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# USING BIOREACTORS TO CONTROL AIR POLLUTION

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# USING BIOREACTORS TO CONTROL AIR POLLUTION

Prepared by

The Clean Air Technology Center (CATC)
U.S. Environmental Protection Agency (E143-03)
Research Triangle Park, North Carolina 27711

U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Information Transfer and Program Integration Division
Information Transfer Group (E143-03)
Research Triangle Park, North Carolina 27711

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# USING BIOREACTORS TO CONTROL AIR POLLUTION

## INTRODUCTION

Bioreactors use a natural process that is as old as life itself. For life to survive, it must have a source of energy (food) and water (moisture). How these needs are used to remove pollutants from contaminated air streams is the subject of this report.

### What is Bioreaction?

In air pollution, bioreaction is simply the use of microbes to consume pollutants from a contaminated air stream. Almost any substance, with the help of microbes, will decompose (decay) given the proper environment. This is especially true for organic compounds. But certain microbes also can consume inorganic compounds such as hydrogen sulfide and nitrogen oxides.

### Why is Bioreaction Important?

In a word, COST! The capital cost of a bioreaction installation is usually just a fraction of the cost of a traditional control device installation.[a] Operating costs are usually considerably less than the costs of traditional technology, too. Thermal and catalytic control units consume large volumes of expensive fuel. Bioreactors only use small amounts of electrical power to drive two or three small motors. Normally, bioreactors do not require full-time labor and the only operating supplies needed are small quantities of macronutrients. Biofilters, the most common type of bioreactor, usually use beds (media on which microbes live) made from naturally occurring organic materials (yard cuttings, peat, bark, wood chips or compost) that are slowly consumed by the biomass (i.e., microbes). These organic beds usually can supply most of the macronutrients needed to sustain the biomass. The beds must be replaced every 2 to 5 years (Ref. 1), depending on the choice of bed material.

Bioreaction is a "green" process, whereas the traditional approaches are not. Combusting any fuel will generate oxides of nitrogen ($NO_x$), particulate matter, sulfur dioxide ($SO_2$), and carbon monoxide (CO). Bioreactors usually do not generate these pollutants or any hazardous pollutants [b]. Products of a bioreaction consuming hydrocarbons are water and carbon dioxide ($CO_2$).

Bioreactors do work, but microbes are finicky in what they will eat. Microbes need the

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[a] Traditional Control Devices include thermal and catalytic oxidation, carbon adsorption and absorption (scrubbers).

[b] Bioreactors in northern states may need to heat emissions to obtain optimum conditions. The source of this heat may generate combustion pollutants.

right pollutant concentration, temperature, humidity and pH. There are many opportunities to make mistakes in design and operations of a bioreaction system. Anyone thinking about bioreaction would be wise to discuss their situation with a manufacturer's representative or an expert in the field. If a particular air pollution control situation qualifies, the cost benefits can be substantial.

## OVERVIEW

### How do Bioreactors Work?

Microbes have inhabited the Earth since the time that the Earth cooled sufficiently to allow any form of life to exist. Microbes have a simple life cycle; they are born, eat, grow, reproduce and die. Their diet is based primarily on carbon-based compounds, water, oxygen (for aerobic reactions) and macronutrients. Bioreactors use microbes to remove pollutants from emissions by consuming the pollutants. The concept is simple, but the execution can be quite complicated.

Bioreactors have been used for hundreds of years to treat sewage and other odoriferous, water-borne waste. About sixty years ago, Europeans began using bioreactors to treat contaminated air (odors), particularly emissions from sewage treatment plants and rendering plants. The initial process used a device called a "biofilter." A biofilter is usually a rectangular box that contains an enclosed plenum on the bottom, a support rack above the plenum, and several feet of media (bed) on top of the support rack. See Figure 1.

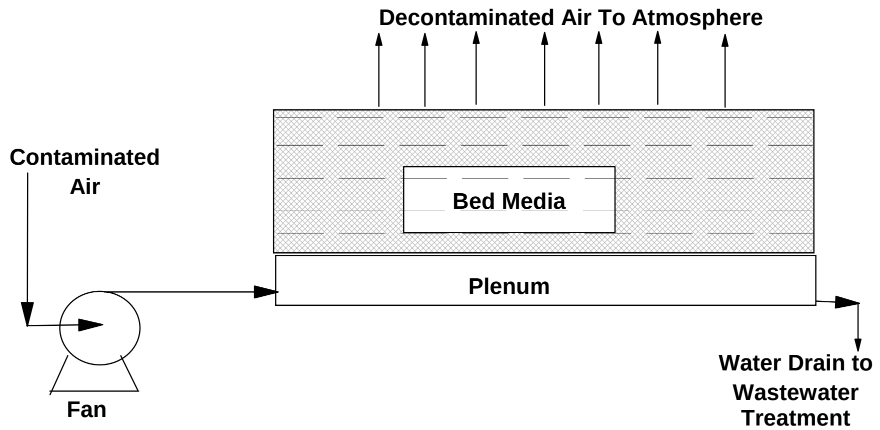

Figure 1. Basic Biofilter

A large number of materials are used for bed media such as peat, composted yard waste, bark, coarse soil, gravel or plastic shapes (Ref. 2). Sometimes oyster shells (for neutralizing acid build-up) and fertilizer (for macronutrients) are mixed with bed media. The support rack is perforated to allow air from the plenum to move into the bed media to contact microbes that live in the bed. The perforations also permit excess, condensed moisture to drain out of the bed to the plenum.

A fan is used to collect contaminated air from a building or process. If the air is too hot, too cold, too dry, or too dirty (with suspended solids), it may be necessary to pre-treat the contaminated air stream to obtain optimum conditions before introducing it into a bioreactor. Contaminated air is duct to a plenum. As the emissions flow through the bed media, the pollutants are absorbed by moisture on the bed media and come into contact with microbes.[c] Microbes reduce pollutant concentrations by consuming and metabolizing pollutants. During the digestion process, enzymes in the microbes convert compounds into energy, $CO_2$ and water. Material that is indigestible is left over and becomes residue.

This is a very simple and brief explanation on how a bioreactor functions. In real-life, things get a bit complicated. Variables that affect the operation and efficiency of a bioreactor include: temperature, pH, moisture, pollutant mix, pollutant concentration, macronutrient feeding, residence time, compacted bed media, and gas channeling. These are crucial variables for which optimum conditions must be determined, controlled and maintained. In the body of this report, a complete explanation of these processes is given.

Is a bioreactor right for your situation? This is not an easy question to answer. The purpose of this report is to provide tools that you can use to determine if a specific contaminated air stream is a good candidate for bioreaction treatment. Why bother? Bioreactors are far less expensive than traditional control technologies to install and operate and, in many cases, bioreactors approach efficiencies achieved by traditional control technologies.

## FACTORS AFFECTING PERFORMANCE: VARIABLES AND LIMITATIONS

Because bioreactors use living cultures, they are affected by many variables in their environment. Below are variables and limitations that affect the performance of all bioreactors, regardless of process type.

### Temperature

All variables discussed here are important. However, probably the most important variable affecting bioreactor operations is temperature. A blast of hot air can totally kill a biomass faster than any other accident. Most microbes can survive and flourish in a temperature range of 60 to 105 ˚F (30 to 41˚C) (Ref. 3). It is important to monitor bed temperature at least daily, but every eight hours would be safer. A high temperature alarm on the emissions inlet is

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[c] Compounds not soluble in water are not good candidates for this technology.

also a good safety precaution.

When emissions from a process are too hot, operators often pass hot emissions through a humidifier that cools gases down by evaporative cooling. This is the most economical method available for cooling emissions from 200 to 300 ˚F (93 to 149 ˚C) to below 105 ˚F (41˚C). Besides the cooling effect, this process also increases the moisture content (humidifies emission stream), a desirable side effect.

