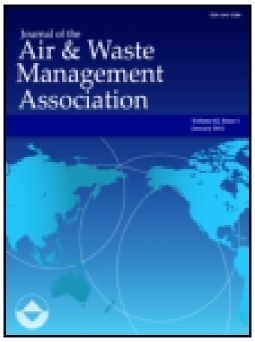

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Biofiltration: An Innovative Air Pollution Control Technology For VOC Emissions

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Biofiltration is a relatively recent air pollution control (APC) technology in which off-gases containing biodegradable volatile organic compounds (VOC) or inorganic air toxics are vented through a biologically active material. This technology has been successfully applied in Germany and The Netherlands in many full-scale applications to control odors, VOC and air toxic emissions from a wide range of industrial and public sector sources. Control efficiencies of more than 90 percent have been achieved for many common air pollutants. Due to lower operating costs, biofiltration can provide significant economic advantages over other APC technologies if applied to off-gases that contain readily biodegradable pollutants in low concentrations. Environmental benefits include low energy requirements and the avoidance of cross media transfer of pollutants. This paper reviews the history and current status of biofiltration, outlines its underlying scientific and engineering principles, and discusses the applicability of biofilters for a wide range of specific emission sources.

The concept of using microorganisms for the removal of environmentally undesirable compounds by biodegradation has been well established in the area of wastewater treatment for several decades. Not until recently, however, have biological technologies been seriously considered in the United States for the removal of pollutants from other environmental media. Moreover, while bioremediation techniques are now being applied successfully for the treatment of soil and groundwater contaminated by synthetic organics, at present there is very little practical experience with biological systems for the control of air contaminants among environmental professionals in the U.S. In fact, few environmental professionals in this country appear to be aware that "biofiltration," i.e., the biological removal of air contaminants from off-gas streams in a solid phase reactor, is now a well established air pollution control (APC) technology in several European countries, most notably The Netherlands and Germany.

In Europe, biofiltration has been used successfully to control odors, and both organic and inorganic air pollutants that are toxic to humans (air toxics), as well as volatile organic compounds (VOC) from a variety of industrial and public sector sources. The development of biofiltration in West Germany, most of which took place in the late 1970s and the 1980s, was brought about by a combination of increasingly stringent regulatory requirements and financial support from federal and state governments. The experiences in Europe have demonstrated that biofiltration has economic and other advantages over existing APC technologies, particularly if applied to off-gas streams that contain only low concentrations (typically less than 1000 ppm as methane) of air pollutants that are easily biodegraded.[1]

The principal reasons why biofiltration is not presently well recognized in the U.S., and has been applied in only a few cases, appear to be a lack of regulatory programs, little governmental support for research and development, and lack of descriptions written in the English language. Specifically, regulatory programs in most U.S. states have not yet addressed, in a comprehensive manner, the control of air toxics, VOC and odors from smaller sources. Moreover, little financial support for investigating the applicability of biofiltration for these sources has been provided by government agencies. Finally, although several important papers on biofiltration have been published in English,[2–4] most of the technical reports summarizing recent results[5,6] were published in German.

Despite these current obstacles, biofiltration is likely to find more widespread application in the U.S. in the near future. In addition to a few existing installations, several full-scale projects are currently in the planning stage or under construction. For example, the first large scale system for VOC control in California, a biofilter to treat ethanol emissions from an investment foundry in the Los Angeles area is being planned with co-funding by the South Coast Air Quality Management District (SCAQMD). A detailed description of this system, and an analysis of its performance is provided elsewhere.[7,8]

The major objective of the present paper is to provide a comprehensive review of important aspects of biofiltration

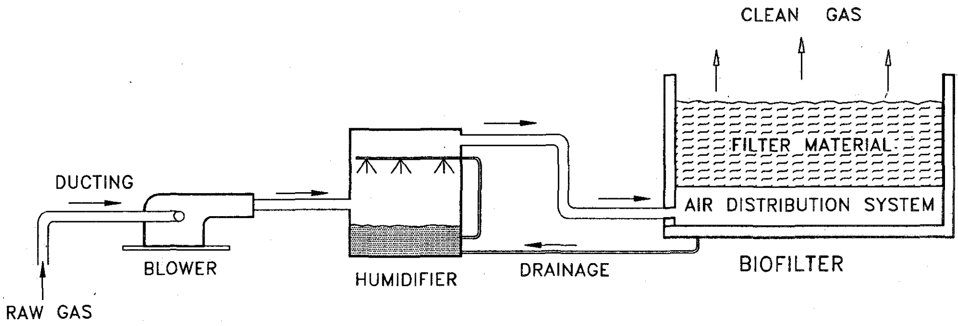

Figure 1. Schematic of an open single-bed biofilter system.

in order to more widely disseminate information about this innovative APC technology, and to encourage its implementation where appropriate in the U.S. Many of the more complex technical and engineering issues related to the development and use of biofiltration cannot be discussed in great depth here. However, we identify and summarize such issues, and refer to more detailed publications. We also note that, in addition to biofiltration, other biological APC systems are now in use in Europe for the control of organic off-gases, including "bioscrubbers" and trickling filters. Various articles on these related technologies, which are not discussed here, are available in other literature.[2,5,6]

Basic Design

A biofilter for control of air pollutants consists of one or more beds of biologically active material, primarily mixtures based on compost, peat or soil. Filter beds are typically 1 meter in height. A conceptual design of an open biofilter is shown in Figure 1 and an illustration of an existing, enclosed biofilter is shown in Figure 2. Contaminated off-gas is vented from the emitting source through the filter. Given sufficient residence time, the air contaminants will diffuse into a wet, biologically-active layer (i.e., biofilm) which surrounds the filter particles. Aerobic degradation of the target pollutant(s) will occur in the biofilm if microorganisms, mainly bacteria, are present that can metabolize them. End products from the complete biodegradation of air contaminants are CO_2, water, and microbial biomass. The oxidation of reduced sulfur compounds and chlorinated organic compounds also generates inorganic acids.

Compost, usually produced from municipal waste, wood chips, bark or leaves has generally been the basis of filter material used in recent applications in Europe, although peat and heather mixtures have also been used. The biofilters originally built in the U.S. were mostly "soil beds" for which biologically active mineral soils were used as filter materials.

The components needed for preconditioning of the off-gas, its transport to and distribution in the filter bed account for the other main elements of a biofilter system. Heat exchangers to cool hot off-gases or filters for the removal of particulates may be required for certain types of emissions. Radial blowers are generally used to overcome the back pressure caused by the filter. The off-gas must also be saturated with water, since it would otherwise remove moisture from the filter material, resulting in drying of the bed, the death of most microorganisms and a total loss of control efficiency. As shown in Figure 1, spray nozzles usually provide the required humidity in the humidification chamber. Additional, automatic irrigation of the filter bed(s) from the top is also used in some systems to maintain the required moisture content in the filter material. Finally, the off-gas is vented, usually through slotted concrete slabs or concrete blocks with distribution canals and air nozzles, into the bottom of the filter bed. Down-flow systems have also been used in several recent installations.

