrm{C}_{B} + \mathrm{C}_{L}\right) \times \mathrm{CRF}_{B} \qquad (1.14(a))$$

where:

CRC_B = bag capital recovery cost ($/year)
C_B = initial bag cost including taxes and freight ($)
C_L = bag replacement labor ($)
CRF_B = capital recovery factor (defined in Chapter 2) whose value is a function of the annual interest rate and the useful life of the bags (For instance, for an 8.5% interest rate and a 3-year life, $CRF_B = 0.3915$.)

The following formula is used for computing the filter bag and cage replacement cost for pulse-jet baghouses:

$$CRC_B = \left[(C_{Bag} + L_{Bag}) \times CRF_{Bag}\right] + \left[(C_{Cage} + L_{cage}) \times CRF_{cage}\right] \qquad (1.14(b))$$

where:

CRC_B = bag and cage capital recovery cost ($/year)
C_{Bag} = initial bag cost including taxes and freight ($)
L_{Bag} = bag replacement labor ($)
CRF_{Bag} = capital recovery factor for bags based on replacing bags once every “h” years, as defined in Section 1, Chapter 2 of the Cost Manual (e.g., for an 8.5% interest rate and a 5-year life, $CRF_{Bag} = 0.2310$.)
C_{cage} = initial cage cost including taxes and freight ($)
L_{cage} = cage replacement labor ($)
CRF_{cage} = capital recovery factor for cages based on replacing cages once every “i” years, as defined in Section 1, Chapter 2 of the cost manual (e.g., for an 8.5% interest rate and a 10-year life, $CRF_{cage} = 0.1295$).

Bag replacement labor cost (C_L) depends on the number, size, and type of bags; their accessibility; how they are connected to the baghouse tube-sheet; and other site-specific factors that increase or decrease the quantity of labor required. For example, a reverse-air baghouse probably requires from 10 to 20 person-minutes to change an 8-inch by 24-foot bag that is clamped in place. Based on a filtering surface area of approximately 50 ft^2 and an assumed hourly labor rate of approximately \$28.38 (including overhead), C_L would be about \$0.10 to \$0.20/ft^2 of bag area. As Table 1-19 shows, for some bags (e.g., polyester), this range of C_L would constitute a significant fraction of the purchased cost. For pulse jets, replacement time would be about 5 to 10 person-minutes for a 5-inch by 10-foot bag in a top-access baghouse, or \$0.20 to \$0.38/ft^2 of bag area. This greater cost is partially offset by having less cloth in the baghouse, but there may be more of the smaller bags. These bag replacement times are based on changing a minimum of an entire module and on having typical baghouse designs. Times would be significantly longer if only a few bags were being replaced or if the design for bag attachment or access were atypical. Cartridge baghouses with horizontal mounting take about 4 minutes to change one cartridge. Older style baghouses with vertical mounting and blow pipes across the cartridges take about 20 minutes/cartridge.

The Manual methodology treats filter bags and bag replacement labor as an investment amortized over the useful life of the bags and cages, while the rest of the control system is amortized over its useful life, typically 20 years. The capital recovery factor values for bags and cages with different useful lives can be calculated based on the method presented in Chapter 2, section 1 (Cost Estimation: Concepts and Methodology).

Electricity

Electricity is required to operate system fans and cleaning equipment. Primary gas fan power can be calculated as described in Chapter 2 of section 2 and assuming a combined fan motor efficiency of 0.65 and a specific gravity of 1.000. We obtain: [96]

$$Power_{fan} = 0.000181\ Q(\Delta P)\vartheta \tag{1.15}$$

where:

$Power_{fan}$ = fan power requirement in kilowatt-hour/year (kWh/year)
Q = system flow rate (acfm)
ΔP = system pressure drop (in H_2O)
Θ = operating time (hours/year)

Cleaning energy for reverse-air systems can be calculated (using equation 1.15) from the number of compartments to be cleaned at one time (usually one, sometimes two), and the reverse A/C ratio (from about one to two times the forward air-to-cloth ratio). Conditions in reverse-air systems are such that the pressure drop typically has a variance of up to 6 or 7 in. H_2O depending on location of the fan pickup (before or after the main system fan). [97] The reverse-air fan generally runs continuously.

