Estimating the Total Cost of Cartridge and Bag Filtration

When changeout and disposal costs are added to the purchase cost of filters, the total cost of disposable filters can more than quadruple. A proven method of reducing total life-cycle cost is larger surface-area filters

Frank Buehner
Filtration & Membrane Technology, Inc.

Bag filters for industrial applications have been in existence longer and are considered by some to be easier and simpler to specify than cartridges for a filtration project. And although cartridge filtration is now one of the mostly widely used filtration technologies in the chemical process industries (CPI), it is not always the first choice.

How does one decide which filtration method should be used? Like any other technology choice, this decision is based upon the strengths and weaknesses of the two options.

There are many factors an engineer should consider when choosing a filtration system. So when does one specify a cartridge filter instead of a bag filter? What are the basic differences between the two? How does one determine filter life for either type? Often the lack of a logical approach to liquid filtration design leads engineers down a "what did we do the last time" approach instead of determining critical properties, such as the total dirt-holding capacity, filter life, filter surface area, flowrates, and other factors. Schooling in this unit operation is not a common university practice, and the lack of ASTM standards, for instance, regarding filtration test procedures and specification of filters adds to system under- or over-design.

Besides the capital costs of a filter, there are additional factors that affect overall filtration economics, namely: (a) design considerations and options, (b) process requirements, (c) maintenance requirements, (d) maintenance procedures, (e) mean-time-between-changeout (MTBC) costs, and (f) disposal costs. This article outlines basic design issues, discusses selection considerations, and presents a cradle-to-grave cost analysis of bag and cartridge filtration.

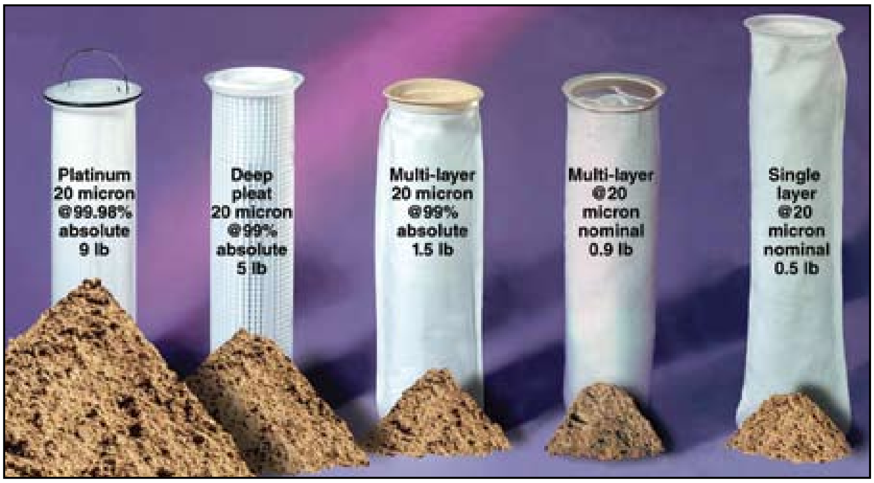


FIGURE 1. The dirt holding capacity of #2 bag filters varies, and is largely dependent on filter surface area

Design factors

Even before selection decisions are made, there is a need to address two important criteria: the chemical and physical compositions of the feedstock stream going into the filter; and the quality and specification of the desired exit liquid.

Other important design considerations include the following:

- Process specifications (metallurgy, temperature, pressure and instrumentation)
- Footprint, weight, clearance
- Filter flux rate
- Filter surface area, length, diameter, design type
- Filter type (bag, cartridge, other)
- Flowrate and pump requirements
- Solids concentration and solids characteristics
- Fluid viscosity, density, specific gravity, pH, volatility, hazards
- Changeout requirements, frequency
- Instrumentation, safety and disposal issues
- Costs of hardware, filters, maintenance, disposal

Important design steps include the following:

- Determine stream composition, flowrate and temperature
- Calculate total solids per day removal, know total suspended solids (TSS) and particle size distribution (PSD)
- Set flux rate (0.5 gal/ft^2/min for pleated cartridges and bags; 60–120 gal/min/bag for regular bags)
- Determine total surface area
- Determine bag or cartridge
- Calculate best fit (number and size of filters required)
- Calculate number of vessels required
- Calculate total pressure drop (clean and fouled)

FIGURE 2. Cartridge filters are available in various lengths and materials of construction

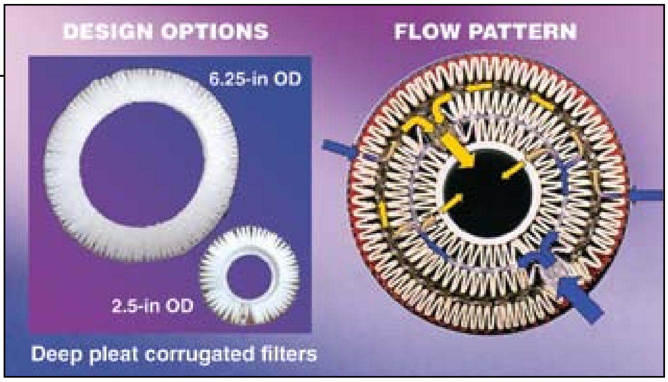


FIGURE 3. Shown here are a deep-pleat corrugated design (left) and the flow channels and chambers of high capacity filters

- Modify design to minimize changeout frequency
- Design vessel layout; then optimize
- Calculate volume and weight of waste

Bag filters

Bag filters come in various configurations and materials of construction. A bag filter usually has inlet flow through the top of the filter and exit flow along the sides and bottom. A metal or plastic perforated basket in the filter vessel keeps the bag from expanding outwards from flow pressure as the filter fills. The typical, maximum fouling pressure for bag filters is 25 psi. With a typical fabric bag filter containing 4.0–4.4 ft^2 of surface area, the dirt holding capacity of a bag filter varies gradually as the construction moves from a mesh or felt, single or multilayer construction, to a pleated bag, which looks similar to a cartridge filter. The reason for the dramatic increase in dirt holding capacity is filter surface area (Figure 1). The surface area of pleated bags jump dramatically from 4.4 ft^2 for standard single or multilayer construction to 30–60 ft^2 for pleated construction.