To date, most biofilters have been built as open single-bed systems. A typical example is shown in Figure 3. Open, multiple story systems are also built if space constraints exist. Some European firms have developed enclosed systems, usually with stacked beds. Figure 4 shows an example of an enclosed biofilter, consisting of two stacked, containerized filter beds that are operated in parallel. Although generally more expensive, the use of enclosed multiple story systems can be appropriate, in applications where minimum maintenance is required, and where space constraints prohibit the installation of a single-bed filter. Other advantages of fully enclosed systems include a lower susceptibility

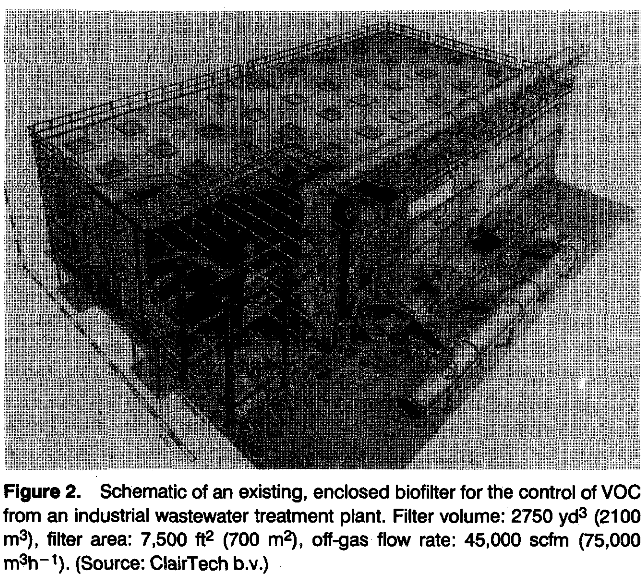

Figure 2. Schematic of an existing, enclosed biofilter for the control of VOC from an industrial wastewater treatment plant. Filter volume: 2750 yd^3 (2100 m^3), filter area: 7,500 ft^2 (700 m^2), off-gas flow rate: 45,000 scfm (75,000 m^3h^{-1}). (Source: ClairTech b.v.)

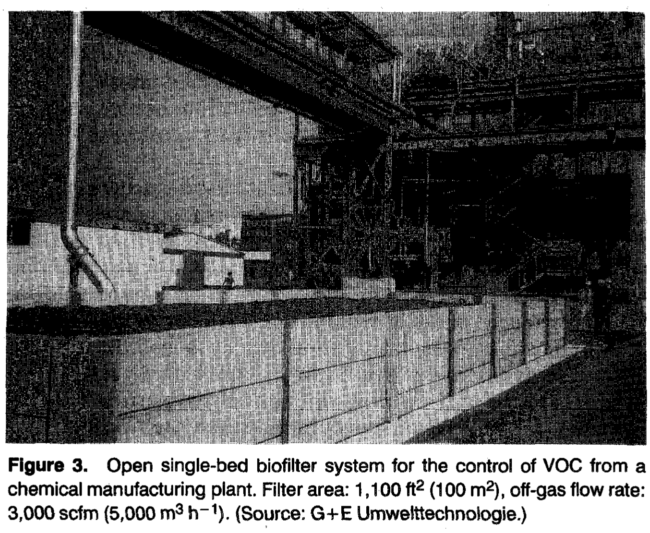

Figure 3. Open single-bed biofilter system for the control of VOC from a chemical manufacturing plant. Filter area: 1,100 ft^2 (100 m^2), off-gas flow rate: 3,000 scfm (5,000 $m^3 h^{-1}$). (Source: G+E Umwelttechnologie.)

Figure 4. Biofilter, consisting of two stacked beds in parallel, for the control of onion odors. Off-gas flow rate: 11,800 scfm (20,000 m^3 h^{-1}). Similar systems are being used for VOC control. (Source: TNO-MT.)

to changing climatic conditions and the possibility of continuous off-gas monitoring.

Mineralization of the organic matter in biofilters will over time lead to compaction of the filter material and a corresponding increase in back pressure. In open filters, the filter material is typically turned over (e.g., by frontloaders) after two years in order to increase its porosity. After another one to two years it is replaced by fresh material. Manufacturers of enclosed systems attempt to extend the usable life of the filter material by selecting its components more carefully. A useful life for filter material of up to five years has been reported.[9] Equipment that will eliminate the need for turnover by plowing through the filter material has also been developed. Eventual replacement of the filter material will still be required.[10] Maintaining the porosity of the compost by turning it over, and/or replacing it entirely, once spent, are the two major maintenance requirements for biofilters with compost-based filter materials.[11]

History of Biofiltration

Suggestions to treat odorous off-gases by biological methods can be found in literature as early as 1923 when Bach[12] discussed the basic concept of the control of H_2S emissions from sewage treatment plants. Reports on the application of this concept dating back to the 1950s were published in the U.S. and in West Germany. Pomeroy received U.S. Patent No. 2,793,096 in 1957 for a soil bed concept and describes a successful soil bed installation in California.[13] Around 1959 a soil bed was also installed at a municipal sewage treatment plant in Nuremberg, West Germany for the control of odors from an incoming sewer main.[14]

In the U.S., the first systematic research on the biofiltration of H_2S was conducted by Carlson and Leiser[15] in the early 1960s. Their work included the successful installation of several soil filters at a wastewater treatment plant near Seattle and demonstrated that biodegradation rather than sorption accounted for the odor removal.

During the following two decades, several researchers in the U.S. have further studied the soil bed concept and demonstrated its usefulness in several full scale applications. Much of the knowledge about the technology is owed to Hinrich Bohn who has investigated the theory and potential applications of soil beds for more than 15 years.[16,17] Successful soil bed applications in the U.S. include the control of odors from rendering plants,[18] and the destruction of propane and butane released from an aerosol can filling operation.[19]

While soil beds have been shown to control certain types of odors and VOC efficiently and at fairly low capital and operating cost, their use in the U.S. has been limited by the low biodegradation capacity of soils and the correspondingly large space requirements for the beds. It is estimated that the total number of biofilter and soil bed installations in the U.S. and Canada is currently less than 50 and that they are predominantly used for odor control.[20,21] Very recently, the treatment of VOC released from soil clean-up operations has been addressed in several bench-scale studies.[22] It can be inferred from the lack of literature published in the U.S. that, during the last two decades, little attention was paid to concurrent developments in at least two European countries, West Germany and The Netherlands. In these countries, biofiltration has developed since the early 1960s into a widely used APC technology which is now considered best available control technology (BACT) in a variety of VOC and odor control applications. An excellent summary of the history of biofiltration prior to 1984 has been presented by Eitner.[11] Shorter historical reviews in English can also be found.[23,24]

The present review emphasizes trends in Germany, but a relatively similar path of development occurred in The Netherlands.[2,4,5,25] A limited number of reports on experiences with biofiltration in other countries can also be found, including Switzerland,[11] Japan[26] and Austria.[27]

As noted earlier, during the 1960s and 1970s, biofilters were successfully used in West Germany to control odors from a variety of sources, including sewage treatment plants, facilities for rendering, composting and food processing, as well as chicken and pig farms.[28,29,30] Various designs, for example for the air distribution system, and several filter materials with higher biological activities and lower flow resistance than soil were investigated. Compost derived from municipal solid waste was used as filter material as early as 1966.[31] The need for humidification of the off-gas at higher flow rates had also been recognized.[29,30]

The basic processes determining the efficiency of a filter were understood qualitatively in the 1960s. However, the approach to designing biofilter systems was usually empirical. Mobile pilot units were often used for treatability studies and the sizing of the full scale system.[29] Economic advantages of biofilters as compared to other APC technologies were discussed by Jäger and Jager.[32] Their investigations suggested that biofilters exhibit comparatively low operating costs if used for the treatment of odorous off-gas from composting facilities for municipal waste.

