The Effect of Legislation and Operational Knowledge on the Bioreactor Market

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ABSTRACT

Bioreactors are used in many countries today for odor control from industrial, agricultural, and municipal sources of air emissions, where the pollutants are usually in concentrations below 50 ppmv. They are also used to bio-oxidize toxic and other volatiles in industrial effluents present in concentrations less than 1000 ppmv. However, the market for abatement technology based on bioreactors is relatively small compared to more traditional add-on control technologies such as incineration and absorption. This paper will present an overview of legislative aspects that help to promote the use of lower pollution technologies such as bioreactor systems. It will compare the costs and aspects of bioreactor operation for several bioreactor designs.

INTRODUCTION

Why are bioreactors not widely used in the U.S. as they are in certain European Union countries like the Netherlands and Germany? Some believe that what has hindered the use of bioreactor systems is the more specific regulatory requirements in the U.S. compared to those in European Union countries. A common cited example is that overall emission control efficiencies of 90 percent or above are often required in US rules, which favors the use of add-on control technologies such as incinerators and adsorbers. Hence, the manufacturers of bioreactors in the U.S. have to compete against add-on control technologies that were already widely used, and whose performance was well understood.

The fact that European countries have odor standards may also help explain why there are more units in use there. The target in this case is overcoming the odor nuisance rather than meeting a specific destruction efficiency. In this paper we will show that there are no real barriers to the widespread use of bioreactors in the United States. Manufacturers of this technology have now understood that it is not always necessary to meet control efficiencies of 90 or 98 percent. In some case it may be enough to maintain destruction efficiencies as low as 65 percent. [1]

This paper will review some of the legislative aspects in the U.S. that affect the level of pollution control, and highlight information that would need to be identified for compliance demonstration. It will also review some of the advances in this technology.

LEGISLATIVE ASPECTS [2]

The Clean Air Act (CAA) has an important impact on U.S. environmental regulations, and many regulatory aspects are contained in its provisions. Guided by the provisions that deal, for instance with urban air pollution, the U.S. Environmental Protection Agency (US. EPA) has issued regulations and guideline documents to control six **criteria pollutants** including ground level Ozone, nitrogen oxides, and sulphur dioxide. Volatile organic compounds (VOCs) are being controlled because they are important contributors to the formation of Ozone. To reduce, VOCs, State agencies develop regulations to achieve the level of emission they have identified in their State Implementation Plans. The level of VOC control, for an existing facility is most often based on those presented in a Control Techniques Guidelines (CTG) document issued by the U.S. EPA, for a source category (industrial sector). A CTG document provides an overview of the different emission points in an industry and the cost of using reasonably available technology (RACT) to reduce emissions from the relevant emission points in an existing facility. An emission point could be a stack or a unit operation.

Many VOCs are also toxics (hazardous air pollutants or HAPs). There are today 188 listed toxic pollutants (section 112(b) of the CAA), which include volatile chemical species such as benzene, Xylenes, and carbon tetrachloride. The U.S. EPA is required to develop rules based on maximum achievable control technology, referred to as MACT. The level of MACT for new sources must be based on the best-controlled similar source, for existing sources with more than 30 facilities the level of MACT must be based on the average of the best performing12 percent of the existing sources. MACT focuses on cancer and irreversible health effects, whereas RACT focuses on reducing ground level ozone reduction because if its effect on human health and welfare. Hence, it should not be surprising to find that MACT levels of control for reducing a compound such as benzene, which is both a HAP and a VOC, would be more stringent control level of RACT.

With the publication of the Pollution Prevention Act in 1990, U.S. EPA has been working to promote pollution prevention (P2), mainly through source reduction. However, there is little evidence that issuance of the P2 Act has resulted in regulations that have precluded the use of add-on controls for meeting, for example, an emission limit. However, P2 is now offered as a competing alternative to add-on controls.