Typical energy consumption in kWh/yr for a shaker system operated 8,760 h/yr can be calculated from:[98]

$$P = 0.053\,A \tag{1.16}$$

where:

A = gross fabric area (ft^2)

Fuel

Fuel costs must be calculated if the baghouse or associated ductwork is heated to prevent condensation. These costs can be significant but may be difficult to predict. For methods of calculating heat transfer requirements, see Perry. [99]

Water

Cooling process gases to acceptable temperatures for fabrics being used can be done by dilution with air, evaporation with water, or heat exchange with normal equipment. Evaporation and normal heat exchange equipment require consumption of plant water, although costs are not usually significant. Chapter 1 of Section 3.1, Carbon Adsorbers, in the Control Cost Manual provides information on estimating cooling water costs.

Compressed Air

Pulse-jet filters use compressed air at pressures from about 60 to 100 psig. Typical consumption is about 2 scfm/1,000 cfm of gas filtered. [98] For example, a unit filtering 20,000 cfm of gas uses about 40 scfm of compressed air for each minute the filter is operated. For each pulse, cartridge filters with nonwoven fabrics use 10 scfm/1,000 ft^2 or 14 scfm/ 1,000 ft^2 at 60 psig or 90 psig pulse pressure, respectively, in one manufacturer's design. [100] When using paper media, the air quantities are 1.7 scfm/1,000 ft^2 and 2.2 scfm/1,000 ft^2 at the respective pressures. Pulse frequency ranges from about 5 min. to 15 min. A typical cost for compressed air is $0.15/1,000 scf in 1998 dollars.

Dust Disposal

If collected dust cannot be recycled or sold, it must be landfilled or disposed of in some other manner. Disposal costs are site-specific, but as one example, typically run from $35 to $55 per ton at municipal waste sites in Pennsylvania, exclusive of transportation. Lower costs may be available for industrial operations with long-term disposal contracts. Hazardous waste disposal can cost $150 per ton or more.

1.5.2.2 Indirect Annual Cost

Indirect annual costs include capital recovery, property taxes, insurance, administrative costs (or general and administrative, G&A), and overhead. The capital recovery cost is based on the equipment lifetime and the annual interest rate employed. (See Section 1, Chapter 2 for a discussion of the capital recovery cost and the variables that determine it.) For fabric filters, the system lifetime (i.e., housing and auxiliary equipment) varies from 5 to 40 years, with 20 years being typical. [95] However, this does not apply to the bags, which usually have much shorter lives. Therefore, one should base system capital recovery cost estimates on the installed capital cost, less the cost of replacing the bags (*i.e.*, the purchased cost of the bags plus the cost of labor necessary to replace them). Algebraically:

$$CRC_s = [TCI - C_B - C_L]\, CRF_s \tag{1.16}$$

where:

CRC_s = capital recovery cost for fabric filter system ($/yr)
TCI = total capital investment ($)
C_B = initial cost of bags (and cages, for pulse-jet baghouses) including taxes and freight ($)[18]
C_L = labor cost for replacing bags (and cages, for pulse-jet baghouses) ($)
CRF_s = capital recovery factor for fabric filter system based on the expected equipment life and annual interest rate (as defined in Section 1, Chapter 2).

For example, for a 20-year system life and 8.5% annual interest rate,[19] the CRF_s would be 0.1057.

The suggested factor to use for property taxes, insurance, and administrative charges is 4% of the *TCI* (see Section 1, Chapter 2 of the Control Cost Manual). Finally, overhead is calculated as 60% of the total labor (operating, supervisory, and maintenance) and maintenance materials, and see Section 1, Chapter 2 for more on the calculation of overhead.

1.5.3 Example Problem

Assume a baghouse is required for controlling fly ash emissions from a coal-fired boiler. The flue gas stream is 50,000 acfm at 275°F and has an ash loading of 4 gr/acf. Analysis of the ash shows a mass median diameter of 7μm. Assume the baghouse operates for 8,640 h/yr (360 days per year), which assumes 120 hours per year for downtime and maintenance.

1.5.3.1 Design Parameters

The A/C can be taken from Table 1-13 as 2.5 for woven fabrics in shaker or reverse-air baghouses, or 5 for felts used in pulse-jet baghouses. If a factor method were used for estimating A/C, Table 1-15 for shakers would yield the following values: $A = 2$, $B = 0.9$, and $C = 1.0$. The A/C ratio would be calculated as follows:

$$V = 2 \times 0.9 \times 1.0 = 1.8$$

This value could also be used for reverse-air cleaning. For a pulse-jet unit, Table 1-16 gives a value of 9.0 for factor *A* and 0.8 for factor *B*. Equation 1.11 becomes:

$$V = 2.878 \times 9.0 \times 0.8 \times (275)^{-0.2335} \times (4)^{-0.06021} \times (0.7471 + 0.0853 ln7) = 4.69$$

Because this value is so much greater than the shaker/reverse-air A/C, we conclude that the pulse-jet baghouse would be the least costly design. This conclusion is based on the inference that a much bigger A/C would yield lower capital and, in turn, lower annual costs. However, to make a more rigorous selection, we would need to calculate and compare the total annual costs of all three baghouse designs (assuming all three are technically acceptable). The reader is invited to

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[18] Cost includes taxes and freight costs, which are typically 8% of the initial cost. For pulse-jet systems, the C_B also includes the cost of the cages.

