Biofiltration — a Primer

Open biofilter for odor and VOC control at a German oil refinery. Photo courtesy of Leson Environmental Consulting.

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Use these guidelines to scale up and design biofiltration processes for the control of volatile organic compounds.

Biofiltration is an emerging energy-efficient technology for the control of volatile organic compounds (VOCs). It has been used extensively for over 40 years in the U.S. and Europe for the control of odors from wastewater treatment facilities, rendering plants, composting facilities, and other odor-producing operations. During the past few years, it has been used increasingly in the U.S. for treating high-volume, low-concentration air streams. Numerous research studies are being conducted to characterize its suitability for a wide variety of air emission control applications.

In biofiltration, off-gases containing biodegradable VOCs and other toxic or odorous compounds are passed through a biologically active bed of peat, soil, or other media. Contaminant compounds diffuse from the gas phase to the liquid or solid phase in the media bed, transfer to the biofilm layer where microbial growth occurs, and subsequently are biodegraded.

Biofiltration is an attractive alternative to conventional air-pollution-control technologies (*e.g.*, thermal oxidizers, scrubbers) for several reasons:

- Removal efficiencies of greater than 90% have been demonstrated for many of the more common air pollutants, including some of those listed by the Environmental Protection Agency as hazardous air pollutants (HAPs).
- Due to lower capital and operating costs, biofiltration may offer economic advantages in applications where the air stream contains contaminants at relatively low concentrations (up to 1,000 ppmv, although this is very contaminant-specific and varies widely) and moderate

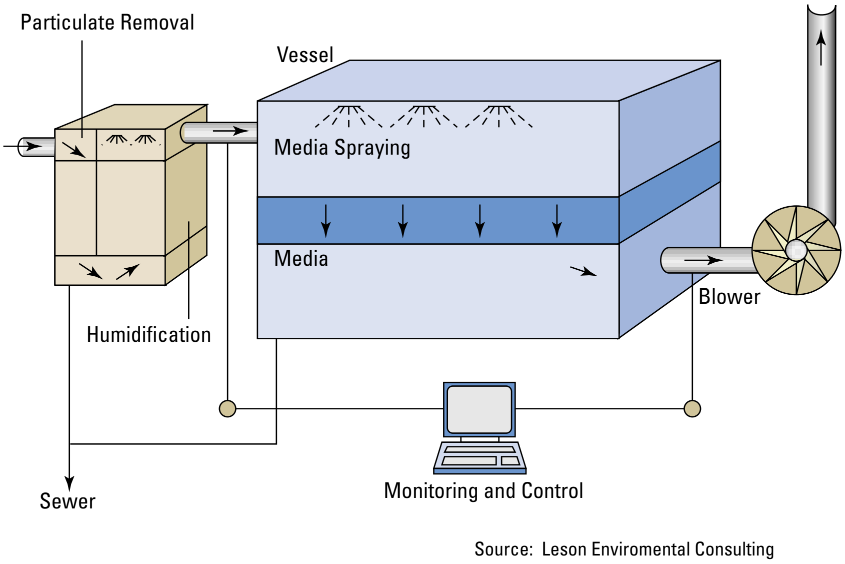
to high flow rates (generally 20,000 to 100,000 scfm depending on the contaminant).

- Biofiltration does not require large quantities of energy during operation and produces a relatively low-volume, low-toxicity waste stream.

However, it does not typically achieve the very high (*e.g.*, >99%) destruction and removal efficiencies (DREs) or maintain the relative consistency of treatment demonstrated by technologies that do not depend on microorganisms. Also, because there is a lack of U.S. application experience, biofiltration is not well understood by federal and state regulators.

This article explains how biofiltration works and provides guidance on process scale-up and design. It is excerpted from the "Collaborative Biofiltration Project Report" and "Biofilter Scale-Up and Design Guide" published by AIChE's Center for Waste Reduction Technologies (CWRT).

Other biological VOC control technologies, such as bioscrubbers and biotrickling filters, are not covered here. However, many of the data, applications, and concepts discussed apply to these systems as well.



Source: Leson Enviromental Consulting

■ Figure 1. Typical biofilter configuration.

Biofiltration technology basics

Biofiltration is a general term applied to the conversion of gas-phase chemical compounds to the common biological degradation products of carbon dioxide, water, and inorganic salts. It relies on two primary fundamental mechanisms — sorption and biodegradation.

Technologies considered to be forms of biofiltration include soil beds, biofilters, bioscrubbers, biotrickling filters, and engineered biofilters. While all of these operate based on the same fundamental mechanisms of contaminant sorption and biodegradation, they have different design and control parameters, operational flexibility, and performance characteristics. Note that the conventional trickling filter used for wastewater treatment is sometimes referred to as a biofilter, but it is a completely different technology.