ACCESSIBILITY OF INFORMATION

It was not an easy task for an owner or operator in the early 1990s to select a bioreactor system to reduce air emissions as a means of compliance. Unlike in the case of microbial treatment of VOCs in wastewater [3], air-bioreactor systems have mostly been used in the US for treating odor and much less for treating VOCs or toxics in air. This is not because the pollutants in air are more complex than in waste water. In fact, the input stream in air systems can be easily analyzed using conventional analytical techniques.

Why is it then still believed that the technology is not yet fully ready (see ref.1)? It is not for lack of technical material. There were many early publications that described what bioreactors could do. [4,5] Most were about packed-bed bioreactor units, which use natural materials such as peat and bark. It was understood that in an aerobic environment, degradation (bio-oxidation) of the pollutants occurred in the biofilm, and the biofilm was attached around the particles, which make up the bed material. The reaction bi-products included carbon dioxide, water, heat, and biomass. Acid products were produced when the pollutants contained, e.g., sulphur or chlorine.

The moisture content was a critical parameter for proper operation of the bioreactor. Hence, water had to be added as needed to prevent drying of the natural support material and because food to the microorganisms is available in the liquid phase. A variant design is the water trickling bioreactor, which involved adding a continuous spray of water over a packed bed made of synthetic material. A side tank enabled better control of the pH and hence these systems could bio-oxidize relatively higher amounts of chlorinated and other pollutants than packed beds made of natural material. A third design that was investigated in the early 1990 combines a wet scrubbing unit and biological treatment unit into a single system.

The parameters that were needed to characterize the size and estimate the cost of building a bioreactor unit were well understood. If we adopt the presently used representation of the design parameters, they included the empty bed residence time (EBRT) in seconds, which is calculated as the volume of the space occupied by the packing material (assuming no void volume) divided by the air-flow rate (Q_g). [6,7]

$$EBRT = \frac{V}{Q_g} \qquad (1)$$

The elimination capacity (EC) is a design parameter, which is now defined as the mass removed per unit volume per time as described by equation 2 below.

$$EC = Q_g \frac{(C_i - C_o)}{V} \qquad (2)$$

Where:
Q_g = volumetric gas flow, $m^3 s^{-1}$
C_i = inlet gas pollutant concentration, $g\ m^{-3}$
C_o = outlet gas pollutant concentration, $g\ m^{-3}$
V = volume of the space occupied by packing material, m^3

Although the literature is abundant, the reader will find that there is less published, operating data for large scale bioreactor systems than one would find in the case of RBC for removing VOCs from water

effluents.[8] Much of the work disseminated represents laboratory or pilot tests. Efforts to model the performance (microbial pollutant removal) of bioreactors are abundant and very specific, as most modeling work is. Hence these studies are not generally helpful to the decision maker or the environmental engineer in a facility.

There were opportunities to promote the technology as an air pollution control. The wood furniture industry was seriously considering the use of bioreactor technology in early 1993 and involved the Office of Air Quality Planning and Standards (OAQPS) of the U.S. EPA. In 1997 OAQPS hosted the 1977 Air Bio-reactor Meeting in Research Triangle Park, North Carolina. [9] The purpose of the meeting was to bring together, mainly, the wood furniture industry, academic institutions, and manufacturers. Thus U.S. EPA would have a better understanding of the state of the technology and participants (industry/academia/manufacturers) would learn about the information that EPA needs to consider such a technology as a control option. Several promising bioreactor designs were discussed during the 1997 meeting. Among the new designs presented was the rotating drum bioreactor system, which used granular activated carbon and was said to be self cleaning of pollutants. Another new design was a system composed of two membrane units. In the first the pollutants were captured from the air and in the other they were bio-oxidized.

BIOREACTOR SYSTEMS

We can classify for our purpose air bioreactor systems (bioreactor unit plus auxiliary equipment) that are sold on the market today or that are under study into four main designs: [10-11]

Type 1. Packed-bed bioreactor system. This type of system includes both open and closed design types, where capture and destruction of pollutants (substrate) occur on a packed bed, or a series of packed beds, as was mentioned before. Nutrients and micro-organisms are provided in the packing material. There are a number of laboratory studies aimed at upgrading the performance of the packed beds, which are focusing on the structure of the packing material (e.g., polyethylene foam, ceramic supports). Several industrial scale systems have been built in the U.S.