[19] The current bank prime rate is available at https://www.federalreserve.gov/releases/h15/.

make this comparison. Assume the use of on-line cleaning in a common housing structure and, due to the high operating temperature, the use of glass filter bags (see Table 1-18).[20]

At an A/C ratio of 4.69, the fabric required is [21]

$$\frac{50{,}000\ acfm}{4.69\ fpm} = 10{,}661 ft^2$$

1.5.3.2 Capital Costs

Purchased Equipment Costs

From Figure 1-26, the cost of the baghouse ("common housing" design) is:

$$Cost = 2{,}307 + 7.163\ \times 10{,}661 = \$78{,}672$$

Insulation is required for this example. The insulation add-on cost is:

$$Cost = 1{,}041 + 2.23\ \times 10{,}661 = \$24{,}815$$

From Table 1-19, bag costs are \$1.69/ft^2 for 5-1/8-inch diameter glass fiber, bottom removal bags. Total bag cost is calculated as follows:

$$10{,}661 ft^2 \times \frac{\$1.69}{ft^2} = \$18{,}017$$

For 10 ft long cages, the fabric area per cage is calculated:

$$Fabric\ area\ per\ cage = \frac{(5.125\ inches)}{(12\frac{in}{ft})} \times \pi \times 10ft = 13.42ft^2$$

$$Number\ of\ cages = \frac{(10{,}661ft^2)}{(13.42ft^2)} = 795\ cages\ (rounded\ up\ to\ next\ integer)$$

From Table 1-20, the cost of each individual cage is calculated as follows:

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[20] Other bag materials (e.g., Nomex) also could withstand this operating temperature; however, fiberglass is the least expensive on a purchased cost basis. For harsh environments, a more expensive, but more durable bag might cost less on a total annual cost basis.

[21] This is the total (gross) bag area required. No bag adjustment factor has been applied here because this is a common housing pulse jet unit that is cleaned continuously during operation. Thus, no extra bag compartment is needed, and the gross and net bag areas are equal.

$$2.5212 \times (13.42)^{0.5686} = \$11.037$$

Total cost of cages is calculated:

$$795\ cages \times \frac{\$11.037}{cage} = \$8{,}774$$

Assume the following auxiliary costs have been estimated from data in other parts of the Manual:

Ductwork	$19,000
Fan	19,000
Motor	12,000
Starter	4,700
Dampers	9,800
Compressor	8,000
Screw conveyor	5,000
Stack	12,000
Total	**$89,500**

Direct and Indirect Installation Costs

Direct and indirect installation costs for the fabric filter system, estimated using the Control Cost Manual methodology, are given in Table 1-22. Assuming site preparation and buildings costs to be negligible, the total capital investment when escalated to 2023 dollars is $1,233,606.

1.5.3.3 Annual Costs

Direct and Indirect Costs

Table 1-23 gives the direct and indirect annual costs, as calculated from the factors given in section 1.5.1. For bag replacement labor, assume 10 minutes to replace each bag and 10 minutes to replace each cage, 795 bags and cages. At an hourly maintenance labor rate of $28.38, the labor cost is $3,775 for 133 hours (rounded to the nearest hour) to replace each bag. The bags are assumed to be replaced every 5 years, which is the median of the range of expected life for each bag. The cages are assumed to be replaced every 10 years (or at every other bag change). The replacement cost is calculated using Equation 1.14(b).

Pressure drop (for energy costs) can be calculated from equations 1.8 and 1.9, with the following assumed values:

$$K_2 = \frac{15\ inch\ H_2O}{1\ ft/min} \times \frac{1}{lb/ft^2}$$

P_j = 100 psig

cleaning interval = 10 min

We further assume that an *A/C* of 4.69 ft/min is a good estimate of the mean face velocity over the duration of the filtering cycle.

$$W_0 = C_i V_f \theta = C_i V \theta = \left(\frac{4gr}{ft^3}\right) \times \frac{lb}{7{,}000gr} \times \frac{4.69ft}{min} \times 10min = 0.0268lb/ft^2$$

The pressures drop across the fabric filter can be calculated using equation 1.8.