Although a blast of really hot air is the most lethal variable for microbes, cold air also stops, but does not kill, microbes. Cold air can reduce microbe activity to the point that they stop consuming pollutants and go into a state of suspended animation. Even freezing does not kill microbes. After thawing, they can be re-acclimated in a relatively short period. For optimum efficiency during winter months, it may be necessary to heat emissions using direct or indirect methods. If heating is required, first look for a waste heat source such as excess steam, boiler blowdown, or product cooling waste heat. As with cooling emissions, analyze your source carefully to assure nothing is being added to the emission stream that will harm microbes in the bioreactor, or will add to the overall pollution load. Additionally, some operators, especially in northern states, insulate the bioreactor's exterior to reduce heat loss.

## Moisture

The second most critical variable is bed moisture. Microbes need moisture to survive and moisture creates the bio-film that removes (absorbs) pollutants from an air stream so that they can be assimilated by microbes. Low moisture problems can be corrected by passing emissions through a humidifier. Having emissions close to saturation (100 % relative humidity) will solve most dry bed problems. Humidifiers need not be fancy, store-bought, stainless steel process vessels. They can be made from an old FRP (fiber reinforced plastic) tank that is surplus, or may be constructed from fiberglass panels with a lumber frame. The design should include several rows of pipes near the top of the vessel with spray heads installed along their length, and on/off valves on each pipe run to provide some control of humidity.

Biofilters are usually operated damp with no running or standing water. Low moisture, for short periods, will not kill the microbes, but low moisture will greatly reduce efficiency. Efficiency will be below optimum while microbes recover (re-acclimate) after a period of dry bed conditions.

Flooding a reactor with water, on the other hand, will cause increased pressure drop across the bed (adding additional load on the blower) and could cause a loss of efficiency because of channeling that by-passes the bio-mass. Channeling could also cause the bed media to collapse. For smooth operations, both conditions are to be avoided.

It is important to remember that a by-product of a bioreaction is water. If emissions are saturated entering the process, there will be water condensing in the bed media. Always provide space in the plenum for water to collect and a method to remove it from the plenum. The optimum bed media moisture range is from 40 to 60 percent water (Ref. 3). One way to monitor bed moisture content continuously is to mount the support rack on load cells with an indicator.

## Care and Feeding

In addition to a comfortable temperature and a moist environment, microbes need a diet of balanced nutrients to survive and propagate. Pollutants provide the main source of food and energy, but microbes also require macronutrients to sustain life. Decay of an organic bed media can provide most macronutrients. However, if a bed is deficient in certain nutrients, microbes will cease to grow and could begin to die.

Nitrogen is an essential nutrient for microbial growth. Microbes use nitrogen to build cell walls (these walls contain approximately 15 percent nitrogen) and nitrogen is a major constituent of proteins and nucleic acids. Microbes are capable of utilizing all soluble forms of nitrogen, but not all nitrogen is available for reuse. Some nitrogen products from digestion processes are gases (nitrogen oxides and ammonia) and small quantities will exit the process with emissions. However, most of the nitrogen containing vapors are re-absorbed into the liquid and are consumed by microbes. Also, some nitrogen products form water-soluble compounds and are leached out of the system with condensing water.

Other essential macronutrients include phosphorus, potassium, sulfur, magnesium, calcium, sodium and iron. Nitrogen, phosphorus, potassium (the NPK code on fertilizer labels) may be added by incorporating agricultural fertilizer into bed media. Lesser soluble macronutrients such as magnesium, calcium, sodium and iron, may be purchased in small quantities at feed and seed stores. The nutrient content of a bed should be checked periodically by submitting samples to a soils lab for analysis.

## Acidity

Most bioreactors perform best when the bed pH is near 7, or neutral.[d] Some pollutants form acids when they decompose. Examples of these compounds are: hydrogen sulfide, organic sulfur compounds, and halogens (chlorine, fluoride, bromine and iodine). Production of acids over time will lower pH and will eventually destroy microbes. If a process emits pollutants that produce acids, a plan must be developed to neutralize these acids.

There are several techniques available to neutralize beds. Some may be incorporated into specification for the bed material. One of the simplest techniques is to mix oyster shells with bed media. The shells will eventually dissolve and have to be replaced (Ref. 5). How long the shells last depends on how much acid is produced. Another simple technique is to install a garden soaking hoses in the packing media during construction (Ref. 4). Periodically, a dilute solution of soda ash (sodium carbonate, $Na_2 CO_3$) may be introduced into a bed when pH begins to

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[d] Bioreactors that treat emissions that contain sulfur or sulfur compounds perform best when the pH is in the range 1 to 2 pH (Ref. 4).

decline. Another technique is to spray dilute soda ash solution over the top of the bed. However, this will probably be less effective than wetting the core of a bed with soaker hoses.

### Microbe Population

Some equipment vendors can simulate a client's emission stream at their laboratory and run bioreaction tests to determine which microbe strains perform best on a particular mix of pollutants. They can then inoculate the bed media with those strains and start up with the "right" microbes in place. Others allow nature to take her course by starting with a bed media that contains a wide variety of living microbes such as compost, peat, or activated municipal sludge. The strains that flourish on pollutants in an emission stream will eventually dominate the bed environment. The natural method will take a little longer to acclimate to optimum efficiency, but, because of the diversity of the strains of microbes, will be more adaptable in the long run. Specific microbes that are developed in the lab are more susceptible to changes in the environment than naturally generated microbes.

Periods of idle time will result in a change in the make-up of a population of microbes. These changes will affect bioreactor performance and time will be required for the microbes population to re-acclimate. Martin and Loehr (Ref.5) were concerned about this and conducted experiments at the University of Texas (1996). They wanted to determine re-acclimation periods after non-use periods of 1.67 days, 3.73 days and 2 weeks. These periods were intended to coincide with plant closing for a 2 day weekend, 4 day holiday, and a two week plant shut down. During periods of non-use, bioreactors were treated two ways: stagnant (no airflow through them), and humidified (saturated air is passed through them). The time required to acclimate microbes in the bioreactor initially and re-acclimate [e] (start-up) and after periods of non-use are shown in Table 1.

Although results from this investigation are meager, they do provide enough information to determine useful trends. For example, the time to re-acclimate during toluene testing more than doubles between 1.67 days and 3.73 days non-use test runs (0.46 day vs. 1.0 day). The time needed to re-acclimate from a two-week (14-day) non-use period is four and half times longer than that to re-acclimate from 3.73 days non-use test (1.80 days vs. 0.39 days). Even though it takes longer to re-acclimate from a 2 weeks non-use period, that time is still shorter than the original acclimation time (1.80 days vs. 4 days).

Data on effects of humidity are even more meager. Only two direct examples of the

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[e] The authors define “re-acclimation” as the time it takes a system to achieve 98 % removal efficiency.

| **Experiment** | **Test 1 (days)** | **Test 2 (days)** | **Test 3 (days)** | **Test 4 (days)** | **Test 5 (days)** |
|---|---|---|---|---|---|
| **Non-Use Period**[a] | Initial Start-up | 1.67 | 3.73 | 3.73 | 14.0 |
| **Humidification**[b] | No | No | No | Yes | Yes |
| **Toluene**[c] | 4.00 | 0.46 | 1.00 | 0.39 | 1.80 |
| **Benzene**[d] | 7.25 | 0.17 | 0.21 | 0.21 | 2.75 |

[a] The number of days bioreactor was out of service
[b] “Yes” indicated humidification system was running during non-use period
[c] Re-acclimation results when only toluene is sent to the bioreactor, days.
[d] Re-acclimation results when only benzene is sent to bioreactor, days

**Table 1. Bioreactor Re-Acclimation Times After Periods of Non-Use (Ref.4)**

effects of humidity are given: 3.73-day non-use period tested with and without humidification using toluene and benzene. In the humidified idle time, the bed re-acclimated to toluene in 0.39 days. In the test without humidification, it took 1 day (61 percent more time). There was no difference in re-acclimate periods during benzene trials with and without humidity. Both took 0.21 days.

How does this research compare with other re-acclimation investigations? In the authors' own words, "Thus, other research has found acclimation periods both shorter and longer than those found in this research. It is difficult to make comparisons among the acclimation periods, as the different studies involved several different chemicals, [bed packing] media types, and operating conditions." (Ref.4) In other words, a pilot plant will probably be a necessity to determine acclimation and re-acclimation periods and other operating parameters for each emission stream and bed media combination.

