THE USE OF A BIOFILTER FOR REDUCING OFF-GAS ODOUR FROM AN INDUSTRIAL FERMENTATION PROCESS

BY

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A Thesis submitted to
the Faculty of Graduate Studies
In Partial Fulfilment of the Requirements for the Degree of

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THE UNIVERSITY OF MANITOBA

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ABSTRACT

Biofiltration is an inexpensive method of odour removal in which a contaminated air stream is passed through a moist, porous medium before being vented into the atmosphere. Contaminants are absorbed onto the surface of the medium and degraded by microorganisms. The objective of this thesis was to establish the optimal performance conditions of a closed bed, vertical biofilter to remove odour in off-gases released from a local fermentation facility. The facility operates in batch mode and off-gasses are released after sterilization of fermentation medium for each batch. A lab-scale system was used to conduct the experiment. The filter was operated for two months, totalling 30 medium sterilizations, and the relationship between odour reduction and off-gas flow rate was examined. Empty bed contact times (EBCT) of 60, 120, 180, and 240s were combined with filter media composed of 20:80 c:w (compost:woodchips) and 40:60 c:w (by volume). Due to intermittent off-gas flow, the filter was subjected to two flow conditions: one from the off-gases of fermentation and the other from a supplemental airline. Despite regular intervals of dry and cool air, the filter maintained an odour reduction above 35% for all conditions tested, and sustained odour reduction over consecutive sterilization cycles.

The optimum condition tested for odour removal was 40:60 c:w medium with an EBCT of 240s. The biofilter exhibited 72% odour reduction immediately after medium sterilization, when odour levels are highest (32800 OU/m^3). The filter had an efficiency of 61% and 67% for 24 h and 50 h after sterilization, respectively. A dispersion analysis, which was performed to describe odour reduction, showed noticeable odour reduction in the atmosphere around the fermentation facility.

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1.0 INTRODUCTION

Many industrial operations generate odours which may be unpleasant to local communities. Although laws may not have been violated, these stack emissions may have adverse impacts on air quality. Therefore, industries constantly seek inexpensive and effective means of reducing these odour emissions as a demonstration of due diligence. Apotex Fermentation Inc. is the largest Canadian-owned pharmaceutical company. They desired a low-cost, non-hazardous means of reducing odorous emissions of volatile organic compounds from local fermentation stacks. The company is exercising due-diligence, and are under no legal obligation to reduce effluent gases.

The gases emitted from Apotex are vented to a stack located on the building roof, leading to the atmosphere. Odours are usually very strong immediately after the sterilization process until approximately 2h later. The odours emitted are characterized as non-toxic, low emissions, intermittent, and being composed of the by-products of fermentation. Typical by-products of fermentation include such compounds as aldehydes, alcohols, esters, ethers, and amines. The intermittent nature of flow poses a challenge to biofiltration, as microorganisms prefer constant concentrations.

Apotex has explored many ways of reducing their fermentation emissions. Among these methods is biofiltration, which is an inexpensive method of odour removal in which contaminated air is passed through a microbe-

containing medium where contaminants are degraded. Although there is much information in the literature on biofiltration, published research relating to the treatment of fermentation off-gases using biofiltration is limited. This thesis investigates the design and performance of a pilot biofilter for odour removal with specific constraints posed by the fermentation process of Apotex.

2.0 OBJECTIVES

1. To design and construct a lab-scale, closed bed, vertical biofilter for reducing odorous emissions generated during medium sterilization of fermentation at Apotex Fermentation.

2. To determine the performance characteristics of the above-mentioned biofilter. The performance parameters examined included pressure, temperature, relative humidity, empty bed contact time, and medium composition.

3.0 LITERATURE REVIEW

3.1 Volatile Organic Compounds

To effectively decrease emissions from industrial facilities and reduce odour levels, the components and characteristics of the emissions must be identified. Odour emissions mainly include volatile organic compounds.

Volatile organic compounds (VOCs) are molecules with high vapour pressure, and are a common group of air pollutants. They usually contain less than twelve carbon atoms (Nevers 1995), and examples include chlorinated organic solvents, aldehydes, phenols, and haloacetic acids. Sulphur and nitrogen are almost always present in odorous emissions (Tchobanoglous *et al.* 2003). To diminish the degradation VOCs place on the environment, their release into the atmosphere should be minimized through various control techniques.

3.2 VOC Treatment Techniques

There are several methods of treating off-gases containing VOCs. The selection of a method will depend strongly on the treatment volume and the nature of the VOCs in the air stream. In certain situations, the off-gas is emitted through a stack as high as 30 to 40 m to increase dispersion (Tchobanoglous *et al.* 2003), however many solutions exist that treat the gas rather than disperse it. Options include vapour-phase adsorption, as occurs

with granular activated carbon; thermal incineration; catalytic incineration; combustion in a flare; combustion in a boiler or process heater, which is used only where a combustion process is included as part of the process; and vapour-phase biological treatment processes (Tchobanoglous *et al.* 2003). An important point to note is that no odour control device produces a completely odour-free gas stream; all have a residual odour. The nature of the odour, however, is changed substantially. The residual odour is sufficiently low such that stack dispersion will reduce odour to an imperceptible level at the plant/property boundary.

3.2.1 Vapour-phase adsorption Adsorption is the process whereby compounds are adsorbed selectively on the surface of a material with large surface areas. The most commonly used substance is activated carbon. The adsorption capacity increases with the molecular weight of the VOC being adsorbed, and generally more unsaturated compounds are adsorbed than saturated compounds (Tchobanoglous *et al.* 2003). Granulated activated carbon (GAC) has proven successful in filtering air containing mixtures of VOCs including alcohols, ketones, esters, and aromatic compounds (Aizpuru *et al.* 2003). Lower operating temperatures and higher concentration improve the GAC performance.

Carbon adsorption often involves multiple beds with two main steps in the operation, namely adsorption and regeneration, usually performed in

sequence. The bed usually consists of small, 0.001m-diameter particles produced from coal, wood, or coconut. Other materials such as nutshells (Wartelle *et al.* 2000), and pellets made of rice straw, sugarcane bagasse, and soy bean hull (Johns *et al.* 1999) have also been used successfully. As the adsorption capacity of the bed is approached, traces of the VOCs will appear in the exit stream. The off-gas is then directed to a parallel bed containing regenerated adsorbent and the process continues (Tchobanoglous *et al.* 2003). The carbon bed can be regenerated to reduce cost by applying heat, and the VOCs are desorbed with only residual amounts remaining in the bed. Hot air or stream regeneration is commonly used, and inert gas generation is used when the contaminants may pose a fire risk, such as with ketones and aldehydes.

One disadvantage of adsorption is that the contaminants are not decomposed. Therefore, the carbon particles often have to be deposited as hazardous waste. Another disadvantage is that adsorption systems generally have a high capital cost. However, adsorption does not produce a secondary contaminated air stream, requires little maintenance of medium and mechanical parts, and has a high efficiency of removal for certain compounds. For example, over 99% hydrogen sulphide removal has been reported by Webster *et al.* (2000) using GAC.

3.2.2 Thermal incineration Thermal incinerators introduce the contaminants into a chamber where they are oxidized at a temperature in the range of 540

to 815°C (1000 to 1500F). Time in the incinerator (approximately 0.5s is typical), temperature, and turbulence are critical design parameters (Wark *et al.* 1997). Turbulence refers to the amount of mechanical mixing necessary to promote sufficient contact between the oxygen and the fuel, and the combustible pollutants with the heat from the flame (Wark *et al.* 1997). Ample mixing may reduce retention times. Thermal incineration is the preferred method to direct flame incineration when combustible materials in a waste gas are low in concentration. When emission streams treated by incineration are of low concentration and therefore low heat content, supplementary fuel is required to maintain the desired combustion temperature (Tchobanoglous *et al.* 2003).

Thermal incinerators have a relatively small space requirement but with very high fuel costs and high mechanical complexity. They are well-suited for treating low-volume, high strength air streams with a broad spectrum of contaminants, and normally achieve efficiencies above 95% for contaminant removal (EPA 2000, Picasso *et al.* 2003). Also, thermal incineration can handle variable loads with a uniform performance, but a secondary waste stream may be produced (Zappa 2000).

3.2.3 Catalytic incineration A catalyst is used in this method, which accelerates the rate of an oxidizing chemical reaction without undergoing a chemical change itself (Wark *et al.* 1997). Typical catalysts used for VOC

incineration include platinum and palladium, and they may be either in the form of pellets or spheres, or meshed into a mat (Tchobanoglous *et al.* 2003). This increased rate decreases the necessary residence time of the contaminant in the incinerator and the ignition temperature is lowered. By subjecting the waste gas to the catalyst, the necessary temperature for an exothermic reaction of organic gases and vapours with oxygen may be reduced by as much as 260°C over thermal incineration. In catalytic incineration, the residence time is represented by space velocity (the reciprocal of residence time), which is defined as the standard cubic feet per hour of gas flow divided by the catalyst volume in cubic feet. Thermal efficiency is usually between 95-98% (Wark *et al.* 1997). Factors affecting the efficiency of catalytic incinerators include operating temperature, space velocity, VOC composition and concentration, catalyst properties, and the presence of catalysts or inhibitors in the waste stream (Tchobanoglous *et al.* 2003).

3.2.4 Combustion in a flare Commonly used for disposal of waste digester gas, flares can be used to destroy most VOCs, and can be designed to handle fluctuations in emission VOC content and inert content. They are also considered effective tools for burning process hydrocarbons, carbon monoxide, and other chemicals (Bourguignon *et al.* 1999).

Several different types of flares exist. For example, steam-assisted flares are used for large volumes of waste gases, whereas air-assisted flares are generally used for moderate off-gas flows. Small flows may use pressure-head flares. Efficiency of flares is variable, ranging between 62% to above 98%, with efficiency decreasing with increasing stack velocity (Bourguignon *et al.* 1999). The removal efficiency in some refineries is as high as 99.5% (Martin 2000). Combustion efficiency of a flare is directly related to the ability of the flare to convert all contaminants to their fully oxidized state, therein producing a secondary waste air stream; in fact, it is considered one of the sources of air pollution in a refinery emissions inventory (Martin 2000). This has caused some public concern and many companies presently using these techniques, including Stampede Oil and Startech Energy, are seeking alternatives (O'Connor Associates 1999).

Although flaring has proven effective in many industries, it has two main disadvantages: firstly, one must know the exact burned gas composition as flaring is not a routine process and the gases sent to burn are inconsistent, and secondly, the gas composition at the end of the flare should be measured it is necessary to catalogue the secondary emissions produced (Martin 2000).

3.2.5 Chemical scrubbers Although less commonly used in the treatment of VOCs, chemical scrubbers are often used to treat odorous gases, and are designed to provide contact between air, water, and chemicals to afford oxidation or entrainment of the odorous compounds (Tchobanoglous *et al.*

2003). Water may be used as the scrubbing liquid, in which case chemicals are not required, or a combination of both water and chemicals may be used. They have been used in a large range of applications, including sewage treatment, mineral processing, and various industries including fertiliser, steel, food, chemical, and automotive. They usually involve treating gases of high pH, and a residence time of approximately 1 to 3 s (Tchobanoglous *et al.* 2003).

Advantages of chemical scrubbers include the ability to remove particulates and absorbable odours in the air stream; as well they can handle a high-temperature air stream with significant temperature reduction. However, some disadvantages are possible channelling due to plugged nozzles, the need for a water treatment pH control system, and significant capital cost. Also, a large ducting system is needed to deliver air to the scrubber along with blower fans, and the scrubbing solutions may require special handling and storage (Nevers 1995).

Odorous chemicals can be decomposed either by oxidation or chlorination. Many molecules have oxygen and chlorine that readily splits from the molecule. The most commonly used oxidation agents are sodium hydroxide (NaClO), sodium hypochlorite (NaOCl), and hydrogen peroxide (H_2O_2). Although NaClO is less expensive, the scrubber effluent contains chlorine and chloride. H_2O_2 has become more cost competitive in recent times and is

available in much higher strengths than NaOCl and NaClO, meaning lower volumes required for transport, smaller storage tanks, and less piping. Also, H_2O_2 does not produce chlorinated by-products. Potassium permanganate is also used as a scrubbing agent.

Although scrubbing has proven successful in treating hydrogen sulphide and other specific contaminants, its effectiveness in treating other odorous compounds is not yet proven. There are numerous types of chemical scrubbers, including single-stage counter-current packed towers, counter-current spray chamber absorbers, and cross-flow scrubbers. In single-stage scrubbers, the scrubbing fluid is re-circulated. The packed bed is irrigated with the scrubbing solution, which is recycled within the scrubber using a pump. Removal efficiencies may exceed 98% (Tchobanoglous *et al.* 2003). For many applications more than one packed bed may be used, each bed using a different scrubbing solution.

3.2.6 Biotrickling filters Biotrickling filters are biological treatment systems which provide moisture continuously or intermittently by spraying a liquid to the packing material. Odorous gas is passed through the packed bed where the contaminant is absorbed and then biodegraded by microorganisms present. The liquid is re-circulated and nutrients are often added (Tchobanoglous *et al.* 2003). Additional water must be added to replace that lost to the exiting gas. Biotrickling filters have proven successful in the

removal of various VOCs, including toluene, acetone, and ethylacetate (Lu *et al.* 2001, Chang and Lu 2003).

