ELSEVIER

Journal of Hazardous Materials 60 (1998) 287–303

JOURNAL OF HAZARDOUS MATERIALS

Effects of periods of starvation and fluctuating hydrogen sulfide concentration on biofilter dynamics and performance

Altaf H. Wani *, Richard M.R. Branion, Anthony K. Lau

Department of Chemical and Bio-Resource Engineering, Pulp and Paper Center, The University of British Columbia (UBC), 2216 Main Mall, Vancouver, BC V6T 1Z4, Canada

Received 20 December 1997; revised 1 March 1998; accepted 14 March 1998

Abstract

The paper describes the results of a systematic study of the transient behavior of biofilters treating reduced sulfur pulping odors and VOCs. They were exposed to variations in contaminant loading and periods of starvation. Three bench-scale biofilters with different filter media were used. Filter media materials used were the mixtures of compost/perlite (4:1), hog fuel/perlite (4:1), and compost/hog fuel/perlite (2:2:1). Hydrogen sulfide, the main malodorous gas produced from kraft pulping processes, was used as the test contaminant. The starvation period comprised of two stages: the 'no-contaminant-loading phase' when only humidified air was passing through the biofilters, and the 'idle phase' when no air was passing through the biofilters. The response of each biofilter to variations in contaminant mass loading was studied by abruptly changing the concentration and/or flow rate of the inlet waste air stream. Contaminant concentration was continuously measured until a new steady state, for each stage, was achieved. Concentration spikes were applied to study the effects of shock loading on the biofilter removal rates. Biofilters responded effectively to H_2S concentration variations and shock loading by rapidly recovering to the original removal rates within 2–8 h. The re-acclimation times to reach full capacity were very short ranging between 15 and 120 h. Extended periods of starvation resulted in longer re-acclimation periods, so does the idle phase as compared to no-contaminant-loading phase.

Keywords: Biofilters; Transient behavior; Starvation periods; Fluctuating concentrations; Shock loads; Pulping odors; Hydrogen sulfide

* Corresponding author. Tel.: +1 604 222 3201, ext. 342; fax: +1 604 822 6003; e-mail: altaf@chml.ubc.ca

0304-3894/98/$19.00
PII S0304-3894(98)00154-X

1. Introduction

Odor from chemical pulp mills is one of the major public perception problems facing the pulp and paper industry. Due to public health concerns and personal comfort of neighboring residential communities, the industry is facing increasingly stringent regulations. The removal of malodorous reduced sulfur emissions has been traditionally accomplished using physical or chemical methods, such as vapor scrubbing, incineration or adsorption. However these control technologies are usually uneconomical if large flow rates and low contaminant concentrations characterize the waste air streams. Biofiltration, a relatively new application of biotechnology in environmental engineering, instead of transferring contaminants from one medium to another, or using large amounts of energy to destroy or remove pollutants, utilizes the efficiency of microorganisms to degrade the pollutants [1–5]. Biofiltration is a viable and potentially cost-effective alternative for the treatment of low-concentration polluted air streams. The low operating cost results from the utilization of microbial oxidation at ambient conditions instead of oxidation by thermal or chemical means. Under the proper conditions, high removal efficiencies can be achieved and the process is environmentally friendly. Biofiltration involves passing the contaminated air stream through a moist bed of compost, peat, soil or other permeable material that acts as an attachment for a rich microbial population. After the contaminants have been sorbed from the air stream while passing through the bed the microorganisms utilize the sorbed contaminants as a food source and convert them into carbon dioxide, water vapor and inorganic salts. As the contaminants are metabolized the binding site to which they were attached again becomes available to sorb additional contaminant molecules from the incoming air stream. Thus biofilters reach a steady state in which sorption, biological destruction and release of innocuous gaseous products are in balance.