Since the early 1980s, biofiltration has increasingly been used in Germany to control VOC and air toxics emitted from industrial facilities such as chemical plants, foundries, print shops and coating operations. This development was brought about primarily by new federal regulations that required the control of emissions of VOC and air toxics from new and existing sources,[33] a well funded development program run by the West German Federal Environmental Agency, Umweltbundesamt (UBA), and the formation of several engineering firms which addressed and resolved some of the initial technical problems with biofiltration.

Experience with Biofilters in Typical Applications

Excellent summaries of recent biofilter applications and discussions of their economic and technical aspects can be found in the proceedings of two conferences on biofiltration that were held in Germany in 1989.[5,6] As many as 500 biofilters are currently believed to be active in Germany and The Netherlands, many of them rather simple systems installed on livestock and food processing applications.[1]

Table I. Examples of successful biofilter applications in Europe.

Adhesive production	Coffee roasting	Industrial wastewater treatment plants
Coating operations	Coca roasting	Residential wastewater treatment plants
Chemical manufacturing	Fish frying	Composting facilities
Chemical storage	Fish rendering	Landfill gas extraction
Film coating	Flavors and fragrances	
Investment foundries	Pet food manufacturing	
Iron foundries	Slaughter houses	
Print shops	Tobacco processing	
Waste oil recycling		

Filter areas typically range from 100 to 22,000 ft^2 (10–2,000 m^2) with off-gas flow rates between 600 and 90,000 cfm (1,000–150,000 m^3 h^{-1}). Brief descriptions of successful applications are given in the literature[34,35] and examples of such applications are listed in Table I. Detailed evaluations of individual projects have also been published.[5,36,37,38]

As seen from Table I, most off-gases that have been treated by biofilters arise from industrial facilities, waste disposal and food processing activities. All of these sources typically emit large volumes of off-gases that contain only low concentrations (typically less than 1,000 ppm as methane) of the organic target pollutant(s). Control requirements for the waste disposal and food processing facilities are usually targeted at odors, whereas for the industrial sources stringent regulatory requirements to control VOC and air toxics have prompted many of the biofilter installations. Most applications in the latter group are relatively recent and it can be expected that new sources will be added to the list as the German UBA continues to fund projects aimed at demonstrating the applicability of biofiltration to specific types of emission sources.

Eitner[35] summarizes the results obtained for some of the sources listed in Table I. The control efficiency for organic carbon ranged between 51 and 94 percent with odor reductions between 82 and 99 percent. These values are given without reference to the pollutant load per volume. As discussed in the next section, an increase in filter volume will usually result in a corresponding increase in control efficiency, provided that no recalcitrant compounds which would limit overall control efficiency are present in the off-gas. Under those conditions, a control efficiency of more than 90 percent will usually be achievable.

A relative ranking of the biodegradability of various groups of common air pollutants in biofilters that is based on experimental results has been reported.[34] Compounds that are typically well degraded include alcohols, ethers, aldehydes, ketones and several of the more common monocyclic aromatics. Their actual degradation rates will vary, depending on filter material, temperature and the presence of suitable microorganisms and co-metabolites (if required). Several nitrogen- and sulfur-containing organics, such as amines and sulfides, are also efficiently controlled by biofilters. Higher chlorinated organics tend to show significantly lower rates of degradation.

Theoretical Basis

Theoretical descriptions of the processes involved in the operation of a biofilter have been published by several researchers.[2,4,39,40] In particular, Ottengraf's work,[2] published in English, provides a comprehensive analysis of the overall process, presents experimental data to support his model, and discusses implications for the design and operation of a biofilter.

For the purpose of his model, Ottengraf distinguishes between micro- and macrokinetic processes in a biofilter. His basic macrokinetic model is a bed of solid filter particles, surrounded by a wet, biologically-active layer, the so-called "biofilm." The biofilm concept is frequently used to describe degradation processes in aqueous systems. Transport across the phase boundary and diffusion into this film make pollutant ("substrate") molecules, in the off-gas vented through the filter, available to microorganisms resident in the film. Oxygen and nutrients are also provided by diffusion from the off-gas and the filter material, respectively. The gas- and liquid-phase concentrations of each pollutant are assumed to be always in equilibrium at the phase boundary and related by Henry's Law. Other major assumptions underlying the overall model are that microkinetics of the biodegradation occurring in the biofilm follow the Michaelis-Menten relationship and that off-gas flow through the filter can be described as plug flow. A conceptual, biophysical model of the biofilm is shown in Figure 5.

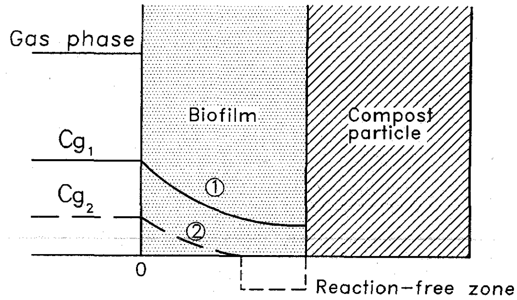

Figure 5. Biophysical model for the biofilm. The concentration profiles shown in the biolayer refer to: (1) degradation limitation, (2) diffusion limitation. (Source: Redrawn from Reference 2 [Fig. 6].)

Finally, Ottengraf assumes that degradation in the biofilm follows zero-order kinetics, i.e., the degradation rate is independent of the substrate concentration. If applied to a one component off-gas this approach suggests the following results: at gas phase concentrations, C_g, above a compound specific, critical concentration (C_{crit}), the film will be fully saturated (Figure 5, Case 1) and pollutant elimination is limited by the biological activity in the film. For this situation, the model predicts a linear decrease in pollutant concentration in the filter bed. At concentrations less than C_{crit} diffusion in the biofilm will limit compound removal. The biofilm is no longer fully penetrated (Figure 5, Case 2) and the removal rate decreases with decreasing pollutant concentration in the off-gas.

The validity of this model is suggested by many experiments. Examples of results are provided in Figures 6 and 7. Figure 6 shows that a linear concentration profile was observed for several common VOC at higher gas phase

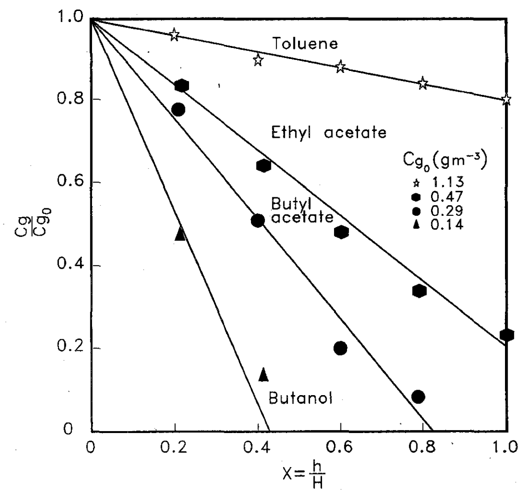

Figure 6. Concentration profiles for several VOC as a function of height within a biofilter. Loading rate: 275 m^3 m^{-2} h^{-1}. (Source: Redrawn from Reference 2 [Fig. 11].)