Biotrickling filters employ a well-defined, non-porous, inorganic packing material instead of the irregular-shaped substances used in biofiltration (Lewandowski *et al.* 1998). GAC is a typical packing material for the filter bed. Lava rock is commonly used, however significant fan power is needed to force air through the filter bed when present. Therefore, biotrickling filters using rock media must be sized for very low gas velocities, resulting in huge surface area requirements. Very high efficiencies can be reached, as was the case for flue gas desulfurization where 100% of influent SO_2 was removed at low concentration (Deshusses 2003).

These filters are simple enough to run without operator attention, and without needing to store hazardous chemicals. Therefore, they are well suited for odour control at facilities where there is no one to operate a conventional wet scrubber, and at a significantly lower cost. Trickling biofilters may function as simple pretreatment stages for conventional biofilters for VOC removal as they can humidify air and greatly reduce its sulfur content. Although VOC removal rates are higher for biotrickling filters than for classic biofilters, instrumentation and operating costs are also much higher (Lewandowski *et al.* 1998).

3.2.7 Biofiltration

Biofiltration is an inexpensive method of secondary air pollution control that can effectively remove biodegradable compounds without the production of further waste air streams. It involves passing a contaminated air stream through a mixture of organic material, such as compost, woodchips, or peat, where contaminants are degraded by microorganisms. The degradation of the contaminants is an important characteristic of biofiltration that is absent from most other air treatment processes.

Biofilters originated in California in the 1960s to treat waste gases, mainly from sewer and wastewater treatment plant emissions (Devinny *et al.* 1999). The technology has flourished in Europe because high-energy costs and strict odour regulations make biofiltration the viable economic alternative for waste air treatment. Conversely, biofiltration has not gained acceptance in North America because of low energy prices, which make high-energy systems more affordable, and a lack of regulatory acceptance due to a lack of common usage. These factors have usually made other methods, such as incineration, more attractive economic alternatives (Devinny *et al.* 1999).

3.2.7.1 Mechanisms of Biofiltration The contaminants dissolve in a stationary water phase in the biofiltration medium, also known as the filter bed, and are then degraded by microorganisms. Water is periodically injected into the bed to maintain the proper moisture level. The microbes

present in the filter bed oxidize the influent VOCs, which are molecules with high vapour pressure present in the air at high concentrations, and oxidizable inorganic vapours. This produces harmless respiratory by-products, including water and carbon dioxide. The bacteria and fungi present on the filter medium acclimate to the absorbed or adsorbed contaminants, and a lower number of species flourish by metabolizing the incoming air contaminants (Cherry *et al.* 1997). Some species may thrive on the surface of the biofilm, which is a film consisting of live microorganisms, materials such as polysaccharides emanated by microorganisms, and debris of microbial and filter bed material origin. Others penetrate deeper into the pores where oxygen is scarce (Devinny *et al.* 1999). Degradation occurs under favourable moisture (between 40 and 80%, wet basis) and temperature conditions (between 20 and 45°C). Because the filter bed consumes the contaminants, the bed constantly contributes to its regeneration. An appropriate contact time between the microorganisms and the contaminants is achieved by controlling the airflow rate by which contaminants are introduced into the system. The biofilter bed itself is non-hazardous and remains non-hazardous after use. Biofilters are composed of an array of variables that can be manipulated to maximize system efficiency. These variables may be related to the influent air, the filter bed, or both.

3.2.7.2 Degrading microorganisms Different organisms are suited for different applications (Webster *et al.* 1997). Bacteria and fungi are the two

dominant groups in biofilters. Bacteria have the advantage of rapid substrate uptake and growth, and will dominate under favourable conditions. To name a few of many examples, the species *Pseudomonas* has proven successful in degrading off-gases from a paint manufacturer (Vinarov *et al.* 2001) and dispersed diesel fuel (Yang *et al.* 2000), while *Crenothrix* sp., *Aspidisca lynceus,* and *Litonotus* sp. have been shown to remove manganese and ammonium from air streams when present in biofilters (Madoni *et al.* 2000). Although an array of organisms expands the number of potential contaminants treated, competitive inhibition may occur. Three strains of bacteria, namely *Rhodococcus fascians, Rhodococcus sp.,* and *Pseudomonas putida* showed competitive inhibition in the removal of ethyl acetate and toluene in a biofilter (Hwang *et al.* 2003).

Over time, diminished nutrient supply or pH buffer depletion may cause a decline in microbial activity (Devinny *et al.* 1999). However, fungi are capable of degrading a larger variety of contaminants and are more resistant to harsh conditions such as pH and temperature fluctuations. Fungi generally grow slower and have a smaller surface to volume ratio by virtue of their larger size, decreasing nutrient uptake. Biofiltration using the fungus *Aspergillus niger* removed hexane from a contaminated air stream (Spigno *et al.* 2003), and *Candida utilis* is a yeast that has been successfully used as an inoculant (Christen *et al.* 2000).

Organisms may be aerobic or anaerobic, or a combination of both. Aerobic degradation is performed in the presence of oxygen and is common in biofilters. Aerobic organisms ideally convert organic materials into the relatively stable compounds, carbon dioxide and water, to produce energy they can use. Anaerobic bacteria degrade contaminants in the absence of oxygen and in a reducing environment. However, an odour can be generated by the sulphate-reducing microbes under anaerobic conditions that convert sulphate and organic compounds to hydrogen sulphide. Also, greenhouse gases can be generated by methanogenic compounds which reduce carbon dioxide producing methane.

Another factor to consider for microbial degradation of VOCs is the air stream temperature. It should not exceed 60°C unless thermophilic bacteria are introduced to the system (Devinny *et al.* 1999), as these bacteria are capable of degrading VOCs at temperatures above 60°C. Rates of microbial activity will increase with temperature, by a factor of two for each 10°C rise up to about 35°C (Devinny *et al.* 1999), and thereafter activity decreases.

There are certain VOCs that can inhibit microbial performance (Deshusses *et al.* 1997), and would therefore detriment the functioning of the filter. Some examples of contaminants that have been successfully removed using biofilters include but are not limited to ammonia, acetone, benzene, toluene, methyl mercaptan, styrene, and propanol (Swanson and Loehr 1997).

3.2.7.3 Filter bed media There are numerous choices of filter bed media available. The bed material can be organic, using materials such as peat, mulch, or woodchips, or may use inorganic materials such as sand, or synthetic materials such as perlite (Groenestijn *et al.* 1996). They vary in such traits as nutrient content, surface area, porosity, moisture retention characteristics, microbial activity, cost, and density. The medium can be composed of a single substance or a mixture, combining the benefits of two or more media.

The medium must satisfy certain criteria, including moisture content between 40-80% (or between water-holding capacity) and the minimum content required for survival of microorganisms), a void volume between 40-80%, and be composed primarily of particles between 1-5 cm in diameter. Moisture is a requirement to sustain the life of the microorganisms, while the void volume produces air spaces to the organisms and lowers the pressure drop through the medium. The medium should be as uniform as possible to prevent channelling, or preferential flow paths. Over time, aging packing material may cause an increase in pressure drop because of microbial degradation and compaction. A common filter bed medium used is that of a woodchip/compost combination (Sadaka *et al.* 2000).

Compost is a natural medium that contains a diversity of microorganisms that facilitate the breakdown of a range of contaminants. Nutrients necessary for the survival and proliferation of the microorganisms are already present and, unlike the case for synthetic or inorganic medium, do not need to be added. Compost also is appealing due to its good water retention properties and neutral pH. Although compost acts as a good medium in the beginning, it compresses with time, breaking up into smaller particles and continually compacting. Compaction raises airflow resistance to unacceptable levels and creates fissures that cause problems (Sadaka *et al.* 2000).

The woodchips are a good bulking agent, intended to reduce pressure build up by decreasing density, without allowing the air to stream through. The pieces serve as a good surface for bacterial attachment as they are rough, porous, and hydrophilic. In addition, the fragments are reasonably light and are therefore resistant to compaction. Wood has a pleasant, natural smell. As wood is a natural product, its disposal is simple and need not be treated as a hazardous waste in this situation.

Careful monitoring of moisture content, pH, and temperature of the filter bed is crucial to encourage microbial proliferation. Moisture content may be monitored through influent and effluent relative humidity values. A saturated air stream will have 100% relative humidity, and values above 95% indicate good medium moisture content. Medium pH can be tested by mixing a

sample of the filter bed in distilled water, and then testing the pH of the water (Schwarz *et al.* 1999). Temperature can be easily monitored by placing thermocouples strategically throughout the filter medium.

3.2.7.4 Filter bed water content Controlling the water content in biofilters is essential to filter success. If the medium becomes too wet, it may compact and increase the pressure drop in the system and therein the cost. Also, leaching may occur that floods the plenum area, which is the dispersion area near the contaminated air inlet, and strips the filter of nutrients and microorganisms. Anaerobic zones may form, generating unfavourable odours (Das and Keener 1997). If the medium dries, microbial activity will be inhibited, and treatment will fail. Biofilter operators distribute water in the medium either by humidifying the incoming air, by sprinkling the bed, or both. Although the water application rate can be calculated, the result is generally inaccurate due to such factors as evaporative losses and uneven spraying. Experience is the best way to determine the application rate.

Temperature is an important factor in water content monitoring. If incoming air is warm and dry, it will dry the filter. If it is warm and humid there may be continual condensation and saturation of the medium. The relative humidity of air in equilibrium with the medium is near 100%. Small changes in relative humidity may cause huge changes in medium water content, as the slope of the humidity-water content curve is very small (Devinny *et al.* 1999).

Therefore, relative humidity should be carefully monitored, and humidifying incoming air may help maintain moisture levels in the filter.

3.2.7.5 Biomass control Biomass is a biologically generated material that may be living or dead, usually measured as a sum of all types of materials. Organic compounds may serve as an energy source or building material, or both, for microorganisms. When the former is the case, carbon dioxide and water are the by-products and they are discharged from the filter (Tang and Hwang 1996). Microorganisms incorporating these compounds into their cell structure use them for growth and reproduction (Devinny *et al.* 1999). This accumulation provides an additional component to the mass balance of carbon around the filter (Deshusses *et al.* 1997). When system loads are large and nutrients are abundant, the biomass may clog the filter, increasing pressure drop and creating flow channels (Deront *et al.* 1998). This makes biomass accumulation an important consideration when evaluating filter bed life.

Biofilters tend to dry fastest at the inlet, and water content is a function of depth. Also, contaminant concentration decreases as air passes through the filter and degradation occurs, such that concentrations near the influent end are much higher than near the effluent end. Therefore, there will be a denser biomass at the inlet and it is more likely to clog. The influent end will also have a higher nutrient demand due to the larger amount of biomass. Some

filters are constructed from a series of trays so that certain areas of the filter that are prone to clogging can be replaced. Areas of the filter can be rearranged so that minimal new medium will need to be introduced.

3.2.7.6 Air flow The inflowing contaminated air must be of sufficient pressure to move the gas through the filter bed. The amount of void space in the medium determines this minimum pressure requirement, and factors affecting these gaps include medium density and porosity. Generally, compost filter beds will operate at pressure drops of less than 500 Pa (Devinny *et al.* 1999).

Vertical biofilters may be either top-loaded or bottom-loaded, each having various advantages and disadvantages. In top-loaded filters, water irrigation and biological activity occur predominantly in similar areas at the top of the bed. The possibility of water hold-up on filter material is eliminated, however by-products such as acids will percolate down through the filter bed, possibly damaging the structure of the filter material. In top-loaded filters, particles may clog the inlet area, as microbial oxidation is diminished there. Particles cannot be flushed readily from the biofilter without possibly affecting the remainder of the bed, and hazardous materials, if present, will be at the surface of the material where maintenance is difficult (Devinny *et al.* 1999).

In bottom-loaded systems, the area of surface irrigation and the majority of biological oxidation occur in separate regions in the bed. Anaerobic zones

may result from water hold-up near areas of the filter. By-products can easily be removed from the system through filter hoses located near the inlet of the bed, minimizing damage to the bed. Particles can be flushed out of the system without damage to the medium, and the surface of the bed can be easily examined since contaminant concentrations should be low at the top (Devinny *et al.* 1999). Leaks through the lid can be minimized using a bottom-loaded system, as the pressure is higher at the inlet.

3.2.7.7 Performance parameters There are some basic variables involved in biofiltration that are essential to the success of the process (Swanson and Loehr 1997) and are outlined below. Note that the filter bed volume and surface area are considered constant after construction. Therefore, modifications of the system will be made through alterable features such as gas flow rate (Q) and concentration of pollutant (C).

Empty bed contact time (EBCT)- A relative measure of gas residence time in the medium, calculated as if the medium were not present.

$$EBCT=V/Q \quad (s)$$

where V= volume of the filter bed (m^3)

Q=air flow rate through the bed (m^3/s)

EBCT is an overestimate of the true residence time. To get the actual residence time of the gas, EBCT is divided by the medium porosity. A typical

range of EBCT is between 15 and 60s (Swanson and Loehr 1997). EBCTs between 45 and 60s are commonly recommended for industrial applications, however agricultural applications generally have lower rates, between 5 and 6s. Some retention times have been reported as high as 10min, as was used to treat gasoline vapour (Namkooong *et al.* 2003). In a two-stage biofilter in Tualatin, Oregon for treating vapours from rag drying and paint sludge, the gas spent 12min in the first stage, and 6min in the second (Devinny *et al.* 1999).