$\Delta P = (PE)_{\Delta w} + K_2 W_o V_f$ Then using the Dennis and Klemm empirical relationship from equation 1.9 can be used to calculate $(PE)_{\Delta w}$. The resulting calculation for the pressures drop (ΔP):

$$\Delta P = 6.08 \times \frac{4.69ft}{min} \times (100\,psig)^{-0.65} + 15\ \frac{inches\ H_2O}{ft/min} \times \frac{1}{\frac{lb}{ft^2}} \times 0.0268\frac{lb}{ft^2} \times 4.69\frac{ft}{min} =$$

$$3.32\ inches\ H_2O \text{ across the fabric when fully loaded}$$

Note that the equation 1.9 for calculating the value of $(PE)_{\Delta w}$ can be used only for baghouses using Dacron felt that is used to collect coal fly ash. For systems using a different type of fabric and/or particulate, then the value of $(PE)_{\Delta w}$ must be determined using laboratory data collected for the specific application.

The baghouse structure and the ductwork typically contribute an additional 3 in. H_2O and 4 in. H_2O, respectively. The total pressure drop is, therefore, 10.3 inches.

Table 1-22: Capital Costs for Fabric Filter System Example Problem (2023$)

Cost Item	Cost
Direct Costs	
Purchased equipment costs	
Fabric filter (with insulation) (EC)	$103,487
Bags and cages	26,791
Auxiliary equipment	89,500
EC + (Bags and Cages) + Auxiliary Equipment = A	$219,778
Instrumentation, 0.1A	21,978
Sales taxes, 0.03A *	6,593
Freight, 0.05A	10,989
Total Purchased equipment cost (B) =1.18A	**$259,338**
Direct installation costs	
Foundation and supports, 0.04B	10,374
Handling and erection, 0.50B	129,669

Electrical, 0.08B	20,747
Piping, 0.01B	2,593
Insulation for ductwork, 0.07B	18,153
Painting, 0.04B	10,374
Total Direct installation cost	**$191,910**
Site preparation	$0
Facilities and buildings	$0
Total Direct Cost (DC)	**$451,248**
Indirect Costs (installation)	
Engineering, 0.1B	25,934
Construction and field expenses, 0.20B	51,868
Contractor fees, 0.10B	25,934
Start-up, 0.01B	2,593
Performance test, 0.01B	2,593
Total Indirect Cost (IC)	**$108,922**
Total Capital Investment (TCI) = DC + IC	**$560,170**
Contingency, 0.1 x TCI	$56,017
TCI with Contingency	**$616,187**
TCI with Contingency, Escalated to 2023$**	**$1,233,606**

*A number of U.S. states offer partial to full exemptions to property and/or sales taxes on pollution control equipment. As one example, Michigan provides a 100% exemption on "facilities facilities that are designed and operated primarily for the purpose of controlling or disposing of air pollution…" as mentioned at https://www.michigan.gov/taxes/property/exemptions/air/air-pollution-control-exemptions.

**Escalation to 2023 prepared using annual value of CEPCI for 2023/annual value of CEPCI for 1998 = 797.9/398.5 = 2.002.

Table 1-23: Annual Costs for Fabric Filter System Example Problem (2023$)

Cost Item	Calculations	Cost
Direct Annual Costs, DC		
Operating labor		
Operator	2hr/shift x 3shifts/day x 360 days/yr x $28.38 /hr	$61,301
Supervisor	15% of operator	$9,195
Maintenance		
Labor	1hr/shift x 3 shifts/day x 360 days/yr x $28.38 /hr	$30,650
Material	100% of maintenance labor	$30,650
Replacement parts, bags[(a)]	[(3,775+(18,017x1.08)) x 0.2310]+[(3,775+(8,774x1.08))x0.1295]	$7,916
Utilities		
Electricity	0.000181 x 50,000 acfm x 10.3inch. H_2O x 8,640hr/yr x $0.0671/kWh	$54,041