## BIOREACTOR PROCESSES

From the basic biofilter design, some new processes have evolved to become environmentally and commercially viable. These new processes address situations not adequately dealt with in the basic biofilter design such as the large quantity of space required, acidic environments (pH control), pollutants requiring longer assimilation times, and nutrient feeding.

## Biofilters

For a brief discussion of the basic design and operation of biofilters see, "Overview". Biofilters are ideal for treating emission that have low concentrations of contaminates and high gas volume, a situation that vexes traditional treatment methods. Other advantages and disadvantages are shown below.

### Biofilter Advantages:

- Installation costs are low. Most biofilters are constructed from common materials locally available such as lumber, fiberglass, and plastic pipe. They can be assembled using carpenters, plumbers, and earthmovers.

- Depending on the amount of pretreatment the emissions require, operating costs are usually low. These costs consist of electricity to operate the primary blower and the humidification pump, part-time labor to check on the process, and small quantities of macronutrients.

- Biofilters have high DREs [f] for certain compounds such as aldehydes, organic acids, nitrous oxide, sulfur dioxide, and hydrogen sulfide.

### Biofilter Disadvantages:

- Large land requirement for traditional design.

- No continuous internal liquid flow in which to adjust bed pH or to add nutrients.

- Traditional design does not have a covered top, making it difficult to obtain representative samples of exhaust emission and to determine DREs.

- Natural bed media used in biofilters must be replaced every 2 to 5 years. Bed replacement can take 2 to 6 weeks, depending on bed size.

Over time, some modifications have been developed to overcome some of the specific deficiencies in the traditional biofilter design. To increase contact time with microbes, some facilities recycle a portion of the exhaust back through the bioreactor. This is done by adding a cover and vent to the biofilter. A slipstream is taken from the vent and is recycled back to the intake of the primary blower. See Figure 2. Also, if land is available, biofilters modules may be added horizontally, in series. This configuration is shown in Figure 3.

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[f] Destruction/Removal Efficiencies of pollutants

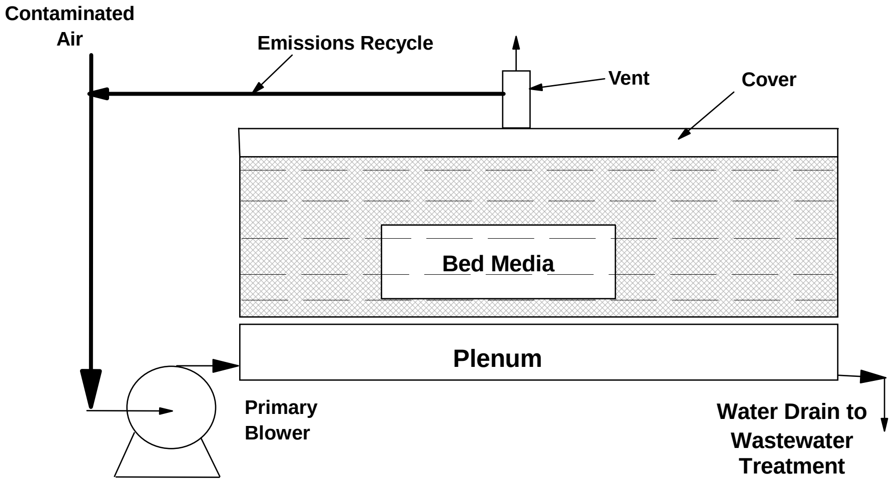

**Figure 2. Biofilter with Emissions Recycle.**

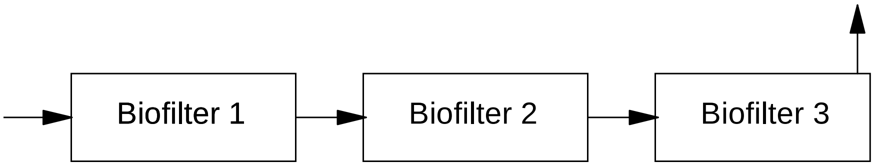

**Figure 3. Biofilters in Series, Horizontally**

To reduce land requirement, some operators have stacked biofilter modules vertically. As mentioned in Factors Affecting Performance, above, some operators have installed soaking hoses in the bed media to control pH and to add nutrients. Some have added sealed top covers to keep rain out and heat in. The cover also provides a vent in which to obtain a representative sample of the exhaust to calculate a more accurate DRE.

One of the earliest modifications was to install the biofilter in the ground, see Figures 4 and 5. This may be done by: digging a hole in the ground the size of the biofilter; placing a lining of coarse gravel several inches thick on the bottom; installing an emissions distribution piping system on top of the gravel; covering the piping system with additional few inches gravel; and covering the gravel with several feet of packing media.

**<u>Biofilter Design Characteristics:</u>** Allen Boyette (Ref. 6) did research and wrote a paper on existing biofilters installations presenting design characteristics and cost information a few

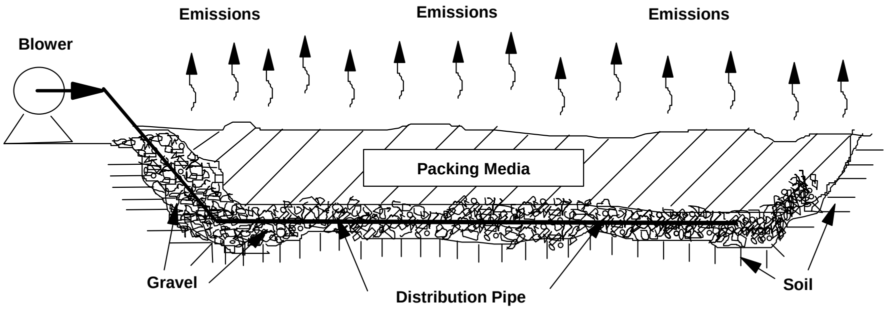

Figure 4 In-Ground Biofilter

Figure 5. Photograph of four Biofilters being installed in Arlington, TX At Central Regional Wastewater System Plant.

years ago.[g] The information, unfortunately, is for biofilters engaged solely in odor control. However, it does provide cost information and limited information on Total Reduced Sulfur (TRS) compounds and one test on VOC. See Table 2. From the information in Table 2, capital costs for bioreactors per unit volume of emissions (CFM) were calculated, see Table 3.

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[g] The paper was not dated, but it appears to have been written around 2000.

| **Facility[a]** | **Odor Source** | **Flow Rate CFM** | **Filter Loading CFM/ft$^2$** | **Area feet$^2$** | **Depth feet** | **Volume feet$^3$** | **Residence Time, Sec.** | **Media Blend** | **Removal Eff, %** | **Cost[b] $ K** |
|---|---|---|---|---|---|---|---|---|---|---|
| CMCMUA, NJ | Compost | 2,400 | 4 | 600 | 4 | 2,400 | 60 | CYW[c], WC[d] | NT[e] | $49.8 |
| CCCSD, CA | WWTP | 3,500 | 5 | 700 | 4 | 2,800 | 48 | CYW[c], WC[d] | NT[e] | $129.7 |
| DMUA, IA | Compost | 210,000 | 5 | 42,000 | 4 | 168,000 | 48 | CYW[c], WC[d] | 86 ordor | $495.5 |
| EHMSW, NY | Compost | 50,000 | 5 | 10,000 | 3 | 30,000 | 36 | CYW[c], WC[d] | NT[e] | $135.4 |
| EWWWTP, NY | WWPT | 15,000 | 2.67 | 5,620 | 4 | 22,480 | 90 | Unknown | NT[e] | NA[f] |
| HRRSA, VA | Compost | 3,150 | 4 | 790 | 4 | 3,160 | 48 | Bio-Solids, WC | NT[e] | $58.0 |
| HWQD, MA | Compost | 15,000 | 3.5 to 5 | 3,600 | 3 | 10,800 | 40-60 | CYW[c], WC[d] | 94 Odor<br>99 TRS | NA[f] |
| RWSA, VA | Sewage | 2,825 | 5 | 565 | 4 | 2,260 | 48 | CYW[c], WC[d] | 76 Odor | $14,3 |
| SBC, TN | Compost | 80,000 | 4.5 | 19,800 | 2.5 to 3 | 54,450 | 30-45 | NA[f] | 91 Odor<br>93 VOC | NA[f] |
| UNISYN, HI | Food Waste | 2,500 | 4 | 625 | 3.5 | 2,188 | 42 | CYW[c], WC[d] | 82 Odor<br>99 TRS | $11.4 |
| WLSSD, MN | WWPT | 50,000 | 4.2 | 11,800 | 4 | 47,200 | 57 | CYW[c], WC[d] | NA[f] | $387.0 |