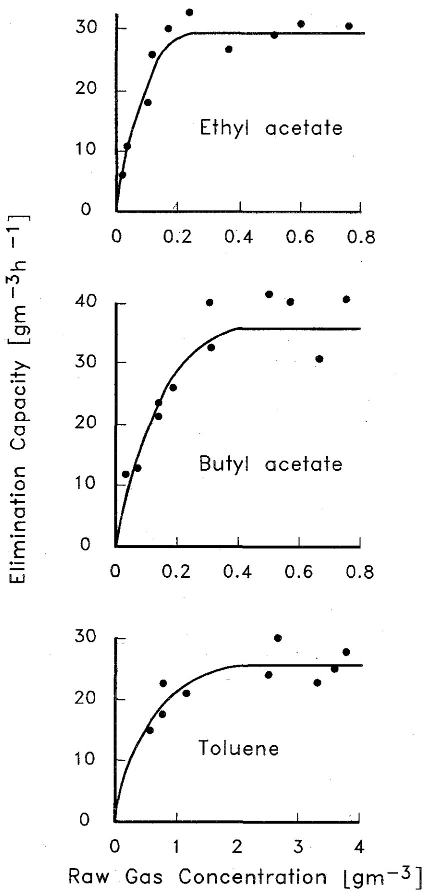

Figure 7. Elimination capacity of a biofilter for several VOC as a function of their inlet concentration. Loading rate: 275 $m^3\ m^{-2}\ h^{-1}$. (Source: Redrawn from Reference 2 [Fig. 13].)

concentrations. Figure 7 demonstrates the predicted decrease in elimination rates caused by diffusion limitation at concentrations less than C_{crit}.

Ottengraf's model allows quantitative description of the basic processes involved in biofiltration and accurate sizing of biofilters for one-component off-gases. Its applicability to a multi-component off-gas, however, is limited by the increasing mathematical complexity needed for multiple components and by the fact that off-gas constituents will often not be biodegraded independently. Since off-gases from industrial sources typically contain a variety of constituents, pilot testing with a smaller filter unit will usually be conducted to allow for accurate sizing of a full-scale system.

Design and Operation

Proper design and operation of a biofilter requires consideration of a number of technical issues which are summarized in the following sections. More detailed discussions of these issues can be found elsewhere.[2,4,6]

Microorganisms

Several groups of microorganisms are known to be involved in the degradation of air pollutants in biofilters, including bacteria, actinomycete, and fungi. Compost-based filter material typically shows significantly higher population densities of these organisms than soil and peat.[11,41] Growth and metabolic activity of microorganisms in a filter depend primarily on the presence of dissolved oxygen in the biofilm, the absence of compounds that are toxic to microorganisms, the availability of nutrients, sufficient moisture, and suitable ranges for temperature and pH. Accordingly, the control of these parameters, as discussed below, is essential for the efficient operation of a biofilter.

Biofiltration relies predominantly on heterotrophic organisms that use organic off-gas constituents as carbon and energy sources. As a result, introduction of these compounds into the filter material upon start-up will generally shift the distribution of existing microbial populations towards strains that metabolize the target pollutants. For common, easily biodegradable organic compounds, acclimation will typically take about ten days.[2] If compounds that are less biodegradable and for which suitable microorganisms are less likely to be initially present in the filter material are to be treated, inoculation with an appropriate culture can reduce the acclimation period, and such inoculation is practiced by several firms.[25,41,42]

Most industrial sources of air pollutants do not operate continuously. It has therefore been of interest whether the biological activity of a biofilter could suffer during extended shut-down periods. Results reported by Ottengraf[2] suggest that filter beds can survive periods of at least two weeks without any significant reduction in microbial activity. If sufficient nutrients are provided by the filter material, survival periods of up to two months can be expected.[43] In order to avoid oxygen starvation and/or dehydration in the filter, periodic aeration of the filter or operation of the blower in a turndown mode, is advisable during shutdown periods.

Off-gas constituents will not always be degraded independently by microorganisms. In particular, for several higher chlorinated aliphatics only co-metabolism appears to be responsible for aerobic degradation.[44] Similarly, biodegradation of benzene appears to be slow if benzene is the only off-gas constituent, while the presence of other organics can significantly increase its biodegradability.[45] On the other hand, inhibition, for example, in the biodegradation of methanol due to the presence of tert-butanol, has been reported.[4]

Whether the operation of a biofilter could result in emissions of microorganisms has been investigated by several researchers.[40,41,46] Concentrations of bacteria and fungi spores between 1,000 and 10,000 per cubic meter of treated off-gas were found. One study concluded that these concentrations are only slightly higher than concentrations found in open air, and that a biofilter can actually achieve emission reductions for raw gases containing high concentrations of microorganisms.[46] Another study concluded that maintenance or replacement of the filter material can result in an increase in emissions of fungi spores and that the use of respiratory protection should be advised for these activities.[38]

Filter Construction and Sizing

The type of construction and installation of a biofilter (e.g., open single-bed, enclosed multiple bed, roof top installation, etc.) for a given application will depend primarily on the availability of space relative to the required filter volume. Other criteria include differences in capital cost and maintenance requirements between the different systems.

For a given off-gas, the filter volume required for the desired removal efficiency depends primarily on the rate of air pollutant loading relative to the filter's degradation capacity, and on the pollutant's concentration in the raw gas. Degradation rates for common air pollutants typically range from 10 to 100 g m^{-3} h^{-1} (for examples refer to Figure 7). If several organic compounds that are degraded by different microorganisms are present in the raw gas, their degradation capacities may behave additively, resulting in higher total degradation rates than for an individual compound.[2] The filter's large mass often provides sufficient

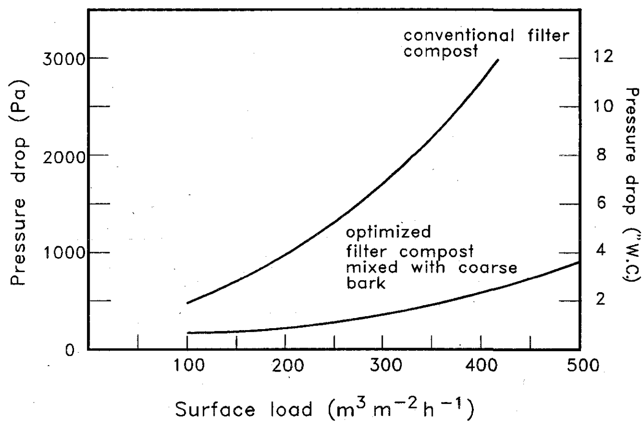

Figure 8. Pressure drop for two filter materials as a function of surface loading rate. (Source: Redrawn from Reference 47 [Fig. 3].)

buffer capacity to prevent breakthroughs during peak loadings, and allows sizing based on hourly average rather than instantaneous peak loads. The buffer capacity of a filter for a particular application will vary depending on the water solubility of the target pollutants and the surface loading rate.