For bag filters, maximum flowrates, dirt holding capacity, and materials of construction and style (microfiber, mesh, felt, needled felt, binder resins, finish coatings/glazing, seams or seamless, and cap seal) vary widely by manufacturer. The design of the bag and materials of construction control the surface area, dirt holding capacity, and maximum flowrates the filter can withstand. A long used rule of thumb employs an estimate of 100 gal/min per bag for a full-sized 4.4-ft^2, surface area, 9–10 oz., 100-micron nominal-rated felt bag. Vessel inlet velocity is usually limited to an 8–10 ft/s maximum range. As the bag becomes tighter, flowrates drop to 85 gal/min and then to 40 gal/min or less per bag. The manufacturer's production method and materials of construction require the design engineer to consult the vendor's data sheet for specific flowrates and pressure-drop data.

Cartridge filters

Cartridge filters are available in various lengths and materials of construction (Figure 2).

A cartridge filter's flow is in the opposite direction of a bag filter — from the outside in. This requires that the construction of a cartridge filter be strong enough to have a core with a high burst strength and does not rely on the filter vessel itself for compression strength. Filter alignment rods, either temporary or permanent, are usually included with a cartridge vessel to assist with installation and removal. These alignment rods allow the filter to slide and be guided over a rod or shaft and become increasingly important to support the filter and help with changeout if the filter vessel is horizontal or on an angle. Orientation of the cartridge filter vessel can be based upon available plot area or the need to reduce the physical height of long-length cartridge vessels to help with access during removal, replacement, and aid with liquid drainage before filter changeout.

Cartridge filters are available in much larger sizes (length and diameter) than bag filters, and different designs allow filters to have much higher surface areas (and dirt holding capacities). Single 2.5-in. × 40-in. pleated cartridges contain from 5 to 9 ft^2 of surface area per cartridge depending upon the number of pleats the manufacturer uses. In comparison, a 20-in.-dia., 40-in.-long cartridge filter can contain up to 1,100 ft^2 of surface area.

High capacity filter cartridges

Today's more-efficient filter cartridges are often referred to as high capacity filters. They offer improved MTBC and mean time between replacement (MTBR), and, this kind of filter will easily offer economic advantages when run until it reaches its maximum dirt-holding capacity. The high capacity filter pays for itself and, in some critical services (such as amine purification loops in sulfur-removal plants), one high capacity unit can replace as many as 200 standard, 2.5-in. cartridges (see box on p. 39). Traditional single or multilayer bag filters cannot approach the dirt holding capacity of a high-capacity pleated cartridge or bag filter, so we must continue this study examining pleated media filters only.

Available worldwide from a number of vendors, high capacity filters are pleated and are made from several types of filter media and pore sizes in order to maximize dirt-holding capacity. Employing the available options of high surface area, materials of construction, and filter efficiency, the high capacity cartridge can handle a wide variety of fluids at various temperatures. The technology utilizes either an optimized deep-pleat design (Figure 3, left) or a continuous pleat employing a series of segregated flow channels and flow chambers (Figure 3, right) to improve the alpha factor (described below).

A close analysis of the high-capacity, filter-flow channels and flow chambers reveals that improved filterability and particle removal capabilities are directly related to the increased amount of filter-surface-area that is available with these high capacity units. The improvement of dirt holding capacity is shown in Table 1. These results identify the dirt holding capacities of the filters employing seven types of test dust from 1 to 70 microns. The design of a pleated bag is accomplished by reversing the pleat pack as shown in Figure 3, for flow from the inside to the outside of the filter and employing the bag filter basket as a filter expansion control device.

TABLE 1. DIRT HOLDING CAPACITIES-CARTRIDGE FILTERS

(2.5-in. O.D. x 40-in. length)		
String wound filters	0.3 lb	nominal filter
Spun bonded filters	1.0 lb	nominal filter
Pleated media filters	2.0 lb	absolute filter
(6.25-in. O.D. x 40-in.length)		
Pleated media filter	18 lb	absolute filter
(12.00 -in. O.D. x 40-in. length)		
Pleated media filter	100 lb	absolute filter
(20.00-in. O.D. x 40-in. length)		
Pleated media filter	300 lb	absolute filter

TABLE 2. DESIGN CONSIDERATIONS

Filter media temperature limitations	
Polypropylene	Max: 180°F
Polyester	Max: 270°F
Fiberglass	Max: 270°F
Cellulose	Max: 385°F
Metal	Max: 550°F
Filter temperature and chemical compatibility considerations	
Not only filter media but also cap, gasket, cores, webbing, netting, and joining materials.	