Surface loading (SL)- a measure of the volumetric gas.

$$SL = Q/A \quad (m^3/m^2/s)$$

where A=surface area of the bed (m^2).

A typical range of SL is between 50-200 $m^3/m^2/h$, or 0.83-3.33 $m^3/m^2/s$ (Swanson and Loehr 1997). This equation accounts for the surface area at the inlet interface, as well as the orientation and shape of the filter (i.e. horizontal or vertical).

Mass loading (ML)- the VOC mass applied to the biofilter medium volume per unit time, often reported as an average for the entire bed. ML is a function of

both airflow and concentration, so a given bed may have varying performances under identical mass loadings.

$$ML=Q\ C_i\ /V \quad (g/m^3/s)$$

Where C_i=inlet air concentration (g/m^3)

A typical range for mass loading is 0.17-2.67 $g/m^3/s$ (Swanson and Loehr 1997).

3.2.7.8 Advantages and disadvantages of biofiltration Biofilters simultaneously treat a wide variety of compounds, including odorous gases and hydrocarbons. They have shown effective removal of contaminants from a variety of sources, from the coatings industry to petrochemical manufacturing. They are very beneficial from an environmental perspective, with removal efficiencies over 90%. These filters operate at ambient temperature and very low pressure drop. Compared to other methods, the financial cost of the system is minimal.

Biofilters have a large space requirement for installation and are not as effective for high concentrations of pollutants. As every situation is different, each biofilter has to be specifically designed and adjusted to treat the influent contaminant. Clogging of the filter may be caused by growth proliferation,

mineralization, excess water, particulate matter, or clumping due to drying. Channelling occurs when air contaminants pass through a biofilter bed without contacting any microorganisms in the biofilm. Channels may be caused by dry cracking, compaction, or non-uniformity in the medium. Channelling or clogging may require the medium to be changed, which results in temporary shutdown of the biofilter, and used medium must be landfilled.

3.2.7.9 Cost The low cost of biofiltration is definitely one of the driving forces for the technology's proliferation. The cost of design, installation, and monitoring of the biofilter is variable. It depends on the required removal efficiency, which should be established before designing the system (Devinny *et al.* 1999). The cost of the system can be broken down into components.

Capital cost Open bed systems will generally cost less than closed bed systems (Devinny *et al.* 1999). Cost per unit volume will decrease with increasing volume of the filter bed, mainly due to large-quantity discounts on purchases. Although costs per unit volume vary greatly, small designs (approximately 100 m^3) cost between US$ 1000 and US$ 3500 per m^3 filter bed, while larger designs (around 3000 m^3) become more cost effective at US$ 300 to US$ 1000 per m^3 filter bed (Devinny *et al.* 1999). The start-up costs for biofiltration are comparable to those for more conventional air pollution control technologies such as carbon adsorption and incineration.

Operating costs Operating costs are primarily due to energy consumption (i.e. fans/blowers), water consumption and disposal, monitoring requirements, maintenance, and medium replacement (Devinny *et al.* 1999). Once again, all of these costs are highly variable and depend strongly on contaminant type. An estimated range is between US$ 0.1 and US$ 3 per 1000 m^3 of waste air treated (Devinny *et al.* 1999). Routine operation of the system produces no waste for disposal.

Energy consumption is a substantial part of the operating cost. Equipment required may include water pumps, analytical and computer equipment (all requiring electricity), with the majority of the cost due to the fan or blower needed to overcome the pressure drop. Most of the electrical demand is a function of porosity, moisture content, and structure of the filter bed. As material degrades, the electrical demand increases (Devinny *et al.* 1999). There are no external fuel costs such as those associated with thermal oxidation technologies, where such costs are ongoing and increase with the cost of inflation.

Medium replacement is required every 3 to 7 yrs (Devinny *et al.* 1999). At that time, there will be labour costs along with medium cost. As the medium ages, biomass accumulates and mineralization occurs, both resulting in an increase in pressure drop in the filter bed. This will increase electrical

demand. Also, pH may decline over time, decreasing microbial efficiency (Schwarz *et al.* 1999).

The degree of monitoring and maintenance required depends on the system. Automation of monitoring devices decrease human interaction, but will increase capital cost and system complexity. A cost/benefit analysis should be done to establish the best solution. Water costs from humidification may become an issue in areas where water is scarce or of poor quality. There are no long-term costs associated with recycling air pollutants, as there are in carbon filtration.

3.2.7.10 Applications The areas in which biofiltration can be applied are numerous. Any industry that emits biodegradable compounds through a contained air stream may benefit from these filters. Examples of successful usage can be found in areas ranging from chemical manufacturing and the petroleum industry, to animal husbandry and food processing (Devinny et al. 1999).

Using biofilters, various levels of odour removal efficiencies have been attained. Odour removal efficiencies between 29.7% and 99.9% were achieved in removing animal rendering process odours, which originally had concentrations between 143 100 and 890 000 OU/m^3 (Luo 2001). Defoer *et al.* (2002) achieved an odour removal efficiency of 97.6% in treating off-gas

from a composting facility using biofiltration. Even with such a diverse range of applications, it was difficult to find literature on a similar situation as exists at Apotex. However, an experiment was careful designed to allow close system monitoring and flexibility in parameters tested.

3.3 Dispersion Modelling

A dispersion model is a mathematical description of the meteorological transport and dispersion process relating to a specific source and set of meteorological parameters. An air dispersion model can predict concentrations of emissions at all points around a source for a range of conditions at a given height. Factors affecting the transport, dilution, and dispersion of air pollutants include stack characteristics, emission rate, nature of contaminant, meteorological conditions, surrounding terrain, and building effects.

The major stack parameters influencing contaminant dispersion are stack height, stack diameter, gas exit rate, and exit temperature. These factors may be optimized to provide maximum dispersion of contaminants. Meteorological conditions have a strong effect on dispersion, making representative sampling problematic. For example, concentration due to stack emissions will always be the highest at a particular location when the wind is blowing directly towards it. Other factors include ambient air temperature, wind speed, atmospheric stability, and mixing height.

Several commercial packages exist for dispersion modeling and one of them is AUSPLUME. AUSPLUME was developed in 1986 in Australia for predicting ground level concentration of air pollutants. The program incorporates into its models local meteorological and terrain conditions, effects of background concentrations, contribution of adjacent sources, and continuing need to surrounding air to accept possible future emissions.

4.0 MATERIALS AND METHODS

All aspects of this experiment were designed to simulate the present fermentation operation procedures at Apotex (Fig. 4.1). An AUSPLUME dispersion model was prepared to compare the theoretical dispersion of stack emissions before and after implementation of a biofilter. Inputs are found in Appendix 1,and concentrations are based on odour panel results. The reactor simulated the fermentation vessel which generates odorous VOCs. Since the fermentation operation is ran in batch mode, compressed air was passed through the biofilter while the reactor was not venting to maintain aerobic conditions in the biofilter. Each component is discussed in detail in the following sections.

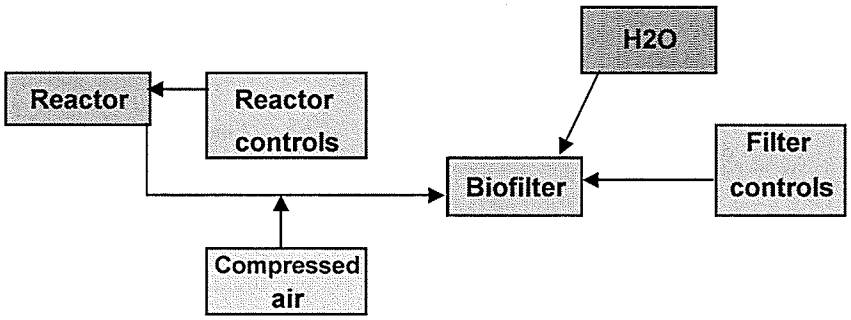


Figure 4.1: Overview of pilot-scale design.

4.1 Biofilter

The filter structure consists of a 23 L, 343 mm inner diameter plastic bucket with a sealable lid (Fig. 4.2). This structure is of sufficient volume to experiment with numerous flow rates and retention times, while keeping the filter a manageable size for potential relocations and changes in filter medium. A plenum is made in the bottom of the bucket by placing three 0.06m long legs to support a mesh screen (Fig. 4.3). A bottom-loaded system was selected to facilitate pH buffering by the water trickling from the top of the filter.

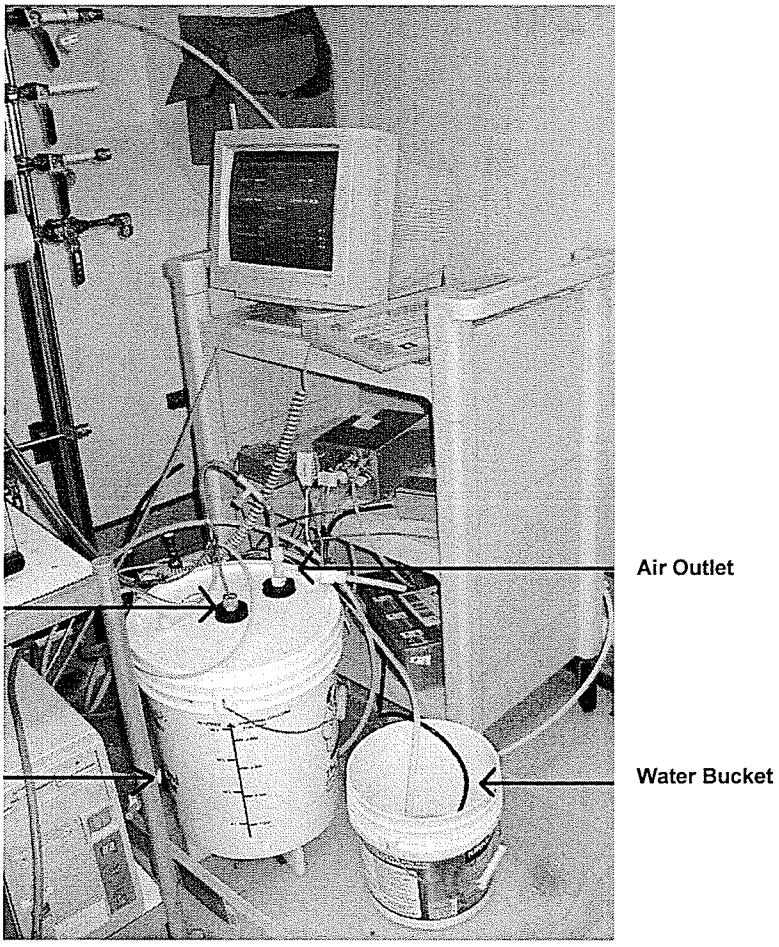


Figure 4.2: Photograph of the biofilter during operation in the research laboratory at Apotex Fermentation.

A bulk head fitting was placed in the bottom of the plenum to drain any water that should accumulate (Fig. 4.3). The filter medium was placed on top of the mesh and filled to 0.09m below the rim, making a total filter medium volume of $0.02m^3$. Air entered the filter from an inlet in the plenum area through tubing connected to the fermentation reactor which was the source of VOCs for the experiment. The inlet tubing had a bypass connector that was attached to a separate air line, such that when the air from the reactor was turned off during sterilization, ambient air would still enter the system to keep the filter aerobic. The lid of the filter had an outlet port for the gas, which was attached to tubing that leads to an effluent pipe. At each of the ends of the outlet and inlet ports closest to the filter shell, there was a sampling valve used to collect air samples. The apparatus sat in a long plastic storage container to collect any spills of the medium material or water.

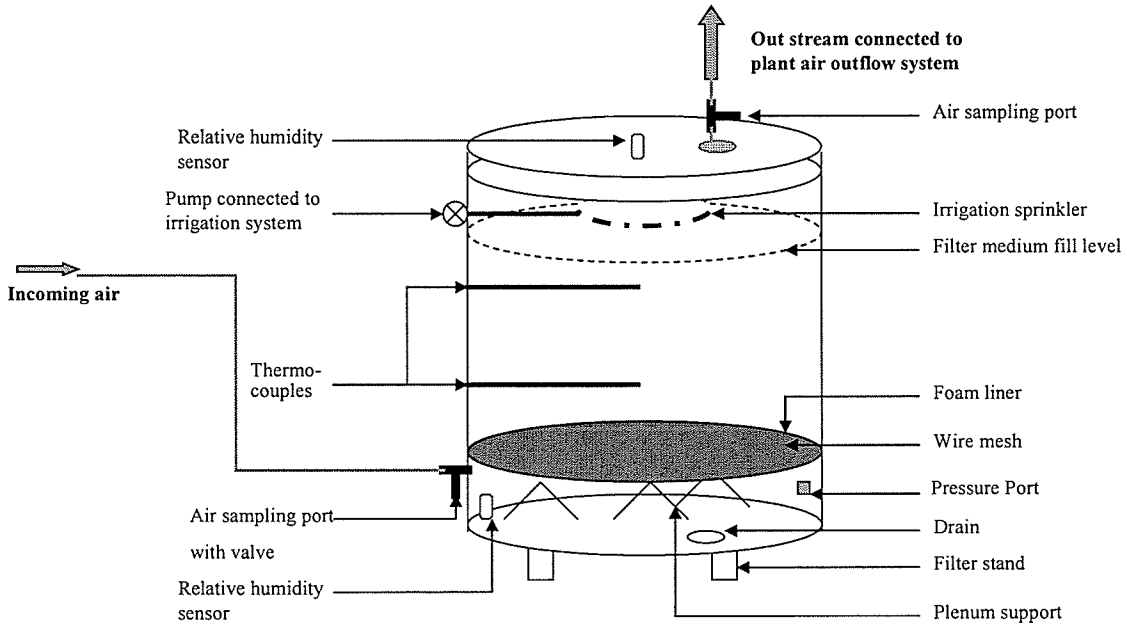


Figure 4.3: Schematics of biofilter

A foam liner (5mm x 32mm, or 3/16" x 1-1/4", foam tape) was added just above the mesh screen inside the filter shortly after commencing the experiment to prevent channelling of air flow along the filter wall. The foam was looped around the inside of the bucket several times to form a 10mm layer. It was then sealed with acrylic silicon caulk, and dried for two hours.