Owing to the variable nature of industrial operations, full-scale biofilters are generally exposed to a multitude of changing conditions as a result of fluctuating loads during process condition changes and/or discontinuous loads during shutdowns for retooling or equipment repair. This highlights the significance of obtaining reliable data on the transient behavior of biofilters under the conditions that will be encountered in field operation, in order to ascertain whether a biofilter could respond effectively to sudden changes in operating conditions, shutdowns and restarts, and contaminant shock loading. The steady state performance of biofiltration process has been widely investigated [6–8]. However, only a few studies [2,3,9–11] have addressed the transient state operation of biofilters and the changes occurring during shutdowns and interruptions; and only minor attention has been given in particular to biofilters treating reduced sulfur gases [12,13]. Obviously, in-depth investigation of the unsteady state behavior of biofilters is required to understand the complex phenomena occurring in the biofiltration process under real world conditions and to generate process data necessary for plant design and scale up.

This paper describes the results of an on-going bench-scale study to examine the effects of changes in airflow rate and contaminant concentration, under constant and variable loading conditions, on biofilter performance treating odors and VOCs. The initial startup, re-acclimation after periods of non-use, and response to shock loads are

also investigated and discussed. H_2S, the main odorous compound that causes pulp mill odor problems, was used as a test contaminant.

2. Materials and methods

2.1. Experimental setup

Three identical bench-scale biofilter columns were used (Fig. 1). The biofilter columns were constructed from transparent, rigid, plexiglass tubing, with an inner diameter of 190 mm and a height of 910 mm. Each of these columns can be packed with the desired filter media up to a height of 660 mm. The filter bed in each column is divided into three equal sections, in series, leaving a 30 mm plenum in between the sections for representative gas sampling. The packed biofilter material in each section is supported by stainless steel sieve plates. There are three ports in each segment allowing for sampling the air stream and biofilter media, and monitoring the temperature and

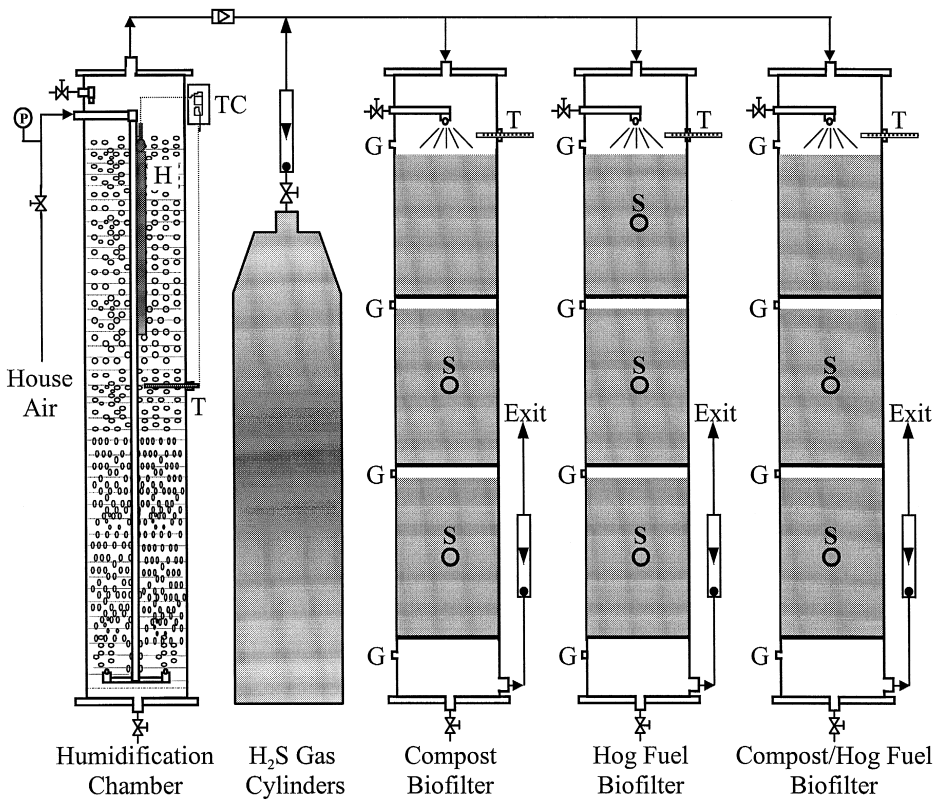

Fig. 1. Schematics of the experimental setup: (G) gas sampling ports; (H) immersion heater; (P) pressure gauge; (S) media sampling ports; (T) thermocouples/thermometers; (TC) temperature controller.