TABLE 3. MONTHLY OPERATING PARAMETERS AND YEARLY OPERATING COSTS
(36-in I.D. vessel, contaminate load = 72 lb/mo)

Monthly operating parameters	String wound	Pleated filter	Platinum, 6.25-in. O.D.	Platinum, 12.75-in. O.D.
Housing depreciation, $	400.00	400.00	400.00	400.00
Filter quantity	120	120	19	5
Filter price, $	7.00	44.00	266.00	1,053.00
Pounds of dirt per filter	0.30	2.0	18.0	100
Change outs per month	2	0.3	0.20	0.15
Change out time, h	4	4	2	1
Labor cost, $/h	30.00	30.00	30.00	30.00
Disposal cost, $/filter	1.00	1.00	15.00	60.00
Yealy operating costs, $				
Depreciation	4,800	4,800	4,800	4,800
Filter cost	20,160	19,000	12,129	9,477
Labor cost	5,760	864	720	360
Disposal cost	2,880	432	684	540
Total cost	**35,600**	**25,096**	**18,333**	**15,177**
Alpha factor (*Å*)	23.3	22.0	14.8	10.5

Holding vessels

The vessels that hold bag (Figure 4) and cartridge (Figure 5) filters are designed to hold single or multiple bags and cartridges. These vessels can obviously become quite large, and their footprints can take up large parcels of valuable real estate. Weight can also be an issue for offshore platforms and where vessels are elevated in the deck structure.

Design and process engineers must recognize that both the filter housing and the pump size are dictated by the desired flowrates, pressure drop limitations and the required level of filtration (micron size of the particles that must be removed). The recommended flow capacity of the filter element is used to determine the total number of cartridges required.

Housing size must be synergistic with filter size, and if absolutely no downtime can be tolerated, then parallel filters (sized to handle the total flowrate of the processing line or the effluent line) should be considered. In doing so, footprint and overhead spacing are both important — particularly overhead spacing if a mechanical lift is used to remove the element from the vessel. Another approach is to employ horizontal filter vessels with single or multiple filters up to 80-in. long. These vessels can be loaded and unloaded without a mechanical lift.

Bag versus cartridge filters

Now, the question of bag versus cartridge filter is addressed.

Bag filter considerations. An often overlooked consideration is that non-pleated bag filters may extrude into the vessel basket holes making removal time consuming and ripping more likely. Not only can maintenance personnel have a problem but robotic equipment cannot operate efficiently when this situation exists.

Each bag vessel manufacturer has slightly different sealing and seating features that may require that a variety of filters be stocked for each vessel type in a facility, even if the design parameters are the same. Absolute rated, high-efficiency bag filters, are available in multi-layer non-pleated construction. Filter hold-down devices are available to assist with filter sealing, and many vessel manufacturers have devised proprietary locking or snap-in systems. The 7.25–7.5-in. dia. inlet for bag filters require large diameter vessels or multiple vessels for large flowrates. The bag filter tubesheet must be designed to withstand pressure and temperature fluctuations to eliminate warping. Newer fabrics and methods of construction allow the use of single, multilayer, and pleated bag filters up to 385°F (Table 2). Pleated-bag-filter caps cannot always be economically fabricated of metal to fit all bag vessels for high temperature applications. Nylon, fiberglass, acetyl (polyoxymethylene), and other plastics can extend the temperature range beyond polypropylene (PP). For pleated bag filters, the O-ring cap seal or gasket is large in diameter, and that cost must be considered if exotic materials, such as Viton, Cal-Rez, TEV, or Teflon are required.

Maximum dirty pressure drop (ΔP) for pleated bag filters is also 25 psi to avoid extrusion or destruction, or both. In some cases, the dirt can act as a filter cake and allow for longer filter life and dirt holding capacity for both pleated and non-pleated designs.

Cartridge filter considerations. Flow is outside-in requiring strong core cages to handle the pressure drop through the filter without crushing it. Common end-cap designs include 222, 226, 335, and 339 double O-rings and a variety of builtin end-cap compression devices that are used to ensure a 100% seal in the vessel receiver. Cartridge filters can be built with metal end caps and other high-temperature (450°F), solvent-resistant materials. The O-rings employed on a cartridge filter are smaller in diameter than those on bag filters, reducing costs when exotic O-ring materials are required. Cartridge filters can be built with very large surface areas and dirt holding capacities. Maximum dirty ΔP for a cartridge filter is normally 35 psig, but can be increased by designing the core to handle higher pressures. Cartridge filters can incorporate cores of oil absorbent materials and internal flow chambers to offer unique high-volume, oil-absorption features and also improve uniform flow in large diameter filters to ensure that the surface area is "effective".

Employing corrugated media and metal cages, filter lengths of 80 in. and longer with diameters of 20 in. are available. However, original cartridge filter designs, and those in service today are largely based on 2.5-in.-dia. filters. This means that to

FIGURE 4. Shown here is a typical bag-filter housing with a capacity of 150 gal/min

FIGURE 5. This cartridge filter (left) and its housing has a capacity of 150 gal/min

handle large flowrates, vessels containing 50–250 or more cartridges per vessel are employed in petroleum refineries and chemical plants. Cartridge filters can be arranged in series to increase surface area and dirt holding capacity.

Filter changeout

Liquid holdup in the filter itself and in the filter vessel must be considered in design. The vessel will normally be blown-down with nitrogen or air or employ pumps to remove liquid from the vessel prior to filter changeout. The value and type of fluid will determine the most economical method of removing the fluid. Hot fluids and those that might vaporize may require a cool-down time, which adds to the cost of the changeout. Some vessels may require a steam-out or vacuum system to remove hazardous fluids and vapors prior to opening the vessel. In some systems the contaminant may be pyrophoric so additional safety issues regarding handling and disposing of spent filters must be considered.

Filter efficiency

A filter has an optimum flowrate to maximize dirt holding. One can push a filter to higher flowrates, but the dirt holding capacity will decrease as shown in Figure 6. By knowing the filter surface area (in this case, 94–115 ft^2) and varying the media micron size and the recommended flux (usually optimized at 0.50 $gal/ft^2/min$) for pleated cartridges, the dirt holding capacity of the system can be maximized.