Type 2. Water-Trickling bioreactor system. This design is in principle quite similar to traditional packed bed bioreactors that use natural materials, except that the system can also treat air streams with large concentrations of halogens. A separate tank containing neutralizing agents and nutrients achieves the necessary pH control. Several pilot scale systems have been built. This type of bioreactor system can achieve high removal rates and efficiencies; however, biomass control at high removal rates can be a problem.

Type 3. Air Scrubber (or Absorption) - bioreactor systems. In this system the pollutants are first absorbed in a non-clogging absorption unit (tray tower), in which biomass originating from the bioreactor unit is pumped, counter current to the incoming air flow containing the pollutants. Nutrients are fed directly to the bioreactor unit (where most of the micro-organisms reside).

Type 4. Rotating drum bioreactor system. There are two designs:

A- In the first, activated carbon housed in a rotating drum (or wheel) is used to capture (adsorb) the pollutants in the air stream. During rotation of the drum the pollutants are leached into a bath of oxygenated water, where most of the micro-organisms reside and destruction of the pollutants occurs. The nutrients are added to the water bath. Rotation of the drum will cause turbulence at the water surface and some of the biofilm will be detached into the water. A working system is in operation in the U.S. and is being used for the bio-oxidation of styrene released from a metal furniture facility. [12]

b- In the second, a drum containing a concentric single-layered or multi-layered support made of inert material (e.g., foam) is mounted on the drum frame. The inert media covers the length of a shaft that is rotated at low speed. The inert material is soaked as it rotates in an oxygenated water bath. The part (volume) that is exposed to the air during rotation is exposed to the air stream containing pollutants and oxygen. Most of the pollutants are destroyed on the inert media-support on which the micro-organisms are attached. The attached biofilm will receive oxygen from the air when it is out of the water and from the water when the drum is submerged. This system is promising, but it has not yet been scaled to a pilot scale system.

All the systems discussed here are able to control the emissions of pollutants from air stream, to the specific designed level. They all bio-oxidize pollutants. When pollutants contain chlorine or sulphur, chlorides and sulfates will be produced and corresponding acids may also be formed. Such by-products could drastically affect the pH in bioreactor unit and thus kill the micro-organism. Hence, bioreactors are designed with specific pollutants in mind and are able to absorb to various extent fluctuations in the inflowing pollutants stream. Certain bioreactor types are more likely to experience uneven biomass distribution and excess biomass accumulation, which if not corrected, can cause performance problems. Excess biomass accumulation occurs at high loading rates. The mass loading rate is often defined as follows:

$$\text{Mass loading (volumetric)} = \frac{Q_g \times C_i}{V} \qquad (3)$$

Where:

Q_g = air flow rate, $m^3\ h^{-1}$

C_i = concentration of pollutant in the incoming air stream, $g\ m^{-3}$

V = volume of packing material space as defined before, m^3

The volume V for the rotating drum designs, is the solid volume occupied by the material (e.g., polyethylene cylinders) onto which micro-organism attach. An operator will need to ensure that the

design rate and load are not exceeded to avoid clogging of the bioreactor unit. Of the four design types, the rotating drum bioreactor systems appear to provide good control of both biomass growth and biofilm moisture.[12]

Once a bioreactor is operating at the desired destruction efficiency it does best when operated according to the schedule that reflects the condition at which the efficiency was evaluated. For example, if the performance test were done for an 8 hour shift and 7 days a week operation, one should not expect the same level of performance during shorter operating periods like 48 hours, unless the bioreactor unit can reacclimatize within those two days. When large fluctuations in pollutants in the air stream of a packed bed type bioreactor are expected, an improvement in performance may be achieved when activated carbon bed is placed downstream of the bioreactor unit. The pollutants are released from the carbon when the inflow of pollutants is low. Designers of water-trickling systems are also finding that the combination of activated carbon and inert materials will help performance. Similar results were found in a study aimed at controlling acetone using a bio-scrubber system. Designers added powdered activated carbon to the bacterial slurry and found that the destruction efficiency increased.[13] Performance is also affected by the selected bed material carrier with the appropriate characteristics. The moisture level and pressure drop are two important parameters that should be controlled daily in packed bed designs (see ref. 4-7 for details).