A typical biofilter configuration is shown in Figure 1. The contaminated off-gas is passed through a preconditioner for particulate removal and humidification (if necessary). The conditioned gas stream is then sent into the bottom of a filter bed of soil, peat, composted organic material (such as wood or lawn waste), activated carbon, ceramic or plastic packing, or other inert or semi-inert media. The media provides a surface for microorganism attachment and growth. The off-gas stream is typically either forced or induced through the system with a blower. A vent stack is employed when necessary to meet monitoring or discharge requirements.

Mixtures of media types are sometimes used to provide operational advantages. In a soil, peat, or compost bed, the media itself may provide some or all of the essential nutrients required for microbial growth. Bulking agents and/or minerals can be incorporated into the media, depending on pH control requirements.

As the contaminated gas stream passes through the bed, contaminants are transferred from the gaseous phase to the media. Three primary mechanisms are responsible for this transfer and the subsequent biodegradation in organic media biofilters:

1. Gas stream → adsorption on organic media → desorption/dissolution in aqueous phase → biodegradation.

2. Gas stream → direct adsorption in biofilm → biodegradation.

3. Gas stream → dissolution in aqueous phase → biodegradation.

Once adsorbed in the biofilm layer or dissolved in the water layer surrounding the biofilm, the contaminants are available to the microorganisms as a food source to support microbial life and growth. Air that is free, or nearly free, of contaminants is then exhausted from the biofilter.

There are many variations to this basic approach.

Biological activity in a filter will eventually lead to degradation of a soil or compost media as organic matter is mineralized and the media particles are compacted. Degradable filter materials typically require replacement every three to five years.

Proper media selection affects biofilter performance with respect to its compaction and useful life. In addition, the media largely determines environmental conditions for the resident microorganisms. These microorganisms are the most critical component of the biofilter, since they produce the actual transformation or destruction of contaminants. Microorganisms can vary significantly in metabolic capabilities and preferences. Naturally occurring microbes are usually suitable and most desirable for treating most gas-phase contaminants. However, some of the more unusual anthropogenic chemicals may require specialized microorganisms. Sometimes these organisms can simply be taken from sewage sludge and acclimated to the specific contaminants that are present; in a few cases, specially grown pure, mixed, or genetically engineered cultures may be preferred.

Microbial cultures require a carefully controlled environment for optimal contaminant degradation. The most important environmental factor for microbial function is the moisture in the contaminated air stream entering the biofilter. Most industrial or remediation off-gases have less than 100% relative humidity, so supplemental humidification is often needed to minimize bed drying. This can be achieved with an upstream humidifier (commonly a spray tower), spray nozzle humidifiers mounted within the biofilter, or steam injection built into the biofilter. (Bioscrubbers and biotrickling filters, which rely on a recycled aqueous-phase solution, do not need prehumidification.) Humidification is also generally the single most influential parameter affecting the sorptive capacity of a biofilter, especially at lower inlet concentrations, where Henry's Law controls mass-transfer rates within the biofilter.

In the past, biofilters were commonly constructed as open, single-bed systems. Recently, fully enclosed biofilters have become more popular. These are frequently required to comply with emission monitoring requirements. Enclosed systems usually contain separate stacked beds in parallel or in series. This allows for a greater contaminant loading over a given footprint area. Fully enclosed systems also provide more precise control of biofilter moisture, thereby reducing the potential for failure due to moisture level fluctuations.

Compounds amenable to biofiltration

Biofiltration has been shown to be efficient for the removal or destruction of many off-gas pollutants, particularly organic compounds, but also some inorganic compounds such as H_2S and NH_3. Several factors contribute to the overall removal efficiency. Since biofiltration functions via contaminant sorption, dissolution, and biodegradation, contaminants that are amenable to treatment by biofiltration must have two characteristics:

1. *High water solubility.* This, coupled with low vapor pressure, results in a low Henry's Law constant, and thus increases the rate at which compounds diffuse into the microbial film that develops on the media surface. The classes of compounds that tend to exhibit moderate to high water solubility include inorganics, alcohols, aldehydes, ketones, and some simple aromatics (BTEX compounds); compounds that are more highly oxygenated are generally removed more efficiently than simpler hydrocarbons. However, some biofilter designs have been developed for less-water-soluble compounds such as petroleum hydrocarbons or chlorinated hydrocarbons.