Some filter manufacturers do not wish to disclose dirt holding capacities or filter surface area. This can be due to competitive pressures to keep this information secret or the lack of a full-scale, test flow loop that validates the dirt holding capacity of the filter. Filter data sheets are notorious for their lack of critical information and may require careful inspection and phone calls, examining the fine print or competitors' product data sheets to obtain the information needed.

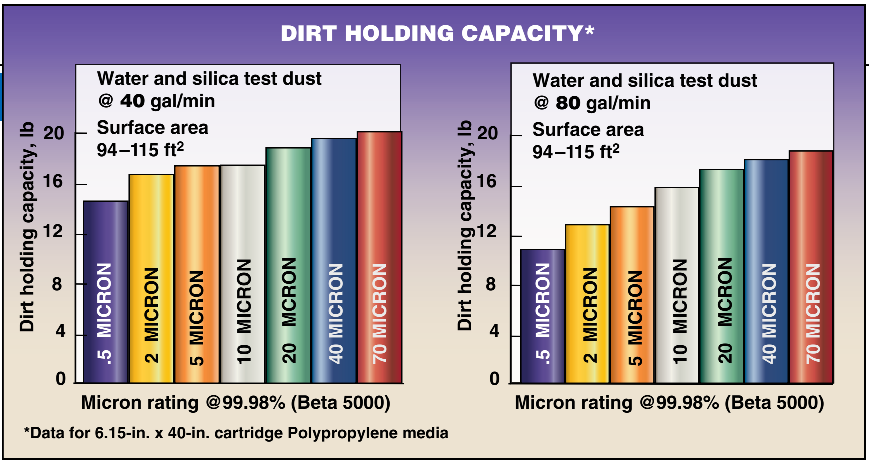
Beta ratios

The tried and true use of efficiency as a percent is difficult to understand and explain to purchasing or management who wants to know why a 99.98% efficiency filter may be significantly higher in price than a 99% filter. A simple-to-calculate parameter, called the beta ratio (see box on p. 40), is much easier to understand (and explain) and can eliminate a host of uncertainties.

As an example, consider a filter with an absolute efficiency rating of 99.98% at 2 microns. Performing the simple calculation, we find that a 99.98% efficiency equates to a beta ratio of 5,000. In contrast, a 99% efficiency filter has a beta ratio of 100. The engineer can now describe the differences in filters in easy to understand terms: a beta 5,000 filter will only pass 1 particle in 5,000 greater than 2 microns. A beta 100 filter will pass 1 in 100 particles greater than 2 microns. So, while percent efficiency is typically what is published in the literature or on a data sheet, the beta ratio better describes what is happening.

Nominal versus absolute rating

The absolute rating of a filter is the diameter (in µm) of the largest particle that will pass through the filter (roughly, the pore size). In contrast,


DIRT HOLDING CAPACITY*

*Data for 6.15-in. x 40-in. cartridge Polypropylene media

FIGURE 6. A filter has an optimal flowrate to maximize the dirt holding capacity. Doubling the flowrate (right) reduces the dirt holding capacity (left)

the nominal rating of a filter is an arbitrary value determined by the manufacturer, and is expressed in terms of percentage retention (normally 90, 95 or 98 wt.%) of a specific contaminant of a given size.

Most nominal-rated filters are found in single-layer bag filters and cartridge filters employing coiled string or media that does not have a uniform pore size, a large average pore size, or if the media can move during filtration (not-fixed in location by binders or of uniform pore size), so its efficiency rating is not uniform from filter to filter or within the same filter or is low in the ability to reproduce uniform tests of efficiency and must be averaged to report a result. Nominal rated filters are used extensively in water and wastewater-treatment applications.

A nominal filter cannot have a beta-ratio rating because the tests of nominal rated filters are not reproducible under tests that include changes in flowrate and pressure, including pressure surges that can move the media or dislodge bridged particles that would change the actual pore size. There are attempts to relate a nominal rated filter to an absolute, but the designs and materials of construction of the two different ratings do not allow a true comparison. Figure 7 shows that even though this filter is rated at 5 microns, reductions in filtered versus unfiltered particles do not become significant until after 19 microns.

Filter testing and sizing

The typical material used to challenge test filters is ISO test dust, formally SAE test dust, which comes in ultrafine, fine, medium, and coarse varieties. Test dust is certainly not a common contaminant, so why use it for filter testing? The answer is that although dust itself is not normally a fluid contaminant, it does have properties of two commonly occurring contaminants: particulate matter and turbidity; dust can be a source of both. However, the main purpose of test dust, in terms of liquid filter testing, is to provide a source of clogging to test mechanical reduction properties of filter systems. These mechanical filtration properties are most stringently tested when pressure drop is high and flowrate is decreased due to clogging, so the purpose of the dust is to eventually blind-off the pores of the filters.

Certainly, the engineer needs to know a filter's dirt holding capacity for various micron ranges to design any filter system. Vendors' data sheets should contain this information. The data must be reliable and reproducible. Most manufacturers have flow loops and in-house laboratories to test their own and competing filters. These laboratories can also be of help to the engineer by measuring PSDs and TSSs from samples from pilot plants or similar operations at other locations. For field work, the engineer can employ a portable filter-test kit and turbidity meter to zero in on a filter of choice. Knowing the flowrate of the stream in question along with the PSS and TSS, one can calculate the pounds of dirt per day by size. In turn, a filter meeting the required dirt holding capacity, while considering changeout frequency, is then selected.