4.2 Filter medium

Two different compositions of filter media were tested: A 20:80 c:w (compost:woodchips) ratio and a 40:60 c:w ratio by volume of compost and cedar woodchips (mass ratio approximately 3:1 c:w, using measured compost density of 800 kg/m^3, woodchip density of 171 kg/m^3). Large pieces of wood and chunks of compost were removed to prevent channelling of the air stream in the filter. The compost was collected from Niverville, Manitoba. All precautions were used to ensure minimal crushing, segregation, and temperature-related damages (such as protein denaturation) to the medium during transport. Moisture-related damages, such as hydrophobicity due to excessive drying, are prevented by moistening the filter medium in stages and allowing the water to soak in. The filter medium arrived at the research lab at Apotex with the infrastructure, such that storage was not necessary. The filter medium was mixed in a cement mixer, and the moisture content of the 40:60 c:w mixture was determined by the oven dry method to be 57.3 $\pm$ 0.6% at the top of the filter and 59.5 $\pm$ 1.5% in the centre of the filter. A total of eight samples were dried for 24h at 130°C. Porosity of 40:60 c:w filter medium was

found to be 48.0 ± 2.3% by Sadaka *et al.* (2002), and they found the 20:80 c:w to be of 57.1 ± 1.9% porosity, and at 54.5 ± 1.6% moisture content. The original filter medium ratio of 20:80 c:w (by volume) was selected as a reasonable starting point, as this ratio is commonly used in other applications (Sadaka *et al.* 2002).

4.3 Sensors

Two relative humidity sensors (General Eastern Model RH5, Wilmington, MA, USA) were installed in the system; one in the plenum area, the other embedded into the centre of the lid. The sensors were not in contact with the filter medium, and were used to monitor the filter medium moisture content. A pressure transducer was located in the plenum area. The air at the filter exit is assumed to be at atmospheric pressure, and therefore a transducer in the plenum area measured the pressure drop through the filter bed. Six constantan/copper thermocouples were located in the filter; three were situated in the middle of the filter depth, staggered to the centre of the filter medium, and another three were situated 0.05 m from the plenum mesh. A 'water bug' sensor (WB 200, AAA Alarms, Winnipeg, MB) was placed in the plenum area and its function was to cease the watering system from moisturizing the filter bed if excessive water accumulated in the plenum. The water bug was used as a safety mechanism to prevent over-watering and leaching.

All of the input received from these sensors was recorded by a data acquisition system situated near the apparatus (HP 3852A, Hewlett-Packard Canada Ltd. Mississauga, Ontario). Output from the sensors was read off of a monitor such that the experimenter had current information on the state of the filter.

4.4 Irrigation System

A small water fountain pump (M60A, Beckett Corp., Irving, Texas) was connected to the data acquisition and control system that intermittently activated the pump. Water to be pumped was placed inside a small bucket with approximately 1L of water to prevent large spills. The timer could be controlled through the computer, therein activating irrigation of the filter, had the system moisture level declined. The system provided a uniform sprinkler irrigation to facilitate frequent watering in short durations. Water was discharged from a perforated polyethylene tube formed into a ring and placed below the lid of the filter. Leaching was easily detected by opening the bulkhead on the bottom of the bucket and visually observing water accumulation.

4.5 Reactor

A reactor was used to generate VOCs for this experiment (Fig. 4.4). The reactor was a 1:1400 scale replica of the full-scale 14000L production fermentation vessel used at Apotex, which exhausts off-gases between 1000-8000L/min, although 4000L/min is rarely exceeded. The 19L experimental

reactor had a working volume of 14L, and contains 2 flat-blade Rushton (D6) impellers and 4 baffles. Pressure inside the reactor was controlled to approximately 550 kPa (80 psi). A pH probe could be inserted into the reactor to automatically take readings, and two sampling ports facilitated collection of samples. Temperature was monitored and control

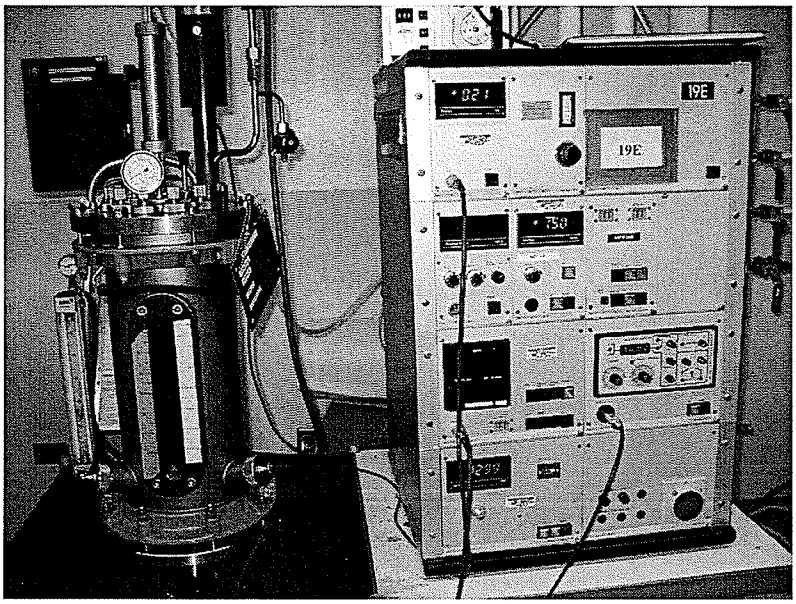


Figure 4.4: The lab-scale reactor vessel and control system used in this study at Apotex to sterilize the fermentation medium generating VOCs. The lab-scale reactor vessel is a 1:1400 scale replica of the full-scale reactor used at Apotex.

4.6 Sterilization of Fermentation Medium

The fermentation medium was sterilized every 2d in the reactor, following an identical procedure each time. Due to strict protocol and training required for equipment use, staff at Apotex performed the sterilizations. Contents of this fermentation medium are privileged information, and therefore not discussed in this thesis. As is done in a full-scale situation, off-gases were retained in the reactor until completion of the sterilization, and were vented through a system of tubes into the biofilter

4.7 Experimental Procedure

The experiment began July 21, 2003 and ended September 26, 2003. A schedule of samples, number of replicates, changes in EBCT, and filter medium changes can be found in Appendix 2. As the volume of filter medium used was constant, EBCT and airflow rate were different ways of describing the same parameter. EBCT of 60, 120, 180, and 240s corresponded to airflows of 20, 15, 10, and 5L/min, respectively.

Fermentation medium was sterilized every two days in the 19L fermenter. Contents of the fermentation medium and sterilization times were kept the same in all trials, as were moisture content, temperatures, and pH of the filter medium. Two filter media and two moisture contents were tested. Two off-gas samples were taken for chromatography analysis using Tedlar bags upon commencement of experimentation to quantify odour constituents, particularly VOCs. Air samples were sent to a commercial lab for component analysis.

Continuous pH sampling of filter medium was not performed, as this would have lead to disruption of the medium and would have promoted channelling (Schwarz *et al.* 1999). The organic filter medium naturally had a high buffering capacity and major changes in pH were not a concern.

Air samples for olfactometry analysis were taken the second week after commencement of sterilizations at the influent and effluent ends at various points in the venting of the off-gas, particularly during the peak emission of medium sterilization. The experiment lasted approximately 65d, with a total of 30 medium sterilizations.

The procedures of sterilization used in the lab-scale testing were the same as those used in large-scale production. The purpose of the medium sterilization is to eliminate foreign organisms from a liquid that will serve as a culture medium for bacteria which are used to produce pharmaceuticals. Each sterilization lasted for approximately 4h. During this time, clean air from a compressed air line was run through the system to prevent development of anaerobic zones. As this air was cooler and drier than the off-gases from the medium reactor (the temperature approximately 12-15°C and relative humidity approximately at 10%), the use of the separate air line was restricted to only during sterilization to avoid cooling and drying of the filter bed.

The off-gasses were vented at a temperature 30°C from the sterilization reactor. After running the experiment for three weeks, the temperature of venting was raised to 34°C to increase the temperature in the biofilter medium, and therein potentially increase microbial activity. Due to a shallow bed, the temperature was only raised slightly; Increased temperature could lead to drying of a small thickness of the bottom layer, which would lead to a significant percentile loss of filter medium.

The back pressure to the reactor was held constant at 0.2bars (20kPa), and the baffles rotated at 300rpm. The rate of venting into the biofilter was initially controlled at 20L/min (60s EBCT), then decreased to 15L/min (120s EBCT) after 12d, then decreased to 10L/min after another 9d to increase the residence time of air flowing through the filter to 180s. Five days later the venting rate was again decreased to 5L/min (240s EBCT).

For each trial, the reactor was first assembled as described in the materials section. The filter medium was mixed in a bucket to the appropriate compost to woodchip ratio and water was added. A lid was placed on the bucket and the medium was allowed to absorb the water for two days prior to its introduction into the filter. A dry run was conducted to test the apparatus for air leaks without the filter medium inside. The pre-soaked filter medium was then added and clean air once again was forced through the system.

4.8 Acclimation Period

The filter required approximately 10d for the organisms to acclimate to the gaseous contaminants (Devinny *et al.* 1999). Acclimation involved the production of enzymes by the organisms necessary to degrade contaminants. For the first day, the influent concentration was kept to 25% of normal flow to allow the organisms more of an opportunity to acclimate (Devinny *et al.* 1999). The concentration was increased in intervals over six days. Schwarz *et al.* (1999) also allowed for an acclimation period when designing their biofiltration experiment to degrade tetrachloroethylene, as did Arulneyam and Swaminathan (2000) in designing their biofilter for the treatment of ethanol vapours.

4.9 Odour Measurement

Odour is multidimensional, and there are several parameters used to describe it including character, hedonic tone or pleasantness, concentration, and intensity. There are numerous factors effecting odour detection, such as sex, age, memory, adaptation, health, and cultural background. These factors make odour description difficult and inevitably somewhat subjective. It is therefore common to use human sensory panels to measure the odour of the whole sample rather than examining its constituents individually, for example through chromatography, as combinations of VOCs may effect how the odour is perceived (Knudsen *et al.* 1999).

Odour concentrations of collected air samples were measured using an olfactometer (Ac'Scent International Olfactometer, St. Croix Sensory, Inc., Stillwater, Minnesota) with odour panels composed of six pre-screened individuals who had odour detection abilities representative of the general population. In olfactometry, the odorous sample is diluted with odour free air in varying ratios. The diluted samples are then presented to a panel of humans to sniff. The measured odour concentration is expressed as an odour unit (OU/m^3), which is defined as the amount of odorant that, when evaporated into 1.0 m^3 of neutral gas, elicits a physiological response from a panel equivalent to that elicited from one reference odour mass. The reference odour mass is equivalent to 123 μg n-butanol evaporated in 1.0 m^3 of neutral gas (Qu *et al.* 2001).

4.10 Sampling technique For each sampling session, three replicate samples were taken in sterile Tedlar bags one after the other, beginning with the outlet samples followed by the inlet samples. Neither of the two sampling ports on the system was used due to insufficient pressure. Therefore, the main air line in or out of the filter for influent and effluent samples, respectively, were disconnected from the filter temporarily and attached directly to the sampling bag.

The olfactometer had limited dilution ability, and could not handle samples of extremely high concentration. Therefore, both the influent and effluent

samples taken immediately after sterilization were diluted. The time to fill the bag was measured, and as the inlet flow rate was steady at 5L/min, the volume inside the bag can be calculated. Outlet airflow was measured using a hot wire anemometer, taking the average of three readings (see Appendix 3). Using a sterile syringe, sterile air filtered in a HEPA filtration system was injected into the Tedlar bag in the appropriate quantity to give the desired dilution ratio. Later trials simply involved filling the bag with sterile air from a syringe, then adding contaminated air with a syringe.

4.11 Dispersion modelling

Concentration values were taken as the 15min average in OU/m^3 immediately after sterilization at a receptor height of 5.1m, which is the air intake height of local buildings. Weather data was taken from a one year period from 1988-1989 in Winnipeg. Complete inputs into the dispersion model are found in Appendix 1.