About the project

Prior to 1997, a number of biofiltration systems were in use industrially, but the engineering basis for their design, scale-up, construction, and operation was largely absent. A collaborative effort was established under the auspices of AIChE's Center for Waste Reduction Technologies (CWRT) to identify the technical information needed to better define biofiltration and to gather that information. In brief, the project's accomplishments included: finding equations for predicting the biodegradability of organics; developing rules for orderly scale-up of biofiltration units; and showing that for certain types of organics biofiltration is economically competitive with commonly used processes in terms of both capital and operating costs.

The collaborative team consisted of representatives from twelve companies. Their identities as well as those of the companies that supplied economic data are not revealed.

This article is based on the work of the project team. For more information about the publications "Collaborative Biofiltration Project Report" and "Biofilter Scale-Up and Design Guide," contact Dr. Jo Rogers, CWRT Director, at jorogers@aiche.org or (212) 591-7727.

2. *Ready biodegradability.* Once a molecule is adsorbed on the organic material in filter media or in the biofilm layer, the contaminant must then be degraded. Otherwise, the filter bed concentration may increase to levels that are toxic to the microorganisms or detrimental to further mass transfer (sorption and dissolution). Either of these conditions will result in decreased biofilter efficiency or even complete failure. More readily degradable organic components include those with lower molecular weights and those that are more water-soluble and polar. Some inorganic compounds such as H_2S and NH_3 can also be oxidized biologically.

Research now underway aims to identify methods of treating contaminants that were previously considered to be untreatable by biofiltration, such as chlorinated hydrocarbons. Use of innovative reactor designs, specialized or anaerobic microbes, or supplemental substrates can help to accomplish this result.

Biofilter design parameters and specifications

Biofilter vessels are typically larger than the reactors of other air-pollution control devices. The relationship between off-gas flow rate, required residence time, and the corresponding reactor volume is the most crucial aspect in biofilter design, since it strongly affects space requirements and capital cost of a biofilter. Figure 2 summarizes the most commonly used biofilter design parameters.

The elimination of a single pollutant in a well-functioning biofilter follows the concentration profiles shown in Figure 3. The rate of removal is linear with the distance into the media, or with the empty bed residence time (EBRT) at higher concentrations. At lower concentrations, the rate of removal decreases and follows a power function. Lowering the off-gas face velocity (Case B) by increasing the filter bed area increases effective residence time and improves performance per unit of bed height, thus causing a steeper concentration profile. However, it also requires more filter volume per unit of air flow.

EBRT is generally considered the primary design parameter for a biofilter reactor. Consequently, the main objective of a pilot test for scale-up purposes is the determination of EBRT.

For a given set of off-gas composition and filter conditions, the pollutant removal efficiency or maximum outlet concentration allowed by regulations dictates a minimum EBRT. In modern biofilter applications, EBRT typically ranges from 15 to 60 s. This corresponds to a required filter volume of 0.25–1 ft^3 of filter media per cfm of off-gas flow rate (4.2–16.7 m^3 filter media/1,000 m^3/h). To avoid media compaction and uneven moisture distribution, individual biofilter beds are typically no higher than 3 to 5 ft (90 to 150 cm). The actual appropriate bed height depends on media type and expected pressure drop.

