Understand the Capabilities of Bio-Oxidation

Relatively uncomplicated design and simple operation and maintenance requirements make biofiltration a good option for many types of air emissions control.

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Biological air-pollution control technology* has been used extensively in Europe for decades and, to a lesser extent, in North America for the past two decades. Most installations in the U.S. have been on air-emission vent streams that were not subject to numerical limits (*i.e.,* odors).

Several factors influenced the limited use of bio-oxidation equipment in the U.S. First, the relatively large size of the units made applications in existing industrial areas virtually impossible because there simply wasn't enough room. (A typical footprint for a single, 1-m deep, compost-bed biofilter to treat an 85,000-m^3/h stream would be approximately 25 m × 30 m.) Second, the weight of these biofilters precluded their placement on a building roof, as is sometimes done with thermal oxidizers. Also, the compost-based media (used exclusively in the 1970s and 80s, and still in use today) are subject to channeling, compaction, bed collapse and short-circuiting of air flow *(2)*. For this reason, as well as the relatively fragile nature of these biological systems and the often variable concentrations of contaminants in the emission streams, regulatory agencies believed that biofiltration was not a reliable technology. Industry was reluctant to install a control device that was looked upon by the regulatory agencies with skepticism. Finally, the compliance assurance monitoring (CAM) regulations of the 1990 Clean Air Act Amendments require verification of control equipment performance on a continuous basis, which is difficult to accomplish for biofilters because of the inherent biological variability (metabolically and by species of microbes).

The changing landscape

Over the last decade, a new generation of biofilters has come into the marketplace. They are based on the same biological principles as earlier systems, but they are more extensively engineered. They use media that provide increased surface area per unit volume (*i.e.,* more air-to-biofilm contact area), with structured components that virtually eliminate problems of compaction and collapse. They are available in a variety of bioreactor designs — biofilters, biotrickling filters and bioscrubbers. In a classic biofilter, microorganisms are attached to a substrate and a non-bioactive humidification system maintains the proper moisture level. In a biotrickling filter, microbes are attached to natural or artificial substrates, and water for humidification and the stream to be treated flow over the substrates and are recirculated. A bioscrubber is a water-scrubbing device with a suspended microbial component through which water recirculates. Bioscrubbers may be designed to use the effluent (non-chlorinated) from an extended-aeration

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* A previous *CEP* article *(1)* provides an overview of biofiltration (or bio-oxidation) and insight into the various types of bio-oxidation systems used to control volatile organic compounds (VOCs), hazardous air pollutants (HAPs) and odors (including hydrogen sulfide and other organo-sulfur compounds).

or activated-sludge type wastewater treatment plant (WWTP) to form a combined treatment system. Combinations of these various bioreactors are being applied to achieve multiple stages of treatment for mixed-contaminant air emission streams.

These new-generation bio-oxidation systems have several things in common. Each needs virtually 100% relative humidity in the air emission stream in order to prevent the media, or sections of it, from drying out; drying creates airflow short circuits that reduce contact times. Relatively long contact times (seconds to minutes) are necessary so that the contaminated air will remain in close proximity to the microbes so that sorption can occur. Each bioreactor must contain a community of microorganisms growing at the air/water interface, or biofilm, which is capable of biodegrading the pollutants in the air stream. The products of this bio-oxidation/biodegradation process are carbon dioxide, water, mineral salts and microbial biomass. This process is much like natural, aerobic decomposition of organic matter in soils and in aquatic and marine environments.

Operational factors

The three most important parameters that determine the overall effectiveness of any bioreactor are moisture, temperature and pH. Other factors that have some influence include nutrients, particulate material in the emission stream (including oil and grease aerosols), direction of airflow, type of contaminant(s) and available oxygen.

Moisture

The bed of biomass must be neither too dry nor too wet (flooded). If the bed is excessively dry, the biomass will die, or too much contaminated air will move too rapidly through the system and treatment will not be complete. Furthermore, as drying occurs in one area, the airflow increases the size of the dry area, allowing even more air to pass and resulting in significant treatment losses. Conversely, if the bed contains too much moisture, the biomass may wash out or be drowned, which can result in the loss of treatment capability, and/or the airflow may be restricted, which increases backpressure and thus power consumption. To avoid these situations and to maintain proper moisture control, the incoming air stream must be adequately humidified.