pressure. The gas sampling ports, located along each column, are fitted with threaded PVC (polyvinyl chloride) stopcocks. The individual sampling ports were identified as inlet, upper, lower and outlet ports. The media sampling and temperature monitoring ports are fitted with threaded PVC stoppers and can be opened as desired. The biofilter columns were sealed at the top and bottom by clear plexiglass covers provided with rubber o-rings. The top cover can be dismantled to replace the filter material and to clean the filter columns before and after use. The air used for creating the synthesized contaminated gas stream was taken from the laboratory compressed air distribution system. Before use the air was filtered to remove water and oil droplets. The airflow rate was controlled using pressure regulators located at the house air outlets. The inlet gas stream was conditioned by humidification to saturation. A transparent plexiglass humidification column (190 mm in diameter and 910 mm in height) was used to add water vapor to saturate the air because the house air had less than 25% relative humidity at room temperature and pressure. Humidification was controlled by sparging the air through temperature controlled water. Maintaining the water at about 5°C above room temperature, by using an immersion heater, provided the necessary driving force to ensure complete saturation of the air stream. The air was then passed through a trap to collect any condensates from the air supply lines before entering the biofilters. A wet/dry bulb apparatus was used to measure the relative humidity of air. The temperature of the inlet air stream was accordingly controlled by the humidifier's water temperature. A metered flow of H_2S (10 vol.%, balance N_2), from a compressed gas cylinder, was injected into the saturated air stream before the gas distribution manifold that carried the humidified air stream to the biofilter columns. The flow rates of the pollutant gas and the humidified air were controlled by needle valves and metered with high precision stainless steel Gilmont compact flow meters at the inlet and outlet lines of the biofilter columns, respectively. 3 mm PFA teflon tubing was used to carry the H_2S from gas cylinder to the distribution manifold, while all other gas lines were 12 mm diameter PVC pipes. A down flow direction in the biofilter was chosen because it allows for efficient moisture control in the filter bed.

2.2. Biofilter media

The biofilter media materials used were: compost, because of its universal application as a biofilter media owing to its inherently diversified microbial communities, hog-fuel, because of its easy availability as on-site waste material from pulp and paper mills, and a mixture of compost and hog fuel as an attempt to combine the advantages of both materials. Compost was obtained from a local composting facility (Consolidated Enviro Waste, Aldergrove, BC) and was mainly composed of yard waste and some animal manure. Hog fuel (raw bark, wood waste and other extraneous materials that are pulverized and used as a fuel for power boilers in a pulp mill) was obtained from Western Pulp's mill, Squamish, BC. Biofilter media materials were analyzed for their physical and chemical characteristics using standard methods for soil analysis [14], and the results are summarized in Table 1. Media materials were stored at room temperature (25°C) in sealed bags to prevent moisture loss.

Table 1
Characteristics of biofilter materials

Characteristic	Unit	Compost	Hog fuel	Mixture
pH_w	–	8.95	4.32	7.89
Water content	%	59.91	53.43	56.67
Organic $matter_{dry}$	%	53.14	90.82	71.98
Total $carbon_{dry}$	%	36.75	54.53	45.64
Total $nitrogen_{dry}$	%	1.340	0.168	0.754
$C/N\ ratio_{dry}$	–	27.42	325.01	60.54
Bulk density	g/ml	0.514	0.251	0.351
Particle density	g/ml	1.479	1.428	1.511
Porosity	%	65.24	82.43	76.76
Average particle size[a]				
> 4.76 mm	wt.%	23.41	22.81	23.11
4.00–4.76 mm	wt.%	8.09	9.37	8.73
2.83–4.00 mm	wt.%	18.21	14.95	16.58
2.00–2.83 mm	wt.%	20.83	17.25	19.04
1.40–2.00 mm	wt.%	13.85	14.80	14.33
0.85–1.40 mm	wt.%	9.95	13.93	11.94
< 0.85 mm	wt.%	5.67	6.88	6.28

[a]Obtained by sieving.