[a] CMCMUS = Cape May County Municipal Utilities Authority, Cape May, NJ
CCCSD = Central Contra Costa Sanitary District, Martinez, CA
DMUA = Davenport Municipal Utilities Authority, Davenport, IA
EHMSW = East Hampton Municipal Solid Waste, East Hampton, NY
EWWTP = Everett Waste Water Treatment Plant, Everett, WA,
HRRSA = Harrisburg/Rockingham Regional Sewer Authority, Mt. Crawford, VA
HWQD = Hoosac Water Quality District, Hoosac, MA
RWSA = Rivanna Water and Sewer Authority, Charlottesville, VA
SBC = Sevierville Bedminister Corp., Sevierville, TN (MSW)
UNISYN = UNISYN Corporation, Wiamanilo, HI (a firm treats food waste)
WLSSD = Western Lake Superior Sanitary District, Duluth, MN

[b] Total cost of design, construction and start-up. Does not include duct work.
[c] Composted yard waste
[d] Wood chips
[e] Not tested
[f] Information Not Available

**Table 2. Existing Biofilter Design Characteristics Summary (Ref. 6)**

| **Facility Location** | **Air Flow CFM** | **Cost[a] $** | **Cost per Air Flow Rate, $/CFM** |
|---|---|---|---|
| Wiamanillo, HI | 2,500 | $11,400 | $4.56 |
| Charlottesville, VA | 2,825 | $14,300 | $5.06 |
| Cape May, NJ | 2,400 | $49,800 | $20.75 |
| Mt. Crawford, VA | 3,150 | $58,000 | $18.41 |
| Martinez, CA | 3,500 | $129,700 | $37.06 |
| E. Hampton, NY | 50,000 | $135,400 | $2.71 |
| Duluth, MN | 50,000 | $387,000 | $7.74 |
| Davenport, IA | 210,000 | $494,500 | $2.35 |

[a] Cost does not include installation of duct work. It does include engineering, construction and start-up cost.

**Table 3. Biofilter Cost per Unit Volume of Air Flow**

Resulting costs figures are all over the map, but cost per unit volume, appears to decrease as the airflow increases, as expected. Cost for the three biofilters with capacities of 50,000 CFM and over, average just $4.24 per cubic foot per minute. This is probably due to economies of scale. Mr. Boyette does not include ductwork installation cost in his cost figures. In his words, "The odorous gas collection system for each case is not included in the capital cost as collection systems vary from simple duct systems to elaborate ducting and controls. The inclusion of collection system can significantly increase the cost of installing an odor control system and would be required with any [other] odor control technology selected."(Ref.2)

As stated earlier in this section, there are many variations to biofilter design that range from very elaborate equipment and controls to a simple hole in the ground. Other factors effecting costs are labor cost in the area and the geo-political situation.

## BIOTRICKLING FILTER

As mentioned in the Biofilter section, the basic design of a biofilter makes it difficult to control pH in the packing. Acid is formed with the biological destruction of many pollutants and acid build-up creates a serious problem for operators. Many of the early biofilters were used to deodorize foul emissions from wastewater (sewage) treatment facilities. These emissions often contain sulfur compounds that produce acid upon degradation. Because of the detrimental effect of acid on microbes, operators began experimenting with processes to control pH that they had used and understood. One of the processes they experimented with was the trickling filter.

Trickling filters have been used for many years and are effective treatment for wastewater.

**What is a Biotrickling filter?** It is probably better to answer the question, "What is a trickling filter?" first, and then describe the modifications that were made to create the biotrickling filter. A trickling filter is a wastewater treatment process that is usually a round, vertical tank that contains a support rack and is filled with aggregate, ceramic or plastic media to a height of 3 to 15 feet. In the middle of the tank is a vertical pipe that has a rotary connection on the top end. A spray arm is attached to the rotary connection and this has spray nozzles installed along its length. The spray nozzles are angled slightly off-center to provide force necessary to rotate the spraying arm around the top of the trickling filter. A recirculating pump is used to pump liquid from the reservoir in the bottom to the spray nozzles. Liquid level in the sump is maintained with an automatic effluent make-up system. A biofilm forms on the packing surface. This is a biologically active mass that removes the pollutants from the effluent and the microbes decompose them. See Figure 6.

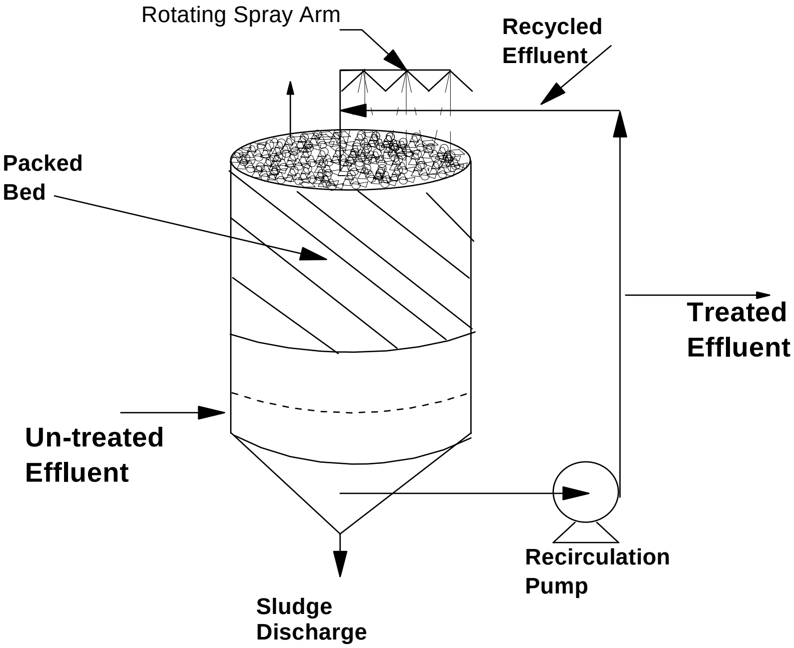


**Figure 6. Trickling Filter**

The biotrickling filter is very similar to the trickling filter. However, the pollutants are contained in an air phase (emissions), and the pollutants must be dissolved into the liquid phase to be available to the microbes. As the air phase passes through the packing, the pollutants are absorbed from the air into the liquid phase to achieve maximum contact with the biomass. This is the difference from the trickling filter because pollutants that enter the system are already in the liquid phase (effluent) in the trickling filter. Water is added to the reservoir to make-up for water that has evaporated. Accumulated bio-sludge is periodically removed from the reservoir and disposed.  See Figure 7.