5.0 RESULTS AND DISCUSSION

5.1 Effects of filter medium and operation conditions

The initial filter medium consisted of 20:80 c:w. After approximately 20d, the medium was demonstrating extreme lack of water retention, and poor odour removal levels (see Appendix 2), suggesting that channelling was occurring. The compost ratio in the filter medium was then increased to 40:60 c:w by volume. The filter medium was soaked for 3d and stored at 28°C to saturate before being introduced into the filter. Airflow into the filter was reduced to 2L/min for the first 3d to acclimate the organisms to the contaminants. It was immediately evident that the higher amount of compost not only absorbed but retained the water for much longer, thus decreasing the possibility of channelling. In the following sections, only the results of 40:60 c:w filter medium mixture are discussed. The watering rate was set constant at 100mL every 2h. Moisture content of the medium (wet basis) was determined by the oven dry method near the end of testing to be 57.3 $\pm$ 0.6% at the top of the filter and 59.5 $\pm$ 1.5% in the centre of the filter. Filter medium samples were dried for 24h at 130°C in a convection oven (see Appendix 4 for details).

Filter parameters were established by using equations presented in section 3.2.7.7 and are summarised in Table 5.1.

Table 5.1. Summary of filter parameters.

Q (L/min)	Q (m^3/s)	V (m^3)	EBCT (s)	Filter V* (m^3)	Surface Loading ($m^3/m^2/s$)	Contaminant Concen'n (g/m^3)	Mass Loading ($g/m^3/s$)
5	8.3E-05	0.02	240	4	0.000901	0.031511	0.472665
10	0.00017	0.02	120	2	0.001803	0.031511	0.94533
15	0.00025	0.02	80	1.33	0.002705	0.031511	1.417995
20	0.00033	0.02	60	1	0.003607	0.031511	1.89066

*Full-scale filter volume, assuming a flow rate of 1000SLPM

The contaminant concentration used in the calculations is determined as the sum of the concentrations of the fore most predominant compounds in the off-gas, as measured with chromatogram. These four compounds made up the vast majority of the influent gas concentration. Compared with values in the literature review, the mass loading values and the surface loading values are much lower than are typically treated in biofiltration. Therefore, the concentration of contaminants treated is not beyond the level which biofiltration has proven effective in degrading. Various levels of reduction were achieved for different flow rates (Table 5.2).

Table 5.2: Comparison of odour removal efficiencies with various filter media and flow rate combinations. The values shown are averages of at least three replicate measurements.

Time of Sampling	Medium Ratio*	EBCT (s)	Influent Concentration (OU/m^3)	Effluent Concentration (OU/m^3)	Average Reduction (%)	Std Dev
Immediately after sterilization	40:60	240	32839	9266	72	10
	20:80	*60*	*43280*	*24653*	*43*	*4*
24 hours after sterilization	40:60	240	1646	646	61	7
	40:60	180	992	802	43	22
28 hours after sterilization	40:60	180	1518	852	44	7
	40:60	240	1367	851	38	2
50 hours after sterilization	40:60	240	2349	778	67	6

*compost:woodchip ratio

Although the 20:80 c:w, 20L/min (EBCT of 60s) flow rate combination showed a reasonable reduction proportion (43%), this filter medium was altered as visual inspection revealed severe drying despite the presence of water in the plenum area.

For the 40:60 c:w filter medium, 240s EBCT immediately after sterilization, odour was extremely strong at the influent end, 32 839 OU/m^3, and was 9266 OU /m^3 after passing through the filter. This effluent odour level immediately after sterilization was higher than the influent odour level for all 24, 28, and 50h tests. Although this may seem to imply that the filter was not effectively removing odour, the odour has been reduced by 72% immediately after sterilization. Although biofiltration is commonly used for lower concentrations, effective treatment of VOCs has been achieved with inlet concentrations of 32 000 OU/m^3 previously. Sironi and Botta (2001) achieved 97% odour abatement, generated at a composting plant, from this initial odour level using biofiltration.

Odour reduction ranged from 38% to 67% 24 h after sterilization, which seem to be low, however, the final odour concentration was only between 640 and 852 OU/m^3, which were two orders of magnitude lower than that immediately after sterilization. This odour level is low enough that dispersion will make the downwind odour imperceptible.

The magnitude of the standard deviations in odour removal efficiency range from 2% to 22% in these trials. Due to the nature of odour panel testing (Zhang *et al.* 2002), the variation is likely not as much a representation of variability of filter efficiency, as it is of perception of odour concentrations. However, some of these variations might be attributed to the experimental errors associated with olfactometry measurement of odour.

In earlier trials with the olfactometer, the sample would adhere to the equipment and contaminated the olfactometer. The panellists did not voice this until later trials, which may have affected earlier trial results for the 20:80 c:w filter medium. Also, one of the 40:60 c:w, 60s EBCT panel samples and two samples immediately after sterilization leaked from the bags The off-gas odour was particularly cohesive to the bags due to its high humidity and the nature of the contaminants present

The filter was exposed to two distinct sets of operating conditions; firstly, the off-gas from the reactor, and secondly the ambient air from the compressed air supply line when the fermentation medium was being sterilized. Reviewing typical profiles of temperature, relative humidity, and pressure gives useful incite into the operating conditions under which the filter was operating during experimentation (Figs. 6.1a, 6.1b, and 6.1c, respectively).

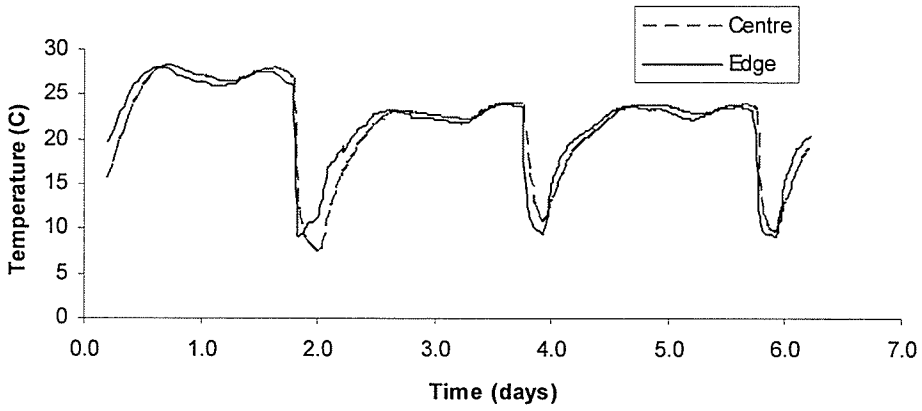


Figure 5.1 a: Typical temperature profile inside biofilter. 'Centre' refers to the thermocouple 0.17m into the bucket. 'Edge' refers to a thermocouple located in the middle height of the filter depth along the edge of the filter medium.

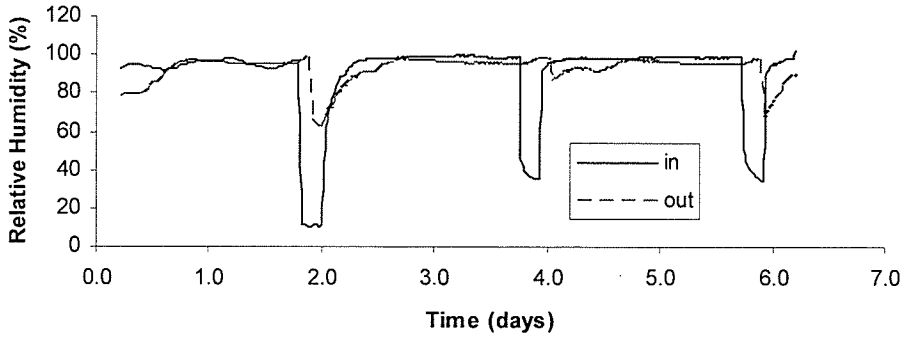


Figure 5.1 b: Relative humidity profile inside the biofilter.

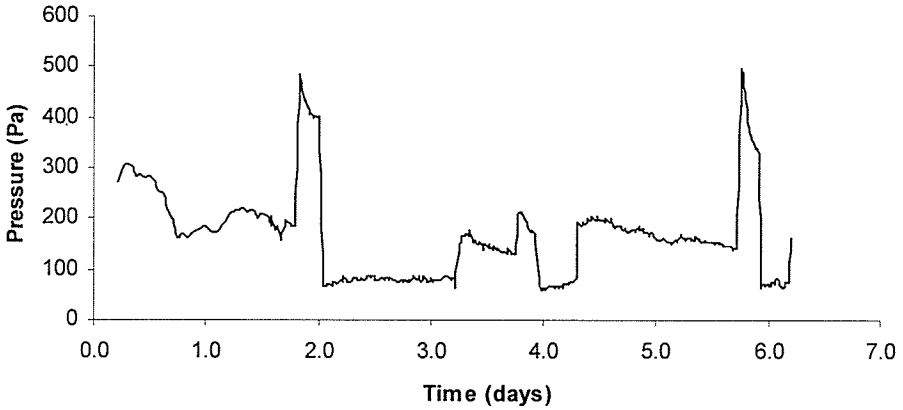


Figure 5.1 c: Pressure profile inside biofilter.

The temperature in the filter rapidly decreased upon introduction of the cool, dry ambient air, and generally stayed between 20 and 25°C when treating the off-gas vented from the reactor (Fig. 5.1 a). Yoon and Park (2002) achieved 93% removal of VOCs at 25°C with their biofilter. There was little variation between the thermocouples in the filter, suggesting uniform temperature distribution. The average temperatures of all six thermocouples ranged between 21.1°C and 21.5°C for the 240s, 40:60 c:w condition. Irrigation water used was at room temperature and could have hindered temperature increases due to the high specific heat of the water.

Large dips in relative humidity were observed as ambient air was passing through the filter (Fig. 5.1 b). The decrease in the influent relative humidity was noticeably greater than that in the effluent relative humidity, indicating that the watering was effective in keeping the filter wet. There was a time lag between a decrease in inlet relative humidity and the decrease in outlet relative humidity. This is because moisture in the filter could humidify the initial burst of dry air. Effects of periodic filter medium drying has been found to decrease contaminant removal efficiency in biofilters deigned to treat VOCs (Deshusses *et al.* 1999).

The pressure was fairly constant upon venting of the reactor (Fig. 5.1 c), however the pressure was not consistent between different sterilizations. A probable explanation is that different operators vented the reactor at slightly

different backpressure, resulting in change in filter pressure (Table 5.3). This is why there are large increases in pressure between sterilizations. Also, some operators forgot to turn off the compressed air after venting of the reactor, causing pressure in the filter to be higher than was normal during venting.

Table 5.3: Pressure variation between sterilization cycles for the 240s EBCT and 40:60 c:w condition. Values are averages over the entire sterilization and venting cycle, including passing the compressed air through the filter. Dates are shown to indicate the introduction of the compressed air after a sterilization venting is complete.

Sterilization Date	Average Pressure (Pa)	Std Dev (Pa)
19-Aug	117.49	41.68
21-Aug	94.14	38.90
23-Aug	133.99	57.96
25-Aug	133.23	105.96
27-Aug	153.32	44.05
29-Aug	162.06	94.09
31-Aug	339.84	615.84
2-Sep	76.00	108.73
4-Sep	73.16	91.80
6-Sep	90.53	31.84
8-Sep	117.15	137.07
12-Sep	94.33	42.17
14-Sep	129.76	63.91
16-Sep	95.77	56.68

Large variations between sterilizations are apparent (Table 5.3), primarily due to the use of compressed air. The standard deviation and pressure for August 31 was exceptionally high, as the compressed air was used excessively during fermentation medium sterilization. Pressure is an important parameter to monitor because it is proportional to the airflow rate (Nicolai and Janni 2001) and therefore EBCT, and it can be an indicator of filter medium compaction due to the accumulation of biomass over time (Thalassa *et al.* 2000).

A challenge of using biofiltration to treat off-gases from the fermentation process at Apotex is the intermittent release of the off-gases. The compressed air was introduced during sterilizations; therefore, the periods immediately after sterilization are indicated by dips in temperature and relative humidity curves. These dips may be detrimental to the filter, and should be avoided in future design by humidifying and heating the supplemental air supply. The temperature was much higher during the periods when only off-gases were entering the filter, as was the relative humidity (Table 5.4). Pressure was higher during the compressed air periods, and there was a large standard deviation among the values (approximately 370 Pa). This is because the amount of dry air introduced was somewhat subjective, as only a manual lever was used. The reactor, however, was vented with a constant backpressure of 20 KPa.

Table 5.4: Comparison of conditions inside filter when exposed to compressed air versus off-gas. 40:60 c:w filter medium was used, with a 240s EBCT.

	Compressed Air	Off-gas
Temperature (°C)	12.79 ± 0.46	22.36 ± 0.12
Inlet RH (%)	49.77 ± 29.37	96.86 ± 4.41
Outlet RH (%)	83.23 ± 14.43	94.06 ± 4.42
Pressure (Pa)	320.28 ± 372.92	90.96 ± 50.08

Temperatures (Table 5.4) are the averages of the six thermocouples in the filter. When the ambient air was passed through the filter, the average temperature was around 13°C, which slows organism proliferation. However, these periods only lasted four hours every two days, and efficient contaminant removal has been proven to occur at temperatures below 10°C (Elsgaard 2000). The filter quickly recovered to a higher temperature, and the average filter temperature during reactor venting was 22°C. Similar observations were made for relative humidity. The relative humidity stayed about 83%, which indicates a high level of moisture in the filter medium.

