Chapter 5

FABRIC FILTERS

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5.1 Process Description

5.1.1 Introduction

A fabric filter unit consists of one or more isolated compartments containing rows of fabric bags in the form of round, flat, or shaped tubes, or pleated cartridges. Particle-laden gas passes up (usually) along the surface of the bags then radially through the fabric. Particles are retained on the upstream face of the bags, and the cleaned gas stream is vented to the atmosphere. The filter is operated cyclically, alternating between relatively long periods of filtering and short periods of cleaning. During cleaning, dust that has accumulated on the bags is removed from the fabric surface and deposited in a hopper for subsequent disposal.

Fabric filters collect particles with sizes ranging from submicron to several hundred microns in diameter at efficiencies generally in excess of 99 or 99.9 percent. The layer of dust, or dust cake, collected on the fabric is primarily responsible for such high efficiency. The cake is a barrier with tortuous pores that trap particles as they travel through the cake. Gas temperatures up to about 500°F, with surges to about 550°F can be accommodated routinely in some configurations. Most of the energy used to operate the system appears as pressure drop across the bags and associated hardware and ducting. Typical values of system pressure drop range from about 5 to 20 inches of water. Fabric filters are used where high-efficiency particle collection is required. Limitations are imposed by gas characteristics (temperature and corrosivity) and particle characteristics (primarily stickiness) that affect the fabric or its operation and that cannot be economically accommodated.

Important process variables include particle characteristics, gas characteristics, and fabric properties. The most important design parameter is the air- or gas-to-cloth ratio (the amount of gas in ft^3/min that penetrates one ft^2 of fabric) and the usual operating parameter of interest is pressure drop across the filter system. 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. Common furnace filters, high efficiency particulate air (HEPA) filters, high efficency air filters (HEAFs), and automotive induction air filters are examples of filters that must be discarded after a significant layer of dust accumulates on the surface. These filters are typically made of matted fibers, mounted in supporting frames, and used where dust concentrations are relatively low. Fabric filters are usually made of woven or (more commonly) needlepunched felts sewn to the desired shape, mounted in a plenum with special hardware, and used across a wide range of dust concentrations.

Another type of fabric filter developed in the 1970s and 1980s is the electrostatically enhanced filter. Pilot plant baghouses employing this technology have shown substantially lower pressure drops than conventional filter designs. Further, some cost analyses have shown that electrostatically enhanced baghouses could have lower lifetime costs than convention baghouses. The purpose of this chapter, however, is to focus only on currently available commercial filters. Readers interested in electrostatically enhanced filtration may consult such references as Van Osdell *et al.* [1], Viner *et al.* [2], or Donovan [3].

In this section, the types of fabric filters and the auxiliary equipment required are discussed first from a general viewpoint. Then, fabric filtration theory as applied to each type of filter is discussed to lay a foundation for the sizing procedures outlined in the Section 5.2.

5.1.2 Types of Fabric Filters

Fabric filters can be categorized by several means, including type of cleaning (shaker, reverse-air, pulse-jet), direction of gas flow (from inside the bag towards the outside or vice versa), location of the system fan (suction or pressure), or size (low, medium, or high gas flow quantity). Of these four approaches, the cleaning method is probably the most distinguishing feature. Fabric filters are discussed in this section based on the type of cleaning employed.

5.1.2.1 Shaker Cleaning

For any type of cleaning, enough energy must be imparted to the fabric to overcome the adhesion forces holding dust to the bag. In shaker cleaning, used with inside-to-outside gas flow, energy transfer is accomplished by suspending the bag from a motor-driven hook or framework that oscillates. 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 descend to the hopper.

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. Forward gas flow to the compartment is stopped, dust is allowed to settle, residual gas flow stops, 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 for filtering. As a result of no forward flow through the compartment, the baghouse collecting area must be increased to compensate for that portion being out of service at any time for cleaning. Figure 5.1 illustrates a shaker-cleaned baghouse.

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 values are about 4 Hz for frequency and 2 to 3 inches for amplitude (half-stroke).[4] Some installations allow easy adjustment of bag tension, while others require that the bag be loosened and reclamped to its attaching thimble.

Compared with reverse-air cleaned bags (discussed below) the vigorous action of shaker systems tends to stress the bags more, which requires heavier and more durable fabrics. In the United States, woven fabrics are used almost exclusively for shaker cleaning.[5] European practice allows the use of felted fabrics at somewhat higher filtering velocities. These higher velocities allow construction of a smaller baghouse, which requires less capital. However, the higher velocities lead to higher pressure drop, which increases operating costs. For any given application, an economic balance exists that must often be found by estimating costs for both types of fabric. Significant research has been done with shaker baghouses and the woven fabrics used in them, and many shaker baghouses remain in service. However, the majority of newly erected baghouses are pulse jets. Where baghouses larger than typical pulse jets are required, they are often custom-built, reverse-air units. The pulse-jet baghouses have become popular because they occupy less space than the equivalent shaker baghouse and are perceived as being less expensive. For high-temperature applications using glass bags, longer bag life may be expected than would be found with shaker baghouses.

5.1.2.2 Reverse-air Cleaning

When glass fiber fabrics were introduced, a gentler means of cleaning the bags, which may be a foot in diameter and 30 feet in length, was needed to prevent premature degradation. Reverse-air cleaning was developed as a less intensive way to impart energy to the bags. In reverse-air cleaning, gas flow to the bags is stopped in the compartment being cleaned and reverse (outside-in) air flow is directed through the bags. This reversal of gas flow gently collapses the bags toward their centerlines, which causes the cake to detach from the fabric surface. The detachment is caused by shear forces developed between the dust and fabric as the latter changes its shape. 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

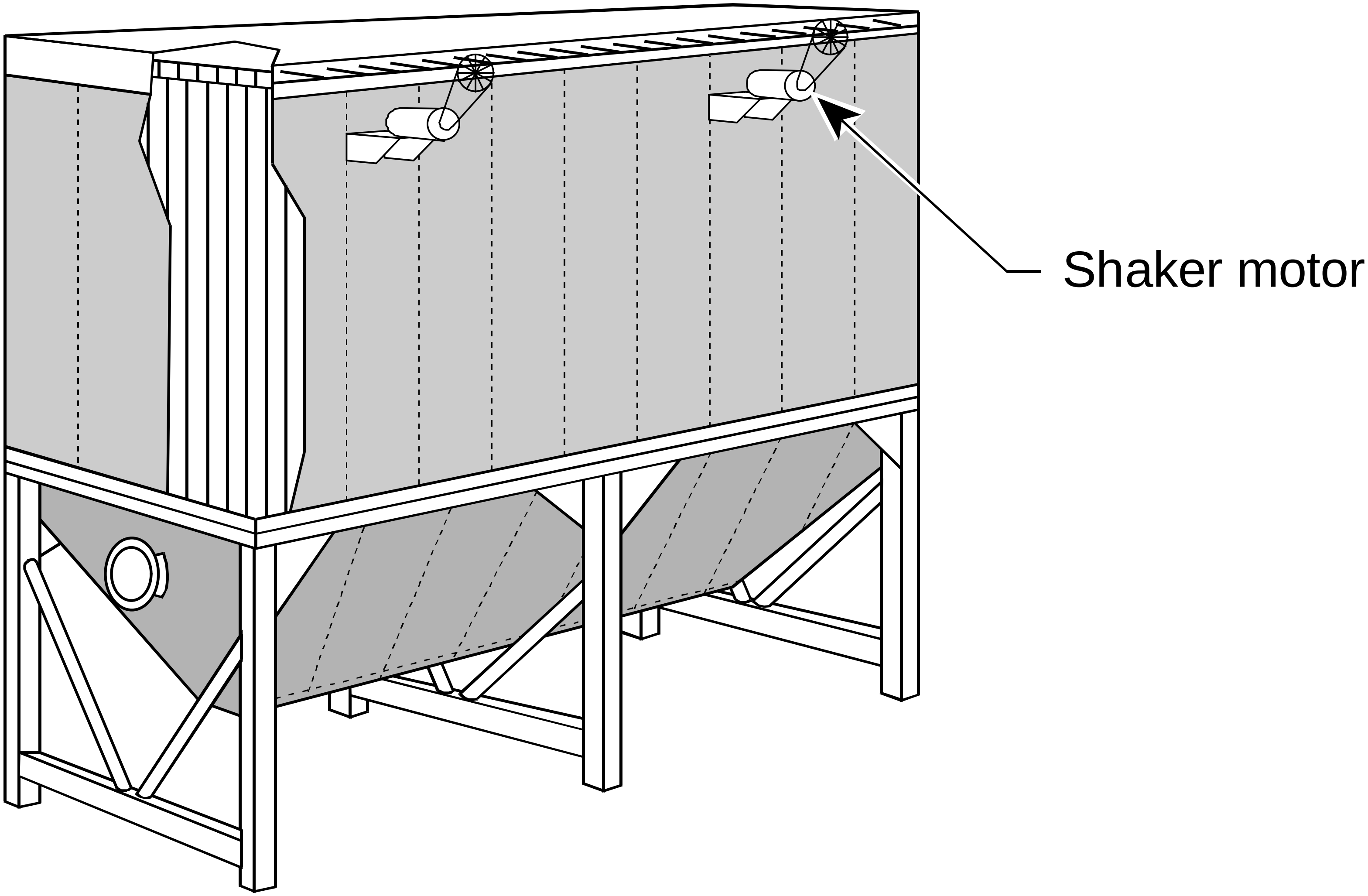

Figure 5.1: Typical Shaker Baghouse
(Courtesy of North Carolina State University)

cleaning. Without these rings, falling collected dust tends to choke the bag as the fabric collapses in on itself while cleaning. As with multi-compartment shaker baghouses, a similar cycle takes place in reverse-air baghouses of stopping forward gas flow and allowing dust to settle before cleaning action begins. Also, as with shaker baghouses, extra filtering capacity must be added to reverse-air baghouses to compensate for that portion out of service for cleaning at any time. Some reverse-air baghouses employ a supplemental shaker system to assist cleaning by increasing the amount of energy delivered to the bag.

The source of reverse air is generally a separate system fan capable of supplying clean, dry air for one or two compartments at a gas-to-cloth ratio as high or higher than that of the forward gas flow. Figure 5.2 illustrates a reverse-air cleaned baghouse.

5.1.2.3 Pulse-jet Cleaning

An advantage of pulse-jet cleaning compared to shaker or reverse-air baghouses is the reduction in baghouse size (and capital cost) allowed by using less fabric because of higher gas-to-cloth ratios and, in some cases, by not having to build an extra compartment for off-line cleaning. However, the higher gas-to-cloth ratios cause higher pressure drops that increase operating costs. This form of cleaning uses compressed air to force a burst of air down through the bag and expand it violently. As with shaker baghouses, the fabric reaches its extension limit and the dust separates from the bag. Air escaping through the bag carries the separated dust away from the fabric surface. In pulse jets, however, filtering gas flows are opposite in direction when compared with shaker or reverse-air baghouses *(i.e.*, outside-in). Figure 5.3 illustrates a pulse-jet cleaned baghouse.

5.1.2.3.1 Caged Filters

In conventional pulse-jet baghouses, bags are mounted on wire cages to prevent collapse while the dusty gas flows from outside the bag to the inside during filtration. Instead of attaching both ends of the bag to the baghouse structure, the bag and cage assembly generally is attached only at the top. The bottom end of the assembly tends to move in the turbulent gas flow during filtration and may rub other bags, which accelerates wear.