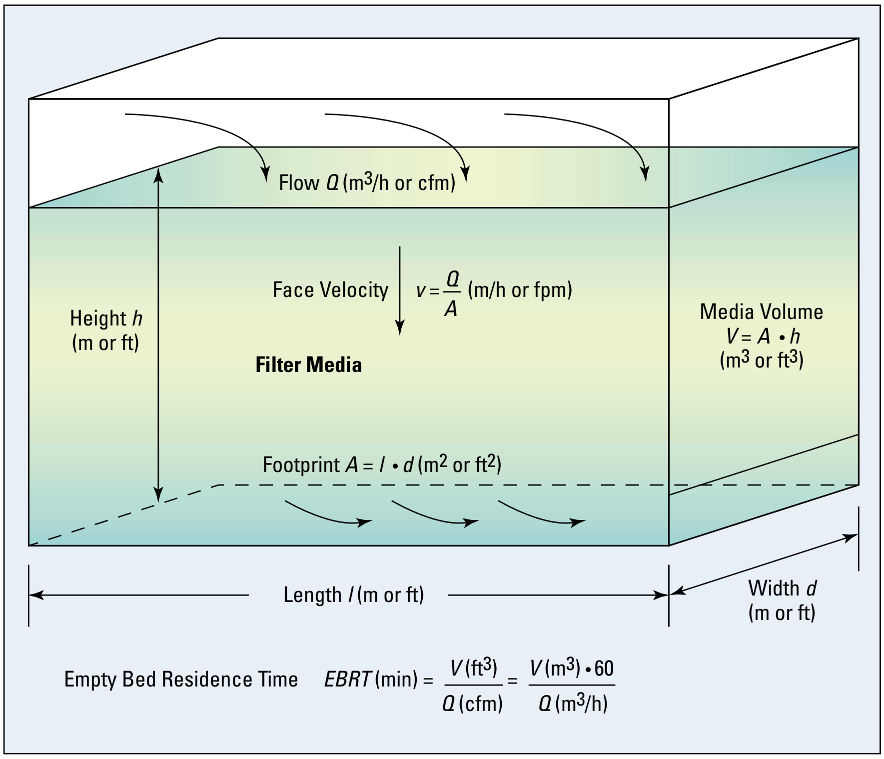


Figure 2. Biofilter design parameters.

The required reactor footprint is calculated by:

$$\begin{aligned} A &= Q/v \\ &= Q[EBRT/(h \times 60)] \end{aligned} \tag{1}$$

where A = cross sectional area or footprint (m^2), Q = volumetric flow rate (m^3/h), v = surface loading rate, or face velocity (m/h), h = filter bed height (m), and $EBRT$ = empty bed residence time (min).

Thus, if treatment of a 20,000-cfm off-gas stream requires an EBRT of 1 min and the biofilter has a single bed 1.5 m high, the required reactor footprint is about 380 m^2.

Stacking of beds reduces the biofilter footprint area. However, in addition to doubling the media height, stacking also increases off-gas face velocity, and the total off-gas pressure drop increases at least four-fold. Thus, to limit power consumption and the risk of off-gas channeling, and because stacked beds are generally more expensive to build, total media height in modern biofilters rarely exceeds 10 ft (3 m).

Another quantity commonly used in biofilter engineering is the system bulk elimination capacity (EC) for the target compound(s) per media volume. It is measured in grams of pollutant removed per cubic meter of media per hour (g/m^3•h) and is defined as:

$$\begin{aligned} EC &= (C_{in} - C_{out})(Q/V) \\ &= C_{in}\,(RE)(Q/V) \\ &= \Delta C(60/EBRT) \end{aligned} \tag{2}$$

where EC = elimination capacity (g/m^3•h), C_{in} = inlet concentration (g/m^3), C_{out} = outlet concentration (g/m^3), V = media volume (m^3), RE = removal efficiency (%), and ΔC = concentration difference = $C_{in} - C_{out}$.

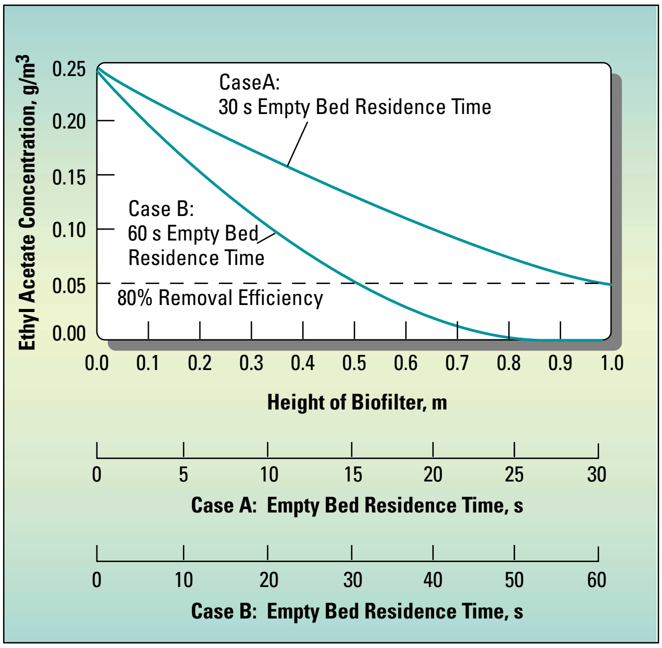
The pollutant loading, L (g/m^3•h), is defined as:

$$\begin{aligned} L &= C_{in}(Q/V) \\ &= (C_{in} \times 60)/EBRT \end{aligned} \tag{3}$$