2.3. Reactor conditions

The filter medium for the three biofilters consisted of compost, hog fuel and the mixture of compost and hog fuel (1:1 w/w), respectively. Each medium was then amended with perlite, to increase the surface area, in a ratio of 4 parts media to 1 part perlite, by weight. Dolomitic lime was also added to the filter media at 25 kg m^{-3} of bed material, as a pH buffer. Waste activated sludge obtained from Western Pulp's mill, Squamish, BC and Howe Sound Pulp and Paper's mill, Port Melon, BC was used as the seeding for reduced sulfur-oxidizing microorganisms. The final moisture contents of the prepared media from compost, hog fuel and the mixture were 59.9, 53.4 and 56.7% respectively. The prepared media were then packed into the biofilter columns and continuously fed with water vapor saturated air containing H_2S. The total volume of filter bed in each biofilter column was 0.018 m^3. The synthetic waste air stream was made by injecting compressed H_2S (10 vol.%, balance N_2) into the saturated air stream coming from the humidification column. H_2S concentrations between 10 and 615 ppmv, and waste airflow rates ranging from 1.7 to 2.9 $m^3\ h^{-1}$ (equivalent to empty bed residence times, τ, of 38 to 22 s) were used. The waste air had a relative humidity of about 100%, and the pressure drop over the filter beds was less than 10 mm water gauge. The biofilter columns were maintained at room temperature (25–27°C).

2.4. Analytical techniques

The concentration of H_2S in the gas phase was determined by gas chromatographic analysis using a Hewlett-Packard (HP) 5890 II gas chromatograph (GC). A flame

photometric detector (FPD) was utilized. The GC was equipped with a HP fused silica capillary column (30 m long, 0.32 mm diameter and 4 μm film thickness, cross-linked methyl silicone). The samples were injected into the GC via a 10-position switching valve (Valco Instruments) with a 1 ml sample loop. The samples were drawn via positive pressure through the valves and the sample loop to the column. The GC oven temperature was programmed from 50 to 230°C in increments of 40°C min^{-1} with a hold of 1 min at 50°C and 2 min at 230°C. The injection and the detector temperatures were set at 100 and 225°C, respectively. Air, helium and hydrogen flow rates were 82, 4 and 85 ml min^{-1}, with a column head of 85 kPa. Increasing the injection sample volume, by regulating the valve opening time, allowed testing at very low concentrations, giving an effective detection limit of approximately 250 parts per billion by volume (ppbv). The H_2S-air calibration standards were prepared at seven concentration levels by injecting small quantities (1–75 ml) of 50 ppmv H_2S (balance nitrogen) into 500 ml pure nitrogen contained in tedlar bags. The volume of pure nitrogen in tedlar bags was measured by a high precision mass flow controller (MKS Instruments, Canada) with a measuring range of 5–1000 ml min^{-1}. The samples were analyzed in triplicate.

The gas samples taken from the inlet and outlet streams as well as axially along the biofilter columns were passed through a concentrated phosphoric acid impinger to remove moisture prior to collection into 1 l tedlar bags [15]. All the gas samples were analyzed within 3 h. The tedlar bags were flushed with activated carbon filtered, house air overnight for reuse.