Stakeholders often ask about the nature of the effluents from an air- bioreactor system, mainly because these add-on control systems use micro-organisms. They also produce biomass during bio-oxidation reaction, which would need to be disposed of. Particulate matter may also be released during filling of a bioreactor bed, replacement of a packed bed, and operation. Water is also drained from such system. It is likely to contain in the effluent, a small amount of unreacted pollutant, minerals, and biomass. The amount and quality of the drain will depend on the type and operation of a system. Bio-oxidation reaction by-products are carbon dioxide and water vapor, except when acid-producing elements such as sulphur and chlorine are present in the pollutant being degraded. The extent of other secondary pollutants will depend on the amount of energy used to power air blowers or compressors. This is generally expected to be low for most of the systems discussed here, when compared with the more traditional add-on control devices.

SIZING AND COSTING OF A BIOREACTOR SYSTEM

The installed cost of a specific type of bioreactor system depends on the amount and pollutant being degraded. There are also variations within a type of system and across types. For odor reduction, it was estimated that the cost for an open bed soil system, would be around $10-15/cfm, 1988 dollars.[14] For a closed bed system, where the input and output streams can be readily measured, the cost are relatively higher, but also can vary considerably. For example, the costs for a 25,000 cfm bioreactor system controlling benzene from a foundry, can vary from $17 to 69/cfm. The operating cost includes energy to power air blowers and humidify the air, for rotating a bioreactor unit (when applicable), and for pumping nutrients and the buffer solution. Operating costs also include replacement of the media to which the micro-organisms attach, such as natural or synthetic surfaces, and the cost of monitoring and

upkeeping of monitoring equipment. The operating costs are believed to be relatively small. For a medium-sized, rotating drum bioreactor system, designed for destruction of styrene, Type 4a (activated carbon), the costs is around $230 per month, and will vary with the cost of electricity. The pre-installation cost is estimated to be approximately ($14/cfm).[12] The actual cost of a bioreactor system and cost of operation may vary with size and loading. Additional cost related aspects are presented in references (6,7,9, and 15).

CONTROL EFFICIENCY AND ELIMINATION CAPACITY

Percent control efficiency is the term that is often defined in a rule. It is the product of capture efficiency and destruction efficiency. If we assume that all the air releases from an emission unit (e.g., spray booth) are captured and directed into the conduit that leads to the bioreactor unit, then the capture efficiency is 100 percent. In this case, the control efficiency is limited by the destruction efficiency defined below in Equation 4:

$$\text{Destruction eff.} = 100\left(\frac{C_i - C_o}{C_i}\right) \qquad (4)$$

Where:

C_i = concentration of pollutants in the incoming air stream, g m^{-3}
C_o = concentration of pollutants in the outgoing air stream, g m^{-3}

The destruction efficiency of an air bioreactor unit may be determined by only monitoring the composition of the input and output air streams, when the amount of pollutant dissolved in the drained water and in the biomass is relatively insignificant. Whereas the destruction efficiency is defined in air regulations, the EC (Equation 2) is used for sizing and costing a bioreactor unit.
The elimination capacity in Equation 2 can be restated in terms of the volumetric mass loading (g m^{-3} h^{-1}) (i.e., mass of pollutant(s) per volume of bed, per unit time) and the destruction efficiency (see ref. 6) as indicated below,

$$\text{EC} = (\text{volumetric mass loading}) \text{ X } (\text{Destruction Eff.}) \qquad (5)$$