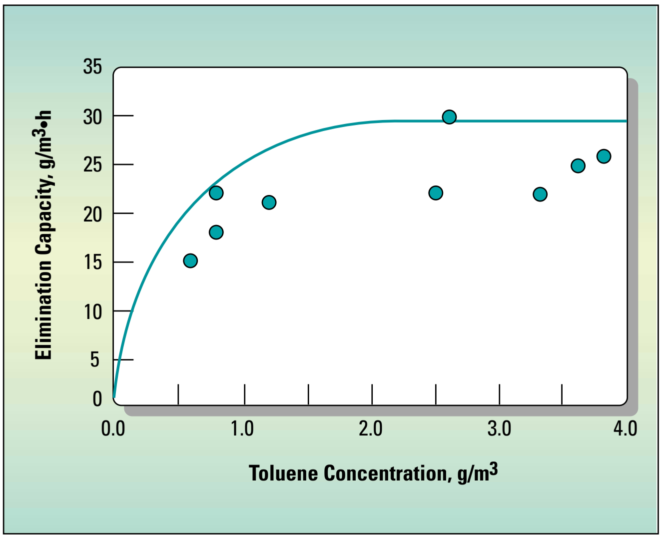
and relates to the elimination capacity and the removal efficiency by:

$$EC = RE \times L \tag{4}$$

Figure 4 shows that, for a given pollutant, the bulk EC for a compound increases with increasing concentration in the air stream (improved mass transfer) until it reaches a maximum. The maximum is determined by the biodegrad-



■ Figure 3. Removal of ethyl acetate in a biofilter as a function of residence time.



■ Figure 4. Typical elimination capacity of a biofilter as a function of inlet concentration.

ability of the compound and/or the availability of oxygen to the microorganisms.

Biofilter performance data

The effectiveness of various biofilter installations around the world is summarized in Table 1. This list is far from comprehensive, but it gives a sense of the range of applications, as well as the effectiveness of biofiltration in those applications.

As the table indicates, removal efficiencies tend to be greater than 85% for most applications and are typically greater than 95% for applications that are highly suited to biofiltration. These include odor control and the treatment of highly soluble and biodegradable compounds.

Technology assessment, design, and operation

The first step is to conduct an initial assessment to determine if biofiltration is a desirable alternative. Biofiltration requires special consideration because of the relative lack of experience with this technology for many off-gas streams. It has only recently become an “off-the-shelf” technology, and generally requires the development of design criteria on a case-by-case basis.

Design, operation, and control of a biofilter are complicated by several characteristics of the technology. First, the microorganisms responsible for degrading air pollutants often are not well characterized and are difficult to monitor directly. Second, a heterogeneous filter media adds complexity to modeling and controlling biofilter behavior. Third, there are a number of sensitive and interrelated variables, such as moisture content, pH, temperature, and influent air stream characteristics (*e.g.,* contaminant concentrations and fluctuations in concentrations) — and small changes in one variable can affect the behavior of others. For anything but the most routine application, a careful pre-design analysis, including some form of pilot testing, is essential.

The following aspects of biofiltration affect biofilter design and operation.

Flow rate and composition variability. Most off-gas or vent streams that originate in industrial processes or tank filling/venting operations have variable flow rates and compositions. The regulatory community generally expects emission controls to be capable of maintaining adequate treatment performance even though these fluctuations may be significant and/or frequent. Meeting performance requirements during peak loads is achieved at the cost of added energy use (operating cost) or over-designed systems (higher capital cost).

In biofiltration, however, over-design is not typically a cost-effective solution for addressing peak load concerns, and inlet fluctuations can result in variations in performance. As a result, selecting biofiltration for applications with fluctuating inlet stream characteristics risks violating emission discharge restrictions. The inability to maintain consistent removal efficiency can be a major limitation unless full support of the regulatory authority and community can be achieved.

Cost. The cost of biofilter installation and operation is highly application-specific. It depends on: the flow rate; concentration and sorptive and biodegradability properties of target pollutants; desired removal efficiency; reactor design; type of media; level of monitoring and control; and

Table 1. Typical biofilter performance data.