2.5. Surface and mass loading, and biofilter elimination capacity

The surface loading rate (L_s) is a measure of the volumetric gas loading to a biofilter. Mass loading rate (L_m), a combination of the waste airflow rate and the contaminant concentration in the waste gas stream, is defined as the mass of pollutant introduced into a biofilter per unit volume of filter material per unit time. Elimination capacity (EC), a measure of the contaminant destruction capacity of a biofilter bed, is defined as the mass of contaminant degraded per unit volume of filter material per unit time; while removal efficiency (RE) is the operating parameter used to judge the success of a biofilter in terms of bio-conversion of a contaminant.

Empty bed residence time (s), waste air surface loading rate (m h^{-1}), contaminant mass loading rate (g m^{-3} h^{-1}), biofilter elimination capacity (g m^{-3} h^{-1}) and removal efficiency (%) were determined using the relationships between the influent and effluent gas phase concentrations, waste airflow rate, and the volume of the biofilter material as follows:

$$\tau = V/Q \tag{1}$$

$$L_s = Q/A \tag{2}$$

$$L_m = Q/V * C_{in} * \left(M * 10^{-3}/24.45\right) \tag{3}$$

$$EC = Q/V * \left(C_{in} - C_{out}\right) * \left(M * 10^{-3}/24.45\right) \tag{4}$$

$$RE = \left[\left(C_{in} - C_{out}\right)/C_{in}\right] * 100 \tag{5}$$

Where, Q is the waste airflow rate ($m^3\ h^{-1}$), A is the area of cross-section of biofilter column (m^2), V is the volume of filter material (m^3), M is the molecular weight of the contaminant (34 for H_2S), and C_{in} and C_{out} are the contaminant concentrations in the influent and effluent waste gas streams (ppmv).

3. Results and discussions

3.1. Biofilter acclimation

The biofilters were acclimated by increasing the H_2S concentration gradually from 10 to 500 ppmv to establish steady state conditions as indicated by H_2S removals remaining constant with time. Waste airflow rate ($1.7\ m^3\ h^{-1}$) was kept constant and the H_2S concentration was increased by varying the compressed H_2S feed rate into the saturated air stream. Relatively high H_2S loading conditions were used during the acclimation period to ensure that there was enough chemical to stimulate the growth of the biofilm microorganisms after saturating the adsorption capacity of the filter material. Due to a break down of the GC, the outlet concentration could not be regularly monitored; rather the effluent concentration was occasionally measured by GASTEC detector tubes (GASTEC, Japan), thus no information on chemical-specific acclimation rates could be obtained.

3.2. Biofilter dynamics in response to step changes

This section deals with some typical responses that might be encountered in real systems, particularly step changes in pollutant concentration and/or in waste airflow rate. Following the acclimation, two sets of experiments were performed with stepwise changes in inlet H_2S concentration with constant residence time and in the waste airflow rate with fixed H_2S concentration, and the transient response of the biofilters was examined. Usually after the step changes 2–8 h were needed in order to reach new stationary conditions.

3.2.1. Step change in contaminant concentration

Keeping the residence time ($\tau = 38$ s) fixed, the effect of abrupt changes in H_2S inlet concentration from 73.6 to 202.4 ppmv, specified in terms of mass loading, on the biofilter dynamics was investigated. The H_2S feed rate was increased stepwise retaining the airflow constant so that the H_2S mass loading changed proportionally. After adjusting the H_2S concentrations the system was allowed to stabilize for 48 h before changing to another mass loading. A series of five test periods (L_m, $2.75 * L_m$, $0.0 * L_m$, $1.92 * L_m$, $1.35 * L_m$) starting with the base case condition of $L_m = 9.7\ g\ m^{-3}\ h^{-1}$ were carried out. The transient response of biofilters to these abrupt changes in inlet H_2S concentrations is presented in Fig. 2.