5.2 Effects of variable contaminant loading

The effluent odour concentrations are consistently lower than the influent throughout the fermentation-sterilization cycles, however the initial concentration of the influent is higher immediately after sterilization than at other points of sampling (Fig. 5.5). This initial release of off-gas is the point where odour reduction is crucial.

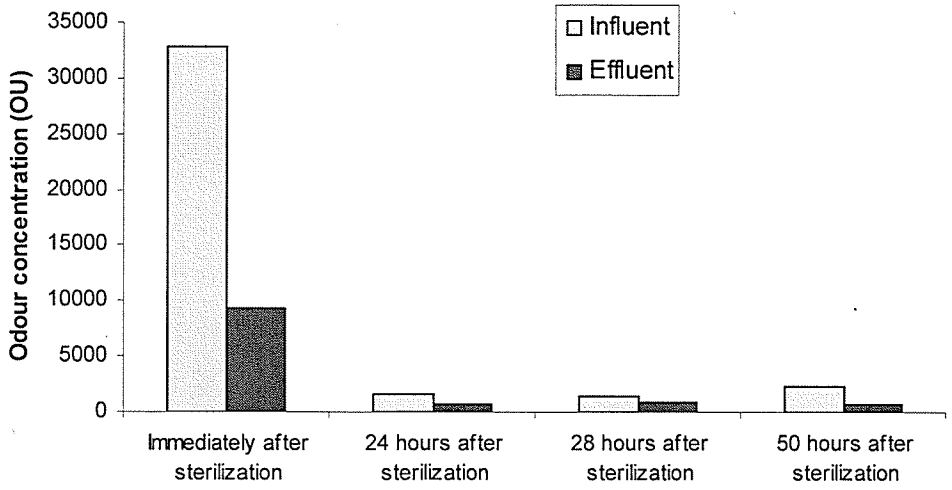


Figure 5.2: Comparison of influent and effluent odour concentration with 40:60 c:w filter medium, 240s EBCT. Odour concentration can be expressed as OU/m^3.

At later points in the sterilization venting, there was a less dramatic reduction in odour. The influent odour level 50h after sterilization was higher than both the influent levels 24 and 28h post-sterilization. This is likely due to error from a lower number of replicates for the 50h sampling (see Appendix 5) and the inherent variation from using human panellists, rather than from an increase in odour level. As the biofilter medium is composed of substances which already contain odour, a residual odour will always be present. Complete elimination of odour is not possible by any existing method, and biofiltration is no exception. Odour panellists commented that, although an odour was frequently apparent in the effluent, it was of a different hedonic tone ("woody" smell). This suggests that the air passing through the filter was picking up an odour from the cedar chips.

A paired comparison test was performed between influent and effluent concentrations for the 240s EBCT, 40:60 c:w condition (see Appendix 6 for calculations) with α=0.05. Influent concentrations were not statistically different among the trials, nor were effluent values. This was as expected, as the sterilization procedure was identical for each trial. All three influents, however, were significantly higher in concentration than all three effluents. This indicates that the odour level at the effluent end was significantly lower than the odour level at the influent end, and the biofilter was reducing odour. The average reduction rates over all of the 240s EBCT, 40:60 c:w condition were 72%, 61%, 38%, and 67% for immediately, 24 h, 28 h, and 50 h after

sterilization, respectively. Because of the intermittent release of off-gases from fermentation, it is important to determine if the filter can withstand shock loads. Continuous odour removal after each sterilization is an important requirement of the filter (Fig. 5.3).

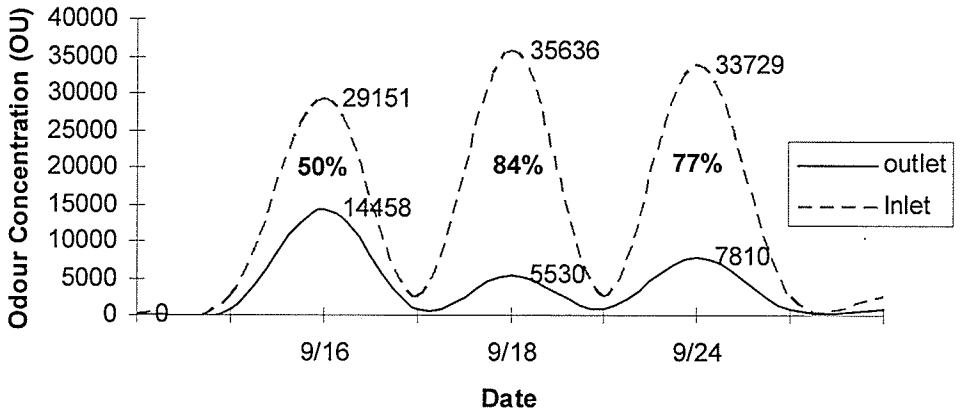
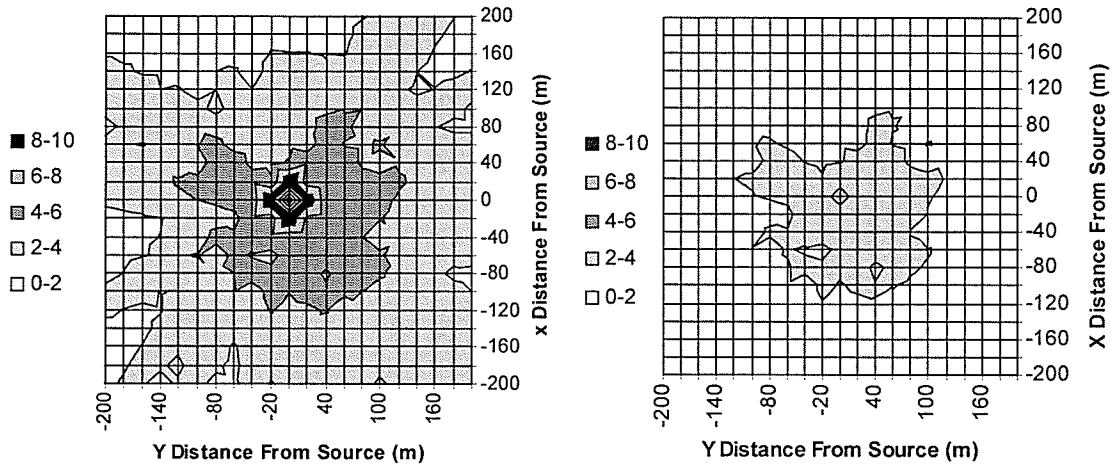


Figure 5.3: Odour levels shown per cubic meter immediately after sterilization at consecutive sterilization cycles for 240s EBCT, 40:60 c:w filter medium. Peak values are indicated in OU/m^3, and percent reduction is also shown. This graph demonstrates differences between extreme influent and effluent values, rather than a continuous plot of odour concentrations. Standard deviations of odour measurements are found in Appendix 5.

Odour panels were performed to show removal for two consecutive sterilizations (on September 16 and 18), followed by a third on September 24 (Fig. 5.3). There was an additional sterilization on September 22, but no odour panel was conducted due to lack of availability of the odour panel and olfactometer. The lowest values for the inlet and outlet were taken from the 50h data, as that was the lowest concentration influent data available. Although the influent and effluent odour levels varied between trials, significant and consistent odour removal remained apparent after four cycles. In other words, the filter withstood shock loads after each cycle.

The initial high odour strength of the off-gases acted as a shock load onto the biofilter, and the gas stream tapered to a low-concentration stream over the two day venting period. Although challenged with an inconsistent flow stream, the biofilter continued to remove contaminants throughout experimentation. The response of biofilters to shock loading with toluene and xylene, and periods of starvation were observed by Metris *et al.* (2001), who found that biological degradation continued throughout these stresses. Also, microbial degradation persisted despite fluctuating hydrogen sulphide levels and starvation of the biofilter, as found by Wani *et al.* (1998).

5.3 Dispersion Modelling



(a) (b)

Figure 5.4: Dispersion models of emissions from fermentation stacks at Apotex, with values in OU/m^3. Dispersion of contaminants before implementation of the biofilter is shown in (a), and (b) shows predicted dispersion after biofilter use. Concentrations in Fig. 5.4b have been reduced to 40% of the concentrations in Fig. 5.4a, reflecting odour reduction by the biofilter within one standard deviation.

It is clear from these plots that the concentration a given distance away from the contaminant source is decreased by the presence of the biofilter. Neighbours of Apotex have air intake to their facilities approximately 65-70m away from the emission stack of Apotex. This dispersion model shows a reduction in odour levels at this distance upon implementation of the proposed biofilter. Odour levels 65m away from emission source were reduced from between 4 and 6 OU/m^3 before the biofilter was inputted, to between 2 and 4 OU/m^3 after. Odour becomes an annoyance between 5 and 10 OU/m^3 for 98% of the population (Sheridan *et al.* 2003). Applying these numbers to the Apotex emissions odour, the biofilter has reduced the odour to a level below the minimum annoyance level of 5 OU/m^3, therein reducing the likelihood of complaints from neighbours.

6.0 CONCLUSIONS

This project demonstrated that biofiltration is an effective means of reducing odour emissions from fermentation at Apotex Fermentation. A closed bed, vertically-loaded biofilter using woodchips and compost as the filter medium consistently showed a reduction in odour levels at various stages in the sterilization off-gas venting. Specific conclusions were:

1- Air entering the filter was found to be of highest concentration immediately after sterilization, at approximately 33 000 OU/m^3, and decreased to 2350 OU/m^3 50h after the commencement of venting.

2- The most effective combination of airflow and filter medium was found to be a 40:60 c:w mixture, at an airflow rate of 5L/min (EBCT of 240s). This design resulted in odour removal rates of 72 ± 10% immediately following sterilization, 61 ± 7% 24h after sterilization, 44 ± 7% 28h after sterilization, and 67 ± 6% after 50h sterilization.

3- Performance conditions were examined in the experiment, and two distinct air cycles were present; the compressed air had an average temperature of 12.8°C, average inlet relative humidity of 50%, average outlet relative humidity of 83%, and average pressure of 373 Pa; whereas the sterilization off-gas air had averages of 22.4°C, 97%, 94%, and 50 Pa, respectively. The biofilter was resistant to changes

in moisture content, and although small depreciations in the effluent relative humidity were observed, they were minor compared to influent changes.

4- The biofilter demonstrated an ability to sustain odour reduction over consecutive sterilization cycles, which shows resistance of the filter to shock loads.

5- A dispersion model revealed a reduction in odour levels upon emission of gases from the proposed biofilter. Neighbouring industries of Apotex fermentation, with air intakes located between 65 and 70m from the stack at Apotex, would experience less odour entering their air intake then before the implementation of the biofilter.

7.0 RECOMMENDATIONS

Upon completion of experimentation, I recommend the following:

1- Research should be conducted on the performance of the filter outdoors. The filter was kept in a relatively constant ambient environment, which would not be the case if stored outdoors in a Manitoba climate. The effect of extreme ambient temperatures should be investigated.

2- Research should be conducted into the degradation of the filter medium after extended exposure to the contaminants present in the off-gases generated from this sterilization. This could be done through long-term observation of the filter medium after extended exposure to the contaminants.

3- The supplemental air flow should be automatically regulated when the filter is not fed with the contaminated air stream. The supplemental air should be heated to approximately 34°C and moisturized to near saturation.

4- A calibration study should be conducted to determine the persistence of the odour, and therein the amount of time the odour 'hangs in the air. Also, the relationship between odour intensity and odour concentration should be examined.

5- A full-scale filter should be implemented. Specifications for the filter are found in Appendix 8.

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APPENDIX 1 Dispersion model Inputs

1

biofilter

Concentration or deposition	Concentration
Emission rate units	OUV/second
Concentration units	Odour_Units
Units conversion factor	1.00E+00
Constant background concentration	0.00E+00
Terrain effects	None
Smooth stability class changes?	No
Other stability class adjustments ("urban modes")	None
Ignore building wake effects?	No
Decay coefficient (unless overridden by met. file)	0.000
Anemometer height	10 m
Roughness height at the wind vane site	0.500 m

DISPERSION CURVES

Horizontal dispersion curves for sources <100m high	Pasquill-Gifford
Vertical dispersion curves for sources <100m high	Pasquill-Gifford
Horizontal dispersion curves for sources >100m high	Briggs Rural
Vertical dispersion curves for sources >100m high	Briggs Rural
Enhance horizontal plume spreads for buoyancy?	Yes
Enhance vertical plume spreads for buoyancy?	Yes
Adjust horizontal P-G formulae for roughness height?	Yes
Adjust vertical P-G formulae for roughness height?	Yes
Roughness height	0.800m
Adjustment for wind directional shear	None

PLUME RISE OPTIONS

Gradual plume rise?	Yes
Stack-tip downwash included?	Yes
Building downwash algorithm:	Schulman-Scire method.
Entrainment coeff. for neutral & stable lapse rates	0.60,0.60
Partial penetration of elevated inversions?	No
Disregard temp. gradients in the hourly met. file?	No

and in the absence of boundary-layer potential temperature gradients given by the hourly met. file, a value from the following table (in K/m) is used:

Wind Speed Category	Stability Class A	B	C	D	E	F
1	0.000	0.000	0.000	0.000	0.020	0.035
2	0.000	0.000	0.000	0.000	0.020	0.035
3	0.000	0.000	0.000	0.000	0.020	0.035
4	0.000	0.000	0.000	0.000	0.020	0.035
5	0.000	0.000	0.000	0.000	0.020	0.035
6	0.000	0.000	0.000	0.000	0.020	0.035

a

WIND SPEED CATEGORIES
Boundaries between categories (in m/s) are: 1.54, 3.09, 5.14, 8.23, 10.80

WIND PROFILE EXPONENTS: "Irwin Urban" values (unless overridden by met. file)

AVERAGING TIME: 15 minutes.