Application (Reference)	Contaminant(s)	Loading	Removal	Biofilter Type
Yeast Production Facility *(1)*	Ethanol, Aldehydes	35,000 cfm/500 yd^3 media, 1 g/m^3	Overall VOC reduction of 85%	Media filter
Plastics Plant VOC Emissions Control *(1)*	Toluene, Phenol, Acetone	1,000 m^3/h	80%–95%	Media filter
Pharmaceutical Production *(2)*	Organic carbon	1,000 m^3/h, 2,050 mg/m^3 (5,800 mg/m^3 peak)	>98% first stage, >99.9% overall	Media filter (two-stage)
Artificial Glass Production *(3)*	Monomer methyl methacrylate (MMA), Dichloromethane (DCM)	125–150 m^3/h, 50–250 mg/m^3	Biofilter: 100% MMA, 20% DCM; BTF: 95% DCM	Media filter plus biotrickling filter (BTF) in series
Hydrocarbon Emissions Control *(1)*	Hydrocarbon solvents	140,000 m^3/h, 500 mg/m^3	95%	Media filter
Compost Plant for Garbage *(4)*	Odor	16,000 m^3/h, 264 m^2 (1 m deep) 60 m^3/m^2•h, 230 mg C/m^3	>95%	Media filter
Gasoline VOCs Emissions Control (Pilot Scale) *(5)*	Total VOCs	16 g/ft^3•h	90%	Media filter
Hydrogen Sulfide Emissions Control (Laboratory Scale) *(6)*	H_2S	1.9–8.6 mg/kg•min (25–2,651 ppmv)	93%–100%	Media filter
Styrene Removal (Bench Scale) *(7)*	Styrene	Up to 22 g/m^3•h, 0.5 min retention time	>99%	Biotrickling filter
Styrene Removal (Bench Scale) *(7)*	Styrene	Up to 100 g/m^3•h	>95%	Media filter (peat)
Rendering Plant *(8)*	Odor	1,100 m^3/h (650 cfm), 420 m^2 (4,500 ft^2)	99.9%	Media filter
Fuel-Derived VOC Emissions Control *(9)*	Nonmethane organic carbon (simulated jet fuel)	500 ppm•cfm/ft^2, 500–1,500 ppm•cfm/ft^2	>95% 30%–70%	Media filter

materials of construction. Capital cost for large biofilters (>100 m^3) is driven by reactor volume and sophistication of design.

Enclosed biofilters. Fully enclosed biofilters are generally more expensive per volume of media than partially open beds. They are preferable where reliable VOC and HAP control needs to be maintained even under very hot, cold, wet, or dry conditions. Enclosed biofilters also allow for better control of media moisture and for more-reliable single-point stack testing, as well as better dispersion of the treated off-gas.

Microbiological hazard concerns. The presence of microorganisms in the biofilter media has raised concern over their potential release into the treated off-gas and resultant exposure to pathogens of workers on-site and individuals off-site. Several European studies have addressed this issue. They have found that biofilter exhaust contains both bacteria and fungal spores. However, particularly for raw gases containing high concentrations of microorganisms such as from composting and rendering operations, biofilters generally reduce levels of entrained microorganisms. Concentrations of microorganisms in biofilter exhaust are typically only a little higher than in ambient air and considerably lower than in ambient air near composting facilities. The potential for unhealthful exposure of off-site persons to airborne microorganisms from a biofilter is low because of dispersion.

However, the high concentrations of microorganisms,

Table 2. Consider these parameters during scale-up.

Parameter	Typical Range
Overall height of bed(s)	0.5–1.5 m
Empty bed retention time (EBRT)	25–60 s
Superficial gas (face) velocity	Volumetric gas flow/biofilter area, m/s
Inlet gas humidity	90%–100% RH
Inlet gas temperature	15–45°C
VOC component concentration	0–1,000 ppmv
Inlet gas oxygen concentration	11–21%
Media composition	(See discussion of media in text)

particularly fungal spores, in filter media could expose workers during installation, monitoring, and possibly fluffing of media, because these activities tend to release some of the fungal spores into ambient air. Thus, the use of respiratory protection by workers involved in such activities is advisable.

Biofiltration equipment manufacturers. Several equipment makers and technology companies supply biofiltration services. Some manufacturing companies and a few engineering and design firms have developed in-house capabilities for biofilter system testing and design. Many vendors also offer biofilter engineering and design services, but typically are restricted to offering basic system design. The complexity of the application will probably determine whether engineering and design expertise is necessary. For relatively common and simple applications (such as off-gas treatment from a leaking underground storage tank remediation system), several vendors offer readily available off-the-shelf systems. The industry is currently undergoing consolidation, and some of the smaller companies with relatively weaker capabilities to provide support are disappearing. The capabilities and services are expected to change significantly in the U.S. over the next few years.

Future developments. The development of biofiltration has relied on the extensive experience gained in Europe, which has provided a significant theoretical and practical knowledge base. Research groups all over the world, particularly in the Netherlands, Japan, and the U.S., are now developing more innovative applications for biofiltration. This expansion of applications is due primarily to:

- advances in filter bed media and packing design and bed loading techniques;
- fundamental microbiological and biochemical research into the mechanisms of microbial degradation and the characterization of microbial cultures suitable for achieving biofiltration;
- development of models to predict biofilter behavior during exposure to mixtures of VOCs, which may reduce the need for extensive pilot and field testing;
- development of alternative vapor-phase biological treatment systems, such as bioscrubbers and biotrickling filters; and
- a growing understanding of the potential economic and environmental advantages of biofiltration within industry and the regulatory community.

Biofilter scale-up and design

Numerous biofilters have achieved generally reliable performance at low operating costs. Yet a number of installations have experienced poor performance and required significant maintenance and repair and repeated replacement of filter media.