The compost and the hog biofilters showed similar responses without any breakthrough with the bio-elimination efficiency for H_2S remaining $> 99\%$ for all the five step changes in inlet concentration. The mixture biofilter exhibited two minor break-

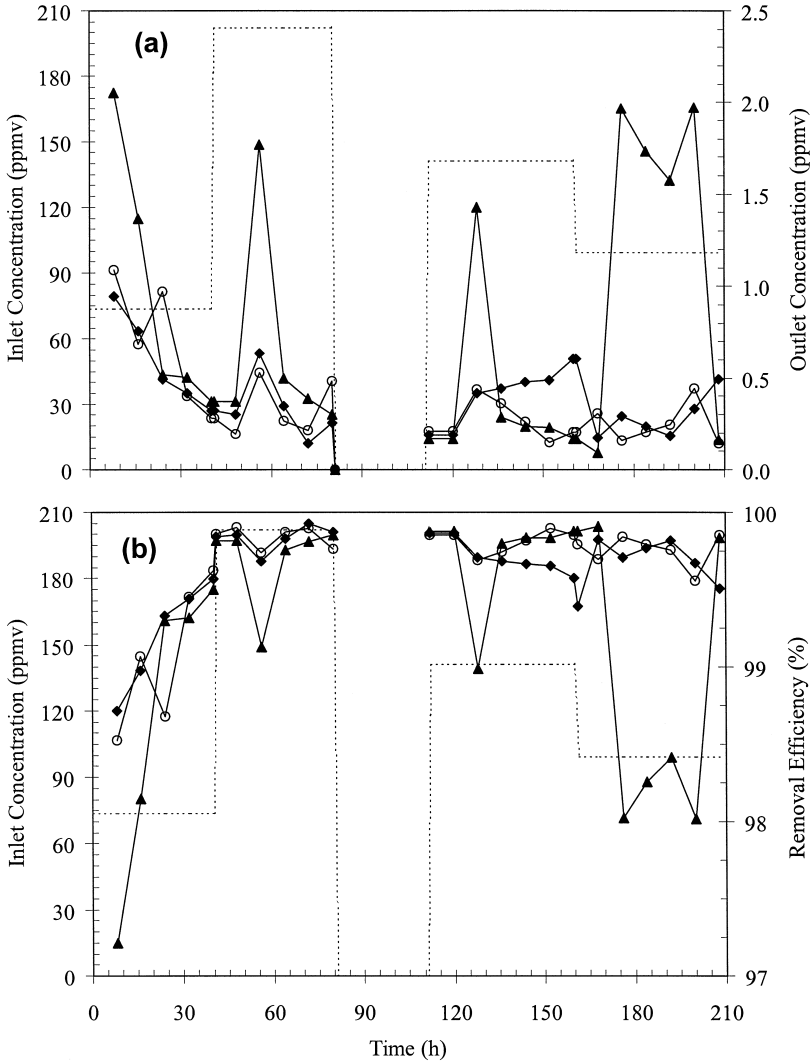

Fig. 2. Transient response of biofilters to step-changes in H_2S concentration ($L_s = 60$ m h^{-1}). --- H_2S inlet concentration; ♦ Compost biofilter; ○ Hog fuel biofilter; ▲ Mixture biofilter outlet concentrations in (a) and H_2S removal efficiencies in (b).

throughs in the second and the third steps and recovered to its original removal rates within 12 h. The third breakthrough in the mixture biofilter for the last step was longer and took 30 h to recover to its initial state.

3.2.2. Step Changes in Waste Airflow Rate

Maintaining the H_2S inlet concentration ($C_{in} = 100$ ppmv) constant, the effect of short time changes in airflow rate from 1.7 to 2.9 m^{-3} h^{-1}, characterized in terms of residence time, on the transient behavior of biofilters was investigated. Airflow rate was

changed stepwise keeping H_2S inlet concentration constant, so that the mass loading of H_2S changed proportionally. After adjusting the airflow rate/H_2S concentrations the system was allowed to stabilize for 48 h before another step change. A sequence of four test periods (τ, $0.85*\tau$, $0.6*\tau$, $0.7*\tau$) starting with the base case condition of $\tau = 38$ s were carried out.