Since no ASTM standards exist for filter or media testing (ASTM F-795 was withdrawn), the engineer must trust the data supplied by the vendor. Test results and procedures for a supplier's filter claiming to be nominal or absolute and of a removal percent or specific beta ratio should be made available to the engineer.

Costly shutdowns

Filters used in refineries and petrochemical plants handle very large volumes of product or processing fluids on a continuous basis. Other plant operations found throughout the CPI are batch. Regardless of whether the process is batch or continuous, online time is extremely critical to optimize profitability. Shutting down due to a filtration problem (or any problem) affects bottom line production income by as much as $10,000/h or more. While batch operations have more flexibility, the choice of the filter is still a major concern. Potential product sitting in holding tanks that cannot be shipped because the filtrate does not meet quality control specifications can halt production just as in a continuous process.

Up to 70% of a firm's products may be in a suspension during processing, and filtration is often used for recovery of an expensive end-product rather than to remove an unwanted contaminant. In these cases, filtration becomes the most important of all processes utilized by many chemical giants.

Consequently, higher efficiency and higher product-holding capacity (in lieu of dirt-holding capacity) is essential to assure profitable operations. And, time online becomes even more critical in these situations. It is not unusual for a return-on-investment (ROI) analysis to include considerations for a duplexed system (two parallel filters) to service a process line so that there is never downtime due to changeout requirements.

Even in light of the above, most plant managers and many engineers do not realize that the filtration operation can be the most expensive process that takes place within the production unit, especially when the filter is handling toxic or hazardous (or lethal) materials, and especially when the employees have to "suit up" in order to perform filter maintenance or replacement.

Consequently, remaining online is imperative, and that means improving MTBC and MTBR are critical issues in filtration. The subtle difference between MTBR and MTBC is that changeout sometimes occurs before a cartridge is totally full, while replacement optimally occurs when a filter

DIFFERENT DEPARTMENTS´ NEEDS

At the heart of a plant design are the needs and wants of the decision makers in the flow chain from raw materials in, to finished product out. There are usually conflicting interests that can challenge the filter choice.

For example, the maintenance department wishes to minimize overall costs including number of filter changeouts, time to changeout, number of filters requiring changeout, individual filter cost, disposal cost, loss of product due to filter changeouts, and also to meet plant safety requirements.

The process department requires the quality of the product to meet customer specifications (specs) or intermediates to meet specs, which ultimately produce a finished product that meets customer specs. The intermediate streams must be clean as not to foul heat exchangers, process equipment, and instrument probes. The process engineers usually have selected several products that meet their specs.

The purchasing department desires a minimum number of vendors that they deal with and also to minimize the costs of the filters and number of different filters they purchase. The budget is always tight and purchasing wishes to find alternatives that meet constantly changing pricing requirements, without intentionally disregarding process specs. The filter spec may now be secondary or just moved further down the line in importance.

When the maintenance shift begins a changeout, does the process group know what filter was purchased and if it meets their specs? Were they informed of any changes in the selection process? Who actually controls what filter ends up in the process stream?

Given different needs and desires within a process plant's internal structure, what happens later may not be immediately obvious. Let's consider a real-life example: an amine system in a petroleum refinery.

An amine system

The main purpose of an amine system is to remove H_2S from the process stream and, as part of the sulfur unit's source, carries one of the dirtiest streams in the refinery. This example amine system is similar to many found around the world. Filtration is limited to 10–15% of the circulation stream. Why? The total amine flow circuit can be greater than 3,500 gal/min. The vessels and equipment to handle 100% of that stream did not exist in an economical size or cost range 15 years ago. So in this case, we are filtering a dirty stream with several filter systems; usually the lean and rich streams, before and after the carbon bed, and those protecting coalescers. What happens when a filter that is less expensive and not very efficient at removing particulate matter is is introduced into this system?

From outward appearances, all is fine initially and can be for months. Maintenance is happy because they change filters less often, purchasing is happy because the filters are less expensive. But, because the filters are not removing the particles they should, these build up in the towers, vessels, piping, low points and any other hiding place they can. All gas plants have surges or an increase in capacity that will fluidize the particles that have now accumulated in the hundreds of pounds throughout the system and create a full system upset. When an upset occurs, the filters are quickly fouled and may require changeouts every 30 min for days or weeks before the system settles down. The finger pointing begins and consultants are called in, the filter distributor or vendor is called in, production has halted and the plant manager wants to know what happened? Even if the plant manager is given the answer, the same situation can happen over and over again.

In truth, a filter that lasts long may be bypassing solids or releasing solids at its capacity but not performing the job it was intended to do. It looks good on paper but costs in the long run. Particulate matter helps create stable foams, and when active corrosion loops form when pipe passivity is upset by high acid from heavy crudes, filters can quickly foul from iron carbonate (Siderite). Heat exchangers are fouled requiring increased energy to the regenerator reboiler, velocities in the towers increase, amine carryover occurs and trays foul. The system becomes unstable and the sulfur plant upsets.