The most frequent problems were caused by changes in the media characteristics: dry-out, rapid degradation, or particulate clogging, resulting in excessive pressure drops and gradual accumulation of acidic byproducts. Clogging of air distribution systems, rapid corrosion of ductwork and concrete parts, emissions of odorous byproducts, overheating, and flooding of media have also occurred. These problems usually result from one or more of the following factors:

- unsuitable off-gases;
- improper sizing of filter beds; and
- design flaws.

These experiences emphasize the need for a careful scale-up and design procedure (assuming that the off-gas has been deemed suitable for biofiltration). Such a procedure should include the following elements.

Compound screening. Search the published literature for evidence that the compound is treatable in a biofilter. (The full CWRT biofiltration report includes a literature database and a compound database that can be used for this purpose.)

Vent stream characterization. Determine the gas flow rate, temperature, and humidity, particulate levels, and component VOC concentrations (estimated from mass and energy balances or from actual data).

Review of regulatory requirements. Consult regulatory experts to determine how regulations may relate to biofilter performance. For example, regulations may require either very high levels of contaminant removal or very consistent levels of removal. Either of these may be more difficult for biofiltration to achieve, especially for refractory compounds like aromatic molecules.

Consideration of scale-up parameters. Measure values for the parameters listed in Table 2.

Experimental considerations. Assess the time available for testing (a period of up to one year is most helpful for predicting performance), plan for proper disposal of leachate from the test unit, identify the proper analyses of the inlet and outlet gases, assess the need for additional air or oxygen, consider the value of working with a vendor as a partner, prepare for downtime and "cold starts," and be ready for the eventuality of drying out and oversaturation of media beds.

A key element of the scale-up process is testing for the technical and economic suitability of biofiltration. Types of testing include shake flasks, bench-scale testing, and pilot testing.

Shake flasks are used to assess the biodegradability and microkinetics of a compound not previously treated in a biofilter, to identify inhibitory effects between compounds in mixtures, and to help isolate suitable microorganisms for target compounds. They are performed for novel applications or where performance problems have occurred.

Bench-scale tests allow for more accurate observation of the interaction between a target compound, other co-pollutants, and the filter media. They are also useful for explaining potential performance problems encountered during a pilot test. However, because of the limitations inherent in using a synthetic stream and given the increasing body of knowledge on the treatability of volatile compounds, bench-scale testing is rarely performed.

Pilot tests are routinely conducted for any new application involving large flows (>10,000 cfm) and requiring quantifiable removal of VOCs or HAPs, unless prior biofilter experience exists for a similar off-gas. The main objectives of a pilot test are: accurate determination of the EBRT required to meet a regulatory control objective; identification of incompatibilities, such as the presence of poorly removed compounds and excessive temperatures; and establishment of other design parameters.

Once it has been determined that a stream is suitable for biofiltration and small-scale evaluations have been completed, a full-scale design must be chosen. Most full-scale biofilters include the following four elements:

1. *Off-gas pretreatment*. Maintain >95% relative humidity with wet bulb temperatures between 70°F and 100°F, and maintain particulate concentrations below10 mg/m^3 to minimize bed clogging.

2. *Biofilter reactor.* For the target range of EBRTs between 0.15 and 60 s, media volume per cfm of gas flow should be in the range of 0.25–1.0 ft^3; media volume is typically in the range of 100–2,000 yd^3 for flow rates from 2,000 to 150,000 scfm; and media bed heights are about 3 ft with pressure drops of 0.5 to 8 in. (w.g.).

3. *Air handling*. Biofilters can be operated with the blower either upstream or downstream.

4. *Monitoring and control*. In addition to controlling moisture, the off-gas temperature, pressure drop, and flow rate of air must be monitored for proper control and to assist in future failure analysis. If the total organic carbon (TOC) measurement is needed for regulatory purposes, flame ionization detection is the analytical method of choice.

The volume and type of media must be determined. The required EBRT, as determined by pilot testing, is typically the primary parameter used for calculating media volume. Other considerations include planning for channeling within the media, reactor heat loss/gain, changed pollutant concentration, interference between compounds, and other operational factors.

Operational issues

The final phase of a successful transition to full-scale operation is maintaining consistent, effective operation of the biofilter.

Maintenance involves media replacement, moisture control of the filter bed, hardware upkeep, and special requirements of the particular biofilter model chosen. Most biofilter systems provide for automatic monitoring and logging of off-gas temperature, pressure, humidity, and flow rate; bed moisture levels and pollutant inlet and outlet concentrations may also be automatically monitored and logged.