Off-gas flow rates will affect the filter size to a lesser degree. Surface loads of up to 300 $m^3\ h^{-1}$ of off-gas per m^2 of filter (16 scfm ft^{-2}) are usually feasible without resulting in excessively high back pressures. Surface loads as high as 500 $m^3\ m^{-2}\ h^{-1}$ have been treated with good removal efficiency and low pressure drop for an optimized filter material mixture of compost and bark[47] (refer to Figure 8). For more compact filter material, at the high surface loads desirable for highly diluted off-gases, the pressure drop would otherwise become the size-determining parameter. At such high surface loads the filter material will also become more susceptible to dehydration and heat losses caused by insufficient raw gas conditioning. Proper control of the temperature and humidity of the filter therefore becomes particularly important at high surface loads.

Since off-gases from industrial processes usually contain a variety of compounds, sizing of the filter should, as already mentioned, be based on a treatability study during which a partial off-gas stream is treated in a biofilter pilot unit, typically several cubic meters in size. The required size for a full-scale filter then can be determined by scaling.

Filter Material

In order for a biofilter to operate efficiently, the filter material must meet several requirements. First, as mentioned earlier, it must provide optimum environmental conditions for the resident microbial population in order to achieve and maintain high degradation rates. Second, filter particle size distribution and pore structure should provide large reactive surfaces and low pressure drops. Third, compaction should be kept to a minimum, reducing the need for maintenance and replacement of the filter material.

Since it provides favorable conditions for microbes, compost derived from municipal waste, bark, tree trimmings and leaves is widely used as basic filter material. Other materials, such as porous clay or polystyrene spheres are sometimes added to increase reactive surface and durability, reduce back pressure and extend the filter material's useful life. Activated carbon can be used to increase the filter's buffer capacity for emissions from sources that operate only intermittently. This can reduce the required filter volume significantly.[2,45]

Eitner[48] has developed a set of easily measured parameters to assess the suitability of a given filter material. For fresh material he recommends a pH between 7 and 8, a pore volume of greater than 80 percent, a d_{60} of greater than 4 mm, and a total organic matter content, measured as loss on ignition, of more than 55 percent.

Usually, compost recycled from waste material is relatively inexpensive. Its use also avoids the generation of solid waste since spent filter material can be returned to composting, used in nurseries or employed as landfill covers. This requires, however, that the fresh material be tested for potentially hazardous constituents (eg, heavy metals) before installation in the filter in order to avoid having to manage a "hazardous waste" upon replacement of the filter material.[49] In that respect, the use of refuse-based filter material requires particular caution. Its contamination with heavy metals is more likely and less easily controlled than with other raw materials. Also, insufficient aeration during the final stages of the composting process will result in odor emission upon start-up of the filter.

Typically, a compost-based filter material will provide sufficient inorganic nutrients for microorganisms and the addition of nutrients will not be required.[41] In some cases, however, depending on the target pollutant and the source of the filter material, the availability of specific nutrients might become process limiting. For example, the addition of nutrients to a filter material has been shown to improve the degradation of toluene significantly[25] and was also successful in other cases.[50]

Raw-Gas Conditioning

Since biofilters can be poisoned by the presence of off-gas constituents that are toxic to microorganisms because of their chemical nature (e.g., SO_2) and/or by excessive concentration, a characterization of type and quantity of all off-gas constituents should always be conducted prior to the design of a filter. In many cases, the elimination of a substance which is toxic to microorganisms from the emitting process, or a change in the ventilation system, can make the off-gas suitable for biofiltration. Depending on the specific off-gas constituent, maximum VOC concentrations of 3,000–5,000 mg m^{-3} in the raw gas should usually not be exceeded.[45]

High particulate loads in the raw gas can adversely affect the operation of a filter in several ways. Clogging of the air distribution system and the filter material itself by grease and resins can occur. The deposition of dust in the humidifier will generate sludge and can result in improper humidification. In such cases the installation of a particulate filter is required.

Biofiltration relies predominantly on the activity of mesophilic and, to some extent, thermophilic microorganisms. While degradation rates typically increase with temperature, this potential gain in efficiency can, depending on the chemical, be counterbalanced by a decrease in the water solubility of the target pollutants. Another important consideration[47] is that operation of the filter at higher temperatures will shift the population towards thermophilic organisms. A shutdown of the system can cause a drop to ambient temperature and a die-off of these organisms, resulting in a longer adaption period after start-up. For optimum results, it is recommended that off-gas temperatures be maintained between 20 and 40 °C (68 and 105 °F). Hotter off-gases will require cooling. Waste heat recovery may be economically feasible in such cases. During winter operation the temperature of the filter can drop to below 10 °C (50 °F) if the raw gas comes from a non-heated production area. A decline in removal efficiency can occur in such cases,[36] particularly when the system is operated at the design pollutant load. The extent of this effect will vary, depending on the characteristics of the off-gas constituents. Off-gas preheating, preferably using process waste heat will eliminate this problem. Alternatively, the system would have to be sized based on low-temperature removal rates. Fully enclosed systems with minimized heat losses are less susceptible to this problem.[11,25,36,40,41]

Moisture Control

Maintaining an optimum moisture content in the filter material is the major operational requirement for a biofilter. Without providing additional moisture, the (usually unsaturated) raw gas would quickly dry out the filter bed. Moisture is essential for the survival and metabolism of the resident microorganisms and contributes to the filter's buffer capacity.[39] Non-optimum moisture content can also result in compaction, breakthroughs of incompletely treated raw gas and the formation of anaerobic zones which emit odorous compounds. A moisture content between 40 percent and 60 percent by weight is considered optimal.[2,11]

In most biofilter installations the raw gas is humidified in a spray humidifier. A degree of saturation of more than 95 percent is desirable. In arid areas, occasional irrigation from the top may be required for open filters. Computer controlled, direct irrigation of the filter bed in addition to humidification of the raw gas is also used frequently.[4] Water consumption by biofilters is generally low, depending on the temperature and relative humidity of the raw gas and, for open filters, on precipitation. As a guideline, a water use of 5–10 gallons per 100,000 scf can be assumed.[7,10]

Excess drainage from the filter bed is the only potential source of wastewater discharge from a biofilter. Drainage will typically have a high biochemical oxygen demand (BOD) of several thousand mg l^{-1} from soluble compost constituents and may contain some of the less biodegradable off-gas constituents that have been flushed out of the filter bed. In cases where acidic degradation products are formed, the drainage will also be characterized by a low pH. In particular, where the drainage contains organic compounds that are regulated by the wastewater authority, recirculation of the drainage to the humidifier in order to minimize wastewater discharge is practiced. However, in order to prevent the build-up of solids in the humidifier, periodic discharge of some drainage is usually required.

Control of pH

Since most microorganisms prefer a specific pH range, changes in the pH of the filter material will strongly affect their activity. The pH in compost filters is typically between 7 and 8, a range preferred by bacteria and actinomycete. In some cases the biodegradation of air pollutants can generate acidic by-products. Examples are the oxidation of sulfur- or nitrogen-containing compounds and chlorinated organics. Depending on the type of microorganisms that are present, the resulting drop in the pH can destroy the resident population and reduce, if not eliminate, the filter's degradation capacity. In such cases chemical buffers, such as lime, are added.[41,43,50]

In addition to the typical recalcitrance of chlorinated organics, the acidification of the filter bed is one of the problems related to the treatment of such compounds in a biofilter. Biological systems where degradation occurs in the liquid phase (e.g., bioscrubbers and trickling filters) allow for easier pH control and have therefore been considered for the treatment of off-gases containing high loads of compounds with acidic degradation products.[40]

Back Pressure and Energy Consumption

In a biofilter, (electrical) energy is predominantly needed by the blower to overcome the filter's back pressure and, to a lesser degree, by the humidifier. Typical pressure drops for different filter materials as a function of the surface load are shown in Figure 8. Due to gradual compaction of the filter material, pressure drop and power consumption will increase with time and eventually require the fluffing or replacement of the filter material. In order to allow for early detection of cracks and the need to replace the filter material, the pressure drop across the filter bed is monitored continuously in most installations. As already mentioned, the proper selection of the filter material will reduce pressure drop and the need for its maintenance and replacement. Covering the surface of an open filter with bark is often practiced to prevent compaction from heavy rains and growth of weeds, both resulting in an increased back pressure.