1

Biofiolter

SOURCE CHARACTERISTICS

STACK SOURCE: APOTEX

X(m)	Y(m)	Ground Elev.	Stack Height	Diameter	Temperature	Speed
0	0	0m	12m	0.10m	30C	4.2m/s

Effective building dimensions (in metres)

Flow direction	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°
Effective width	30	30	30	30	30	30	30	30	30	30	30	30
Effective height	10	10	10	10	10	10	10	10	10	10	10	10

Flow direction	130°	140°	150°	160°	170°	180°	190°	200°	210°	220°	230°	240°
Effective width	30	30	30	30	30	30	30	30	30	30	30	30
Effective height	10	10	10	10	10	10	10	10	10	10	10	10

Flow direction	250°	260°	270°	280°	290°	300°	310°	320°	330°	340°	350°	360°
Effective width	30	30	30	30	30	30	30	30	30	30	30	30
Effective height	10	10	10	10	10	10	10	10	10	10	10	10

(Constant) emission rate = 8.77E+02 OUV/second
No gravitational settling or scavenging.

---

b

1

Biofilter

RECEPTOR LOCATIONS

The Cartesian receptor grid has the following x-values (or eastings):

-200.m	-180.m	-160.m	-140.m	-120.m	-100.m	-80.m
-60.m	-40.m	-20.m	0.m	20.m	40.m	60.m
80.m	100.m	120.m	140.m	160.m	180.m	200.m

and these y-values (or northings):

-200.m	-180.m	-160.m	-140.m	-120.m	-100.m	-80.m
-60.m	-40.m	-20.m	0.m	20.m	40.m	60.m
80.m	100.m	120.m	140.m	160.m	180.m	200.m

METEOROLOGICAL DATA : Winnipeg data: Surface Roughness 0.3m Anemometer Hei
g

ApotexSource

Concentration or deposition	Concentration
Emission rate units	OUV/second
Concentration units	Odour_Units
Units conversion factor	1.00E+00
Constant background concentration	0.00E+00
Terrain effects	None
Smooth stability class changes?	No
Other stability class adjustments ("urban modes")	None
Ignore building wake effects?	No
Decay coefficient (unless overridden by met. file)	0.000
Anemometer height	10 m
Roughness height at the wind vane site	0.500 m

DISPERSION CURVES

Horizontal dispersion curves for sources <100m high	Pasquill-Gifford
Vertical dispersion curves for sources <100m high	Pasquill-Gifford
Horizontal dispersion curves for sources >100m high	Briggs Rural
Vertical dispersion curves for sources >100m high	Briggs Rural
Enhance horizontal plume spreads for buoyancy?	Yes
Enhance vertical plume spreads for buoyancy?	Yes
Adjust horizontal P-G formulae for roughness height?	Yes
Adjust vertical P-G formulae for roughness height?	Yes
Roughness height	0.800m
Adjustment for wind directional shear	None

c

PLUME RISE OPTIONS

Gradual plume rise? Yes
Stack-tip downwash included? Yes
Building downwash algorithm: Schulman-Scire method.
Entrainment coeff. for neutral & stable lapse rates 0.60,0.60
Partial penetration of elevated inversions? No
Disregard temp. gradients in the hourly met. file? No

and in the absence of boundary-layer potential temperature gradients given by the hourly met. file, a value from the following table (in K/m) is used:

Wind Speed Category	Stability Class A	B	C	D	E	F
1	0.000	0.000	0.000	0.000	0.020	0.035
2	0.000	0.000	0.000	0.000	0.020	0.035
3	0.000	0.000	0.000	0.000	0.020	0.035
4	0.000	0.000	0.000	0.000	0.020	0.035
5	0.000	0.000	0.000	0.000	0.020	0.035
6	0.000	0.000	0.000	0.000	0.020	0.035

WIND SPEED CATEGORIES
Boundaries between categories (in m/s) are: 1.54, 3.09, 5.14, 8.23, 10.80

WIND PROFILE EXPONENTS: "Irwin Urban" values (unless overridden by met. file)

AVERAGING TIME: 15 minutes.

1

ApotexSource

SOURCE CHARACTERISTICS

STACK SOURCE: APOTEX

X(m)	Y(m)	Ground Elev.	Stack Height	Diameter	Temperature	Speed
0	0	0m	12m	0.10m	125C	4.2m/s

Effective building dimensions (in metres)

Flow direction	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°
Effective width	30	30	30	30	30	30	30	30	30	30	30	30

d

Effective height	10	10	10	10	10	10	10	10	10	10
10	10									

Flow direction	130°	140°	150°	160°	170°	180°	190°	200°	210°	220°
230°	240°									
Effective width	30	30	30	30	30	30	30	30	30	30
30	30									
Effective height	10	10	10	10	10	10	10	10	10	10
10	10									

Flow direction	250°	260°	270°	280°	290°	300°	310°	320°	330°	340°
350°	360°									
Effective width	30	30	30	30	30	30	30	30	30	30
30	30									
Effective height	10	10	10	10	10	10	10	10	10	10
10	10									

(Constant) emission rate = 2.19E+03 OUV/second
No gravitational settling or scavenging.

1

ApotexSource

RECEPTOR LOCATIONS

The Cartesian receptor grid has the following x-values (or eastings):

-200.m	-180.m	-160.m	-140.m	-120.m	-100.m	-80.m
-60.m	-40.m	-20.m	0.m	20.m	40.m	60.m
80.m	100.m	120.m	140.m	160.m	180.m	200.m

and these y-values (or northings):

-200.m	-180.m	-160.m	-140.m	-120.m	-100.m	-80.m
-60.m	-40.m	-20.m	0.m	20.m	40.m	60.m
80.m	100.m	120.m	140.m	160.m	180.m	200.m

METEOROLOGICAL DATA : Winnipeg data: Surface Roughness 0.3m Anemometer Hei
g

e

APPENDIX 2 Sampling Schedule

Table A1. Schedule of relevant events in 2003.

Date m/dd	Activity	No. of Replicates
06/20	Sterilization gas introduced to 20:80 c:w medium	
06/26	Foam seal added to inside of filter	
	Medium acclimation complete	
06/27	Flow rate set at 20L/min (EBCT 60s)	
06/30	Long weekend- air spurged through medium & into filter	
07/01	Influent samples taken for chromatogram analysis	2
07/09	Odour panel sample taken immediately after sterilization	3
	Airflow reduced to 15L/min (EBCT 120s)	
07/12	Temperature increased to 34°C	
07/14	New 40:60 c:w media introduced	
07/18	Airflow reduced to 10L/min (EBCT 180s)	
07/22	Odour panel sample taken immediately after sterilization	2
	Odour panel sample taken 3h after sterilization	3
07/23	Odour panel sample taken 24h after sterilization	2
	Odour panel sample taken 28h after sterilization	3
	Airflow decreased to 5L/min (EBCT 240s)	
07/28	Odour panel sample taken 24h after sterilization	4
	Odour panel sample taken 28h after sterilization	4
08/10	Odour panel sample taken 50h after sterilization	3
08/16	Odour panel sample taken immediately after sterilization	3
08/18	Odour panel sample taken immediately after sterilization	3
08/24	Odour panel sample taken immediately after sterilization	3
08/25	Sterilizations terminated	

APPENDIX 3 Flow Rate Calculation

$(v\rho A)in = (v\rho A)out$ Assuming constant density of air,

$vA=vA \quad v_{in\ filter}=v_{inlet}*A_{inlet}/A_{in\ filter}$

where 'in filter' refers to the average velocity of air entering the filter bed, and 'inlet' is the velocity of air entering the inlet hose.

$vA=vA \quad v_{out\ filter}=v_{outlet}*A_{outlet}/A_{out\ filter}$

where 'out filter' refers to the average velocity of air exiting the filter bed, and 'outlet' is the velocity of air entering the inlet hose.

Table A2. Selection of tank for full-scale filter. Plenum height and the upper air gap were both considered in the height.

V (US Gal)	V (m3)	Outer D (inch)	Outer D (m)	Height (inch)	Height (m)	List Price (CD)
1250	4.73	87	2.21	65	1.65	947
1417	**5.36**	**87**	**2.21**	**72**	**1.83**	**1440**
1750	6.62	87	2.21	87	2.21	1893
2000	7.57	100	2.54	79	2.01	1798

Tanks are from 'Septics Unlimited' in Winnipeg, Manitoba, and prices are for September 19, 2003. The tanks are large poly vertical cylindrical tanks made from 100% polyethylene material, and have a sealable lid. The row that is bolded is the tank selected for system scale-up.

Table A3. Calculation of inlet and outlet filter flow velocity using an Omega HHF-330A digital anemometer.

Reactor Flow Rate (L/min)	Influent				Effluent			
	FPM	v (m/s)	vA	v(filter)	FPM	v(m/s)	vA	v(filter)
5	102	0.51816	0.0033	0.0356	1580.80	264	0.00765	0.0827
	107	0.54356	0.0035	0.0374	1820.92	456	0.00881	0.0953
	104	0.52832	0.0034	0.0363	2021.02	616	0.00977	0.1058
Average	*104*	*0.530013*	*0.0034*	*0.0364*	*181*	*0.917787*	*0.00874*	*0.0946*
EBCT (s)		0.451178				0.260551		
10	335	1.7018	0.0108	0.117	1740.88	392	0.00842	0.0911
	355	1.8034	0.0115	0.1239	1830.92	964	0.00885	0.0958
	402	2.04216	0.013	0.1403	1760.89	408	0.00852	0.0922
Average	*364*	*1.84912*	*0.0117*	*0.1271*	*178*	*0.902547*	*0.0086*	*0.093*
EBCT (s)		0.129321				0.264951		
15	540	2.7432	0.0174	0.1885	2921.48	336	0.01413	0.1529
	526	2.67208	0.017	0.1836	3081.56	464	0.0149	0.1613
	546	2.77368	0.0176	0.1906	3011.52	908	0.01456	0.1576
Average	*537*	*2.729653*	*0.0173*	*0.1876*	*300*	*1.525693*	*0.01453*	*0.1573*
EBCT (s)		0.087605				0.156736		
20	677	3.43916	0.0218	0.2363	3491.77	292	0.01689	0.1828
	674	3.42392	0.0217	0.2353	3621.83	896	0.01752	0.1896
	704	3.57632	0.0227	0.2458	3681.86	944	0.01781	0.1927
Average	*685*	*3.4798*	*0.0221*	*0.2391*	*360*	*1.827107*	*0.0174*	*0.1883*
EBCT (s)		0.06872				0.130879		

The term 'filter' in Table A6 refers to a velocity of air that passes through the filter medium. 'Reactor flow rate' is the rate read off of the reactor at Apotex. FPM denotes 'feet per minute,' which is the unit that the anemometer gave the velocity in. EBCT is the empty bed contact time, calculated using values measured with the anemometer.

EBCT=V/Q, where Q=vA

APPENDIX 4 Medium Moisture Content

Numbers used to calculate the moisture content in the filter when the reactor was venting at 5L/min, with 40:60 medium, is shown in Table 2 below.

Table A4. Summary of measurements used to calculate medium wet basis moisture content on September 23, 2003.

	Mass (g)				
Sample	**Tray**	**Before**	**After**	**MC (%)**	**Std Dev**
Top					
1	9.76	23.24	15.53	57.20	
2	5.73	10.15	7.59	57.92	
3	9.97	19.44	13.99	57.55	
4	6.22	17.89	11.29	56.56	
Average				57.30	0.58
Middle					
1	5.87	16.85	10.12	61.29	
2	5.90	16.04	10.12	58.38	
3	9.55	26.61	16.55	58.97	
Average				59.55	1.54

In Table A4, 'top' refers to samples taken from just below the upper surface of the filter, each sample at different points along the surface area, and similarly 'middle' refers to samples taken in the centre of the filter depth. Samples were dried at 130°C for 24 hours.

$$MC = \frac{(\text{sample mass before drying}) - (\text{sample mass after drying})}{(\text{sample mass before drying})} * 100$$

For top sample 1,

$$MC = \frac{(23.24-9.76)-(15.53-9.76)}{(23.24-9.76)} * 100 = 57.20\%$$

APPENDIX 5

Table A5. Efficiency calculations and summary of odour panel results.