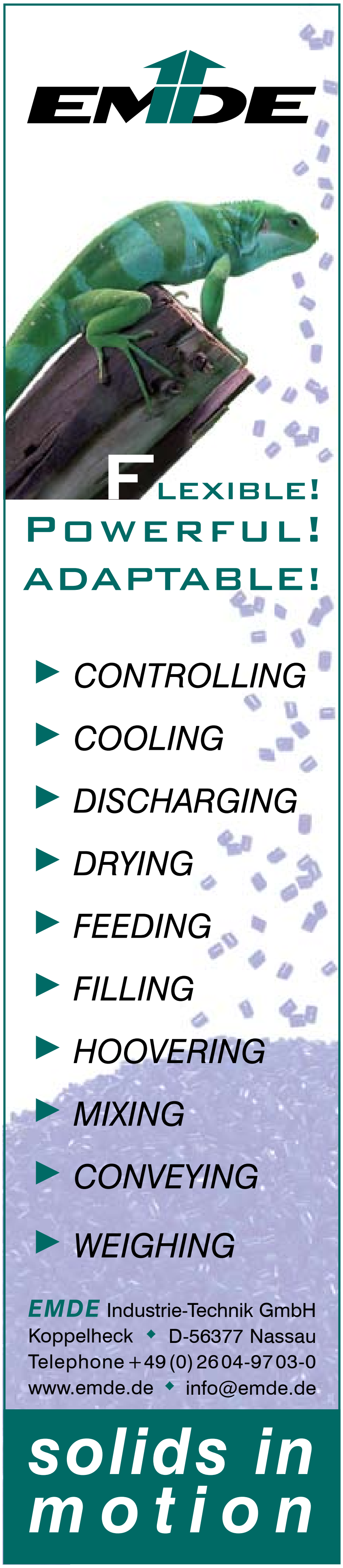
Fortunately, many plants are replacing or upgrading their amine filtration systems to handle flows up to 100% of full circulation flowrates. These systems are more stable, and upsets are shorter in duration. Stable systems still require filters that keep the system clean.

What micron range is best for amine systems? Micron ranges for filters range from 10 to 48 microns are in the field with an average at 20 microns for most systems at beta 100 efficiency (99%). ❑

has completely reached its capacity to remove particulate matter, that is, it has reached its maximum dirt- (or product-) holding capacity. But it is important to recognize that cost-savings associated with improved dirt- (or product-) holding capacity should begin with an economic analysis tied to the original filter specification.

Filtration costs

The goal of the filtering process is to obtain the lowest total cost of removing one pound of solids from the system.



FILTER EFFICIENCY (ABSOLUTE RATED FILTERS)

$$\text{Beta ratio} = \frac{\text{Upstream particle count at specified size and larger}}{\text{Downstream particle count at specified size and larger}}$$

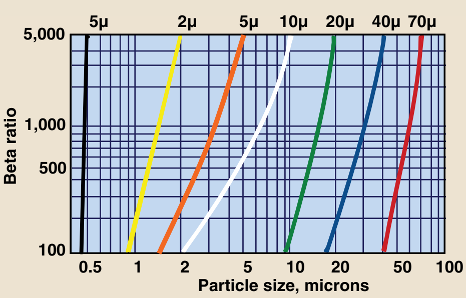
The beta ratio (β) at a given particle size can be correlated to the filter efficiency at that particle size according to the following formula:

Filter efficiency (%) = [(β-1)/β] x 100%

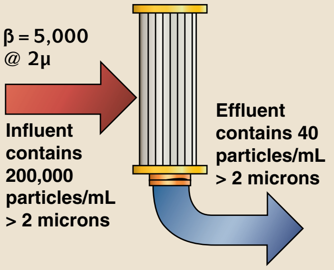
Beta ratio (β)	Filter efficiency (%)
100	99.00
1,000	99.90
5,000	99.98

Each filter element will have a different beta ratio for every specified particle size. The determination of a variety of beta values for the same filter provides a filter efficiency profile commonly referred to as a beta curve.

BETA CURVES



BETA EXPLANATION



If we disregard equipment depreciation, we can express filtration cost efficiency, *E*, as the total costs (direct and indirect) that are associated with removing one pound of solids from a processing stream. Direct cost is the filter price, *P*, and indirect costs include labor, *L*, and disposal, *D*. These latter two items can dramatically affect total-filtration cost calculations.

Filter price and dirt holding capacity are the dominant components in operating costs, and the ratio of these two items defines the alpha factor, *Å* (*Å* = *P*/*H*). With the expression for filtration cost efficiency,

$$E = Å + (L + D)/H$$

we see that indirect costs are reduced as the dirt-holding capacity (*H*) of the filter increases. Therefore, the alpha factor becomes the dominant number in the equation and overall cost as shown in Tables 3 and 4.

TABLE 4. TYPICAL DATA
20 micron (Absolute)
Beta 5,000-rated
polypropylene cartridges

Filter type	Dirt-holding capacity, lb	Typical cost, dollars	Alpha factor
2.5-in. O.D., pleated	2.0	44.00	22.0
6.25-in. O.D., pleated	18.0	266.00	14.8
12.75-in. O.D., pleated	100.0	1,053.00	10.5
20.0-in. O.D., pleated	300.0	2,829.00	9.43

MTBC and dirt-holding costs

Both operations and maintenance engineers recognize that having more on-line time, extended MTBC or MTBR, higher efficiency and higher dirt holding (or product-holding) capacity are essential to lower overall

TABLE 5. COMPARING FILTER CHANGEOUT COSTS FOR A FILTER USING STANDARD 2.5-IN. O.D. CARTRIDGES

Item	Non-hazardous service		Hazardous or toxic service	
	Basis	Cartridge	Basis	Cartridge
Purchase price of filter(s)	Same	Same	Same	Same
Disposal cost	$60/drum per changeout	$240	$800/drum per changeout	$3,200
Changeout time, h	1 h	-	8 h	-
Changeout labor (cost per hour for one person)	$30/man, two men needed	$60	$100/man, three men needed	$2,400
Protective clothing	Tyvek throw-away	$30	$10/h See note #1	$240
Respiratory equipment	None	-	$100/man	$300
Oxygen costs	None	-	$100 per man	$300
Decontamination expense	None	-	$100 per man	$300
Training expense per changeout	-	$100	$4,500	$4,500
Cost subtotal	-	$430	-	$11,240
Number of changeouts	Four changeouts per year	$1,720 Total annual cost (non-hazardous)		$44,960 Total annual cost (hazardous)

NOTE #1: Protective clothing is as much as $500/h in lethal service
NOTE #2: All dollars are U.S. (2008)

filtration costs. This is especially true when the filter is handling toxic or hazardous (or lethal) materials.