Often, pulse-jet baghouses are not compartmented. Bags are cleaned one row at a time when a timer initiates the burst of cleaning air through a quick-opening valve. A pipe across each row of bags carries the compressed air. The pipe has a nozzle above each bag so that cleaning air exits directly into the bag. Some systems direct the air through a short venturi that is intended to entrain additional cleaning air. The pulse opposes and interrupts forward

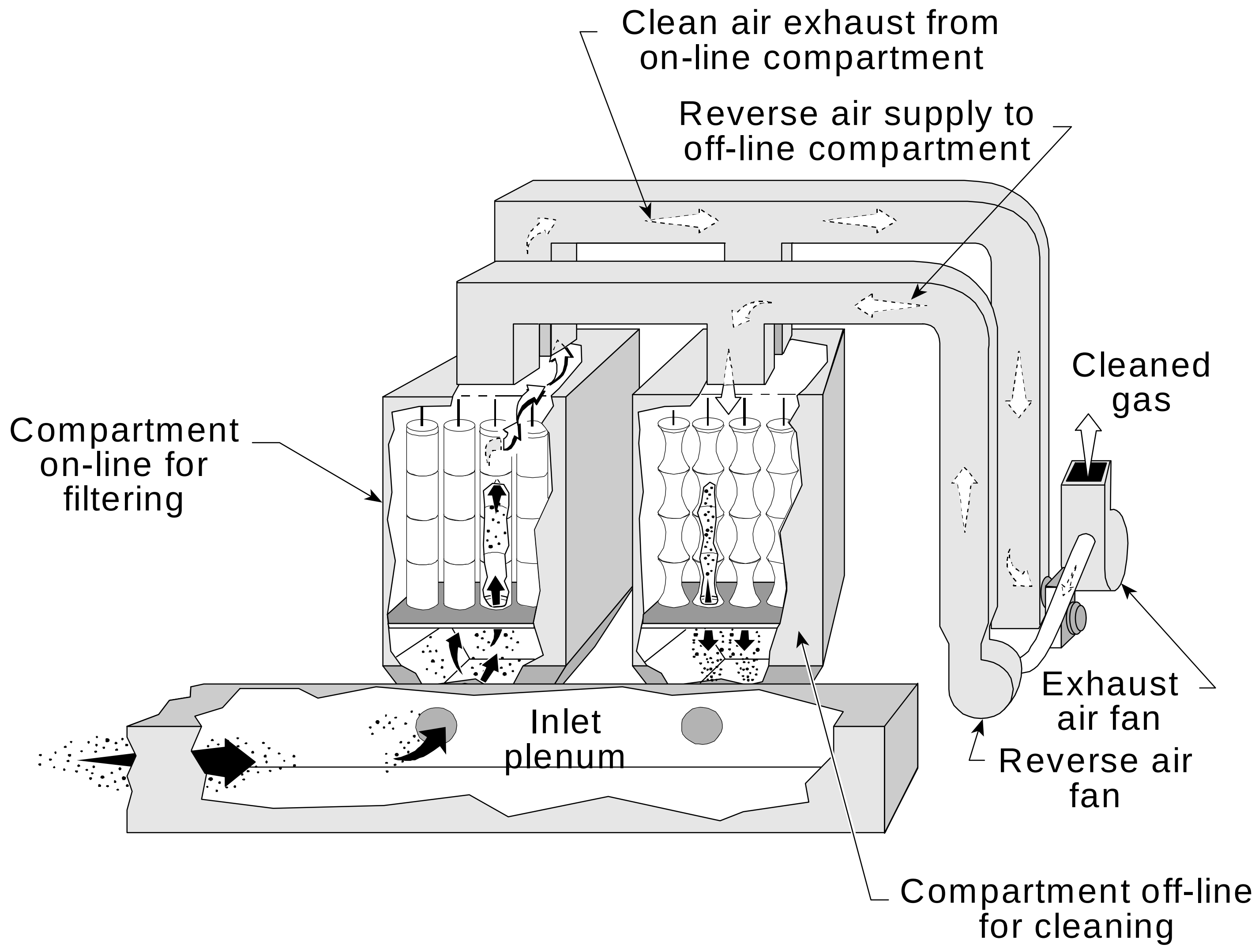

Figure 5.2: Typical Reverse-Air Baghouse
(Courtesy of North Carolina State University)

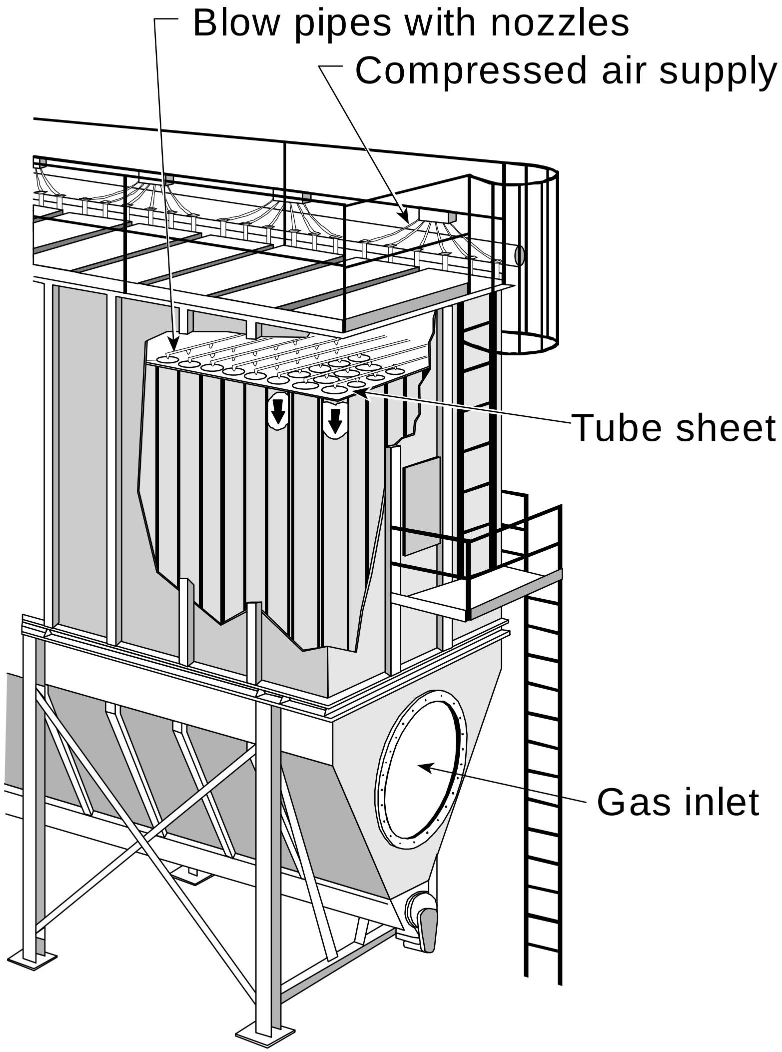

Figure 5.3: Typical Pulse-Jet Baghouse
(Courtesy of North Carolina State University)

gas flow for only a few tenths of a second. However, the quick resumption of forward flow redeposits most of the dust 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.

To increase filter area in the same volume of baghouse, star-shaped and pleated (in cross section) bag/cage configurations have been developed. The bag/cage combination is designed as a unit to be installed similarly to a standard bag and cage unit. Such units can be used as replacements for standard bags and cages when additional fabric area is needed, or may be used in original designs. Normal pulse cleaning is used, i.e., no special changes to the cleaning equipment are required. Costs for star-shaped bags and cages are about three to three-and-a-half times normal bags and cages.

5.1.2.3.2 Cartridge Filters

Further increases in filter area per unit of baghouse volume are obtained by using finely pleated filter media supported on a wire framework. This cartridge can be mounted vertically as a nearly direct replacement for standard bags and cages in existing baghouses, or mounted horizontally in original designs. When used as a direct replacement for standard bags and cages, retrofit costs for one case are 70 % of the cost of building a new baghouse.[6] Cleaning of early cartridge baghouse designs is by typical pulse equipment using a blow pipe across a row of cartridges. More recent designs use individual air valves for each pair of cartridges.

One type of cartridge[7] 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. Cleaning air is pulsed through the same open end, but in a reverse direction from the gas being cleaned. 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. Horizontal cartridges are typically 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.

Filter media for cartridges may be paper, spunbonded monofilament plastics (polyester is predominant), or nonwoven fabrics. Cartridges may be from 6 in. to 14 in. in diameter and 16 in. to 36 in. in length. The filtering surface is from about 25 ft^2 to 50 ft^2 for cartridges with nonwoven fabrics, about three to four times as much with spunbondeds, and more than six times as much with paper. A typical cartridge may have 36 ft^2 of nonwoven fabric, 153 ft^2 of spunbonded fabric, or 225 ft^2 of paper. Pleat spacing is important for two reasons: closer spacing increases filter area for a specific cartridge volume, but closer spacing increases the likelihood of dust permanently bridging the bottoms of the pleats and reducing available filtering area. For nonagglomerating dusts of small particle size, (up to a few micrometers) and benign characteristics for paper, the cartridge may have 12 pleats/in. to 16 pleats/in. Nonwovens under more difficult conditions may have 4 pleats/in. to 8 pleats/in. Pleat depth is 1 in. to 3 in. Pleat arrangement and available volume of cleaning air determine the cleanability of the media for a specific dust. An advantage of paper media is their ability to collect particles less than 2.5 µm in diameter with high efficiency. Overall efficiency can be 99.999+ percent. Nonwoven media may be an order of magnitude less efficient. However, even glass fiber bags in reverse-air baghouses on combustion sources can collect 2.5 µm particles with 99.9 percent efficiency.

Cartridge filters are limited in temperature by the adhesives that seal the media to the end caps. Operating temperatures of 200 °F are common, with temperature capability to 350 °F soon to be marketed. Figure 5.4 illustrates a cartridge collector.

5.1.2.4 Sonic Cleaning

Because reverse-air cleaning is a low-energy method compared with shaking or pulse-jet cleaning, additional energy may be required to obtain adequate dust removal. Shaking, as described above, is one such means of adding energy, but another is adding vibrational energy in the low end of the acoustic spectrum. Sonic horns powered by compressed air are a typical means of applying this energy. The horns (1 to several per compartment for large baghouses) typically operate in the range of 125 to 550 Hz (more frequently in the 125 to 160 Hz range) and produce sound pressures of 120 to 145 db. When properly applied, sonic energy can reduce the mass of dust on bags considerably, but may also lead to increased dust penetration through the fabric. Increased penetration reduces the efficiency of the baghouse. Sonic horns are effective as supplemental equipment for some applications that require added energy for adequate cleaning, Occasionally sonic horns are used as the only source of cleaning energy.

Horn construction includes a horn-shaped outlet attached to an inlet chamber containing a diaphragm. Compressed air at 45 to 75 psig enters the chamber, vibrates the diaphragm, and escapes through the horn. Sound waves leaving the horn contact and vibrate dust-containing fabric with sufficient energy to loosen or detach patches of dust that fall through the bag to the hopper below. Compressed air consumption varies from 45 to 75 scfm depending on the size

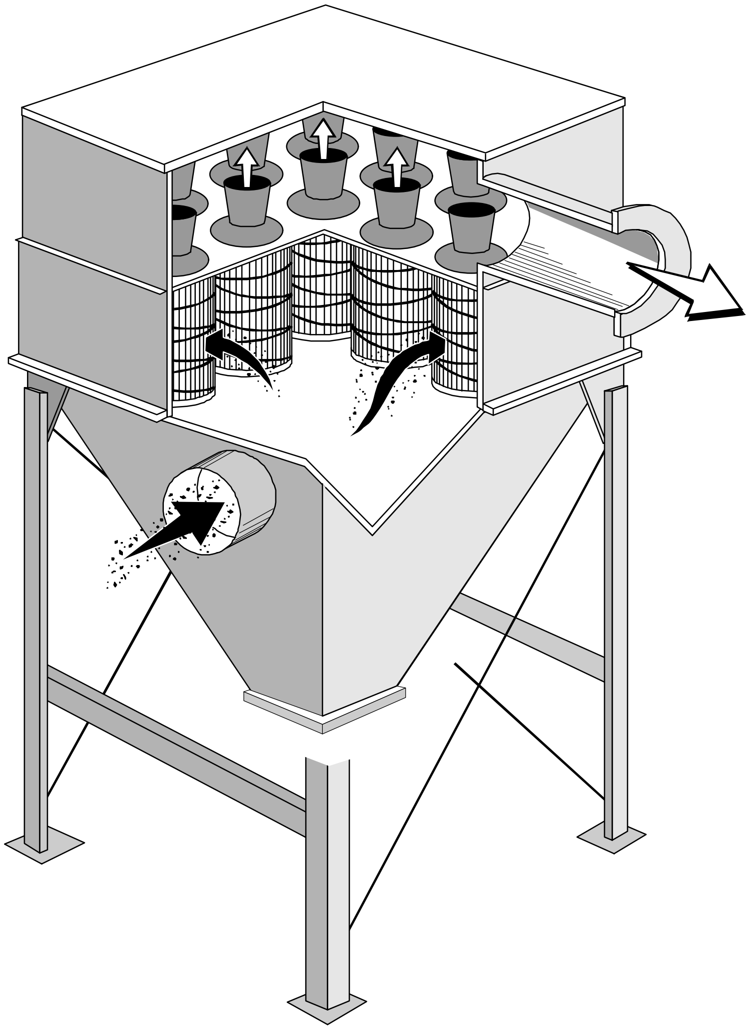

Figure 5.4: Typical Vertical-Mount Cartridge Baghouse
(Courtesy of North Carolina State University)

of the horn. 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.