Time	Influent OU	Std Dev Influent OU	Effluent OU	Std Dev Effluent OU	% Reduction	Std Dev
With medium 40:60, 10l/min						
3 H after	3893.98		2791.60			
Immediately after sterilization	64968.59	31034.30	7254.18	2781.31	31158.69	0.5
24 hours after sterilization	2426.12		1528.29			
24 hours after sterilization	2426.12		1248.24			
Average	**2426.12**		**1388.26**		**42.78**	**22.2**
28 hours after sterilization	2159.47		1361.44			
28 hours after sterilization	991.87	592.37	802.05	485.83	19.14	0.3
28 hours after sterilization	1401.78		393.69			
Average	**1517.70**		**852.40**		**43.84**	**7.0**
With medium 40:60, 5l/min						
28 hours after sterilization	1611.77		1008.28			
28 hours after sterilization	1611.77	289.82	560.03	223.77	65.25	0.0
28 hours after sterilization	1199.69		1044.25			
28 hours after sterilization	1044.25		792.13			
Average	**1366.87**		**851.17**		**37.73**	**2.3**
24 hours after sterilization	2253.31		499.83			
24 hours after sterilization	2253.31	701.03	707.76	256.65	68.59	0.1
24 hours after sterilization	1039.10		978.89			
24 hours after sterilization	1039.10		397.79			
Average	**1646.20**		**646.07**		**60.75**	**6.7**
50 hours after sterilization	3425.08		962.78			
50 hours after sterilization	2167.36	729.18	963.76	244.25	55.53	0.1
50 hours after sterilization	2156.92		540.21			
Average	**2348.89**		**778.20**		**66.87**	**6.4**
Immediately after sterilization	24221.32		21410.27			
Immediately after sterilization	31615.88	4269.258148	.19	6654.38	74.23	0.0
Immediately after sterilization	31615.88		13814.74			
Average	**29151.03**		**14457.73**		**50.40**	**1.3**
Immediately after sterilization	26467.36		3822.72			
Immediately after sterilization	23581.51	18436.07	7117.86	1650.85	69.82	0.6
Immediately after sterilization	56858.70		5650.30			
Average	**35635.85**		**5530.29**		**84.48**	**42.6**
Immediately after sterilization	31181.52		5881.64			
Immediately after sterilization	38824.61	4412.749738	.76	2727.40	74.92	0.0
Immediately after sterilization	31181.52		-------			
Average	**33729.22**		**7810.20**		**76.84**	**0.9**
Average for Above 3 CONSECUTIVE TRIALS	**32838.70**	12484.47	**9266.07**	6535.46	**71.78**	**10.3**
With media 20:80, 20L/min						
Immediately after sterilization	25301.49		24398.89			
Immediately after sterilization	64968.59	20092.15	24903.71	252.45	61.67	0.1
Immediately after sterilization	39569.60		24659.30			
Average	**43279.89**		**24653.97**		**43.04**	**4.1**

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Note in Table A5 that dashed lines indicate a sample was lost due to bag leakage, and values used are the final values calculated after outlying panellists have been removed.

Percent reduction= average influent- average effluent concentration *100

average Influent concentration

Standard deviation of reduction= $\mu\sqrt{\left(\frac{devX-Y}{X-Y}\right)^2+\left(\frac{devX}{X}\right)^2}$

Where X= influent concentration

Y= effluent concentration

APPENDIX 6 Sample calculations

Paired comparison test

Table A6. Paired comparison test for immediately after sterilization. Values shown in the table are averages of three replicate samples taken, $\propto$=0.05.

Sample Day	Concentration (OU)	Letter Designation
Influent		
16-Sep	29151.02882	A
18-Sep	35635.85241	B
24-Sep	33729.21905	C
Effluent		
16-Sep	14457.73309	D
18-Sep	5530.291712	E
24-Sep	7810.197111	F

Error degrees of freedom=treatments*(replicates-1)
=6(3-1)=12

Error sums of squares= $S^2 = \frac{\Sigma (Y_i - \mu)^2}{n-1}$

Where n= population size = treatments*replicates= 6*3=18

Y_i = treatment mean

μ= population mean= 18136 OU

Error sums of squares= 53226402

Least significant difference= $LSD = t_{(0.05,\ error\ df)} * \sqrt{(2 * s^2/r)}$

$t_{(0.05,\ error\ df)}$= 2.179

LSD= 12980.01

Table A7. Summary of pair comparison test calculations.

	Reduction	E-X	F-X	D-X	A-X	C-X
E	5530.291712	0				
F	7810.197111	-2279.905399	0			
D	14457.73309	-8927.441381	-6647.536	0		
A	29151.02882	**-23620.7371**	**-21340.83**	**-14693.3**	0	
C	33729.21905	**-28198.92734**	**-25919.02**	**-19271.5**	-4578.19	0
B	35635.85241	**-30105.56069**	**-27825.66**	**-21178.1**	-6484.82	-1906.63

Negative values are due to the choice of formula, where X denotes a given sample value. Values greater in magnitude than LSD indicate a significant difference between the two subtracting values, and values less than LSD in magnitude are not significantly different. Bolded values are significantly different.

Influent concentrations (represented by A, B, and C in the above tables) were found not to be statistically different from each other, nor were effluent values (represented by D, E, and F in the Tables). All three influents, however, are significantly higher in concentration than all three effluents.

Summary of filter dimensions

Inner D=0.343m
Surface area=0.0924 m^2
V=Ah=0.022m^3
Inner diameter of inlet hose= 1/2 inch
Inner diameter of outlet hose= 3/8 inch

m

APPENDIX 7 Design Parameters

Table A8. Calculations summary.

Q (L/min)	Q (m^3/s)	V (m^3)	EBCT (s)	Filter V* (m^3)	Surface Loading ($m^3/m^2/s$)	Contaminant Concentration (g/m^3)	Mass Loading ($g/m^3/s$)	Cost** (CD$)
5	8.3E-05	0.02	240	4	0.000901876	0.031511	0.472665	91.41
10	0.00017	0.02	120	2	0.001803752	0.031511	0.94533	80.70
15	0.00025	0.02	80	1.33	0.002705628	0.031511	1.417995	77.14
20	0.00033	0.02	60	1	0.003607504	0.031511	1.89066	75.35

*Full-scale filter volume, assuming a flow rate of 1000SLPM

**Materials plus delivery, assuming a 60woodchip:40compost ratio

In Table A4, concentration is calculated by adding the concentrations of the 4 most predominant compounds from chromatogram, which made up the vast majority of the influent gas concentration. Compared with value in the literature review, the mass loading values and the surface loading values are much lower than are typically treated in biofiltration.

For 5L/min,

$SL = Q/A$

$= 8.3E\text{-}05\ m^3/s\ /0.0924\ m^2$

$= 0.000901876\ m^3/m^2/s$

$ML = Q\ C_i\ /V$

$= (8.3E\text{-}05\ m^3/s * 0.031511\ g/m^3)/0.022 m^3$

$= 0.472665\ g/m^3/s$

n

Table A9. Summary of minimum pressure required to overcome the medium resistance.

Q (L/min)	Q ($m^3/s/m^2$)	Pressure (Pa)
5	0.000901876	0.79447
10	0.001803752	1.59306
15	0.002705628	2.39579
20	0.003607504	3.20262

Where surface area=0.092401309 m^2.

Pressure drop=$\Delta P = \frac{aQ^2L}{\log_e(1+bQ)}$

where a=21233, b=5.8 for 40:60 mulch to compost. Mulch was chosen as larger pieces of woodchips were removed, making the mixture finer than would be a normal batch of woodchips. Note that this formula is valid for airflows in the range of Q=0.055 - 0.148 $m^3/s/m^2$ (Sadaka *et al.* 2002).

54 APPENDIX 8 Scale-up

The full-scale biofilter may be placed outdoors, as opposed to an indoor filter as was the case with the pilot scale trial. It may be moved as convenience of location changes. To maintain as many similarities between the pilot model and the full-scale system, the full-scale filter will be bottom-loaded and cylindrical in shape.

Assumptions

The sterilization process will occur every 2.5 days as previously specified by Apotex. Air will be vented at 5L/min at 34°C, and vented air will have characteristics very similar to that used in the pilot testing. A ratio of 40:60 c:w will be used, and the design flow rate of 5L/min (240s EBCT) will bring the total filter volume to $4m^3$. As the infrastructure for the sterilization process is already conducive to biofiltration installation, the following costs are not included:

1- Excavation/site preparation- Assuming that, as the filter will be going on the roof, no site excavation is necessary, nor is any site preparation.
2- Fans/blowers- Air leaving effluent stack is already at sufficient pressure
3- Piping costs
4- A data acquisition unit and monitor
5- Mobilization/demobilization of construction crew

Filter structure High-density polyethylene will be used for the filter vessel. Pre-fabricated cylindrical vessels are readily available in convenient sizes, and are easily adapted as biofilters. High-density polyethylene will withstand repeated relocations of the filter (using a forklift, for example) should Apotex decide to do so. However if care is not taken, the structure may be easily cut. The structure is easily modified once constructed, and it is lightweight and does not require a weatherproof coating. The structure may break down with UV exposure, causing cracks. As there are no corrosive gases present in the effluent stream, this material will be effective in maintaining structural integrity (Devinny *et al.* 1999). The tank selected is 1417 USGal (5.36m^3) with an 87in (2.21m) outer diameter and 72in (1.83m) in height. This unit costs $1440 CD. Filters are generally between 1 and 1.5 m deep, and the extra height will allow for a plenum and an effluent air space.

Irrigation system A simple irrigation system will be used similar to that in the pilot model. It will consist of a polyethylene tube formed into a ring and perforated to allow water to pass through. The tube will have an open end connected to a water line or, if more convenient, a tube connected to a pump similar in principle to that used in the pilot-scale system. There will be a solenoid valve at the inlet to control system watering through a timer in the former case, otherwise watering will be controlled by regulating the on/off time of the pump.

Humidification The effluent air stream from the reactor during venting of the off-gas is of high relative humidity and need not be humidified. However, the clean air line is both cold and dry and should be treated if used as the supplemental air supply during medium sterilization. Passing the air stream over a bed of hot water (at approximately 90°C) will both heat the air and humidify it. The air line could be connected to a small chamber that has a pool of hot water in it, maintained through an automatic irrigation system and electrically heated, the air then would pass into the influent of the biofilter.

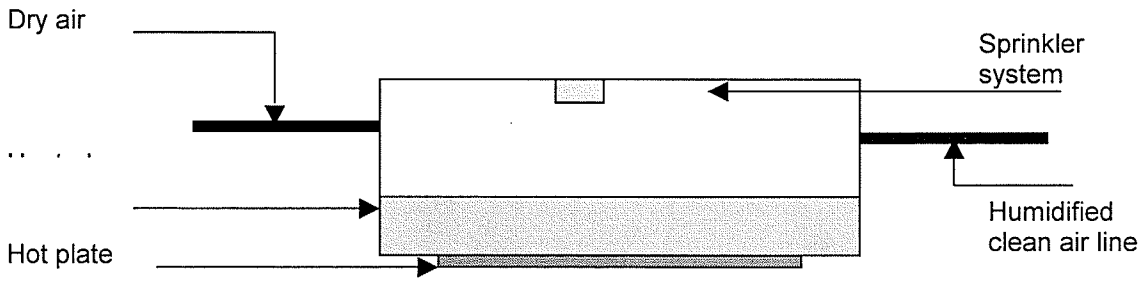

Figure B1: Schematic of potential humidification line. The humidified clean air line would lead to the inlet of the reactor.

Controls Relative humidity sensors, thermocouples, and a pressure transducer identical to the ones used in the pilot scale will be used in the full-scale design. A data acquisition unit and analytical equipment will also be needed. Accumulation of biomass and medium compaction will be evident from changes in the reactor pressure. With an increase in medium density either due to compaction, which causes a decreased porosity, or through biomass build-up, more pressure will be needed to overcome the backpressure cause by the medium.

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Assuming an emission rate of approximately 1000 SLPM, according to Apotex,

Volume of medium in bed= Q x EBCT

V= $1000m^3/60s$*EBCT

=4 m^3

Cost estimate for Scale-up

Assuming a ratio of 40:60 c:w is used and the design flow rate is 5L/min (bringing the total filter volume to $4m^3$), the cost of the medium is approximately $92 CD. A quote from Perfect Landscaping in Winnipeg on September 16, 2003:

Woodchips- $\$5/yd^3$ plus $35 delivery

Compost- $\$10/yd^3$ plus $35 delivery

Therefore,

Woodchips= $\$3.80/ m^3$

Compost= $\$7.65/ m^3$

Total cost of medium= V*COST

= $0.6(4m^3)(\$3.80) * 0.4(4m^3)(\$7.65)$= $21.36 + $70 delivery

Relative humidity sensors= $350 each

s

Pressure transducer= $200

Thermocouples= $2.00

Miscellaneous (ex. plenum mesh, tubing and pump for irrigation system, bulk head fittings) = $100

Infrastructure cost= $1440

Total capital cost= 1440 + 92 + 2(350) + 200 + 100 =$2532

Total electrical cost= 4% capital cost

=0.04(2532)1.14tax= $111

(includes power to water pumps, analytical equipment, computer equipment, blower/fan)

Equipment installation= 4% capital cost= $111

Total equipment cost= 111+111+2532= $2754 ≈ $3000

Labour=situationally dependant

Hot water bath, hot plate (approximately $150), sprinkler, and casing required for the humidification system would be approximately an additional $400. The life of the medium is not known, however pressure increases will indicate an accumulation of biomass, and therein the need to replace the medium.

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