Temperature

Temperature controls the metabolism of the microbes. Psychrophiles operate best at somewhat lower temperatures, generally less than 20°C, while mesophiles perform best in the 15–40°C range, and thermophiles typically function in hot springs and thermal vents at 60–100°C, but cannot exist at even high ambient temperatures. A biofilter can operate at temperatures all along this overall range. However, a warm (approximately 25–35°C) bio-oxidation unit will generally support more organisms, both in terms of the number of organisms and the number of species, at higher activities (metabolic rates). The drawback to higher-temperature operation is that less of a specific contaminant will dissolve in the water, and sorption of the compound(s) will also be decreased *(3)*. Microbial activity approximately doubles with each 10°C increase in temperature, as long as the organisms remain within their thermal tolerance zone. (Above each species' upper thermal limit, metabolism begins to decrease and, if temperatures are sufficiently elevated, the organisms die.) Thus, a warmer bioreactor will oxidize incoming organic compounds faster, enabling it to handle higher loadings of contaminants per unit time with good destruction and removal efficiency (DRE).

Because bioreactors contain hundreds and often thousands of species of microbes, the temperature-metabolism relationship is not simple. The microbial community in a bioreactor contains so many species with different thermal tolerances that relatively good bio-oxidation can be maintained over a wide temperature range. A recent installation of four 17,000-m^3/h pilot-scale bioreactors treating the water-soluble compounds formaldehyde and methanol from particleboard-press vent emissions has achieved consistent DREs in excess of 92% at bed temperatures ranging from 31°C to 18°C (the seasonal temperature change from September 2001 to January 2002).

Although a bioreactor can operate successfully over a wide temperature range, there are several reasons to control temperature within a narrower operating range. Sudden and extreme temperature changes can be very detrimental to the biodegradation of incoming contaminants *(3)*. The recordkeeping and compliance demonstration is made easier if operation can be maintained within a relative narrow temperature range; otherwise, demonstration of removal efficiency may have to be assessed over the entire operating range, and the larger that range is, the more extensive and costly the stack testing will be. Finally, moisture control is more easily handled over a narrow temperature range.

pH

Each specific microbe has defined upper and lower limits and an optimal pH operating range. Bioreactors can function at pHs ranging from as low as 2–3 to as high as 8 or 9, with pH often changing (usually decreasing) after operation begins.

Since chlorinated and sulfur-containing compounds produce acids upon biological degradation, careful attention must be paid to the pH of the system. For the biodegradation of H_2S and organo-sulfur compounds (which produce sulfuric acid), irrigation of the media bed is needed to counteract acidification. Thus, water removal must be increased to prevent an unacceptably low

Table. Comparison of VOC control technologies.

	Bio-Oxidizer	**Bio-Oxidizer**	**RTO**	**RTO**	**RCO**	**RCO**
	VOC-1	**VOC-2**	**VOC-1**	**VOC-2**	**VOC-1**	**VOC-2**
Equipment Costs	$280,000	$255,000	$300–400,000	$300–400,000	$325–425,000	$325–425,000
Installation Costs	$20,000	$20,000	$25–35,000	$25–35,000	$25–35,000	$25–35,000
Dimensions, ft	20 × 30 × 26	20 × 30 × 22	20 × 24 × 18	20 × 24 × 18	20 × 24 × 18	20 × 24 × 18
Operational Costs						
Natural Gas @ $3/therm	$0	$0	$95,000/yr	$125,000/yr	$35,000/yr	$45,000/yr
Electricity @ $0.065/kWh	$26,000/yr	$26,000/yr	$28–30,000/yr	$28–30,000/yr	$28–30,000/yr	$28–30,000/yr
Water @ $6/1,000 gal	< $1,000/yr	< $1,000/yr	< $1,000/yr	< $1,000/yr	< $1,000/yr	< $1,000/yr
Other Heat	$0–25,000/yr	$0–25,000/yr	$0	$0	$0	$0
Wastewater Discharge, gal/wk	750–1,500	750–1,500	0	0	0	0
Media Replacement*	$6,500/yr	$6,000/yr	$3,000/yr	$3,000/yr	$7,000/yr	$6,500/yr
Parts and Upkeep	$2–5,000/yr	$2–5,000/yr	$5–12,000/yr	$5–12,000/yr	$5–12,000/yr	$5–12,000/yr
Operator Support, h/yr	200–300	200–300	300–400	300–400	300–400	300–400
Emissions						
VOC DRE[†]	85–95%	85–95%	95–99%	95–99%	95–98%	95–98%
VOC, ton/yr[‡]	136–407	17–51	27–136	4–17	54–136	7–17
CO, ton/yr	0	0	4–8	4–8	4–8	4–8
NO_x, ton/yr	0	0	2–4	2–4	1–2	1–2
SO_2, ton/yr	0	0	< 1	< 1	< 1	< 1