Typical power consumption rates for a biofilter range from 1.8–2.5 kWh/1000 m^3 (5–7 kWh/100,000 scf)[35] but can vary significantly, depending on the type and state of compaction of the filter material. Energy requirements for competing APC systems can, depending on the application, be significantly higher. For environmental as well as economic reasons the low specific energy consumption of biofilters is therefore one of their most attractive features.

Maintenance

The routine and periodic maintenance of biofilters includes a number of operations. A daily check of the major operating parameters, such as the off-gas temperature and humidity, and the filter's temperature and back pressure, should be conducted. Most open systems do not automatically control the moisture content or pH in the filter bed. Periodic sampling of the filter material to detect potential failures of the humidifier or changes in pH should therefore be conducted. Turning the filter material over, and replacing it after several years are the two major maintenance items needed for an open system. Usually the air distribution system will be cleaned at the same time. Eitner estimates maintenance requirements at 0.8 –1 person hours per m^2 of filter area per year for single-bed filters.[35] Fully enclosed systems are usually designed to further reduce maintenance requirements since access to, and visual inspection of, the filter material is restricted. This is typically accomplished by controlling the moisture in the filter material automatically and by selecting filter materials that will compact more slowly.

Monitoring

For most biofilter installations, regulatory agencies will require a source test to verify the control efficiency claimed by a vendor. Since pollutant concentrations in the filter effluent do not react instantaneously to variations in the raw gas, grab samples can provide false results for the control efficiency. The continuous off-gas monitoring for total organic carbon (TOC) with a flame ionization detector (FID) or photoionization detector (PID) addresses this problem, and is widely used for compliance testing in Germany. Simultaneous monitoring with a two channel FID allows the concurrent determination of TOC concentrations in raw and clean gas. However, in the case of multi-contaminant off-gases, different FID/PID response factors and removal rates for different components can result in inaccurate figures for TOC and control efficiency. Calibration of the FID/PID results with those obtained from a grab sample are advisable in such a case.

Source tests on enclosed systems can be conducted similar to other APC devices. For open systems, monitoring hoods are used to cover a defined filter area, typically 1 m^2. Monitoring the flow rate and TOC at the hood outlet then allows determination of TOC emissions per filter area. During a source test, such measurements are usually conducted in various locations in order to detect potential variations in flow and organic load across a filter bed.

Potential System Failures

Past experiences have shown that biofilters can fail for various reasons. For example, insufficient treatment will occur if the filter has been undersized (e.g., because of inadequate knowledge of the raw gas characteristics). The presence in the off-gas of compounds that are toxic to resident microorganisms (e.g. SO_2) can inactivate the filter material. Particulates in the raw gas can, depending on their load and chemical characteristics, result in sludge formation in the humidifier and clogging of the air distribution system. Insufficient humidification has often been the cause for system failures. This can result from, for example, underdesigned humidifiers, inappropriate configuration of humidifier and blower and too high a temperature increase across the filter bed, resulting in net moisture loss to the off-gas. Rapid compaction of inappropriate filter material can, often in combination with inhomogeneous humidification, result in the formation of cracks and breakthroughs of untreated off-gas. Generation of acidic degradation end- and by-products can result in a drop in pH and destruction of the microbial population.

Many improvements in earlier installations have resulted from these experiences. Given proper design and operation of a filter these failures can be avoided in most modern installations, and their causes minimized.

Technical Trends

Several ongoing trends in the development of biofiltration can be noted, some of them in response to the system failures cited above. Increasing biodegradation rates, particularly for less biodegradable organics, by introducing appropriate microorganisms and improving their environmental conditions is of high priority since it allows reductions in the required filter size and makes biofiltration an even more competitive APC technology. At the same time, further improvements to the physical properties and longevity of the filter material are needed because they will result in reduced cost for energy and maintenance. Finally, full control of operating parameters allows further reduction in maintenance requirements and reduces the likelihood of system upsets.

Comparison with other APC Methods

Several established APC technologies currently compete with biofilters in the area of VOC removal from off-gases, including thermal and catalytic oxidation (incineration), adsorption by activated carbon and condensation by refrigeration. All of these technologies will control organic emissions cost effectively in many cases but suffer from technological and/or economic disadvantages if applied to other types of off-gases.

While incinerators are appropriate for off-gases with higher concentrations of organics, energy costs will become prohibitive if large volumes of dilute off-gas must be treated. Regenerative thermal oxidizers with energy recovery rates of more than 95 percent can reduce these costs, and systems without a direct flame emit only low levels of NO_x. However, even these systems will still require concentrations of several thousand ppm of organic carbon in the off-gas in order to be energy self-sufficient.

Carbon adsorption systems are appropriate if on-site regeneration of the carbon is feasible and recovers a valuable raw material, or if only small amounts of organics need to be removed from the off-gas. Otherwise the cost for off-site carbon regeneration can become significant. Carbon systems will achieve only low removal rates for poorly sorbed compounds, such as methylene chloride. In other cases, moisture or strongly sorbed chemicals present in the off-gas will take up available surface, thereby limiting the removal of less easily sorbed chemicals.

Refrigeration is an efficient method of material recovery if used on a highly concentrated and relatively pure off-gas stream. The removal of highly volatile compounds from dilute off-gas streams, however, results in the need for large compressors involving high energy cost.

As discussed above, the size required for a biofilter to remove air pollutants efficiently depends primarily on loading rate and concentration of these compounds in the off-gas, and the rate of biodegradation per volume. Since system cost will increase with filter size, biofilters will be most competitive if applied to low concentration off-gases with easily biodegradable constituents. The use of biofiltration will usually not be advisable in cases of high organic loading rates and/or if poorly biodegradable compounds, such as some of the chlorinated organics, are present. In both cases, large filter volumes would be required for efficient pollutant removal. Capital cost will increase correspondingly and the required space may often not be available.

In many instances, source reduction will be the most efficient APC technology, for example the internal recovery of process fluids or the use of alternative process materials with lower VOC contents. However, in many situations an additional off-gas treatment may still be required, for example if product quality requirements do not allow complete material substitution, or operation in a closed system is not feasible, such as in print shops. In such cases a biofilter could be an appropriate treatment for organic emissions that have already been reduced by primary measures and require a correspondingly smaller filter size.

Economic Considerations

An economic comparison of available control options should always be conducted on a case-by-case basis and requires some initial knowledge about the physical and chemical characteristics of the off-gas. As an example, the filter size and capital cost for a biofilter are mainly determined by the pollutant load in the off-gas whereas for incineration systems the off-gas flow rate is the major design parameter. A sophisticated conditioning of the raw gas or a treatment of an incinerator flue gas may be required in some cases resulting in higher capital cost.