Compressed Air	2scfm/1,000 acfm x 50,000acfm x $0.25/1,000scf x 60min/hr x 8,640hr/yr	$12,960
Waste Disposal	At $25/ton on-site for essentially 100% collection 4 gr/ft^3 x 1lb/7,000gr x 50,000ft^3 x 60min/hr x 8,640hr/yr x 1ton/2,000lb x $25/ton	$185,143
Total Direct Costs (DC)		**$391,856**
Indirect Annual Costs, (IC)		
Overhead	60% of sum of operating, supervisor and maintenance labor , and maintenance materials	$83,827
Administrative Charges	2% of Total Capital Investment (0.02*1,233,606)	$24,672
Property Tax	1% of Total Capital Investment (0.01*1,233,606)	$12,336
Insurance	1% of Total Capital Investment (0.01*1,233,606)	$12,336
Capital Recovery(b)	(0.1057 x 1,233,606) + –	$130,392
Total Annual Indirect Costs (IC)		**$263,563**
Total Annual Cost		**$655,419**

(a) The 1.08 factor is for freight and sales tax. The capital recovery factor of 0.1524 for filter bags is based on a bag life of 5 years and the recovery factor of 0.2538 is based on a cage life of 10-years. The current U.S. bank prime rate of 8.5% (available at http://www.federalreserve.gov/releases/h15/). Also, a number of U.S. states offer partial to full exemptions to sales and/or roperty taxes on pollution control equipment. As one example, Michigan provides a 100% exemption on “facilities facilities that are designed and operated primarily for the purpose of controlling or disposing of air pollution…” as mentioned at https://www.michigan.gov/taxes/property/exemptions/air/air-pollution-control-exemptions. Property tax is only applicable if purchase of land is required as part of the fabric filter installation. Otherwise, this value is zero.

(b) The capital recovery cost factor, CRF, is a function of the fabric filter or equipment life and the opportunity cost of the capital (i.e., interest rate). For example, for a 20-year equipment life and the 8.5% current bank prime rate (available at http://www.federalreserve.gov/releases/h15/), CRF = 0.1057.

For this example, the total annual cost is $655,419, 28 percent of which is for ash disposal. The total annual cost is extremely sensitive to the dust disposal cost. In this and in similar cases, we recommend the site-specific disposal cost be used. The site-specific disposal costs should include shipping costs if disposal is off-site. If a market for the fly ash could be found, the total annual cost would be greatly reduced. For example, if $2/ton were received for the ash, the total annual cost would drop to $455,476 ($655,419 – $185,143 – $14,800), or about 69% of the cost when no market for the fly ash exists.

1.6 Alternative Cost Methodology for a Pulse-Jet Fabric Filter Installed on a Coal-fired Utility Boiler

We present two different methodologies for estimating capital and annual costs for fabric filters. Both cost methodologies provide study-level estimates of capital and annual costs. This second cost methodology, which is based on installations for utility boilers, is based on a methodology developed by Sargent & Lundy, LLC (S&L) for EPA’s CAMD and used with the

Integrated Planning Model (IPM). [2] The IPM equations estimate capital costs in 2016 dollars based on cost data available from various industry publications and other data collected by Sargent & Lundy for fabric filters retrofitted to utility boilers. The equations themselves do not take into consideration site-specific cost issues and are for multiple lump-sum contracts. However, appropriate use of a retrofit factor applied to the capital cost, as mentioned in Section 1.2.6.4.2 of the Control Cost Manual's cost estimation methodology chapter, can allow this fabric filter cost methodology to provide consideration and calculation of site-specific cost issues, as discussed below in Section 1.6.1. Turnkey contracts, where the price for a capital good or investment is fixed at the time the contract is signed and the contractor undertakes responsibility and a large share of the risks (financial and otherwise) for the completion of the project, are generally 10 to 15% higher than the multiple lump-sum contracts.[22]

1.6.1 Capital Costs

Total capital investment (TCI) includes direct and indirect costs associated with purchasing and installing the fabric filter and auxiliary equipment. The TCI includes the equipment cost for the fabric filter, the cost of auxiliary equipment (e.g., ductwork modifications, new fans, fly ash handling), direct and indirect installation costs, costs for buildings and site preparation, cost of land and working capital. A more detailed discussion of what is included in TCI can be found in Section 1, Chapter 2 of this Manual.