Notes:
RTO = Regenerative Thermal Oxidizer; RCO = Regenerative Catalytic Oxidizer; Conc = Concentrator.
All values are estimates based on discussions with suppliers of VOC control equipment.
Assume that the VOC stream is a mixture of xylenes, MEK, MIBK, *n*-butyl acetate and naphtha.
Operation is 24 h/d, 7 d/wk (8,760 h/yr).
* Media replacement costs are prorated annual costs; biofilter media replacement is at 4-yr intervals over a 15-yr period; oxidizer media replacement includes ceramic media, catalyst, and concentrator substrate over a 15-yr period.
[†] DRE = Destruction and Removal Efficiency.
[‡] VOC emissions have an average molecular weight of 100 (VOC-1 = 2,000 ppmv, VOC-2 = 250 ppmv), flowrate = 20,000 dry scfm (34,000m ^{3}/h), temperature = 65°F.

pH in the system. Another factor to consider is that H_2S is most effectively biodegraded at a relatively low pH of 2–4, whereas organo-sulfur compounds are best oxidized at a pH of 5–7. If both types of sulfur compounds are present (*e.g.,* as in emissions from pulp and paper mills), a multi-stage biofilter is the best choice, with the media bed(s) near the inlet operating at a low pH (3–4) and the beds further downstream operating at a higher pH.

A bioreactor's pH can also be managed by the addition of crushed limestone in the media, adding a buffering solution to the irrigation/humidification water, and by more or less frequent water removal or addition.

Other factors

Food for the microorganisms comes from the bio-oxidation of the contaminants in the air emission stream. However, these contaminants often contain little or none of the vital compounds and trace elements needed for proper cell growth and maintenance. These include nitrogen, phosphorus, potassium, calcium, zinc, selenium, iron, manganese, magnesium, sulfur and sodium; certain others may be necessary for specific microbes to metabolize "exotic" compounds.

One advantage of compost-based media is that they contain a reservoir of these macro- and micronutrients

Table. Comparison of VOC control technologies. (con't.)

	RTO + Conc	RTO + Conc	RTO + Conc	RTO + Conc
	VOC-1	**VOC-2**	**VOC-1**	**VOC-2**
Equipment Costs	\$350–450,000	\$350–450,000	\$375–475,000	\$375–475,000
Installation Costs	\$35-45,000	\$35–45,000	\$35–45,000	\$35–45,000
Dimensions, ft	26 × 36 × 18	26 × 36 × 18	26 × 36 × 18	26 × 36 × 18
Operational Costs				
Natural Gas @ \$3/therm	\$0\$15,000/yr	\$20,000/yr	\$8,000/yr	\$11,000/yr
Electricity @ \$0.065/kWh	\$30–32,000/yr	\$30–32,000/yr	\$30–32,000/yr	\$30–32,000/yr
Water @ \$6/1,000 gal	< \$1,000/yr	< \$1,000/yr	< \$1,000/yr	< \$1,000/yr
Other Heat	\$25–35,000/yr	\$25–35,000/yr	\$25–35,000/yr	\$25–35,000/yr
Wastewater Discharge, gal/wk	0	0	0	0
Media Replacement*	\$20–25,000/yr	\$20–25,000/yr	\$22–27,000/yr	\$22–27,000/yr
Parts and Upkeep	\$7–15,000/yr	\$7–15,000/yr	\$7–15,000/yr	\$7–15,000/yr
Operator Support, h/yr	350–450	350–450	350–450	350–450
Emissions				
VOC DRE†	92–97%	92–97%	92–97%	92–97%
VOC, ton/yr‡	82–217	10–27	82–217	10–27
CO, ton/yr	4–8	4–8	4–8	4–8
NO_x, ton/yr	2–4	2–4	1–2	1–2
SO_2, ton/yr	< 1	< 1	< 1	< 1

for the microorganisms to extract as needed *(4)*. Compost-based media, depending on the amount of biological activity, typically last four to six years, with adequate micronutrients available for release and maintenance of structural integrity. When rock, granular activated carbon (GAC), polyurethane foams or plastics are used as the media, nutrients must be supplied. This is usually done by adding a micronutrient mix containing nitrogen, phosphorus, potassium and various trace elements (similar to liquid plant fertilizer).