Written troubleshooting guidelines may help prevent or minimize such common problems as:

- *Failure of the moisture monitoring and control system*. The biofilter media beds must not dry out (because of insufficient moisture addition) or flood (because of excessive moisture addition). If the bed dries out, the bacteria will become inactive and biodegradation will rapidly decrease. If the bed floods, gas flow will be impeded and biological activity will decrease. Moisture problems can be minimized by prehumidifying the air stream, circulating warm water, installing a sprinkler, fluffing the beds, shortening the bed height, or switching from manual to automatic water addition.
- *Excessively high or highly variable pollutant loadings*. Pollutants, typically acidic gases, can affect the filter

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Table 3. Economic data for various emission control technologies.

Technology	Control Efficiency	Installed Capital Cost	Annualized Operating Cost
Methanol, 100 ppmv, 100,000 scfm			
Biofilter	95%	$962,500	$204,743
Conc/CO	95%	$1,405,000	$296,767
Biofilter	95%	$1,500,000	$385,114
Biofilter	95%	$1,885,000	$456,235
Conc/TO	95%	$2,987,000	$757,085
RTO	90%	$1,600,000	$834,900
RTO	95%	$1,905,000	$963,290
Toluene, 30 ppmv, 100,000 scfm			
Conc/CO	95%	$1,385,000	$286,829
Conc/TO	95%	$1,472,600	$350,289
Conc/CO	82%	$1,346,000	$369,697
Conc/TO	95%	$1,670,000	$475,690
Conc/RTO	90%	$1,866,000	$495,973
Biofilter	80%	$2,230,000	$515,780
Biofilter	80%	$2,156,000	$532,026
Conc/TO	85%	$2,000,000	$538,600
Conc/CO	95%	$1,837,000	$539,648
Conc/TO	95%	$1,937,250	$545,947
Conc/RTO	95%	$2,110,000	$597,210
Conc/RTO	95%	$2,500,000	$633,791
RCO	99%	$1,759,000	$733,399
Biofilter	90%	$3,900,000	$791,335
RTO	95%	$1,600,000	$822,600
RTO	95%	$1,905,000	$822,750

RCO = Regenerative Catalytic Oxidation
RTO = Regenerative Thermal Oxidation
Conc/CO = Concentrator plus Catalytic Oxidation
Conc/TO = Concentrator plus Thermal Oxidation
Conc/RTO = Concentrator plus Regenerative Thermal Oxidation

media. If the level of acidic pollutants is too high, the pH of the media can drop from the optimum level of 6–8 to less than 3. Below a pH of 3, media activity falls off and an alkaline wash is necessary. When the level of acidic pollutants is not as high, the bacterial load in the filter bed can acclimate itself, provided that the conditions do not change too much. For this reason, even a low level of acidic pollutants is not tolerable if the concentration of pollutants is too variable.

- *Media clogging by particulates*. Particulate loadings should preferrably be kept below 10 mg/m^3. Higher particulate concentrations will cause bed clogging and a drop-off of activity. Both blocking of active bacterial sites and channeling of gas around the active media cause a decrease in biodegradation activity. Particulate problems can be avoided by installing particulate-removal equipment upstream of the biofilter.
- *Media poisoning by acidifying or bactericidal compounds*. Compounds that cause either a pH decrease or poisoning of bacteria will cause temporary or irreversible loss of biodegradation activity.

Capital and operating costs

Underestimation of the capital and operating costs of biofilters has been a common occurrence. This may have happened because a biofilter was incorrectly perceived to be simpler than competing, more complex and highly engineered processes.

Capital costs for biofiltration are very much a function of the complexity of the biofilter internals, whether the biofilter is open or enclosed, the degree of sophistication of the control system, and the moisture control and monitoring system.

Electricity, water and steam use, direct labor, maintenance materials, and media replacement (media life 2–5 yr, \$50–\$300/m^3) influence operating costs. Other cost elements, which account for upwards of 50% of total operating costs, include items depreciation, overhead, and insurance.

Alternative technologies vs. biofiltration

Table 3 compares the capital and operating costs of biofiltration and a number of alternative emission-control technologies. Two cases are considered — 100 ppmv of methanol at 100,000 scfm, and 30 ppmv of toluene at 100,000 scfm.

The first case involves a readily biodegraded molecule, methanol. For this application, biofiltration is exceptionally good relative to the other technologies based on operating costs.

The second case involves toluene, a molecule that is relatively resistant to biodegradation. Here, biofiltration is (at best) in the middle to the upper end of operating costs among the technologies that were considered.

(Additional economic information is available in the complete CWRT report.) CEP

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