The TCI equation for a fabric filter is presented in Equation 1.18:

$$TCI = 1.3 \times C \times RF \times L^{0.81} \tag{1.18}$$

where:

TCI = total capital investment for a fabric filter, $
C = constant based on baghouse air-to-cloth ratio, 530 for air-to-cloth ratio of 6.0; 600 for air-to-cloth ratio of 4.0)
RF = retrofit factor (RF = 0.77 for new construction; RF = 1 for retrofits with average level of difficulty)
L = flue gas flow rate, afcm

The TCI calculation includes a factor of 1.3 to estimate engineering and construction management costs, installation, labor adjustment, and contractor profit and fees.[23] The TCI

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[22] EPA notes that the IPM cost model is designed to produce generic costs on an electric power system wide basis, and thus cost analysis algorithms from this model are included in the Control Cost Manual only when consistent with the cost methodology of the Control Cost Manual, and when the underlying data in the cost algorithm is consistent with the emission units being analyzed. Limitations on the use of the IPM for cost estimation are mentioned in the model documentation at [to be added]. The suitability of the IPM Cost Model as applied to each control technology analysis should be a case-specific determination by the reviewing agency, and case-specific cost vendor data is to be used where possible and in preference to in place of generic cost data.

[23] Although included in the IPM cost methodology, the TCI as estimated in this chapter does not include the owner's costs (for owner activities related to engineering, management, and procurement) and allowance for funds used during construction (AFUDC). The owner's costs and AFUDC are inconsistent with the overnight cost method used in the EPA's Control Cost Manual. The overnight cost estimation method presumes costs are incurred as if the project

equation also includes a retrofit factor (RF) that can be adjusted based on the type and difficulty of installation. A retrofit factor of 1 should be used for retrofits with an average level of difficulty. Retrofit costs can vary significantly from site to site and depend on the amount of space available and whether significant modifications to existing equipment are needed. For example, a higher retrofit factor should be used for congested sites or in situations where significant modifications are needed to existing ductwork and fly ash handling equipment. Sites that require longer ducts are much more expensive than those that can accommodate the baghouse near the combustion unit.. Estimates prepared by US EPA for its recently finalized MATS indicate that fabric filter retrofit costs at different EGUs can range from \$179/kW to \$223/kW (2019\$). Since new construction projects typically have lower costs than retrofit projects, a retrofit factor of 0.77 should be used to estimate TCI for new construction projects.

The flue gas flow rate (L) can be estimated based on the gross unit size (A), gross heat rate (HR) and type of coal burned:

$$L = A \times GHR \times CoalF \times ELVF \tag{1.19}$$

where:

A = gross unit size, MW
GHR = gross heat rate, Btu/Wh
$CoalF$ = coal factor ($CoalF$ = 0.362 for bituminous; $CoalF$ = 0.4 for PRB; $CoalF$ = 0.435 for Lignite)
$ELVF$ = elevation factor (calculated using Equation 1.20 and 1.21 if plant is located at or above 500 feet above sea level; ELVF = 1 for plants located at elevations below 500ft above sea level)

The elevation factor, *ELVF*, adjusts for the effects of elevation on the flue gas volumes encountered at elevations of 500 feet or more above sea level. The elevation factor, *ELVF*, is calculated using Equations 1.20 and 1.21 for plants located at 500 feet or more above sea level.

$$ELEVF = \frac{P_0}{P_{ELEV}} \tag{1.20}$$

where:

$ELEVF$ = elevation factor
P_0 = atmospheric pressure at sea level, 14.7 pounds per square inch absolute (psia)
P_{ELEV} = atmospheric pressure at elevation of the unit, psia.

The P_{ELEV} can be calculated using Equation 1.21 [100]:

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in question incurred no interest during construction or was built "overnight." Another description of this method is the present value cost that would have to be paid as a lump sum up front to completely pay for a construction project. For more information, see "Conducting Technical and Economic Evaluations – As Applied for the Process and Utility Industries," Recommended Practice 16R-90, American Association of Cost Engineering International. April 1991, and Section 1, Chapter 2 of this Control Cost Manual.

$$P_{ELEV} = 2116 \times \left[\frac{59-(0.00356\times h)+459.7}{518.6}\right]^{5.256} \times \frac{1}{144} \tag{1.21}$$

where:

P_{ELEV} = atmospheric pressure at elevation of the unit, psia
h = altitude, feet.

For plants located at elevations below 500 feet elevation, an elevation factor of 1 should be used in Equation 1.19 to calculate the flow rate.

1.6.2 Total Annual Costs

The total annual costs (TAC) consist of direct costs and indirect costs. Direct annual costs are those costs directly associated with the operation of the control system, whereas indirect annual costs are fixed costs that are independent of the operation of the control system and would be incurred even if it were shut down. Each of these costs is discussed in the sections below. In applications where the fly ash is collected and sold for beneficial use (e.g., used in concrete), the TAC should be adjusted by subtracting the recovery credit from the sum of the direct and indirect annual costs.