This article cannot discuss all of the requirements of regulating bodies, but, when filter changeout must include suiting up and breathing protection tied to opening a vessel and handling the filters, filter changeout costs can skyrocket. As shown in Table 5, these costs can go far beyond the simple purchase price of the filter itself.

Some hazardous chemicals (for example, bromine compounds that release Br_2 fumes) can require a team of three people to work the changeout, and each of these personnel may have to undergo annual training (40 h) at a cost to the company (or cost to service companies who may be called in to handle a hazardous work project). Training is estimated at a minimum of $6,000/yr per person.

Assuming a typical MTBC of three months (that is, changing out the filters four times a year), one might select a filter that will reduce the number of changeouts down to one per year, which would result is a savings of $33,720/yr. There can also be a saving in the actual costs of the filters.

One can compare filters using only the basic, actual, annualized costs (no training or other costs) comparing non-hazardous versus hazardous operation. The saving when using high-surface-area filters for toxic, hazard or lethal service is very significant.

Disposal costs

Let's consider the saving discussed above in light of what is happening in the real world with a discussion of filter disposal.

Case 1. First consider a specialty chemical manufacturer that is located on the Houston Ship Channel. This company handles various petrochemicals starting with C_4 compounds and higher with almost all filtration operations considered hazardous (flammable). The filter most commonly used in the plant is a standard cartridge (2.5-in. O.D.). In the disposal effort, about 60 of these filters fit into a standard 55-gal drum.

To avoid having to send these filters to incineration or to a hazardous waste disposal site, management chose to neutralize the used filters by a process known as fixation. That way, the filters can leave the plant classified as a non-hazardous waste. The disposal cost of a drum of these used filters is $60. So, the disposal cost can be considered as $1.00 per filter.

If one considers the total cost of filter disposal, the company must also address the time and economics of fixation. In this case, the fixation agent is flyash. Some companies following a similar disposal ethic, use lime or other agents that can effectively tie up the hazardous materials via oxidation or neutralization, and the filters may have to be cut up or shredded in order to attain the desired level of fixation.

Fixation itself can be a concern; one environmental engineer suggests

TABLE 6: DISPOSAL COST FOR A TYPICAL U.S. GULF COAST REFINERY

Waste classification	Comments and costs
Non-hazardous	Class 2 or 3 Industrial waste (Texas) NA due to high TPH Must be less than 1,500 ppm
Non-hazardous	Class 1 Industrial waste (Texas) $180/drum
Hazardous	Debris that meets LDR for direct burial into landfill $2,000
Hazardous	Debris that must be treated using an immobilization technology prior to landfill $3,200 to $4,200 per drum

Codes and Acronyms: NA Not applicable LDR Land disposal restrictions
TPH Total petroleum hydrocarbons in parts per million (ppm)

that the process can become so hot that one might actually see a blue flame emitted from fixated drums. (The drums used are usually open-top drums that allow for easy entry of the used filters).

In light of the above, consulting engineers have addressed the cost issues by suggesting the following:

- It takes one man-day to remove the filters from their vessel and to gather the filters into a location in order to cut into pieces or shred them
- There is a cost for receiving and handling the flyash
- There is a footprint cost for the processing area as well as a storage cost for flyash (or whatever is used to fixate)
- Protective clothing must be worn, and if the filters contain benzene, one must suit up to avoid exposure
- There is processing time to cut up or shred the filter, add the flyash, assure neutralization and load the spent filters into the filter drum
- There are handling costs (and handling time) for the drum
- There are transportation costs, which are separate from the $60 disposal cost

In total, the fixation for a single drum can utilize two or more man-days, actual flyash material costs of $30/drum, warehousing and storage costs for the ash that has a footprint of (say) 200 ft^2, which amounts to $400/mo. Movement and material handling and transportation adds another $50. Tyvek clothing can cost $40/mo (this assumes that there is no suiting up with breathing apparatus).

In total, the above cost components add $520 to the $60 drum disposal cost for a total cost of $580/drum.

If the plant produces 1 drum/wk of spent filters, the monthly cost reaches $2,320, enough for the plant to consider a high-surface-area filter, which may last for three months thereby freeing personnel for operations and reducing overall disposal costs.

Case 2. Next consider some real numbers from a U.S. Gulf Coast petroleum refinery making (mainly) gasoline and diesel fuel. Filter disposal costs can fluctuate widely depending on volume, density, state taxes, transportation costs and fuel surcharges. The rates (below) are based on approximately 20 yd^3 (one rolloff container) and are for the disposal cost only. Other change-out costs are similar to the numbers found in Table 6.

Land Disposal Restrictions are set by the U.S. Environmental Protection Agency (EPA) and are usually part of a State Implementation Plan (SIP). These restrictions (sometimes published as guidelines) must be met in order to place a hazardous waste into a hazardous waste landfill. If the waste does not meet that standard or cannot be treated to meet the standards, then an alternative must be used, such as incineration or thermal desorption. These latter options are often much more expensive than using a landfill.