Many of the parameter presented in equations 1 through 5 are first obtained during laboratory scale tests. For pilot testing or for scaling up to industrial sized units, some of the conditions may need to be changed. For a constant mass loading the destruction efficiency of a unit is proportional to EC, as may be deduced from equation 5. However, if the destruction efficiency needs to be fixed and the mass loading needs to be increased above that used to achieve the laboratory scale EC value, the designer would have to increase the value of EC. This is achieved by adjusting a few design variables (see equation 1) and that could result in an increase in the cost of a bioreactor unit and hence of the system. This illustration shows the importance of the EC as a design parameter for scaling up bioreactor units.

DISCUSSION AND CONCLUSIONS

The bioreactor systems, especially the open bed systems, were widely used in the early 1990s in Europe, because odor standards were in place, which required controlling nuisance from species in amounts less than less than 50 ppmv. However, in the U.S. the focus was to destroy VOCs and HAPs in amounts equal or greater than 50 ppmv where this technology was not yet proven. This may more accurately explain why bioreactor technology gained a much smaller share of the U.S. market than more traditional technologies. However, according to Govind, [16] the bioreactor technology market for 1996 was approximately $10 million and a 10-fold increase was estimated for the year 2000. Although we have not yet been able yet to verify these predictions, which were based on economic growth models, there is evidence that several industrial scale units were built in the U.S. Many of the units appeared to have been designed for odor control, where this technology is often said to be both reliable and economic. Odor treatment remains the largest market for this technology. This includes odor from waste water treatment, such as sludge treatment, pulp and paper production, tobacco production, and bakeries.

It seems that there is much work that needs to be done before this technology becomes more widely used in the U.S. as an add-on control for VOCs and HAPs, beyond just odor control. Bioreactor systems must first be able to meet performance requirements that are required in U.S. regulations and that are being met by more traditional add-on controls, such as incinerator and adsorption technologies. The destruction efficiency is not the main hurdle, as is often claimed by some in the air-bioreactor manufacturing industry. There are many U.S. rules, e.g., coating rules that only require 80% destruction efficiencies and many of the new rules published since 1995 provide enough flexibility so that add-on controls that achieve 80 percent or lower destruction efficiencies can be used together with another control option, such as reformulation of the coating, to meet an emission limit defined in a rule. However, P2 (source reduction) remains a competing control option, which will be considered by a facility, when it is evaluating the cost of different control options. Many rules have specific compliance requirements: continuous compliance is most often required, [17] with some minor variation between rules for different source categories. A good overview of some of the factors that need to be taken into account when considering this technology, was recently published.[18]

There is very little published before 1995 [19] on the effect of periods of non-use on the performance of a bioreactor. Any testing for compliance purposes, would need to determine the acclimation time. Otherwise, the perception that there is a long acclimation time necessary following an upset, will prevent this technology from being widely used (see ref. 1).

Lastly, many factors are involved in the design of a bioreactor system. These are discussed in a number of documents, which mainly address bioreactor systems, types 1 through 3. [20, 21] The first document

provides a good background for sizing a bioreactor unit and costing the bioreactor system. The report by the Center of Waste Reduction Technologies includes a good learning tool for assessing different factors affecting degradation kinetics of single compounds. But these models cannot be used for sizing a full-scale bioreactor unit as indicated in Appendix B of reference 21.

DISCLAIMER

This work represents the views of the author.

REFERENCES

1. Final Staff Report for: Proposed Rule 1132, *Further Control of VOC Emissions from High-Emitting Spray Booth Facilities*, (Rivera, A.R. and Lee P.E.), SCAQMD, California, Attachment F, January 4, 2001, pp 20 -21.

2. Douben, P.E.T.; and Serageldin, M. A. The Basis for Industrial Process Regulations, in *Pollution Risk Assessment and Management*, (Chapter 3), John Wiley & Sons ltd, Chichester, UK, 1998, pp 49 - 93.