1.6.2.1 Direct Annual Cost

The direct annual cost (*DAC*) includes electricity costs, waste disposal costs, maintenance labor and materials. Labor costs associated with daily operation can be estimated as described in Section 1.5.2.1. The annual maintenance cost consists primarily of the labor and materials costs for replacing of filter bags and cages. The annual maintenance cost varies based on the size of the combustion unit, gas flow rate and whether the fabric filter is the primary particulate collection device or is used downstream from an ESP. The annual maintenance cost is calculated using Equations 1.22(a).

$$Annual\ Maintenance\ Cost = \frac{L}{(J\times 341{,}640)} \times R \times T \tag{1.22(a)}$$

where:

T = operating time per year, hours
J = A/C ratio for fabric filter[24]

The factor R for a fabric filter used downstream from an ESP is calculated using Equation 1.22(b). Bag and cage replacement is assumed to be every 3 and 9 years, respectively, for a fabric filter with a 6.0 A/C ratio.

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[24] When a fabric filter is installed after another collection device that will remain in service, such as an ESP, then a net A/C of 6.0 can be used. This type of polishing fabric filter would be considered if the fabric filter, with activated carbon injection for mercury removal or sorbent injection for acid gas removal, is to be installed downstream of the existing ESP. An A/C ratio of 4.0 should be used when the fabric filter will be the primary particulate collection device.

$$R = \frac{\mathrm{AC}}{3} + \frac{AD}{9} \qquad (1.22(b))$$

For a fabric filter used as the primary particulate collection, the factor R is calculated using Equation 1.22(c). Bag and cage replacement is assumed to be every 5 and 10 years, respectively, for a fabric filter with a 4.0 A/C ratio.

$$R = \frac{\mathrm{AC}}{5} + \frac{AD}{10} \qquad (1.22(c))$$

where:

AC = Cost for each replacement bag, \$
AD = Cost for each replacement cage, \$

The amount of fly ash waste generated can be calculated using equation:

$$W = A \times GHR \times Coal_{Ash} \times \frac{0.8}{(2 \times HHV)} \qquad (1.23)$$

where:

A = gross unit size, MW
GHR = gross heat rate, Btu/kWh
$Coal_{Ash}$ = Ash content of coal (0.12 for bituminous coal, 0.06 for PRB, 0.08 for lignite)
HHV = High heating value of coal, Btu/lb

The cost of waste disposal is calculated as follows:

$$Annual\ waste\ disposal\ cost = W \times Cost_{disposal} \times T \qquad (1.24)$$

where:

$Cost_{disposal}$ = unit cost of waste disposal, \$/ton
T = operating time per year, hours

The annual cost of electricity is calculated as follows:

$$\text{Annual electricity cost} = 0.6 \times Cost_{elec} \times 10 \times A \times T \qquad (1.25)$$

where:

$Cost_{elec}$ = unit price of electricity, \$/kWh
A = gross unit size, MW
T = operating time per year, hours

1.6.2.2 Indirect Annual Costs

In general, as consistent with the Control Cost Manual's cost estimation methodology, indirect annual costs (*IDAC*) are the fixed operating costs associated with capital recovery cost, property taxes, insurance, administrative charges, and overhead. Capital recovery cost is based on the anticipated equipment life and the annual interest rate employed. The equipment life is the expected service life of the control device. As noted in Section 1.3.7, we expect an equipment life of 20 years for fabric filter units. However, the remaining life of the combustion unit may also be a determining factor when deciding on the correct equipment life for calculating the total annual costs.

Taxes may be assumed to be zero since property taxes generally do not apply to air pollution control equipment, except if purchase of land is required as part of the installation. The plant overhead costs can be estimated as described in Section 1.5.2.2. However, the costs for insurance, payroll, plant protection, etc. are expected to be minimal. The *IDAC* in $/year consists of overhead, administrative charges and capital recovery, which can be expressed as:

$$\text{IDAC} = \text{OC} + \text{AC} + \text{CR} \qquad (1.26)$$

where *OC* represents the overhead costs, *AC* represents the administrative charges and *CR* represents the capital recovery cost. Administrative charges may be calculated as follows:

$$AC = 0.03 \times (Operator\ Labor\ Cost + 0.4 \times Annual\ Maintenance\ Cost) \qquad (1.27)$$

Labor costs associated with daily operation can be estimated as described in Section 1.5.2.1. The annual maintenance costs are calculated using Equation 1.22(a).