Information on capital and operating cost for various biofilter systems installed in Germany and The Netherlands has been reported.[10,25,35,51] These data suggest total operating and maintenance costs of approximately $0.60–$1.50 per 100,000 cubic feet of off-gas, depending on the size of the filter. Cost figures obtained from systems installed in the U.S. of $0.30–$0.60 per 100,000 scf do not include the replacement of the filter material and also reflect the generally lower cost of electricity in the U.S.[20] Capital costs for open single-bed filters installed in Germany are estimated at $25–$95 per ft^2 of filter area, depending on the size of the system. Cost for filters with multiple beds are about twice as high.[1,35] For open single-bed filters installed in the U.S., cost per ft^2 of filter area are estimated at $55–$90.[20] Capital cost for enclosed systems range, depending on size and degree of process control, from $90–$500 per square foot.[9,20,43]

Regulatory Considerations

As mentioned earlier, the development of biofiltration into a BACT for many applications in The Netherlands and Germany was triggered predominantly by regulatory APC requirements for the control of odors and later of VOC and air toxics. There are indications that similar regulatory trends will soon evolve in the U.S., and in some states they have already done so.

APC regulations in the U.S. tend, depending on the significance of regional air quality problems, to vary considerably between, and even within, states. Nevertheless certain trends in regulatory developments are common to metropolitan and/or heavily industrialized areas.

VOC Control

Until recently, attempts to control volatile organic compounds as precursors of photochemical air pollution have mainly focused on automobiles and major stationary sources such as refineries and large coating operations. In ozone nonattainment areas, APC districts are increasingly forced to target smaller stationary sources that emit on the order of a few hundred pounds of VOC per day. As an example, in California both the San Francisco Bay Area AQMD and the SCAQMD now require large commercial bakeries to control ethanol emissions from dough fermentation released during the baking process.

Except for several halogenated VOC, most of the organics targeted by regional control agencies are readily biodegradable. Many of the targeted sources release the VOC in low concentrations, often from the general ventilation system. In such cases biofiltration is particularly competitive as compared to existing APC technologies.

Air Toxics

While it remains to be seen how the EPA will implement the recently amended federal Clean Air Act, several states and regions have already adopted their own regulatory programs for the control of emissions of carcinogenic compounds and other air toxics from industrial operations. Examples include Wisconsin where the control of emissions of a variety of air toxics from existing and new sources is now required if risk thresholds and/or OSHA standards are violated.[52] In Southern California the SCAQMD has recently adopted a rule which limits the maximum lifetime cancer risk from new and modified sources to 10^{-6} unless "Best Available Control Technology for Toxics (T-BACT)" is installed.

The available literature,[5,34] suggests that several of the potentially carcinogenic organics, such as benzene, formaldehyde and even methylene chloride have been successfully removed in biofilters. Several inorganic air toxics, such as hydrogen sulfide and ammonia are also efficiently controlled.

Odors

The traditional separation in the U.S. of industrial areas and public works facilities from residential areas has in the past often been effective in preventing odor complaints. However, rapid urban growth, combined with a growing attention to environmental pollution among the U.S. population, increasingly results in public protest against odor nuisances. Increased enforcement of existing, though often vague, odor regulations is usually the result. While odor control is not a high regulatory priority when compared to issues such as airborne toxic chemicals, requirements to control VOC and air toxics emissions will in many cases address the source of odors at the same time. Since odor problems are usually caused by compounds with low odor thresholds, off-gas concentrations will often be in the low ppmv range. It can be expected that biofiltration, which was originally developed as an odor control technology, will be a cost-effective control alternative as long as the odor constituents are biodegradable.

Summary and Outlook

Over the last decade, biofiltration has developed in Europe into a cost-effective and environmentally benign control technology for gaseous air contaminants. If used to treat low concentration off-gases it can provide treatment at significantly lower cost than competing APC technologies. Biofiltration is particularly attractive because of the savings in operating costs and its low specific energy demand. Current research efforts are primarily targeted at improving the control of essential operating parameters and increasing biodegradation rates, in particular for recalcitrant compounds.

Continued regulatory trends toward more stringent control of VOC, air toxics and odors similar to controls in Germany and several other European countries, will soon generate demand in the U.S. for this technology. Several experienced European biofilter companies have entered the U.S. marketplace, usually in cooperation with U.S. engineering or equipment firms.

In order to successfully apply biofiltration in the U.S. to appropriate projects, several requirements are necessary. First, all available APC alternatives must be thoroughly evaluated. In particular, for off-gases with high concentrations of poorly biodegradable organic compounds, other options will usually be more feasible. Second, off-gases must be accurately characterized and biofilters carefully designed. Pilot testing may be required, as well as the pretreatment of the off-gas (e.g., by a particulate filter). Finally, a minimum level of attention and maintenance must be provided by the operator of a biofilter.

However, if these requirements can be met, biofiltration is likely to be used in a variety of APC applications over the next few years. Agency support of such projects could assist in overcoming the natural reluctance of regulated industries to try unknown technologies. It will be the responsibility of environmental consulting and engineering firms to identify the APC needs of an industrial operation on a case-by-case basis and, if biofiltration is found to be the method of choice, to design and build the appropriate system.

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References

1. Koch, W., Umweltbundesamt, Berlin, Germany, personal communication, 1990.
2. Ottengraf, S. P. P. "Exhaust gas purification," Rehm, H. J.; Reed, G., Eds., in *Biotechnology,* Vol. 8; VCH Verlagsgesellsch., Weinheim, 1986.
3. Eitner, D.; Gethke, H.-G. "Design, Construction and Operation of Bio-filters for Odour Control in Sewage Treatment Plants," presented at the 80th Annual Meeting of APCA, New York, NY, June 21–26, 1987.