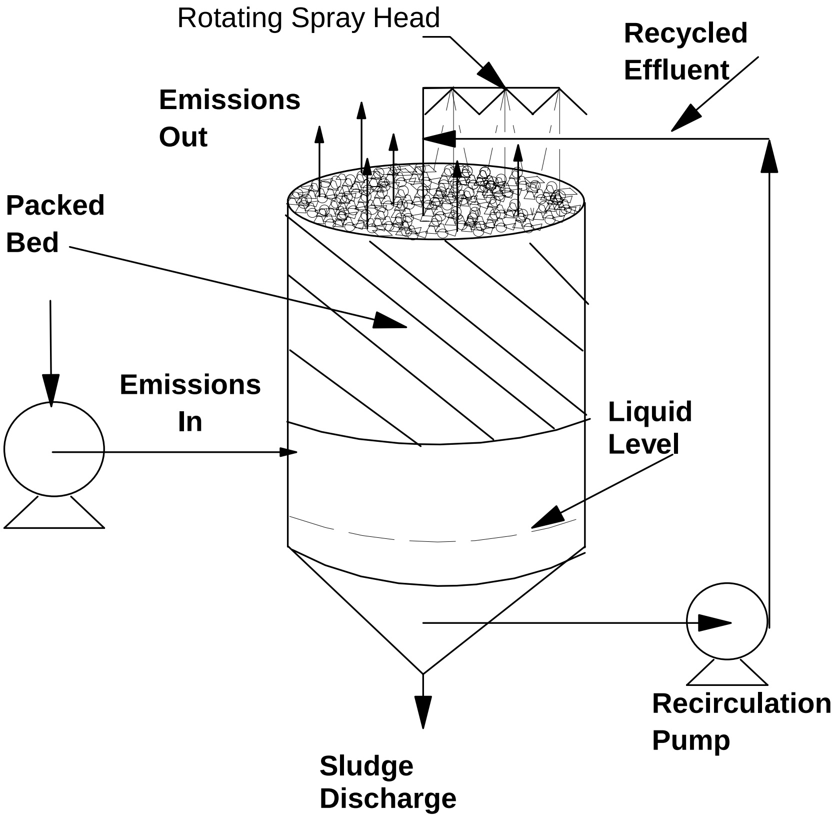


**Figure 7. Biotrickling Filter**

Emissions may be routed through the biotrickling filter co-current or counter-current to the effluent flow.  Because of the continuous flow of a liquid phase, it is an easy matter to automatically neutralize acid build-up.

Use of ceramic or plastic packing rings achieve a void space of up to 95 percent, which greatly reduces pressure drop across the packing.  This means that 15 feet of plastic packing in a biotrickling filter will have about the same pressure drop as 3 feet of natural packing in a biofilter.  In other words, the 15 feet of plastic packing is equivalent to a 5 stage biofilter. Typical characteristics of biofilters found in the United States are shown in Table 4 (Ref. 7) . Design characteristics of four existing biotrickling filters are shown in Table 5 (Ref. 6).  The cost of three of theses biotrickling filters per unit volume of air flow is presented in Table 6.

| | |
|---|---|
| Height of Bed Packing, ft | 3 to 6 |
| Packing Cross-Sectional Area, ft$^2$ | 10 to 32,000 |
| Emissions Flow Rate, CFM | 600 to 600,000 |
| Packing Void Volume, % [a] | 90 to 95 |
| Empty Bed Gas Retention Time, Seconds [b] | 2 to 60 |
| Pressure Drop Across Bed, inches $H_2O$ | 0.36 to 2 |
| pH of Recycled Liquid Phase | |
| When Treating VOC | ~ 7 pH |
| When Treating $H_2S$ | 1 to 2 pH |
| VOC Concentrations, grains ft$^3$ | 4.57 E-3 to 45.7 |
| Removal Efficiency, % | 60 to 99.9 |

[a] Using packing rings, random dump, or structured packing

[b] Empty bed gas retention (EBGR) time is defined as the packed bed volume/emission flow rate

**Table 4. General Characteristics of Biotrickling Filters (Ref. 7)**

Cost results in Table 6 require an explanation. The Hyperion unit was designed, built and operated by chemical engineers from the University of California at Riverside. It was intended to be used as a multi-use research device and was constructed on a moveable trailer. Because of this, much more flexibility and instrumentation than normally needed was built into this application. As a result, the cost per volumetric flow rate for this installation was not used in this comparison.

Costs per flow rates for the remaining two applications are not very far apart and average $25.10/CFM. This is almost six times as high as $4.25/CFM, the average cost of the three largest biofilters. This is to be expected, as trickling filter equipment is closer in design to industrial process equipment than traditional biofilters.

## BIOSCRUBBER

Just as the biotrickling filter is an enhancement of the biofilter, the bioscrubber is an enhancement to the biotrickling filter. The bioscrubber attempts to solve two problems with the biotrickling filter: 1. improve the absorption of pollutants into the liquid, and 2. lengthen the time the microbes have to consume the pollutants. These are accomplished in two ways: the tower packing is flooded with a liquid phase and the discharge effluent from the bioscrubber is collected in a storage tank (sump) before being recycled back to the bioscrubber. See Figure 8.

| **Facility** [a] | **Operation** | **Packing** | **Filter Dimension** | | **Flow CFM** | **EBRT Seconds** | **ΔP in H2O** | **Bed Temp ˚ F** | **Cost $ K** | **Op. Cost $/MMCFM** | **Eff. %** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Diameter** | **Height** | | | | | | | |
| Hyperion | WWTP | Stacked | 5 ft | 11 ft | 380 | 21 | 0.32 | 94 | $175 | $0.23 | 98 |
| Grupo | Resins | Stacked | 12 ft | 38 ft | 26 K | 10 | 1.0 | 92 | $525 | $0.68 | 85-99 |
| Reemtsma | Tobacco | Foam | NA | NA | 100 K | 11 | 6.0 | 104 | $3,000 | $0.23 | 90 |
| US Navy | Fuel Vents | Random | 10 ft | 10 ft | 1,750 | 37 | 5.0 | 80 | NA | $0.72 | |

[a] Hypeiona = Hyperion Wastewater Treatment Plant, Los Angeles, CA
Grupo = Grupo Cydsa, Monterey, Mexico (Cellophane)
Reemtsma = Berlin, Germany (Cigarette Production)
US Navy, North Island, San Diego, CA

**Table 5. Design Characteristics for Existing Biotrickling Filters (Ref. 7)**

| **Facility** | **Flow Rate, CFM** | **Cost, $** | **$/CFM** [a] |
|---|---|---|---|
| Hyperion WWTP | 380 | $175 K | $460.00 |
| Grupo | 26,000 | $525 K | $20.20 |
| Reentsma | 100,000 | $ 3,000 K | $30.00 |

[a] NOTE: Cost per unit volume of air flow ($/CFM) is calculated from data in Table 5.

**Table 6. Cost for Biotrickling Filter per Unit Volume of Air Flow**

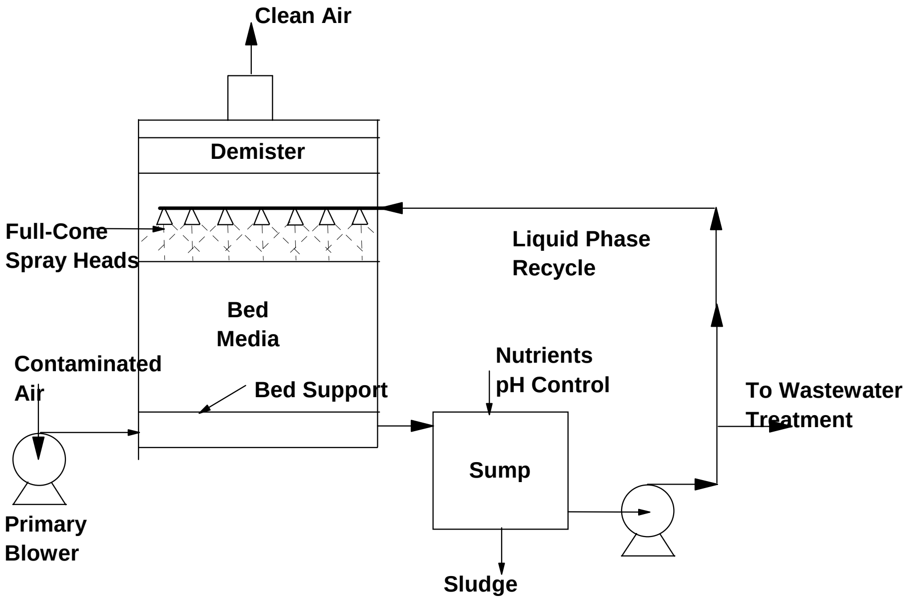


**Figure 8. Bioscrubber**

Flooding the bed increases the ability of the liquid phase to absorb pollutants because as the gas phase (emissions) impacts the bed media it forms tiny bubbles that greatly increases the surface-area of the interface between the gas and liquid phases. Increasing the interface-area improves the liquid phase's ability to absorb pollutants.