In any bioreactor application, it is prudent to add a complete and balanced mix of nutrients on a regular basis, particularly with respect to nitrogen consumption and availability. Soluble or available nitrogen should be determined periodically in both the matrix and the water collected (and recirculated) in the bioreactor. If organic nitrogen compounds (*e.g.,* amines) are being oxidized or ammonia is present in the air emissions stream, then sufficient nitrogen may be available throughout years of operation.

Odor control

Many early biofilters were installed at wastewater treatment plants to treat off-gases from the incoming wastewater and the in-plant operations, and this practice continues today. Such bio-oxidation systems are typically open-top, in-ground units that are 1–3 m deep. A series of perforated pipes set in coarse gravel serves as the air distribution system. Humidification is usually provided by spray nozzles in the header leading to the air distribution pipes; additional water may be added through soaker hoses or surface sprinklers. The biofilter media is usually some type of compost/bark mulch layered over a base of bark, wood chips or porous lava rock to prevent collapse into the gravel in the distribution system base *(3)*. The odors being controlled are primarily H_2S and skatols from the headworks and digesters, with flows ranging from about 2,000 to 15,000 m^3/h. When properly designed and installed, these units should operate for many years. However, poor design and improper materials selection may lead to compaction and channeling, with rapid loss of removal efficiency and the need to replace the media or the entire system.

Compact biofilters can be used to control odors from manholes, pressurized sewer vents, transfer and lift stations, and virtually any other odor source that can be collected and routed to a biofilter. They are relatively inexpensive and can be set in place and made operational with little manpower. They may need only a 115-V power source, a freshwater connection, an air collection duct (10–15 cm) from the contamination source, and a wastewater return to the collection point.

Large, single- or dual-bed, completely enclosed biofilters are being built to control flavors, fragrances and insect-repellent compound odors in air streams with flowrates of 8,000–85,000 m^3/h. Many of these flavors and fragrances are mixtures of alcohols, ketones, esters and ethers, all of which are easily biodegradable, and most of which are highly soluble in water. Odor removal efficiencies are usually very good, often exceeding 98%. Many facilities that have had significant odor complaints from their neighbors have usually seen those complaints fall to near zero after installation and a few months of operation of a biofilter.

VOC and HAP control

Small bioreactors (< 850 m^3/h) have been used to control emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) in several industries. Small biofilters have been designed to control gasoline vapors from the remediation of contaminated water and soil *(5)*. Experimental units treating glycol dehydrator emissions, composed primarily of benzene, ethylbenzene, toluene and xylene at tens of thousands of parts per million with air flows of 0.5 m^3/h, have achieved DREs in excess of 98% over more than a year of experimental operation *(6)*. Since 1993, biofilters have been used to bio-oxidize spent volatiles from the depressurization (puncturing) of aerosol cans at a number of household-hazardous-waste collection operations throughout the U.S. *(7)*.

These small biofilters offer several advantages over thermal oxidation or GAC adsorption. They do not generate NO_x or CO, and there is no VOC-saturated carbon to be regenerated or disposed of. Their costs vary from approximately $10,000 to $45,000. Operating costs are generally low, ranging from less than $100 to several hundred dollars per month. The capital costs of other VOC/HAP-control devices, such as thermal oxidizers or GAC adsorption systems, may be similar or slightly higher than those of a bioreactor, but the operating costs (fuel for the thermal oxidizer and carbon regeneration or disposal) are typically two to six times those of a bioreactor.

Bioreactor designs have been much refined since the initial units were put into service 30 to 40 years ago.

Large biofilters and bioreactors (> 1,700 m^3/h) are also finding industrial applications for the control of VOCs, HAPs and other air emissions. In the early 1990s, several large (almost the size of a football field) compost-based, single- or dual-bed biofilters were installed on panel-board plants in the wood products industry *(8)*. They are operating successfully, but some have had recurring problems with bed drying and short-circuiting, with a resultant reduction in treatment efficiency. A new 765,000-m^3/h biofilter has been installed by a wood products company at its mill in Montana, and operation began in September 2001 at one-half the design airflow and contaminant loading rate. The huge size of this type of biofilter makes its installation difficult or impossible at many existing facilities that will require controls for this industry's HAPs (methanol and formaldehyde).