4. Van Lith, C. "Design Criteria for Biofilters," presented at the 82nd Annual Meeting of A&WMA, Anaheim, CA, June 25–30, 1989.
5. *VDI Berichte 735: Biologische Abgasreinigung;* VDI Verlag, Düsseldorf, 1989.
6. Fischer, K. et al., *Biologische Abluftreinigung;* Expert Verlag, Ehningen, 1990.
7. Leson, G. "Biofiltration—Investigation of a novel air pollution control technology for the South Coast Air Basin," D.Env. Thesis, University of California, Los Angeles, CA, 1992.
8. Leson, G.; Winer, A.; Hodge, D. "Application of Biofiltration to the Control of Air Toxics and other VOC Emissions," presented at the 84th Annual Meeting of AWMA, Vancouver, B.C. June 16–21, 1991.
9. de Waal, K. TNO-MT, Apeldoorn, The Netherlands, personal communication, 1990.
10. Maier, G. "Biofiltration von Giessereiabgasen," in *VDI Berichte 735;* VDI Verlag, Düsseldorf, 1989; p. 285.
11. Eitner, D. "Untersuchungen über Einsatz und Leistungsfähigkeit von Kompostfilteranlagen zur biologischen Abluftreinigung im Bereich von Kläranlagen unter besonderer Berücksichtigung der Standzeit," Dissertation Technische Hochchule Aachen, 1984.
12. Bach, H. "Schwefel im Abwasser," *Gesundheits-Ingenieur* **46:** 370 (1923).
13. Pomeroy, R. D. "Controlling sewage plant odors," *Consulting Engineer* **20:** 101 (1963).
14. Hartmann, H. "Geruchsbekämpfung in Kläranlagen am Beispiel der Klärwerke der Stadt Nürnberg," *Korrespondenz Abwasser* **23:** 275 (1976).
15. Carlson, D. A.; Leiser, C. P. "Soil beds for the control of sewage odors," *J. Wat. Poll. Contr. Fed.* **38:** 829 (1966).
16. Bohn, H. L. "Soil and compost filters of malodorant gases," *JAPCA* **25:** 953 (1975).
17. Bohn, H. L.; Bohn, R. K. "Soil bed scrubbing of fugitive gas releases," *J. Environ. Sci. Health.* **A21:** 561 (1986).
18. Prokop, W. H.; Bohn, H. L. "Soil bed system for control of rendering plant odors," *JAPCA* **35:** 1332 (1985).
19. Kampbell, D. H.; Wilson, J. T.; Read, H. W.; Stocksdale, T. T. "Removal of volatile aliphatic hydrocarbons in a soil bioreactor," *JAPCA* **37:** 1236 (1987).
20. Neff, C. R., Biofiltration, Inc., Gainesville, Fl., personal communication, 1990.
21. International Process Systems, Inc. (IPS), "Odor control—completing the composting process," 1990.
22. Proceedings of the Battelle International Symposium on In Situ and On-Site Bioreclamation, San Diego, CA, March 19–21, 1991.
23. Kosky, K. F.; Neff, C. R. "Innovative biological degradation system for petroleum hydrocarbons treatment," presented at the NWWA/API conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, Houston, TX, November 9–11, 1988.
24. Hartenstein, H.-U. "Assessment and redesign of an existing biofiltration system," M.S. Thesis, University of Florida, Gainesville, FL, 1987.
25. Don, J. A. "The rapid development of biofiltration for the purification of diversified waste gas streams," in *VDI Berichte 561;* VDI Verlag, Düsseldorf, 1985; p. 63.
26. Ando, S. "Odor control of waste water treatment plants," *J. Wat. Poll. Contr. Fed.* **52:** 906 (1980).
27. Windsperger, A.; Buchner, R.; Stefan, K. "Reinigung lösungsmittelhaltiger Abluft mit Biofiltern," *Staub-Reinhaltung d.Luft* **50:** 465 (1990).
28. Helmer, R. "Desodorisierung von geruchsbeladener Abluft in Bodenfiltern," *Gesundheits-Ingenieur* **95:** 21 (1974).
29. Dratwa, H. "Das Bio-Filter, ein Verfahren zur Geruchsbeseitigung— Wirkungsweise und Einsatzmöglichkeiten," *Staub-Reinhaltung d.Luft* **28:** 516 (1968).
30. Lachnit, F. "Abbau geruchsintensiver Stoffe durch Biofilter," *Schriftenreihe des Vereins für Wasser-, Boden- und Lufthygiene* **35:** 65 (1971).
31. Frechen, B.; Ernst, A. A. "Kompostwerk Duisburg-Huckingen. Erfahrungs- und Betriebsbericht," Stadtreinigungs- und Wasserbauamt: Duisburg, 1972.
32. Jäger, B.; Jager, J. "Geruchsbekämpfung in Kompostwerken am Beispiel Heidelberg," *Müll und Abfall* **2/78:** 48 (1978).
33. *Technische Anleitung Luft—Technical Instructions on Air Quality Control;* First General Administrative Regulation pertaining to the Federal Imission Control Law: Bundesanzeiger Verlagsgesellschaft, Köln, 1986.
34. *VDI Richtlinie 3477: Biological Waste Gas/Waste Air Purification, Biofilters;* Entwurf, VDI Handbuch Reinhaltung der Luft, Band 6, 1989.
35. Eitner, D. "Biofilter in der Praxis," in *Biologische Abluftreinigung;* Expert Verlag, Ehningen, 1990; p. 55.
36. Scherer, K.-H. "Entwicklung einer Abgasreinigungsanlage zur Verminderung geruchsintensiver und kanzerogener Luftverunreinigungen bei Anlagen zur Aushärtung von Reibbelägen," UBA Forschungsbericht, 87–020, 1987.
37. Koch, W.; Liebe, H.-G.; Striefler, B. "Betriebserfahrungen mit Bio-Filtern zur Reduzierung geruchsintensiver Emissionen," *Staub-Reinhaltung d.Luft* **42:** 488 (1982).
38. Liebe, H.-G.; Herbig, V. "Reduzierung geruchsintensiver Emissionen einer Anlage zum Trocknen und Weiterverarbeitung von Bierhefe durch den Einsatz eines Biofilters einschliesslich lüftungstechnischer Anlagen," UBA Abschlussbericht II, 1.1-50441-4/51, 1986.
39. Sabo, F. "Verfahrenstechnische Grundlagen der biologischen Abluftreinigung," in *Biologische Abluftreinigung;* Expert Verlag, Ehningen, 1990; p.13.
40. Diks, R. M. M.; Ottengraf, S. P. P. "Verfahrenstechnische Grundlagen der biologischen Abgasreinigung und insbesondere der Abscheidung von chlorierten Kohlenwasserstoffen," in *VDI Berichte 735;* VDI Verlag, Düsseldorf, 1989; p.7.
41. Bardtke, D. "Mikrobiologische Voraussetzungen für die biologische Abluftreinigung," in *Biologische Abluftreinigung;* Expert Verlag, Ehningen, 1990; p.1.
42. Hippchen, B. *Mikrobiologische Untersuchungen zur Eliminierung organischer Lösungsmittel im Biofilter,* Stuttgarter Berichte zur Siedlungswasserwirtschaft, Band 94, Oldenbourg, München, 1985.
43. Van Lith, C., Clairtech b.v., Utrecht, The Netherlands, personal communication, 1990.
44. Janssen, D. B.; Oldenhuis, R.; van den Wijngaard, A. J. "Degradation of xenobiotic compounds by microorganisms," in *VDI Berichte 735;* VDI Verlag, Düsseldorf, 1989; p.25.
45. ClairTech b.v., Vendor information on BIOTON[R] filter system.
46. Ottengraf, S. P. P.; Konings, J. H. G. "Emission of microorganisms from biofilters," submitted for publication in *Bioprocess Engineering,* (1991).
47. Don, J. A.; Feenstra, L. "Odour abatement through biofiltration," lecture given in Louvain-La Neuve (Belgium) in April 1984 at a symposium on Characterization and Control of Odoriferous Pollutants in Process Industries, 1984.
48. Eitner, D. "Biofilter in der Abluftreinigung," *Umwelt* **19:** L24 (1989).
49. Eitner, D. " Vergleich von Biofiltermedien anhand mikrobiologischer und boden-physikalischer Kenndaten," in *VDI Berichte 735;* VDI Verlag, Düsseldorf, 1989; p.191.
50. Eitner, D., G&E Umwelttechnologie, Aachen, Germany, personal communication, 1990.
51. Liebe, H.-G. "Einsatz von Biofiltern zur Minderung der Emissionen von Anlagen zum Verarbeiten von Fleisch und Fisch für die menschliche Ernährung," in *VDI Berichte 735;* VDI Verlag, Düsseldorf, 1989; p.215.
52. Rickun, J., RMT, Inc., Madison, WI, personal communication, 1990.

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