The sump acts as reservoir for the liquid phase and permits additional reaction time for the microbes to consume pollutants. Reaction times can be increased to an hour or more, depending on the recirculation rate of the liquid phase and the size of the sump. This increases the time available for microbes to attach and destroy pollutants. Below are more advantages and disadvantages of bioscrubbers.

**Bioscrubber Advantages:**

- It is not necessary to humidify emissions prior to treating them. This could save the cost of installing a humidification process.
- The bioscrubber has a smaller footprint than other bioreactors. This is an important consideration in congested facilities with limited available real estate.
- Because pH control and nutrient feed can be automated, it requires less attention than other bioreactors.
- Process is ideal for emissions that produce acids upon treatment.
- Bioscrubber can treat emissions containing particulate matter.

**Bioscrubber Disadvantages:**

- Considerably more expensive to install than other bioreactors. It has a chemical scrubber at the heart of the process and resembles chemical-processing equipment more so than other bioreactors.
- Over feeding can cause excessive biomass growth, which can plug the bioscrubber.
- Operating cost can be higher than other bioreactor processes.
- Needs expensive and complex feeding and neutralizing systems.
- To control biomass growth, toxic and dangerous compounds must be inventoried and handled.

Operating characteristics and cost data were scarce on the Internet. However, some information was found for three installations. This information is presented below in Table 7.

| | **Roloflex, UK (Ref. 10)** | **Trinity River Authority (Ref. 11)** | |
|---|---|---|---|
| Service | Dryer Exhaust, Printing Ink Solvents | 1 Stage, WWTP | 3 Stage WWTP |
| Volumetric Flow Rate | 8,541 CFM | 300 CFM | 1,200 CFM |
| Capital Cost (US $) | $284,591 | $50,000 | $275,000 |
| Inlet Concentration | 500 mg/m$^3$, C | ~200 ppm, $H_2S$ | ~400 ppm, $H_2S$ |
| Outlet Concentration | 50-100 mg/m$^3$, C | 1 ppm, $H_2S$ | Not Detected |
| Cost/Flow Rate (US $) | $33/CFM | $170/CFM | $230/CFM |

**Table 7. Bioscrubber Design Characteristics**

Unfortunately, there is insufficient information on Roloflex's web-site to determine why their bioscrubber installation cost is an order-of-magnitude less, on a flow rate basis, than the two Trinity River Authority's (TRA) bioscrubber installations. TRA's site did claim they estimated the cost of a non-proprietary, home designed bioscrubber using lava rocks as packing media. They claim the vendor's bids were comparable to their estimated cost, and they selected the vendor's bids. TRA appears to be satisfied with the performance of their two bioscrubbers.

## OTHER BIOREACTION TECHNOLOGIES

During the course of this study, other bioreaction technologies were identified. Because no reference to commercial applications of these technologies was found, no detailed information is provided on these processes in this report. These technologies are biomembrane and self-cleaning activated carbon bioreactors.

The biomembrane uses membranes to concentrate pollutants and as a support structure for a biofilm. However, problems inherent in membrane technology (low flows and high pressure drop) seem to have inhibited development of this technology’s commercial utilization.

The self-cleaning bioadsorber (formally the rotary bioreactor or filter) is a horizontal cylinder that is constructed of a granulated active carbon (GAC) bed mounted on a shaft that is supported on both ends. The bed is one third submerged in a trough of water. Microbes are embedded in the GAC and the bed rotates through the water bath. The bed is enclosed and emissions enter from one end and exit the other end. In theory, the GAC adsorbs pollutants from the emission stream and microbes consume pollutants as the bed rotates through the water bath and emission stream. It is not clear why this technology has not become commercially viable.

## CONTROL OPTIONS AND COST COMPARISONS

Costs of installing and operating emissions control equipment are very important to the affected facility. In fact, a number of marginal operations have been forced out of business because the costs of controls made them unprofitable. To avoid this from happening, a facility must look at all its options to determine which process technologies are viable and what they cost.

Unfortunately, it is difficult to obtain consistent, reliable and accurate information on construction and operating costs for existing bioreaction installations. There are a number of reasons for this. One reason is that bioreaction is an emerging technology and there are not that many installations in use by process industries. Another reason is that facilities that are using bioreactors are reluctant to publish installation and operating costs information for competitive reasons.

Estimates for bioreaction processes are based on bare bones designs. They do not include any pretreatment such as humidification or particulate matter (PM) removal. These additional processes may be required. The estimates also assume that the cost of ductwork and instrumentation were simple and minimal.

Estimates for processes using incineration (thermal and catalytic processes) were obtained using U.S. EPA's <u>Air Compliance Advisor</u>, Version 7.0. These estimates, under the best conditions, are plus or minus thirty percent accurate. Unfortunately, the situation presented here is out of the equation's range (too low) for emissions flow rate. Therefore, the results obtained may be even more unreliable. The attempt here was to generate order of magnitude estimates of bioreactor and traditional technologies for comparison purposes.

For head-to-head comparisons, the model plant technique was used. A hypothetical plant and emission stream were used to design and estimate the costs of various viable technologies. About a decade ago, EPA issued an alternative control technology (ACT) report on the bread-baking industry (Ref. 11). That report contained nine model bakeries with capacities ranging from 5,400 to 19,000 tons bread per year. It was decided to use a model bakery approximately in the middle of this range, 14,000 tons per year.

The following criteria were used for the specifications for the model bakery:

- The baking oven consumes the equivalent of 5 million BTUs of natural gas per hour.
- Bakery oven operates 24 hours per day, 7 days a week, and 8,000 hours per year.
- The bakery only makes white bread from the sponge-dough process.
- The oven is direct-fired with natural gas and has only one stack.
- Emissions contain 10 percent moisture, 2,000 parts per million, volume basis (ppmv) ethanol and 20 ppmv acetaldehyde.
- Emissions from the baking oven average 1,579 actual cubic feet per minute (ACFM), and are around 375 ˚F.

A recent state implementation plan (SIP) now requires the bakery to remove and destroy 98 percent of the pollutants in their emissions. To determine which emission control technologies are viable for controlling emissions from this bakery, available technologies must be reviewed. Emission control techniques can be divided into two groups: combustion (incineration) and non-combustion technologies.

## Combustion Control Devices

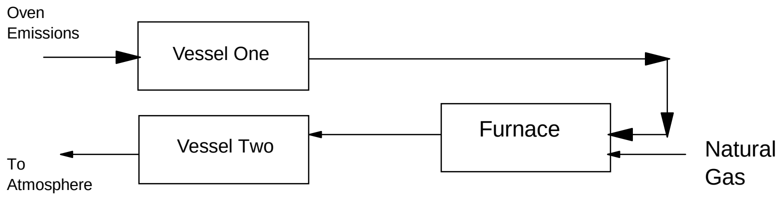
This category relies on heat to burn VOC molecules in the presence of oxygen. Exhaust from a bakery oven contains insufficient volatile organic material to support combustion. In this situation, it is necessary to supply additional fuel (usually natural gas) to bring the emissions temperature up to the level where the pollutants will combust. EPA has found that emissions exposed to 1,600 ˚F for at least 0.75 seconds will destroy at least 98 percent of most VOC. Combustion technologies include thermal oxidation, regenerative oxidation, recuperative oxidation, catalytic oxidation and flares.

**Thermal Oxidation:** In this technology, emissions are mixed in the flame of the supplemental fuel fire and fed into a refractory-lined furnace that contains sufficient volume to allow the gas mixture to reside for at least 0.75 seconds before being exhausted. This technology works very well, and this type of incinerator is simple to operate. The problem with this technology is that it wastes large quantities of energy. Exhaust gases are 1,600 ˚F and could be used to preheat the emissions prior to entering the furnace. Because thermal oxidation is such a wasteful option, it will not be considered in this analysis.