Suppliers are redesigning biofiltration systems in an attempt to "fit" bioreactors into existing plant sites. For example, the four 17,000-m^3/h pilot bioreactors recently installed on a particleboard mill in Oregon that were discussed earlier have a much smaller footprint than conventional biofilters. They are made of stainless steel and contain multiple beds of balled, structurally enhanced compost media. Optimum operating temperatures can be maintained by using the condensate from the steam-heated board press (utilizing waste heat). The systems also combine humidification and scrubbing in a biotrickling filter design upstream of the biofilter media beds. Removal of formaldehyde and methanol, the target HAPs in this case, has exceeded 90% on a continuous basis and has usually been is excess of 95% since approximately two weeks after operation began over a year ago *(9)*.

Applications of industrial bioreactors may also be found in the printing industry for the control of VOCs emitted during printing and ink drying *(3)*. A two-unit system installed at a Wisconsin facility in 1997 allows plant operations at all times with continuous emission controls. Removal efficiency has generally been in excess of 80%.

Recent installations have also been completed in the paint manufacturing industry, and on a paint booth exhaust in the coating industry *(10)*. These two units have provided more than 85% removal efficiency for total VOCs. Both have small steam generators for maintenance of optimum operating temperatures and maximum removal efficiency. They operate at 17,000 m^3/h (their design capacity) with variable VOC loading rates.

A new system has recently begun operation at a casting facility for the control of VOCs, oily vapor and oil mist from a metal casting process. Initial observations indicate a successful application. Other bioreactors have been installed to remove contaminants from air streams at pharmaceutical, plastic manufacturing and rendering plants. However, many of these applications may be more for odor control than to meet an hourly or annual emission limit.

Is there a bioreactor in your future?

Bioreactor designs have been much refined since the initial units were put into service 30 to 40 years ago. Additional design changes are taking shape and are being evaluated at this time that are expected to increase industry's reliance on this technology for applications where control must be evaluated based on actual numerical emission limits rather than reduction of odors.

These air-pollution-control devices eliminate the production of NO_x, SO_2 and CO, and greatly reduce CO_2, compared to conventional thermal oxidizers. Annual savings in operating costs for a biofilter over the costs to run a regenerative thermal oxidizer (RTO), each treating an 85,000-m^3/h air stream with less than 500 ppmv of a VOC, may exceed $300,000. This savings alone could pay for the biofilter or bioreactor in two to three years.

So, is a biofilter the correct choice for your plant? Here is some general guidance to help you determine if your application is a good candidate for bio-oxidation.

The table will allow you to make some preliminary evaluations. It provides a general assessment of five control options for two hypothetical VOC/HAP air streams. The 2,000-ppmv stream (VOC-1) is typical of emissions from a paint manufacturing operation, while the 250-ppmv stream (VOC-2) is fairly representative of the exhaust from a paint booth. The compounds in these streams are what would be expected from these types of operations, and the values noted are for total VOCs, as carbon, based on a routine U.S. EPA Method 25A measurement. The last four lines (for VOC, CO, NO_x and SO_2 in ton/yr) represent estimates of expected emissions from each of the control devices.

Early biofilters were most often used to control odorous or very dilute (less than a few hundred parts per million VOC) emission streams. Airflow rates usually did not exceed 50,000 m^3/h. However, several systems have been installed within the last several years on emission streams with VOCs in excess of 1,000 ppmv and applications where airflows were in excess of 100,000 m^3/h.

If your application requires a DRE greater than 95%, then a biofilter is probably not a viable option. An exception to this rule-of-thumb is if you can achieve additional emission reductions from other plant emission sources that could be applied to an overall plantwide bubble emission limit. That would allow the bio-oxidation system to be used for control at a lower DRE than the originally required 95%, while total emissions from the facility would remain the same or actually decrease. Regulatory agencies are now more open to this technique than before, since control of VOC and HAP emissions via bio-oxidation uses little or no additional fuel and does not produce NO_x, CO or SO_2, as do conventional thermal oxidizers. If, on the other hand, your regulatory needs are for air emissions reductions or controls less than 90% DRE, or you simply have odors to control, a biofilter may be the preferred choice.

VOC and/or HAP concentrations less than 3,000 ppm can be treated effectively in a bio-oxidation system. Air emissions with temperatures above 80°C and with high moisture content are marginal candidates for bio-oxidation, because water quenching to less than 44°C, a generally accepted maximum inlet temperature, would be virtually impossible. Also, the amount of dilution air necessary, two to four times the airflow volume, would increase the unit's size and cost to substantially more than those of conventional control technologies. CEP

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