An example of sonic horn usage is a 10-compartment, reverse-air baghouse cleaning combustion gases at 835,000 acfm. Bags being cleaned are 12 in. in diameter and 35 ft in length. Each compartment has a horn mounted in each of the four corners and angled towards the center of the compartment. Compartments are cleaned every 30 minutes with reverse air for 1 minute and sonic horns for 30 seconds during the reverse-air cleaning. The horns operate at 75 psig and consume 65 scfm of compressed air. For baghouses requiring less intensive cleaning, the cleaning cycle might be extended to 1 hour or more.

For a 6-compartment baghouse requiring 1 horn per compartment, the system investment for horns was $13,500 (the BHA Group). The installed horns operated at 125 Hz and used 75 scfm of compressed air at 75 psig. In this case, each horn cleaned 8,500 ft^2 of fabric. The same size horn can clean up to 15,000 ft^2 of fabric.

5.1.3 Auxiliary Equipment

The typical auxiliary equipment associated with fabric filter systems is shown in Figure 5.5. Along with the fabric filter itself, a control system typically includes the following auxiliary equipment: a capture device (*i.e.*, hood or direct exhaust connection); ductwork; dust removal equipment (screw conveyor, etc.); fans, motors, and starters; and a stack. In addition, spray chambers, mechanical collectors, and dilution air ports may be needed to precondition the gas before it reaches the fabric filter. Capture devices are usually hoods or direct exhaust couplings attached to a process vessel. 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 control device and stack. Spray chambers and dilution air ports decrease the temperature of the pollutant 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), mechanical collectors such as cyclones are used to reduce the load on the fabric filter. Fans provide motive power for air movement and can be mounted before (pressure baghouse) or after (suction baghouse) the filter. Stacks, when used, vent the cleaned stream to the atmosphere. Screw conveyors are often used to remove captured dust from the bottom of the hoppers under the fabric filter and (if used) mechanical collector. Air conveying (pneumatic) systems and direct dumping into containers are also used as alternate means for dust removal from the hoppers.

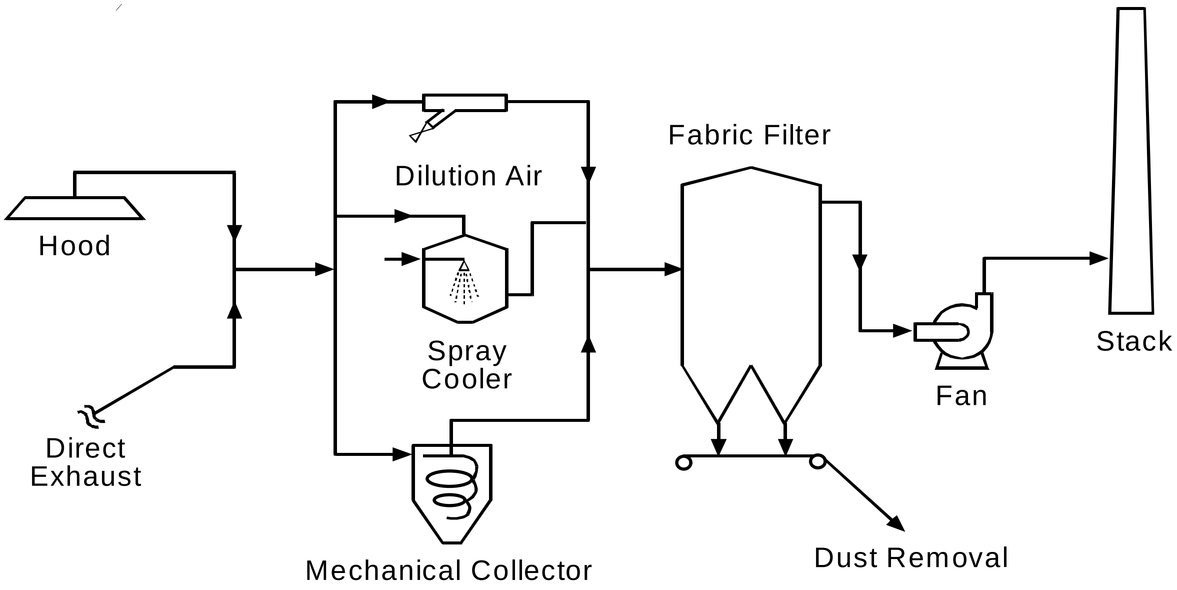

Figure 5.5: Typical alternative auxiliary equipment items used with fabric filter control systems.

5.1.4 Fabric Filtration Theory

The key to designing a baghouse is to determine the face velocity that produces the optimum balance between pressure drop (operating cost that increases as pressure drop increases) and baghouse size (capital cost that decreases as the baghouse size is reduced). Baghouse size is reduced as the face velocity (or gas-to-cloth ratio) is increased. However, higher gas-to-cloth ratios cause higher pressure drops. Major factors that affect design gas-to-cloth ratio, discussed in Section 5.2, include particle and fabric characteristics and gas temperature.

Although collection efficiency is another important measure of baghouse performance, a properly designed and well run baghouse will generally have an extemely high particulate matter (PM) collection efficiency (i.e., 99.9+ percent). Baghouses are particularly effective for collecting small particles. For example, tests of baghouses on two utility boilers[8],[9] showed efficiencies of 99.8 percent for particles 10 µm in diameter and 99.6 percent to 99.9 percent for particles 2.5 µm in diameter. 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[3] 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 $70,000 (in 1998).

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.[1]

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 gas-to-cloth 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.[10][11][12] Knowledge of the effects can lead to selection of fabrics that interact favorably regarding dust collection and cleaning.

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

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[1] A procedure for estimating duct pressure losses is given in chapter 10 ("Hoods, Ductwork, and Stacks") of this *Manual*.

5.1.4.1 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:

$$\Delta P(\theta) = S_{sys}(\theta) V_{f\ (avg.)} \tag{5.1}$$

where

$\Delta P(\theta)$ = the pressure drop across the filter, a function of time, θ (in. H_2O)
$S_{sys}(\theta)$ = system drag, a function of time [in. H_2O/(ft/min)]
$V_{f\ (avg.)}$ = average (*i.e.*, design) face velocity or G/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:[13]

$$S_{sys}(\theta) = \left[\frac{1}{M}\sum_{i=1}^{M}\frac{1}{S_i(\theta)}\right]^{-1} = \frac{1}{\frac{1}{M}\sum_{i=1}^{M}\frac{1}{S_i(\theta)}} = \frac{M}{\sum_{i=1}^{M}\frac{1}{S_i(\theta)}} \tag{5.2}$$

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:

$$S_{i,j}(\theta) = S_e + K_2 W_{i,j}(\theta) \tag{5.3}$$

where

S_e = drag of a dust-free filter bag [in. H_2O/(ft/min)]
K_2 = dust cake flow resistance {[in. 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 5.2:

$$S_i(\theta) = \frac{N}{\sum \frac{1}{S_{i,j}(\theta)}} \tag{5.4}$$

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:

$$W_{i,j}(\theta) = W_r + \int_0^{\theta} C_{in}\ V_{i,j}(\theta)\ d\theta \tag{5.5}$$

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, (gas-to-cloth 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:

$$V_{avg} = \frac{\sum_i \sum_j V_{i,j}(\theta)\ A_{i,j}}{\sum_i \sum_j A_{i,j}} \tag{5.6}$$

$$= \frac{\sum_i \sum_j V_{i,j}(\theta)}{M}$$

(for M compartments with equal area)

Equations 5.1 through 5.6 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 5.1 through 5.5, with Equation 5.6 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 5.1 through 5.6 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 [13].

5.1.4.2 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[14] proposed the following model of drag across a pulse-jet filter:

$$S = S_e + (K_2)_c \mathrm{W}_c + K_2 W_o \tag{5.7}$$

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 5.1 to 5.6, the drag, filtration velocity and areal densities are functions of time, θ. 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:

$$\Delta P = (PE)_{\Delta w} + K_2 W_o V_f \tag{5.8}$$

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 5.8 describes the pressure drop behavior of an individual bag. To extend this single bag result to a multiple-bag compartment, Equation 5.7 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 5.1. It seems reasonable to extend this analysis to the case when the dust is distributed unevenly on the bag and then apply Equation 5.7 to each area on the bag, followed by an equation analogous to 5.4 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 5.7 and 5.8 is that the constants, S_e, $(K_2)_c$, and W_c, cannot be predicted at this time. Consequently, correlations of laboratory data must be used to determine the value of $(PE)_{\Delta w}$. For the fabric-dust combination of Dacron felt and coal fly ash, Dennis and Klemm[14] 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:

$$(PE)_{\Delta w} = 6.08 V_f P_j^{-0.65} \tag{5.9}$$

where

V_f = face velocity, (ft/min)
P_j = pressure of the cleaning pulse
(usually 60 to 100 psig; see Section 5.4.1)

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 5.9 may not be valid for other dusts or fabrics. Consequently, more data should be collected and analyzed before the model represented by Equation 5.9 can be used for rigorous sizing purposes.

Another model that shows promise in the prediction of noncake filtration pressure drop is that of Leith and Ellenbecker[15] as modified by Koehler and Leith.[16] In this model, the tube-sheet pressure drop is a function of the clean fabric drag, the system hardware, and the cleaning energy. Specifically:

$$\Delta P = \frac{1}{2}\left[P_s + K_1 V_f - \sqrt{(P_s - K_1 V_f)^2 - 4 W_o K_2 / K_3}\right] + K_v V_f^2 \tag{5.10}$$

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 5.10 [15,16] are in close agreement for a variety of dust/fabric combinations. The disadvantage of Equation 5.10 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.

5.2 Design Procedures

The design procedure requires estimating a gas-to-cloth 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. Estimating a gas-to-cloth ratio that is too high, compared to a correctly estimated gas-to-cloth ratio, leads to higher pressure drops, higher particle penetration (lower collection efficiency), and more frequent cleaning that leads to reduced fabric life. Estimating a gas-to-cloth ratio that is too low increases the size and cost of the baghouse unnecessarily. Each of the parameters for design is discussed below.

5.2.1 Gas-to-Cloth Ratio

The gas-to-cloth 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 gas-to-cloth ratios and for reverse-air or shaker baghouses at their application-specific gas-to-cloth ratios.

The methods outlined below pertain to conventional baghouses. Use of electrostatic stimulation may allow a higher gas-to-cloth ratio at a given pressure drop; thus a smaller baghouse structure and fewer bags are needed. Viner and Locke[17] 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 gas-to-cloth ratios, but do allow installation of more fabric in a given volume.

5.2.1.1 Gas-to-Cloth Ratio From Similar Applications

After a fabric has been selected, an initial gas-to-cloth ratio can be determined using Table 5.1. Column 1 shows the type of dust; column 2 shows the gas-to-cloth ratios for woven fabric; and column 3 shows gas-to-cloth ratios for felted fabrics. Notice that these values are all *net* gas-to-cloth 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 5.2. The net cloth area is determined by dividing the exhaust gas flow rate in actual cubic feet per minute (acfm) by the design gas-to-cloth 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 5.2 provides a guide for adjusting the net area to the gross area, which determines the size of a filter requiring off-line cleaning.

5.2.1.2 Gas-to-Cloth Ratio From Manufacturer's Methods

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

For shaker baghouses, Table 5.3 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. Gas-to-cloth ratios for reverse-air baghouses would be about the same or a little lower compared to the Table 5.3 values.