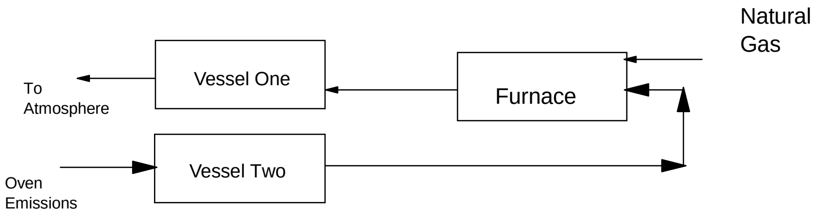
**Regenerative Oxidation:** This technology uses two vessels to capture some of the waste heat from the thermal oxidizer. Each vessel is filled with ceramic packing, which is heated in the first vessel with exhaust gases from the thermal oxidizer. When packing in the first vessel is hot, exhaust gases are switched to the second vessel and bakery oven emissions are routed through the first vessel to be preheated by the residual heat in the ceramic packing. See Figure 9. It is possible to recover as much as 70 percent of the waste heat, which reduces fuel cost by 70 percent (Ref. 12).

In Mode A, emissions from the bakery oven are directed through Vessel One and are heated by the residual heat contained in the ceramic packing. Exhaust gases from the thermal oxidizer are directed to Vessel Two to heat its packing.

At a predetermined time the flows are switched to Mode B. In sequence, Furnace exhaust begins heating the packing in Vessel One, and the residual heat in Vessel Two heats the Oven emissions. In both Modes, additional natural gas is burned in the thermal oxidizer furnace to keep its temperature above 1,600 ˚F. Regenerative Thermal Oxidizer is a viable option for the treatment of the bakery oven's emissions.



**MODE A**
**Oven Emission being heated in One**
**and Furnace Exhaust being cooled in Two**



**MODE B**
**Oven Emission being heated in Two**
**and Furnace Exhaust being cooled in One**

**Figure 9 Regenerative Thermal Oxidizer Operating Modes**

**Recuperative Thermal Oxidizer:** This technology has somewhat similar to a Regenerative Thermal Oxidizer. They both recover and use waste heat, but in a different way. In a Recuperative Thermal Oxidizer, emissions from the oven flow through the tube side of a shell and tube heat exchanger, and exhaust from the thermal oxidizer is routed through the shell side. Heat is transported from the hot oxidizer exhaust to the cooler oven emissions. See Figure 10.

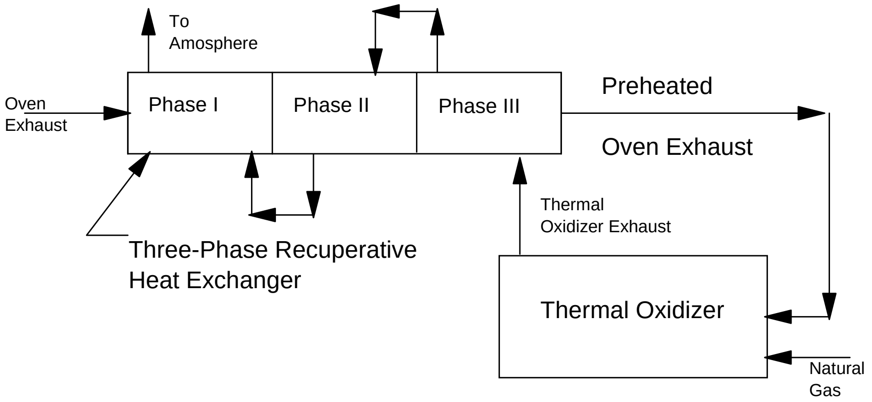


**Figure 10. Three-Phase Recuperative Thermal Oxidizer**

The Recuperative Thermal Oxidizer is a viable option for treating bakery oven exhaust.

**Catalytic Oxidation:** This technology uses metals that act as catalyst to facilitate the reaction between oxygen and the pollutants so the oxidation reaction takes place at a much lower temperature than the thermal oxidation temperature. Typically, catalyst assisted reactions take place in the range of 600 to 1,200 ˚F, instead of the 1,600 ˚F required by thermal oxidation. As a result, significant fuel savings can be realized by using a catalyst assisted control device. See Figure 11.

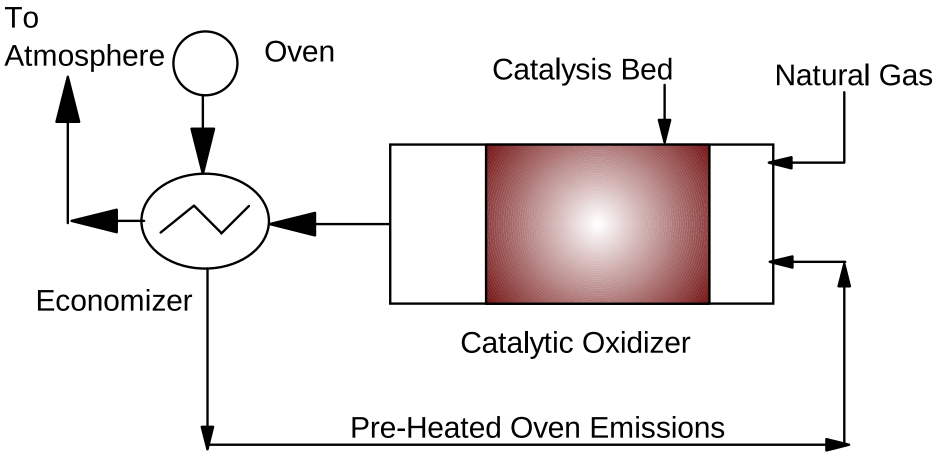


**Figure 11. Catalytic Oxidizer**

Disadvantages of using catalyst include higher capital cost. A precious metal catalyst can cost as high as $600 to $800 a cubic foot. Also, the use of catalyst requires an extremely clean emissions stream that is low in particulate matter. Particulate matter can coat catalyst surfaces, reducing their effectiveness. Catalytic oxidation is a viable option for treating bakery oven emissions and is the preferred choice of bakeries with controls on their ovens (Ref. 11).

## Non-Combustion Control Devices

**Carbon Adsorption:** This technology uses vessels filled with granulated activated carbon (GAC) to adsorb pollutants onto their surfaces. With continuous operations, at least two vessels are required. When the first units GAC becomes saturated with pollutants, emissions must be directed to the second unit while the first unit is re-generated. Re-generation is the process of removing the pollutants from the GAC and restoring it to capacity. This is usually done with steam and/or heat. The pollutants are not destroyed in the carbon adsorption process, they are just transferred to another phase. Ethanol, the primary pollutant in bakery oven emissions, has a high affinity for carbon and is difficult to remove from the GAC beds. Because of this problem, carbon adsorption is not considered a viable option in this situation.

**Chemical Scrubbers:** This technology uses a column packed with ceramic or plastic rings and is flooded with a liquid phase. The pollutants in the emissions are absorbed by the liquid and the contaminated liquid requires additional treatment. The pollutants are not destroyed by the scrubbing process, but report to the liquid phase creating another pollution problem. Because of this, chemical scrubbing alternative is not an option in this situation.

**Condensation:**. Condensation of ethanol from bakery emissions would require refrigerated cooled coils. Because of the low temperatures required, water, fat and oils would also condense from the emissions. Water would freeze to the coils and the fats and oils would foul them, inhibit heat transfer and reduce the effectiveness of the condenser. This process would also create large volumes of wastewater that require additional treatment. This technology is not considered a viable option.

**Process/Formulation Changes:** This alternative is not considered an option. All modified yeast products that lower VOC emissions produce products that have unacceptable taste.

**Bioreaction:** During the last decade, significant advances have been made in various biological processes. More facilities are evaluating various bioreaction processes as viable options to traditional technologies. Because of large land requirements, biofilters may not be an option. Other options that are potentially viable are biotrickling filter and bioscrubbers.

## Cost Comparisons

Costs of thermal and catalytic destruction of the pollutants emitted from the bakery oven were calculated using EPA's Air Compliance Advisor. Cost assumptions and emissions stream data can be found in **Appendix A**. These costs are shown in Table 8, below.

| **Process** | **Total Capital Cost, $** | **Annual Utilities[a] Costs, $** | **Other Direct Costs[b], $** | **Indirect Costs[c], $** | **Total Annual Costs, $** |
|---|---|---|---|---|---|
| Recuperative | $227,375 | $6,300 | $25,700 | $24,760 | $52,300 |
| Regenerative | $60,100 | $2,680 | $26,800 | $18,830 | $48,257 |
| Catalytic | $44,100 | $2,970 | $28,700 | $18,600 | $50,270 |

[a] Annual Utilities Costs include electrical and natural gas costs.