Transportation costs are becoming more and more significant. In 2007 one could estimate that a rolloff dumpster could travel at $3.50 per mile, but that cost is quickly reaching $5.00/mi because transporters tack on added fuel charges. Typically, a refinery in Texas experiences a 75-mi haul (one way) and the size of the load is a 20-yd^3 rolloff.

In a refinery, cartridge filters that are typically used (and disposed of) include the following:

- Amine pleated-paper cartridges
- Reformer naphtha feed filters
- Fuel gas filters
- Lube oil filters for big compressors
- Wastewater treatment filters
- Filters that handle gases or liquids from the coking operation
- Fuel filters (both gasoline, diesel and jet fuel filters)

The latter are often metal filters that must handle high temperatures. These are sent out for chemical and physical cleaning — an additional cost not covered here.

Case 3. As a final example, consider costs related to having an outside contractor to handle filters used in hazardous or toxic chemical service. It is common for outside contractor to charge $250/drum to dispose of spent filters — and this does not necessarily include pickup at the plant or delivery to the disposal site.

A full service provider must be strict in respect to the MSDS (Material Safety Data Sheet) taking a close look at flammability, toxicity and heavy metals. Personal protective equipment will be utilized to be on the safe side. Levels of safety (for example, either A, B, C or D will be dictated by either NIOSH, OSHA or the EPA). Level "A" personnel will cost $850 per shift per person. Tyvek clothing will be worn (then thrown away) — a typical cost for that uniform can be $50. Even simple jobs that are non-hazardous are billed at $70–90/h per individual. It is not unusual that safety or risk assessment managers will be required to sign off on a plant's filter disposal procedures.

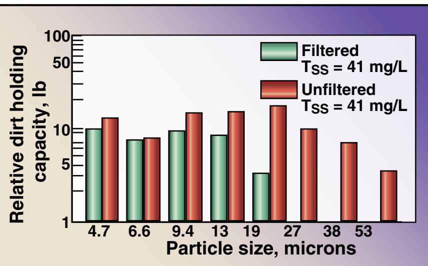
A service provider is expensive. Even non-emergency fee schedules can be exorbitant, both for personnel and expendables, such as: $14 for a 5-gal pail; $20 for a broom; $288 for an 85-gal polymer drum; $70 for a roll of polyethylene.

The point is, operating companies often do not know the true cost of their filtration operations and especially have room for improving their analyses of disposal costs.

It would be unfair not to mention large volumes of waste that are toxic and hazardous, but have energy value, are used in cement kilns for between $1,000 and 1,500/ton. Cement kilns are dramatically short of low-cost fuel but some can still charge for waste disposal.

The kilns are accepting some used filters (if they do not contain vinyl chloride polymers) at $65/drum. This is based on four layers of upright, standard cartridge filters and twenty, 12-in. filters per layer, or about 80 filters per drum.

On the plus side, (from the standpoint of filter disposal) the incineration business (in the U.S.) has been so bad that companies are charging as little as $0.60/lb of waste — even those containing heavy metals or chloride ions because incineration fixates the solids going though the furnace with the ash suitable to go into a regular landfill.



Cartridge filter, 2-5 µm nominal. 9.6 lb.gal NaCl.

Note the distribution of filtered particles greater than the cartridge's nominal micron rating.

(after McLeod & Crawford, copyright 1982 SPE-AIME)

FIGURE 7. Even though this filter is rated at 5 micron, reductions in filtered versus unfiltered do not become significant until after 19 micron

Conclusions

In summary, we can conclude that:

- It is much more expensive to changeout and dispose of filters that have been used in hazardous or toxic service
- Overall performance and cost reductions occurs when a plant can utilize high-surface-area cartridge filters
- By comparison, a high-surface-area filter may only have to be changed out two or three times a year compared to as many as 18 changeouts when using standard cartridges
- By improving MTBC or MTBR, high-surface-area cartridge filters used in toxic or hazardous service gives less exposure to operating and maintenance personnel
- The total cost of ownership should address MTBC and MTBR
- High-surface-area filters offer an increase in effective surface area and in dirt-holding capacity leading to longer filter life
- A filter element's alpha factor is easy to calculate; the lowest alpha factor offers the lowest filter cost

It is not surprising that ROI is dramatically affected by filter selection and filter costs (including replacement and disposal). Yet, this unit operation is often ignored by many companies that heavily depend on fluid-particle separation to assure plant profitability. ■

Edited by Gerald Ondrey

References

1. Buehner, F.W. and Rossiter, A.P., Minimize Waste by Managing Process Design, *Chemtech*, pp. 64–72; April, 1996.
2. Hampton, J., Cartridge Filtration Principles for the CPI, *Chem. Eng.*, pp. 40–44, January 2007.
3. Andrews, R., Ashes to Ashes, Dust to Dust: The Use of Test Dust in NSF/ANSI 42 and 53, Water Conditioning & Purification, November 2007.
4. Filter disposal-cost-data acquisition, interpretation and averaging performed by Weismantel International (Kingwood, Tex.).

Author

Frank W. Buehner is a technical sales engineer for Filtration & Membrane Technology, Inc., Houston, TX. Phone: 713-870-1120; Fax: 713-422-2533; E-Mail: fmt-houston@att.net). For the past 30 years, Buehner has been involved in promoting liquid separation methods employing polymeric and metallic membranes, high-vacuum thin-film distillation and liquid filtration. He has authored nine papers on these subjects. His current responsibilities include liquid-filtration-system optimization, filter selection. filtration processes, filtration-media-rating optimization, and pollution reduction for the petroleum refining, petrochemical and environmental industries. Buehner holds B.S.Ch.E. and M.S.Ch.E. degrees from Fenn College of Engineering at Cleveland State University. He is a member of AIChE and AFS.