Table 5.1: Gas-to-Cloth Ratios for Baghouse/Fabric Combinations[a,b]
(actual $ft^3/min)/(ft^2$ of net cloth area)

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
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] Reference[18]

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

Table 5.2: 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	Multiply by	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] Reference[19].

For pulse-jet baghouses, which normally operate at two or more times the gas-to-cloth ratio of reverse-air baghouses, another factor method[20] has been modified with equations to represent temperature, particle size, and dust load:

$$V = 2.878\ A\ B\ T^{-0.2335}\ L^{-0.06021}\ (0.7471 + 0.0853 \ln D) \tag{5.11}$$

where

V = gas-to-cloth ratio (ft/min)
A = material factor, from Table 5.4
B = application factor, from Table 5.4
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,

Table 5.3: Manufacturer's Factor Method for Estimating Gas-to-cloth Ratios for Shaker Baghouses

A

4/1 RATIO	
Material	**Operation**
Cardboard	1
Feeds	2, 3, 4, 5, 6, 7
Flour	2, 3, 4, 5, 6, 7
Grain	2, 3, 4, 5, 6, 7
Leather Dust	1, 7, 8
Tobacco	1, 4, 6, 7
Supply Air	13
Wood, Dust, Chips	1, 6, 7

CUTTING - 1
CRUSHING - 2
PULVERIZING - 3

3/1 RATIO	
Material	**Operation**
Asbestos	1, 7, 8
Aluminum Dust	1, 7, 8
Fibrous Mat'l	1, 4, 7, 8
Cellulose Mat'l	1, 4, 7, 8
Gypsum	1, 3, 5, 6, 7
Lime (Hydrated)	2, 4, 6, 7
Perlite	2, 4, 5, 6
Rubber Chem.	4, 5, 6, 7, 8
Salt	2, 3, 4, 5, 6, 7
Sand*	4, 5, 6, 7, 9, 15
Iron Scale	1, 7, 8
Soda Ash	4, 6, 7
Talc	3, 4, 5, 6, 7
Machining Operation	1, 8

MIXING - 4
SCREENING - 5
STORAGE - 6

2.5/1 RATIO	
Material	**Operation**
Alumina	2, 3, 4, 5, 6
Carbon Black	4, 5, 6, 7
Cement	3, 4, 5, 6, 7
Coke	2, 3, 5, 6
Ceramic Pigm.	4, 5, 6, 7
Clay and Brick Dust	2, 4, 6, 12
Coal	2, 3, 6, 7, 12
Kaolin	4, 5, 7
Limestone	2, 3, 4, 5, 6, 7
Rock, Ore Dust	2, 3, 4, 5, 6, 7
Silica	2, 3, 4, 5, 6, 7
Sugar	3, 4, 5, 6, 7

CONVEYING - 7
GRINDING - 8
SHAKEOUT - 9

2/1 RATIO	
Material	**Operation**
Ammonium Phosphate Fertilizer	2, 3, 4, 5, 6, 7
Diatomaceous Earth	4, 5, 6, 7
Dry Petrochem.	2, 3, 4, 5, 6, 7, 14
Dyes	2, 3, 4, 5, 6, 7
Fly Ash	10
Metal Powders	2, 3, 4, 5, 6, 7, 14
Plastics	2, 3, 4, 5, 6, 7, 14
Resins	2, 3, 4, 5, 6, 7, 14
Silicates	2, 3, 4, 5, 6, 7, 14
Starch	6, 7
Soaps	3, 4, 5, 6, 7

FURNACE FUME - 10
REACTION FUME - 11
DUMPING - 12

1.5/1 RATIO	
Material	**Operation**
Activated Carbon	2, 4, 5, 6, 7
Carbon Black	11, 14
Detergents	2, 4, 5, 6, 7
Metal Fumes, Oxides and other Solid Dispersed Products	10, 11

INTAKE CLEANING - 13
PROCESS - 14
BLASTING - 15

B

FINENESS FACTOR

Micron Size	Factor
> 100	1.2
50 - 100	1.1
10 - 50	1.0
3 - 10	0.9
1 - 3	0.8
< 1	0.7

C

DUST LOAD FACTOR

Loading gr/cu ft	Factor
1 - 3	1.2
4 - 8	1.0
9 - 17	0.95
18 - 40	0.90
> 40	0.85

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.

$$3{,}500\ \frac{lb}{hr} \div 60\ \frac{min}{hr} \div 26{,}000\ \frac{cu\ ft}{min}\ x\ 7{,}000\ \frac{gr}{lb} = 15.7\ \frac{gr}{cu\ ft}$$

*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 5.4: Factors for Pulse-Jet Gas-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 Fiborous and cellulosic material Foundary shakeout Gypsum Lime (hydrated) Perlite Rubber chemicals Salt Sand Sandblast dust Soda ash Talc	Alumina Aspirin Carbon black (finished) Cement Ceramic pigments Clay and brick dusts Coal Fluorspar Gum, natural Kaolin Limestone Perchlorates Rock dust, ores and 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 (molecular) Detergents Fumes and other dispersed products direct 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] Reference [20]

[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.

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 5.5 provides the factors.

5.2.1.3 Gas-to-Cloth Ratio From Theoretical/Empirical Equations

Shaker and reverse-air baghouses The system described by Equations 5.1 through 5.6 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 5.1 through 5.6, 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.*[13] 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.[14],[21],[22] 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 5.1 through 5.6, 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

Table 5.5: Manufacturer's Factor Method for Estimating Gas-to-Cloth Ratio for Horizontal Cartridge Baghouses

Factor A Table for Selected Materials

	2.5	**2.1**	**1.9**	**1.3**	**Dust Sample Required**
MATERIALS	Rock dust and ores Salt, Mineral[a] Sand (Not foundry)	Activated carbon Alumina (transfer) Cake Mix[a] 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[a] Welding fumes	Fertilizers[a] Talc	Alumina (air lift) Dyes Fumes, metallurgical Pigments, paint Stearates	Detergents Feeds Grains Perlite Pharmaceuticals Powdered milk Resins Soap Tobacco
			1.7	**0.7**	**Excluded dusts**
			Aspirin Cement Clay & brick dust Cocoa[a] Coffee[a] 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

[a] Under controlled humidity (40 %R.H.) And room temperature only.

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

For example, G/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.

Courtesy of Hosokawa Mikropul

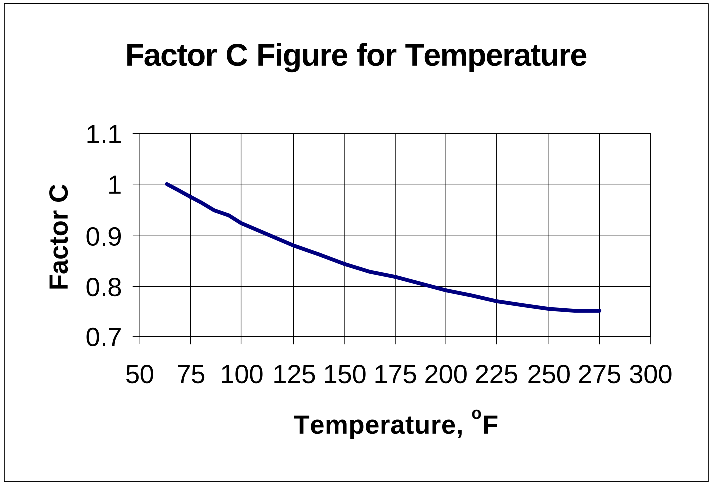
Table 5.5: (Cont.)

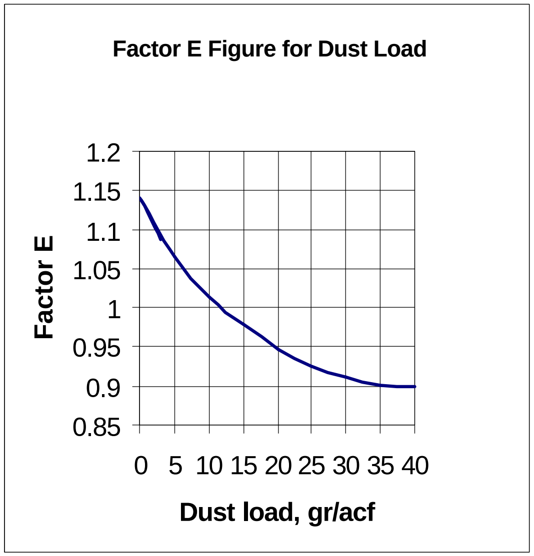
Factor B Table for Applications

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

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





Courtesy of Hosokawa Mikropul

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.*[13,22] A critique on the accuracy of the model is presented by Viner *et al.*[23]

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 5.9 or Equation 5.10 from field, pilot plant, or laboratory measurements. Fourth, a value is estimated for the face velocity and the appropriate equation (Equation 5.8 or 5.10) 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.

5.2.2 Pressure Drop

Pressure drop for the bags 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 5.1 and 5.3 that may be used for estimating the maximum pressure drop across the fabric in a shaker or reverse-air baghouse is:

$$\Delta P = S_e V + K_2 C_i V^2 \theta \tag{5.12}$$

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 gas-to-cloth ratio (ft/min)
K_2 = specific resistance coefficient of the dust {[in. 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 5.8 and 5.9 to estimate ΔP, after substituting $C_iV\theta$ for W_o and $(PE)_{\Delta w}$ for S_eV.

5.2.3 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 5.3 and 5.5 and Equation 5.11, the effect of decreasing average particle size is a lower applicable gas-to-cloth 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.

5.2.4 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.)

5.2.4.1 Temperature

The temperature of the pollutant stream must remain above the dew point of any condensables 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, precooling 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" section of the *Manual [to be written]*) Table 5.6 lists several of the fabrics in current use and provides information on temperature limits and chemical resistance. The column labeled "Flex Abrasion" indicates the fabric's suitability for cleaning by mechanical shakers.

5.2.4.2 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.

5.2.5 Equipment Design Considerations

5.2.5.1 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.

Table 5.6 Properties of Leading Fabric Materials[a]

Fabric	Temp °F[b]	Acid Resistance	Alkali Resistance	Flex Abrasion
Cotton	180	Poor	Very good	Very good
Creslan[c]	250	Good in mineral acids	Good in weak alkali	Good to very good
Dacron[d]	275	Good in most mineral acids; dissolves partially in concentrated H_2SO_4	Good in weak alkali; fair in strong alkali	Very good
Dynel[e]	160	Little effect even at high concentration	Little effect even in high concentration	Fair to good
Fiberglas[f]	500	Fair to good	Fair to good	Fair
Filtron[e]	270	Good to excellent	Good	Good to very good
PTFE membrane	Depends on backing	Depends on backing	Depends on backing	Fair
Nextel[g]	1,400	Very good	Good	Good
Nomex[d]	375	Fair	Excellent at low temperature	Excellent
Nylon[d]	200	Fair	Excellent	Excellent
Orlon[d]	260	Good to excellent in mineral acids	Fair to good in weak alkali	Good
P84[h]	475	Good	Good	Good
Polypropylene	200	Excellent	Excellent	Excellent
Ryton[i]	375	Excellent	Excellent	Good
Teflon[d]	450	Inert except to fluorine	Inert except to trifluoride, chlorine, and molten alkaline metals	Fair
Wool	200	Very good	Poor	Fair to good

[a] Reference [24]

[b] Maximum continuous operating temperatures recommended by the Institute of Clean Air Companies.

[c] American Cyanamid registered trademark.

[d] Du Pont registered trademark.

[e] W. W. Criswell Div. of Wheelabrator-Fry, Inc. trade name.

[f] Owens-Corning Fiberglas registered trademark.

[g] 3M Company registered trademark

[h] Inspec Fibres registered trademark

[i] Phillips Petroleum Company registered trademark

5.2.5.2 Standard or Custom Construction

The design and construction of baghouses are separated into two groups, standard and custom. [19] Standard baghouses are further separated into low, medium, and high capacity size categories. Standard baghouses are predesigned 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.