[b] Other Direct Costs include labor, maintenance, supervision and capital recovery.

[c] Indirect Costs include overhead, insurance, taxes and capital recovery.

## Table 8. Estimated Control Cost for Thermal and Catalytic Processes

The estimates range from $48,257 for the regenerative technology to $52,300 for the recuperative process. Total costs are often expressed as cost per thousand cubic feet treated. Annual emissions are 758 million cubic feet per year, which results in a control cost of $0.064 per cubic foot when using the regenerative technology.

Bioreaction control costs were estimated from values found in literature and on the Internet (Ref. 8). Cost elements are shown in Table 9, below.

Total annual cost estimates for bioreaction processes have a much wider range than estimates for incineration controls. Annual cost estimate for bioreaction processes ranged from $5,225 for a biofilter, and $54,144 for a bioscrubber. The biofilter's costs in dollars per CFM is $0.0069 per CFM, which is an order of magnitude less than regenerative incineration technology. Bioscrubber total annual costs are comparable to the annual costs of the incineration processes. Thus, it has no financial advantage over thermal technologies.

## REGULATORY ISSUES

Very little information was found on how bioreactors are regulated or permitted. One paint producer that installed a bioreactor system on the west coast was contacted to determine how they permitted their installation. The environmental manager there said that facility was granted a pilot plant type permit that allowed them to experiment to determine optimum DRE and operating conditions. The initial bioreactor installed was later determined to be undersized and was replaced with a unit thirty percent larger. They are pleased with the new installation, which they say easily exceeds the vendor guaranty of 75 percent DRE. They are confident they will eventually achieve 85 to 90 percent DRE. He now feels they can easily qualify as a

| **Process** | **Total Costs, $** | **Labor[b], $** | **Nutrients** | **Bed Cleanings[c], $** | **Indirect Costs[d], $** | **Total Annual Costs, $** |
|---|---|---|---|---|---|---|
| Biofilter | $8,560[a] | $1,780 | $640 | $1,605 | $1,200 | $5,225 |
| Biotrickling Filter | $42,800[e] | $1,780 | $640 | $1,605 | $6,000 | $10,025 |
| Bioscrubber | $337,900[f] | $3,420 | $1,284 | $2,140 | $47,300 | $54,144 |

[a] Estimated based on $5 per CFM and a flow rate of 1,579 CFM + CPI adjustment to January 2003.

[b] Includes operations, maintenance and supervision.

[c] Two per year.

[d] Includes overhead, taxes, insurance and capital recovery.

[e] $25 per CFM + CPI.

[f] $200 per CFM + CPI.

**Table 9. Control Costs Using Bioreaction**

“synthetic minor” designation under new source review permitting procedures instead of a “major source” designation.

## CONCLUSIONS

EPA promulgated a new MACT standard for miscellaneous organic processes in late summer of 2003. These new regulations will subject over 25 new organic source categories to MACT standards. A number of smaller operators will now have to meet new emissions standards. Plant engineers will be scratching their collective heads trying to determine what must be done and how much it will cost to meet these new standards. A bioreactor system may be the answer to their prayers. However, this may be a difficult road to go down, and much research must be done before final decisions are made.

Like many other control technologies, bioreaction works in many cases, but not all. The trick is knowing when it will work and when it won't. This involves research, testing and talking to knowledgeable people with experience building and running bioreactors. Your first question should be: Is bioreaction applicable for my emission stream? If emissions are very acidic or basic, they must be neutralized before entering a bioreactor. If not at or near 100 percent relative humidity, they must be humidified if planning to use a biofilter. If the emission stream is too hot or too cold, it must be cooled or heated. If its too dirty (particulate matter), the emission stream should be cleaned before going into a biofilter (suspended solids are not a problem in biotrickling filters or bioscrubbers). If emissions are very concentrated or extremely toxic, they are probably not suitable for bioreaction.

If the emission stream is suitable, or can be pretreated to be suitable, which bioreactor technology is a right? This answer depends on the characteristics of the emission stream. If the emission stream contains pollutants that generate acids upon degradation (sulfur compounds or halogens), a biotrickling filter or bioscrubber may be the correct choice. If emissions do not generate acids, and space is available, a biofilter may be the answer. If a high DRE is required, a bioscrubber may be required. However, as shown in the cost section of this report, if a bioscrubber is required, the high capital cost of a bioscrubber may offset by lower fuel cost when comparing it to thermal processes. In addition, the environmental advantages of not producing additional NOx or CO still apply. If a facility is near an emission limit or a threshold for either of these pollutant, this may be significant.

Yes, bioreaction is a viable, low cost option in some circumstances, for the facilities that have emissions that qualify for this technology.

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# APPENDIX A
# CONTROL DEVICE OPERATING COST ASSUMPTIONS

| | |
|---|---|
| Interest Rate % | 7% |
| Operating Labor Pay Rate $/hr | $16.73 |
| Maintenance Labor Rate, $/hr | $18.41 |
| Electrical Cost, $/kW-hr | $0.06 |
| Natural Gas Cost, $/M$^3$ | $0.15 |
| Cooling Water Cost, $/M$^3$ | $0.05653 |
| Water Disposal Cost, $/M$^3$ | $1.007 |
| Steam Cost, $/kg | $0.01097 |
| Dust Disposal Cost, $/kg | $0.02949 |
| Yearly Operating Hours | 8,000 hr |
| Duty Cycle | Continuous Operation |

| **Emission Stream Data** | |
|---|---|
| Oven Exhaust Temperature, ˚R | 258.9 |
| Pressure, Atmospheres | 1 |
| Volumetric Rate - Actual M$^3$/sec | 0.3806 |
| Pollutant: Ethanol, ppmv | 2000 |
| Pollutant: Acetaldehyde, ppmv | 20 |

# TECHNICAL REPORT DATA

*(Please read Instructions on reverse before completing)*

| | | |
|---|---|---|
| 1. REPORT NO.<br>EPA-456/R-03-003 | 2. | 3. RECIPIENT'S ACCESSION NO. |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>Using Bioreactors to Control Air Pollution | 5. REPORT DATE<br>September 2003 |
| | 6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S) | 8. PERFORMING ORGANIZATION REPORT NO. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Clean Air Technology Center (E 143-03)<br>Information Transfer and Program Integration Division<br>Office of Air Quality Planning and Standards<br>U.S. Environmental Protection Agency<br>Research Triangle Park, NC 27711 | 10. PROGRAM ELEMENT NO. |
| | 11. CONTRACT/GRANT NO. |
| 12. SPONSORING AGENCY NAME AND ADDRESS<br>Office of Air Quality Planning and Standards<br>Office of Air and Radiation<br>U.S. Environmental Protection Agency<br>Research Triangle Park, NC 27711 | 13. TYPE OF REPORT AND PERIOD COVERED<br>Final |
| | 14. SPONSORING AGENCY CODE<br>EPA/200/04 |

15. SUPPLEMENTARY NOTES

For more information, call the Clean Air Technology Center (CATC) Information Line at (919) 541-0800 or access the CATC Web page at <http://www.epa.gov/ttn/catc>.

16. ABSTRACT

Because of increasing fuel cost and tightening environmental regulations, alternative air pollution control technologies are being considered to replace or supplement expensive combustion control technologies. This technical bulletin addresses one of these technologies, bioreactors. Bioreactors use micro-organisms to destroy pollutants in air emission streams. Using publicly available data, this report: presents information on commercially available bioreaction processes used to control air pollution; considers the limitations of bioreactors; assesses the effectiveness of bioreactors for removing pollutants; and provides information on the capital and operating costs of bioreactors.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Bioreaction<br>Bioreactor<br>Biofilter<br>Trickling Biofilter<br>Bioscrubber | Air Pollution Control<br>Volatile Organic Compounds<br>VOC<br>Odor Control<br>Organic Hazardous Air Pollutants<br>Organic HAP | |

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