Capital recovery is calculated using Equation 1.28:

$$\text{CR} = \text{CRF} \times \text{TCI} \qquad (1.28)$$

Where TCI is the total capital investment in dollars and *CRF* is the capital recovery factor. The capital recovery factor (*CRF*) is defined in Section 1, Chapter 2 of the Manual as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (1.29)$$

Where i is the assumed interest rate[25] and n is the equipment life of the fabric filter.

1.6.2.3 Total Annual Cost

The total annual cost, *TAC*, for owning and operating the fabric filter is the sum of direct and indirect annual costs as given Equation 1.30:

$$\text{TAC} = \text{DAC} + \text{IDAC} \qquad (1.30)$$

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[25] The current U.S. bank prime rate is available at https://www.federalreserve.gov/releases/h15/.

1.6.3 Cost Effectiveness

The cost in dollars per ton of particulate removed per year, is calculated as follows:

$$Cost\ Effectiveness\ = \frac{TAC}{PM\ Removed/yr} \tag{1.31}$$

where:

Cost Effectiveness = the cost effectiveness, \$/ton
PM Removed/yr = annual mass of particulate removed by the fabric filter, ton/yr
TAC = total annual cost, \$/year.

1.7 Methods for Estimating Costs of Fabric Filter Modifications to Increase Removal of Particulates

In this section, we present methods for estimating costs for two modifications to existing baghouses that are designed to increase the removal of particulates.

1.7.1 Estimating Costs for Upgrading Existing Filter Bags

As discussed in section 1.3.3, lower particulate emissions can be achieved by replacing existing bags with upgraded filter bags. For example, replacing standard fiberglass filter bags with new filter bags that have a PTFE membrane coating can significantly reduce emissions. If the upgrade is performed during a normally scheduled bag filter replacement, no additional costs for labor would be incurred as the replacement does not require any additional changes to the fabric filter. Hence, the cost of upgrading fabric filter bags on an existing baghouse is the difference in cost between the standard filter bags and the PTFE membrane filter bags.

Cost of Filter Bag Upgrade = Number of Bags x (Cost of Upgraded Bags – Cost of Standard Bag)

1.7.2 Estimating Costs for Increased Frequency of Filter Bag Replacement

Another method for decreasing particulate emissions is to increase the frequency of filter bag replacement, which is mentioned in section 1.3.3. The incremental costs are calculated as follows:

Incremental Replacement Costs (\$/year) = New Replacement Costs – Current Replacement Costs

where:

$$Current\ Replacement\ Cost = \frac{(Number\ of\ Bags) \times (Bag\ Price + Labor\ Cost)}{Current\ Replacement\ Frequency}$$

$$New\ Replacement\ Cost = \frac{(Number\ of\ bags) \times (Bag\ Price + Labor\ Cost)}{New\ Replacement\ Frequency}$$

Where the replacement frequency is the number of years between filter bag replacement.

In the methodology presented in section 1.6.2, the cost for replacing the filter bags and cages is an annualized costs based on the expected equipment life and the interest rate. Use the following equations to calculate the increase in annualized costs for replacing filter bags and cages more frequently:

$$Current\ Annual\ Replacement\ Cost =$$

$$N\ \times [CCRF_{Bag} \times ((BC \times 1.08) + L_{Bag}) + (CCRF_{Cage} \times \left((CC \times 1.08) + L_{cage}\right))]$$

$$New\ Annual\ Replacement\ Cost =$$

$$N\ \times [NCRF_{Bag} \times ((BC \times 1.08) + L_{Bag}) + (NCRF_{Cage} \times \left((CC \times 1.08) + L_{cage}\right))]$$

Incremental Annual Increase in Cost = New Replacement Cost - Current Replacement Cost

where:

N = Number of bags
BC = Unit price for one bag
CC = Unit price for one cage
L_{Bag} = Labor cost to replace one bag.
L_{Cage} = Labor cost to replace one cage.
$CCRF_{Bag}$ = Current Capital Recovery Factor for bags based on replacing bags once every “h” years.
$CCRF_{Cage}$ = Current Capital Recovery Factor for cages based on replacing cages once every “i” years.
$NCRF_{Bag}$ = Current Capital Recovery Factor for bags based on replacing bags once every “j” years.
$NCRF_{Cage}$ = New Capital Recovery Factor for cages based on replacing cage once every “k” years.

The labor costs for replacing the filter bags can be calculated as described in Section 1.5.2 by multiplying the number of bags by the estimated time required to replace one bag and the hourly labor rate. Impacts on the other operating and maintenance costs, such as power and waste disposal, are expected to be minimal.

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