5.2.5.3 Filter Media

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. Some applications are difficult, i.e., they have small or smooth particles that readily penetrate the cake and fabric, or have particles that adhere strongly to the fabric and are difficult to remove, or have some other characteristic that degrades particle collection or cleaning. For some of these applications Gore-Tex, a polytetrafluoroethylene (PTFE) membrane laminated to a fabric backing (felt or woven) may be used. Backing materials are chosen to be compatible with the application for which they are used. Other PTFE membrane laminated fabrics are supplied by Tetratec (Tetratex) and BHA (BHA-Tex). These membranes, because of their small pores (1 or 2 µm to less than 1 µm) are advantageous in being able to collect small particles almost immediately after filtration begins. In contrast, woven fabrics and nonwovens, (with pores about 10 µm to 100 µm) allow particles to penetrate the filter for a short time before the cake covering the fabric is reconstituted. Overall mass collection efficiency for a baghouse with membrane bags may not appear to be greater than a baghouse with other fabrics, but the efficiency may be greater for fine particles. For applications able to use paper media, cartridge filters can be particularly effective for particles in the submicron range.

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. Needlepunched felts are typically used for pulse-jet baghouses. These heavier fabrics are more durable than wovens 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°F), while of the commonly used fabrics, Fiberglas has the most (about 500°F).[2] If condensibles are contained in the gas stream, its temperature must be well above the dew point because liquid particles will usually plug the fabric pores within minutes or hours. However, the temperature must be below the maximum limit of the fabric in the bags. These maximum limits are given in Table 5.6.

5.3 Estimating 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. These costs are described below. (Costs for improving baghouse performance with electrical enhancement are not discussed in this section, but are mentioned in the example problem.)

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[2] Technically, Nextel can withstand even higher temperatures--up to 1400°F. However, at approximately \$15 to \$20/ft^2, its price reserves its use for the relatively small number of cases in which filtration is required at temperatures above 550 °F. A less expensive version of the fabric, with temperature capability to about 900 ° F, may be available.

5.3.1 Equipment Cost

5.3.1.1 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 5.7.

Table 5.7: List of cost curves for seven baghouse types

	Baghouse Type	**Figure No.**
	Preassembled Units	
Intermittent	Shaker (intermittent)	5.6
Continuous	Shaker (modular)	5.7
Continuous	Pulse-jet (common housing)	5.8
Continuous	Pulse-jet (modular)	5.9
Continuous	Pulse-jet (cartridge)	5.10
Continuous	Reverse-air	5.11
	Field-assembled Units	
Continuous	Any method	5.12

Each figure displays costs for a baghouse type and for additional cost items.[3] 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.

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[3] Costs in Figures 5.6 to 5.12 are in second quarter 1998 dollars. For information on escalating these prices to more current dollars, refer to the EPA report *Escalation Indexes for Air Pollution Control Costs* and updates thereto, all of which are installed on the OAQPS Technology Transfer Network at http://www.epa.gov/ttn/catc.

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.

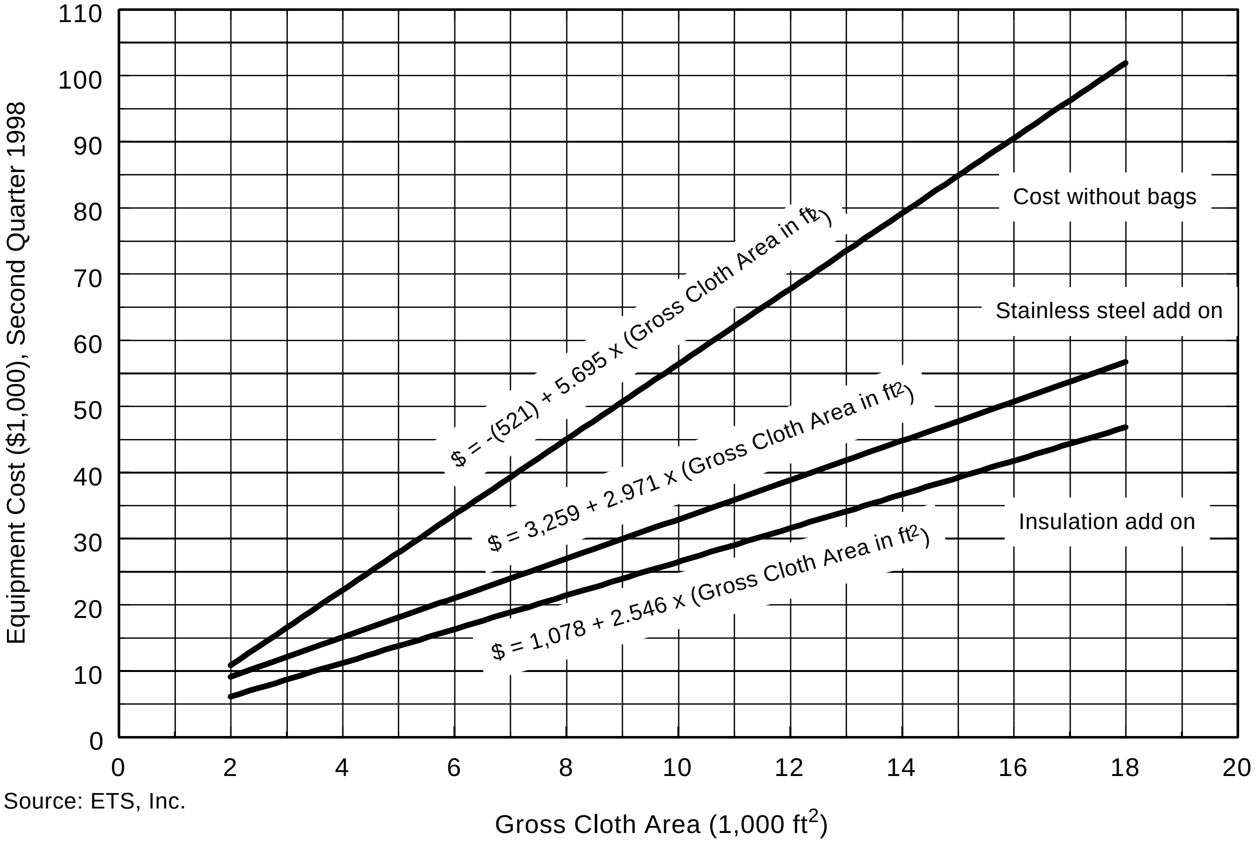
Figure 5.6 represents an intermittent service baghouse cleaned by a mechanical shaker. [24] This baghouse is suitable for operations that require infrequent cleaning. It can be shut down and cleaned at convenient times, such as the end of the shift or end of the day. Figure 5.6 presents the baghouse 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 5.7 presents costs for a continuously operated modular baghouse cleaned by mechanical shaker.[24] Again, price is plotted against the gross cloth area in square feet. Costs for these units, on a square foot basis, are higher than for intermittent shaker baghouses because of increased complexity and generally heavier construction.

Figures 5.8 and 5.9 show [24] 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 5.10 shows costs for cartridge baghouses cleaned by pulse.

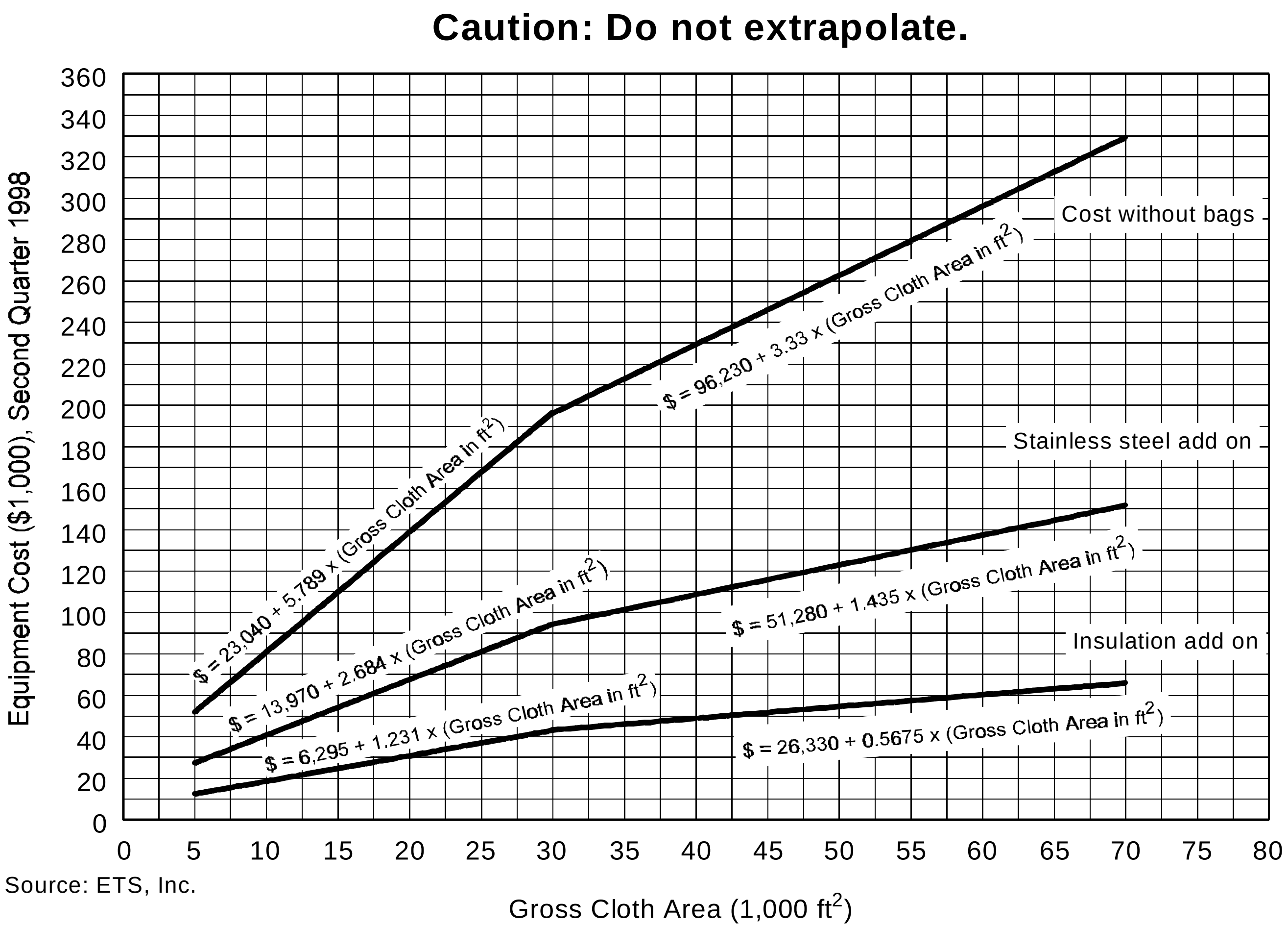
Figures 5.11 and 5-12 show costs for modular and custom-built reverse-air baghouses, respectively.[24] The latter units, because of their large size, must be field assembled. They are often used on power plants, steel mills, or other applications too large for the factory-assembled baghouses. Prices for custom-built shaker units are not shown, but are expected to be similar to custom-built reverse-air units.

Caution: Do not extrapolate.