3. *Wastewater Engineering Treatment: Disposal and Reuse* (3rd Edition), Revised by Tchobanoglous, G. and Burton, F.L. McGraw Hill, Inc. New York, NY, 1972.

4. Ottengraf, S.P.P.; and Disks, R. Biological Purification of Waste Gases, Chimicaoggi, May **1990**, pp 41-45.

5. Van Lith, C.; David, S.L.; and March, R. Design Criteria for Biofilters, *Trans. IchemE.*, 68, Part B, May **1990**.

6. Devinny, J.S.; Dehusses. M.A.; and Webster, T.S. *Biofiltration for Air Pollution Control*, Lewis Publishers, CRC Press, LCC, 1999, pp 1 – 22.

7. Biofiltration. Project Report and Scale-up and Design Guide, *Chapter 2*, Center of Waste Reduction Technologies of the American Institute of Chemical Engineers, New York, 1990.

8. Design of Facilities for the Biological Treatment of Waste Water, in *Wastewater Engineering Treatment: Disposal and Reuse* (3rd Edition), Revised by G. Tchobanoglous, F. L. Burton, McGraw Hill, Inc. New York, 1972, pp 529 - 662.

9. U. S. Environmental Protection Agency (EPA). *1997 Air Biotreatment Meeting -US EPA, NC*, Office of Air Quality Planning and Standards (OAQPS), Research Triangle Park (RTP), NC 27711. http://www.epa.gov/ttn/atw/bio/bio_rsch.html (accessed February, 2003).

10. Serageldin, M. A. Air Bio-Reactor Systems: different designs and operational aspects, Paper #42952, Proceedings of A&WMA=s 95th Annual Conference & exhibition, , June 23-27, 2002.

11. Yang, C.; Suidan, M.T.; and Zhu, X. Removal of Diethyl Ether in a Rotating Drum Biofilter at High Organic Loading Rates, Paper #42988, Proceedings of A&WMA=s 95th Annual Conference & exhibition, , June 23-27, 2002.

12. Communication with Edward Seagle, Agri. Microbe Sales, Inc. This is one of the five types of bioreactors discussed in reference 9, above, March 22, 2003.

13. Kemme, R. M.; and Lateulelere. *Reducing Air Pollutant Emissions from Solvent Multi-base Propellant Production*, CERL Technical report 99/71, US Army Corps of Engineers, pp 22-24.

14. *Biofiltration Industry Release White Paper*, Institute of Clean Air Companies, Inc. (Contact. Dr. Michael J. Wax), Washington, D.C, September 27, 1993, 18 pp.

15. Deshusses, M.A. Cox, H.J. A Cost Benefit Approach to reactor Sizing and Nutrient Supply for Biotrickling Filters for Air Pollution Control, *Environmental Progress*, **1999**, 18, (3), 188 - 196.

16. Govind, R. Treating Organic and Inorganic Emissions in the Next Millennium, May 1999. PRD Tech. Inc. -- http//prdtechnic.com/voc.html#top (accessed February 2003)

17. NESHAP: Surface Coating of Metal Furniture , Proposed Rule, *Fed Reg*. Vol. 67 (Wednesday, April, 2002), pp. 20206 -20248.

18. Standefer, S. Evaluating Biofiltration for Air Pollution Control. http.//ppcbio.com/ppcbiopaper8.htm (accessed February, 2003).

19. Martin, F.J.; and Loehr, R.C. Effects of periods of Non-Use on Biofilter Performance, *Air and Waste Manage. Assoc*. **1996**, *46*, 539-546.

20. Devinny, J.S.; Dehusses. M.A.; and Webster, T.S. Biofiltration for Air Pollution Control, Lewis Publishers, CRC Press, LCC, 1999.

21. Biofiltration: Project Report and Scale-up and Design Guide, Center of Waste Reduction Technologies of the American Institute of Chemical Engineers, New York, NY, 1990; pp 163-175.

KEY WORDS
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