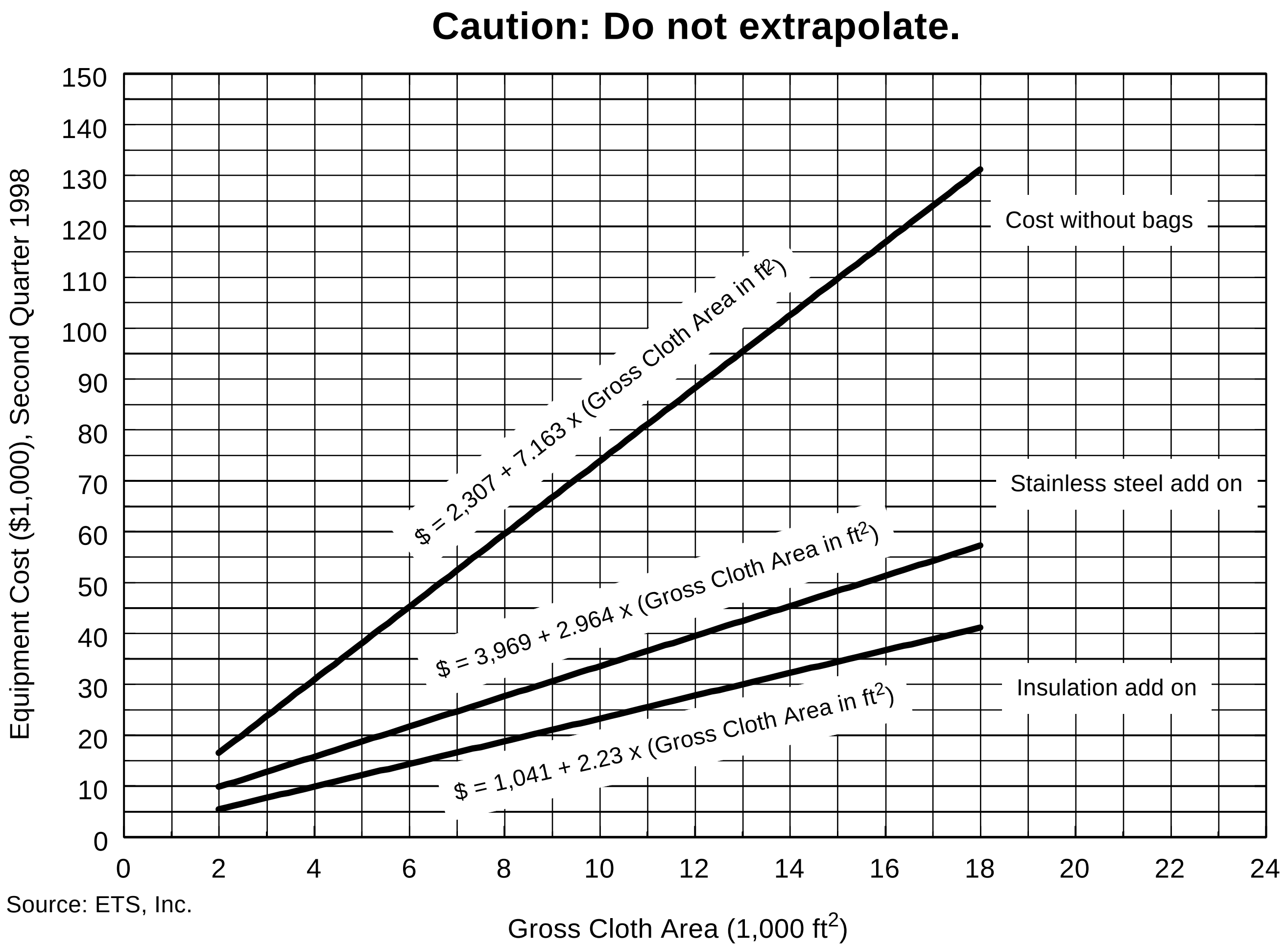
Source: ETS, Inc.

Figure 5.6: Equipment costs for shaker filters (intermittent)



Source: ETS, Inc.

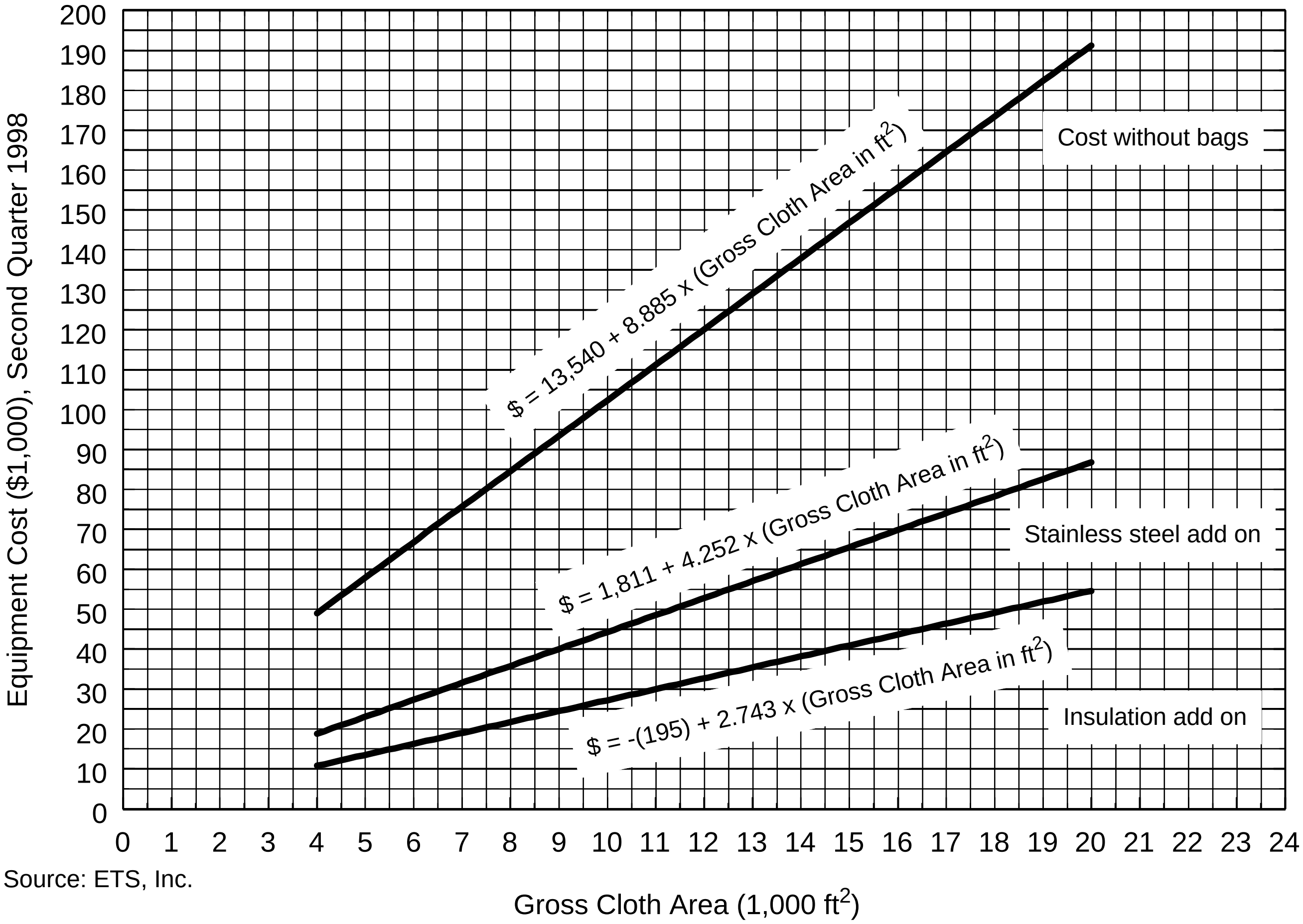
Figure 5.7: Equipment costs for shaker filters (continuous)



Source: ETS, Inc.

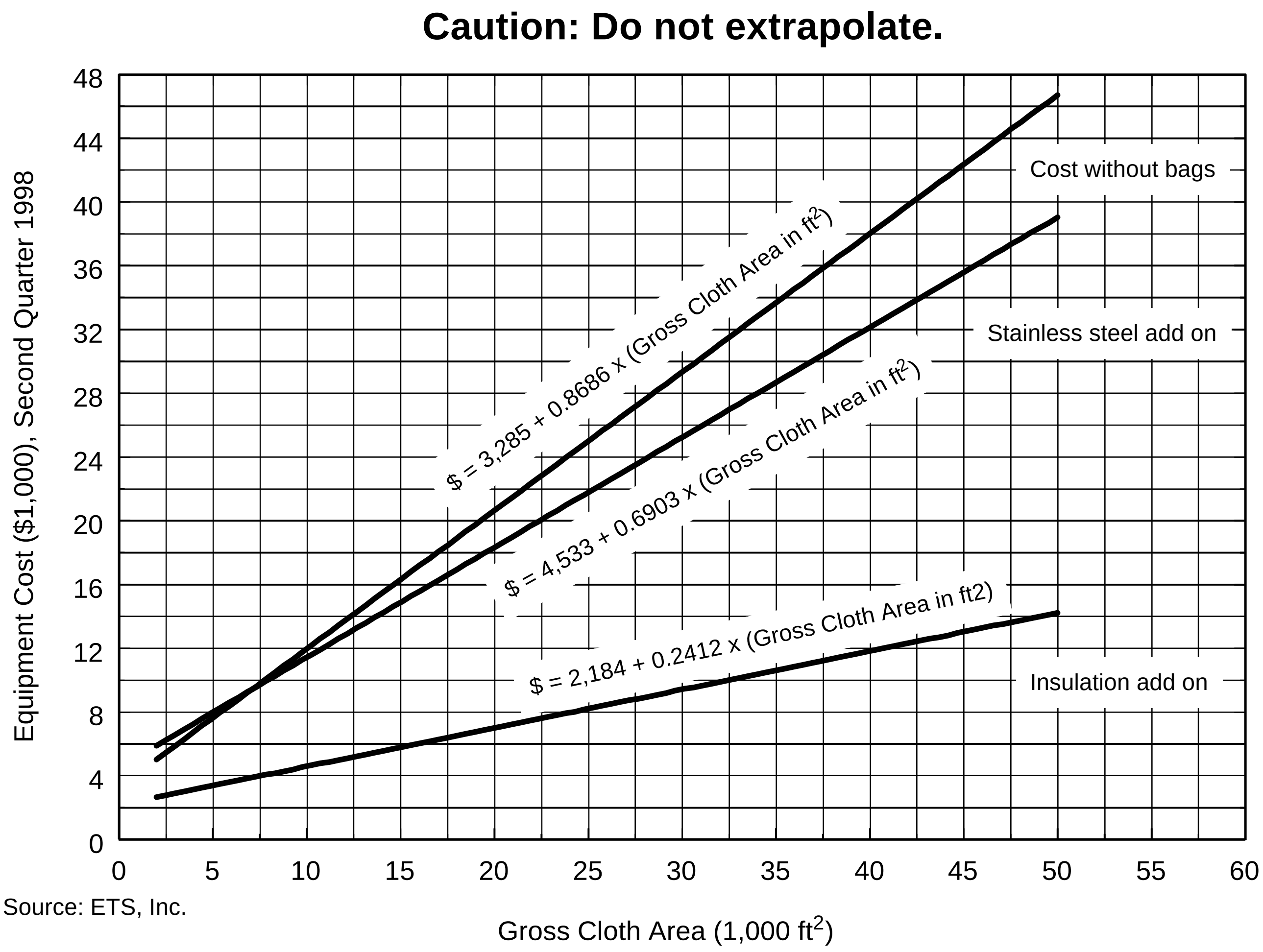
Figure 5.8: Equipment costs for pulse-jet filters (common housing)

Caution: Do not extrapolate.



Source: ETS, Inc.

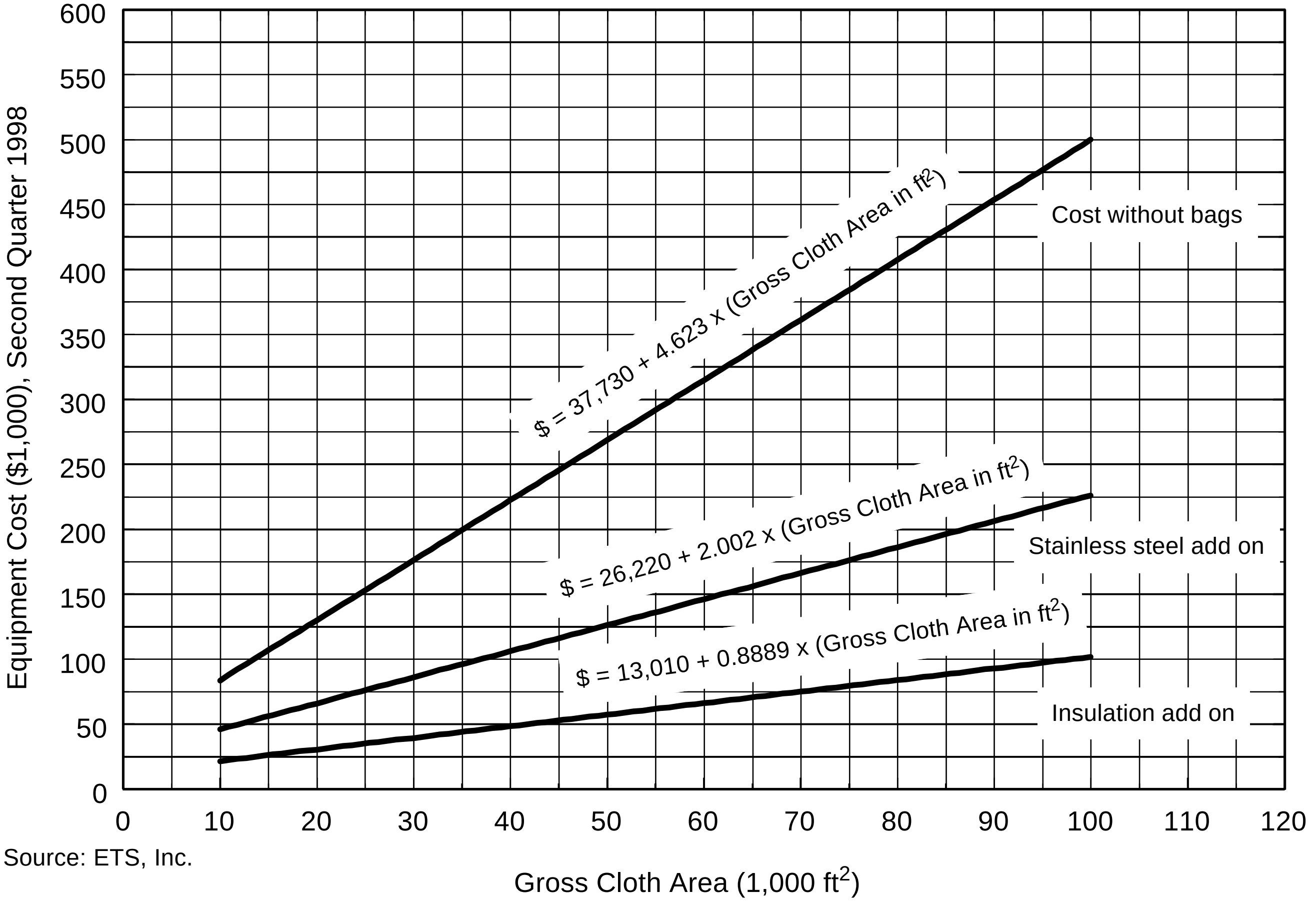
Figure 5.9: Equipment costs for pulse-jet filters (modular)



Source: ETS, Inc.

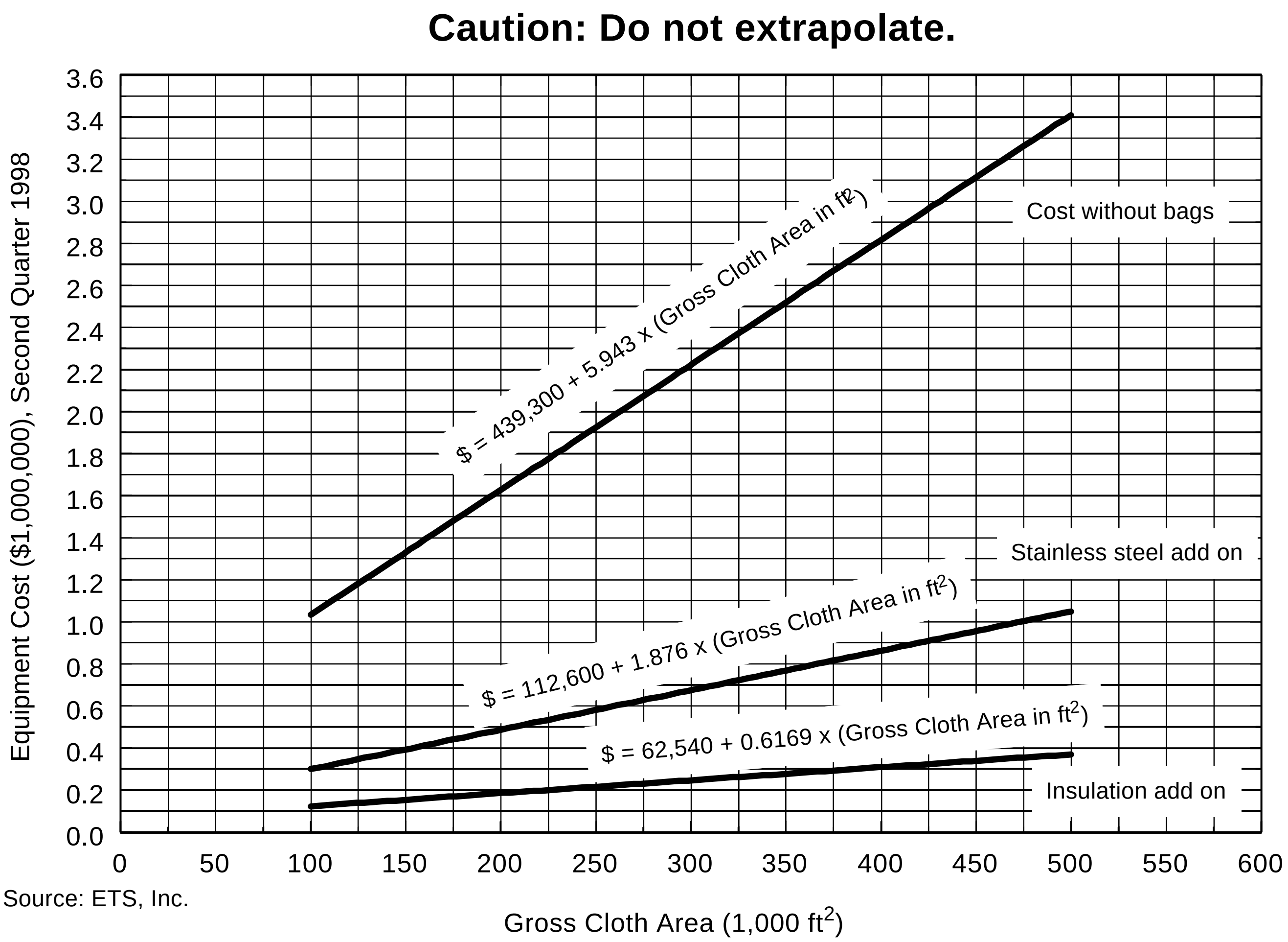
Figure 5.10: Equipment costs for cartridge filters

Caution: Do not extrapolate.



Source: ETS, Inc.

Figure 5.11: Equipment costs for reverse-air filters (modular)



Source: ETS, Inc.

Figure 5.12: Equipment costs for reverse-air filters (custom built)

5.3.1.2 Bag Costs

Table 5.8 gives the 1998 price per square foot of bags by type of fabric and by type of cleaning system used. 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 5.2 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.

5.3.1.3 Auxiliary Equipment

Figure 5.1 shows auxiliary equipment, which is discussed elsewhere in the *Manual*. Because hoods, ductwork, precoolers, cyclones, fans, motors, dust removal equipment and stacks are common to many pollution control systems, they are (or will be) given extended treatment in separate chapters. For instance, Chapter 10 provides sizing and costing procedures and data for hoods, ductwork, and stacks.

5.3.2 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 Chapter 2, 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.

5.3.3 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 are

Table 5.8: Bag Prices
(2nd quarter 1998 \$/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	0.75	0.81	2.17	1.24	1.92	NA	12.21	4.06	2.87	20.66
	6 to 8	0.67	0.72	1.95	1.15	1.60	NA	9.70	3.85	2.62	NA
Pulse jet, BBR	4-1/2 to 5-1/8	0.53	0.53	1.84	0.95	1.69	NA	12.92.	3.60	2.42	16.67
	6 to 8	0.50	0.60	1.77	0.98	1.55	NA	9.00	3.51	2.30	NA
Pulse jet, Cartridge[c]	4-7/8	2.95	NA	6.12	NA	NA	NA	NA	NA	NA	NA
	6-1/ 8	1.53	NA	4.67	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	0.63	1.52	1.35	NA	1.14	NA	NA	NA	NA	NA
	11-1/2	0.62	NA	1.43	NA	1.01	NA	NA	NA	NA	NA
Reverse air w/o rings	8	0.44	NA	1.39	NA	0.95	NA	NA	NA	NA	NA
	11-1/2	0.44	NA	1.17	NA	0.75	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
CO = 9-oz cotton
TF = 22-oz Teflon felt
P8 = 16-oz P84
RT = 16-oz Ryton
NX = 16-oz Nextel

[b] Bag removal methods:
TR = Top bag removal (snap in)
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/ft^2 for 226 ft^2) and \$126.00 for spunbonded polyester (\$1.26/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. The equation form 5.6542 ft^2 ^(0.4018) means
5.6542 x {ft^2 raised to the power (0.4018)}.

Table 5.8: (Cont.)

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	$\$ = 5.6542\ ft^2\ \hat{}(0.4018)$ in 25 cage lots
$\$ = 6.0211\ \exp(0.0423\ ft2)$ in 50 cage lots	$\$ = 4.3080\ ft^2\ \hat{}(0.4552)$ in 50 cage lots
$\$ = 4.2635\ \exp(0.0522\ ft^2)$ in 100 cage lots	$\$ = 3.0807\ ft^2\ \hat{}(0.5249)$ in 100 cage lots
$\$ = 3.4217\ \exp(0.0593\ ft^2)$ in 500 cage lots	$\$ = 2.5212\ ft^2\ \hat{}(0.5686)$ 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 shakers 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.[24]

given in Table 5.9. The Table 5.9 factors may be too large for "packaged" fabric filters—those pre-assembled baghouses 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 5.9 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 *Means Construction Cost Data* 1998.[25] Land, working capital, and off-site facilities are not normally required and have been excluded from the table. When necessary, these costs can be estimated.

5.4 Estimating Total Annual Costs

5.4.1 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. For example, current labor rates may 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*.

5.4.1.1 Operating and Supervisory Labor

Typical operating labor requirements are 2 to 4 hours per shift for a wide range of filter sizes.[26] When fabric filters are operated to meet Maximum Achievable Control Technology (MACT) regulations, it is likely that the upper end of the range is appropriate. 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.

5.4.1.2 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

Table 5.9 Capital Cost Factors for Fabric Filters[a]

Cost Item	Factor
Direct costs	
Purchased equipment costs	
Fabric filter (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 & supports	0.04 B
Handling & erection	0.50 B
Electrical	0.08 B
Piping	0.01 B
Insulation for ductwork[b]	0.07 B
Painting[c]	0.04 B
Direct installation cost	0.74 B
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost	**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
Contingencies	0.03 B
Total Indirect Cost, IC	**0.45 B**
Total Capital Investment = DC + IC	**2.19 B + SP + Bldg.**

[a] Reference [26], revised

[b] 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.

[c] The increased use of special coatings may increase this factor to 0.06B or higher. [The factors given in Table 5.8 are for average installation conditions. Considerable variation may be seen with other-than-average installation circumstances.]

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).

5.4.1.3 Maintenance

Maintenance labor varies from 1 to 2 hours per shift.[26] As with operating labor, these values may be reduced or exceeded depending on the size and operating difficulty of a particular unit. The upper end of the range may be required for operation to meet MACT regulations. Maintenance materials costs are assumed to be equal to maintenance labor costs.[26]

5.4.1.4 Replacement Parts

Replacement parts consist of filter bags, which have a typical operating life of about 2 to 4 years. The following formula is used for computing the bag replacement cost:

$$CRC_B = (C_B + C_L) \times CRF_B \tag{5.13}$$

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 a 7% interest rate and a 2-year life, $CRF_B = 0.5531$.)

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 a labor rate of $29.15/h (including overhead), C_L would be $0.10 to $0.19/$ft^2$ of bag area. As Table 5.8 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 $0.19 to $0.37/$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 min/cartridge.

The *OAQPS Control Cost Manual* methodology treats bags and bag replacement labor as an investment amortized over the useful life of the bags, while the rest of the control system is amortized over its useful life, typically 20 years (see Subsection 5.4.2). Capital recovery factor values for bags with different useful lives can be calculated from Equation 2.3.

5.4.1.5 Electricity

Electricity is required to operate system fans and cleaning equipment. Primary gas fan power can be calculated from Equation 2.7, substituting into this equation a combined fan-motor efficiency of 0.65 and a specific gravity of 1.000. We obtain:[27]

$$\text{Power}_{fan} = 0.000181Q(\Delta P)\theta \tag{5.14}$$

where

Power_{fan} = fan power requirement (kWh/yr)
Q = system flow rate (acfm)
ΔP = system pressure drop (in. H_2O)
θ = operating time (h/yr)

Cleaning energy for reverse-air systems can be calculated (using equation 5.14) from the number of compartments to be cleaned at one time (usually one, sometimes two), and the reverse gas-to-cloth ratio (from about one to two times the forward gas-to-cloth ratio). Reverse-air pressure drop varies up to 6 or 7 in. H_2O depending on location of the fan pickup (before or after the main system fan).[28] 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:[5]

$$P = 0.053A \tag{5.15}$$

where

A = gross fabric area (ft^2)

5.4.1.6 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.[29]

5.4.1.7 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. Section 4.4 of Chapter 4 provides information on estimating cooling-water costs.

5.4.1.8 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.[5] 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.[30] 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 $0.25/1,000 scf in 1998 dollars.

5.4.1.9 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 typically run $35 to $55 per ton at municipal waste sites in Pennsylvania, exclusive of transportation (see Section 2.4, Chapter 2). Lower costs may be available for industrial operations with long-term disposal contracts. Hazardous waste disposal can cost $150 per ton or more.

5.4.2 Indirect Annual Cost

Indirect annual costs include capital recovery, property taxes, insurance, administrative costs ("G&A"), and overhead. The capital recovery cost is based on the equipment lifetime and the annual interest rate employed. (See Chapter 2 for a discussion of the capital recovery cost and the variables that determine it.) For fabric filters, the system lifetime varies from 5 to 40 years, with 20 years being typical.[26] However, this does not apply to the bags, which usually have much shorter lives. (See Section 5.4.1.) 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:

$$CRC_s = [TCI - C_B - C_L]CRF_s \tag{5.16}$$

where

CRC_s = capital recovery cost for fabric filter system ($/yr)
TCI = total capital investment ($)
C_B = initial cost of bags *including* taxes and freight ($)[4]
C_L = labor cost for replacing bags ($)
CRF_s = capital recovery factor for fabric filter system (defined in Chapter 2).

For example, for a 20-year system life and a 7% annual interest rate, the CRF_s would be 0.09439.

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

5.4.3 Recovery Credits

For processes that can reuse the dust collected in the baghouse or that can sell the dust (e.g., fly ash sold as an extender for paving mixes), a recovery credit (RC) should be taken. As used in equation 5.17, this credit (RC) is subtracted from the TAC.

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[4] Typically, 8% of the bag initial cost.

5.4.4 Total Annual Cost

Total annual cost for owning and operating a fabric filter system is the sum of the components listed in Sections 5.4.1 through 5.4.3, *i.e.*:

$$TAC = DC + IC - RC \tag{5.17}$$

where

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

5.4.5 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 325°F and has an ash loading of 4 gr/acf. Analysis of the ash shows a mass median diameter of 7 μm. Assume the baghouse operates for 8,640 h/yr (360 d).

The gas-to-cloth ratio (G/C) can be taken from Table 5.1 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 G/C, Table 5.3 for shakers would yield the following values: A = 2, B = 0.9, and C = 1.0. The gas-to-cloth ratio would be:

$$2 \text{ x } 0.9 \text{ x } 1.0 = 1.8.$$

This value could also be used for reverse-air cleaning. For a pulse-jet unit, Table 5.4 gives a value of 9.0 for factor A and 0.8 for factor B. Equation 5.11 becomes:

$$\begin{aligned} V &= 2.878 \times 9.0 \times 0.8(275)^{-0.2335}(4)^{-0.06021}(0.7471 + 0.0853 \ln 7) \\ &= 4.69 \end{aligned} \tag{5-18}$$

Because this value is so much greater than the shaker/reverse-air G/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 G/C would yield lower capital and, in turn, 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 make this comparison. Further discussion of the effects of G/C increases, and accompanying pressure drop increases, on overall annual costs will be found in Reference 30.[5] 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 5.6).[6] At a gas-to-cloth ratio of 4.69, the fabric required is[7]

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

From Figure 5.8, the cost of the baghouse ("common housing" design) is:

$$\text{Cost} = 2{,}307 + 7.163(10{,}661) = \$78{,}672 \qquad (5\text{-}19)$$

Insulation is required. The insulation add-on cost from Figure 5.4 is:

$$\text{Cost} = 1{,}041 + 2.23(10{,}661) = \$24{,}815 \qquad (5\text{-}20)$$

From Table 5.8, bag costs are \$1.69/ft^2 for 5-1/8-inch diameter glass fiber, bottom removal bags. Total bag cost is

$$10{,}661 \text{ ft}^2 \times \$1.69/\text{ft}^2 = \$18{,}017.$$

For 10 ft long cages,

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[5] In addition, the *CO$T-AIR* control cost spreadsheet for fabric filters computes capital and annual costs for all three designs. Download *CO$T-AIR* at: *HTTP://WWW.EPA.GOV/TTN/CATC/PRODUCTS.HTML#CCC.INFO*.

[6] As Table 5.6 shows, other bag materials (*e.g.*, Nomex) also could withstand this operating temperature. But Fiberglas 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.

[7] 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.

fabric area per cage = (5−1/8 in.) / (12 in./ft) × π × 10 ft
= 13.42 ft^2.
The number of cages = (10,661 ft^2) / (13.42 ft^2)
= 795 cages (rounded up to next integer)

From Table 5.7, individual cage cost is

$$2.5212 \text{ x } 13.42 \text{ ft}^2 \text{ \^{}}(0.5686) = \$11.037.$$

Total cage cost is

$$795 \text{ cages x } \$11.037/\text{cage} = \$8,774.$$

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 costs for the fabric filter system, based on the factors in Table 5.9, are given in Table 5.10. (Again, we assume site preparation and buildings costs to be negligible.) Total capital investment is $569,000. Table 5.11 gives the direct and indirect annual costs, as calculated from the factors given in Section 5.4.1. For bag replacement labor, assume 10 min per bag for each of the 795 bags. At a maintenance labor rate of $29.65 (including overhead), the labor cost is $3,943 for 133 h. The bags and cages are assumed to be replaced every 2 yr. The replacement cost is calculated using Equation 5.13.

Pressure drop (for energy costs) can be calculated from Equations 5.8 and 5.9, with the following assumed values:

$$K_2 = 15\frac{\text{in. } H_2O/1(\text{ft}/\text{min})}{\text{lb}/\text{ft}^2}$$

$$\begin{aligned} P_j &= 100 \text{ psig} \\ \text{cleaning interval} &= 10 \text{ min} \end{aligned}$$

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

$$\begin{aligned} W_o &= C_i V \theta \\ &= 4\frac{\text{gr}}{\text{ft}^3} \times \frac{1 \text{ lb}}{7{,}000 gr} \times 4.69\frac{\text{ft}}{\text{min}} \times 10 \text{ min} \\ &= 0.0268 \text{ lb}/\text{ft}^2 \end{aligned}$$

$$\begin{aligned} \Delta P &= 6.08 \times 4.69\frac{\text{ft}}{\text{min}} \times (100 \text{ psig})^{-0.65} + 15\frac{\text{in. } H_2O/(\text{ft}/\text{min})}{\text{lb}}/ft^2 \\ &\times 0.0268\frac{\text{lb}}{\text{ft}^2} \times 4.69 \frac{\text{ft}}{\text{min}} \\ &= 3.32 \text{ in. } H_2O \text{ across the fabric (when fully loaded).} \end{aligned}$$

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

The total annual cost is $474,000, 39 percent of which is for ash disposal. 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 $274,000 ($474,000 – $185,000 – $14,800), or 58% of the cost when no market exists. Clearly, the total annual cost is extremely sensitive to the value chosen for the dust disposal cost in this case. In this and in similar cases, this value should be selected with care.

Table 5.10 Capital Costs for Fabric Filter System
Example Problem (2nd quarter 1998 $)

Cost Item	Cost
Direct Costs	
Purchased equipment costs	
Fabric filter (with insulation)(EC)	$103,847
Bags and cages	26,791
Auxiliary equipment	89,500
Sum = A	$220,138
Instrumentation, 0.1A	22,014
Sales taxes, 0.03A	6,604
Freight, 0.05A	11,007
Purchased equipment cost, B	$259,763
Direct installation costs	
Foundation and supports, 0.04B	10,391
Handling and erection, 0.50B	129,882
Electrical, 0.08B	20,781
Piping, 0.01B	2,598
Insulation for ductwork, 0.07B	18,183
Painting, 0.04B	10,391
Direct installation cost	192,226
Site preparation	-
Facilities and buildings	-
Total Direct Cost	**$451,989**
Indirect Costs (installation)	
Engineering, 0.10B	25,976
Construction and field expenses, 0.20B	51,953
Contractor fees, 0.10B	25,976
Start-up, 0.01B	2,598
Performance test, 0.01B	2,598
Contingencies, 0.03B	7,793
Total Indirect Cost	**$116,894**
	W4444444
Total Capital Investment (rounded)	**$569,000**

Table 5.11 Annual Costs for Fabric Filter System
Example Problem (2nd quarter 1998 $)

Cost Item	Calculations	Cost
Direct Annual Costs, DC		
Operating labor		
Operator	$\frac{2\ \text{h}}{\text{shift}} \times \frac{3\ \text{shifts}}{\text{day}} \times \frac{360\ \text{days}}{\text{yr}} \times \frac{\$17.26}{\text{h}}$	$37,282
Supervisor	15% of operator = 0.15 x 37,282	5,592
Operating materials		—
Maintenance		
Labor	$\frac{1\ \text{h}}{\text{shift}} \times 3\ \frac{\text{shifts}}{\text{day}} \times \frac{360\ \text{days}}{\text{yr}} \times \frac{\$17.74}{\text{h}}$	19,159
Material	100% of maintenance labor	19,159
Replacement parts, bags	[3,943 + (26,791 x 1.08[a])] x 0.5531	18,184
Utilities		
Electricity	$0.000181 \times 50{,}000\ \text{acfm} \times 10.3\ \text{in H}_2\text{O} \times \frac{8{,}640\ \text{h}}{\text{yr}} \times \frac{\$0.067}{\text{kWh}}$	54,041
Compressed air (dried and filtered)	$\frac{2\ \text{scfm}}{1{,}000\ \text{acfm}} \times 50{,}000\ \text{acfm} \times \frac{\$0.25}{1{,}000\ \text{scf}} \times \frac{60\ \text{min}}{\text{h}} \times \frac{8{,}640\ \text{l}}{\text{yr}}$	12,960
Waste disposal	at $25/ton on-site for essentially 100% collection efficiency: $\frac{4\ \text{gr}}{\text{ft}^3} \times \frac{1\ \text{lb}}{7{,}000\ \text{gr}} \times 50{,}000\ \text{ft}^3 \times \frac{60\ \text{min}}{\text{h}} \times \frac{8{,}640\ \text{h}}{\text{yr}} \times \frac{1\ \text{ton}}{2{,}000\ \text{lb}} \times \frac{\$25}{\text{ton}}$	185,134
Total DC	(rounded)	**351,500**
Indirect Annual Costs, IC		
Overhead	60% of sum of operating, supv., & maint. labor & maint. materials = 0.6(37,282+5,592+19,159+19,159)	48,715
Administrative charges	2% of Total Capital Investment = 0.02 ($568,883	11,378
Property Tax	1% of Total Capital Investment = 0.01 ($568,883)	5,689
Insurance	1% of Total Capital Investment = 0.01 ($568,883)	5,689
Capital recovery[b]	0.09439 (568,883- 3,943 - 28,934 x 1.08)	50,594
Total IC (rounded)		**122,100**
Total Annual Cost	**(rounded)**	**$474,000**

[a] The 1.08 factor is for freight and sales taxes.

[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 a 7% interest rate, CRF = 0.09439.

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