The transient behavior of the biofilters to fluctuating airflow rates (Fig. 3), was similar to that of step changes in the H_2S concentration, with the compost and the hog

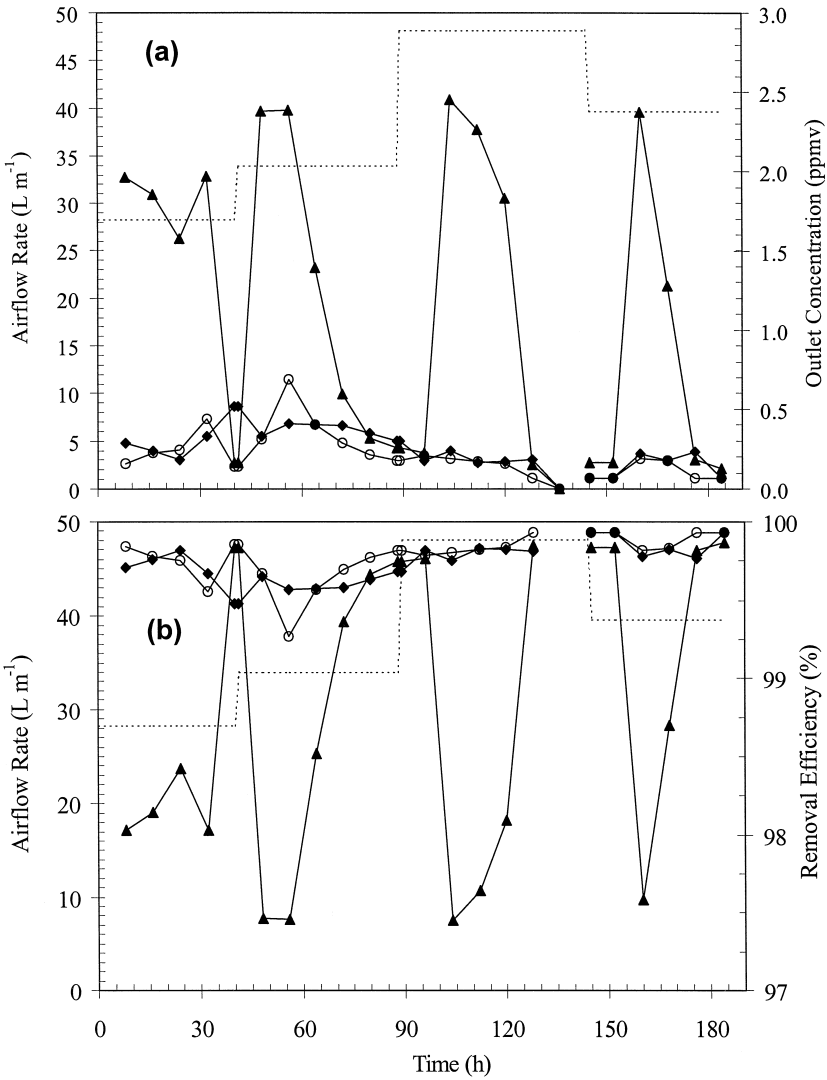

Fig. 3. Transient response of biofilters to step-changes in airflow rate ($C_{in} = 99$ ppmv). --- H_2S inlet concentration; ♦ Compost biofilter; ○ Hog fuel biofilter; ▲ Mixture biofilter outlet concentrations in (a) and H_2S removal efficiencies in (b).

fuel biofilters showing no breakthrough. The mixture biofilter showed short-lived peaks that lasted for 10–20 h, with each increment in the waste airflow rate that eventually increased the contaminant mass loading.

However, the reason why the mixture biofilter exhibited short-lived peaks after every step change in H_2S mass loading, in both the tests, is not clear. One probable explanation may be the reduced adsorptive capacity of the mixture filter bed, that was evident in the first test as the mixture biofilter started with lowest removal efficiency, while in case of compost and hog fuel biofilters H_2S was essentially removed by sorption after the step increases during the time the inactive microorganisms located in the unexposed parts of biofilter became active to turn on pollutant degrading mechanisms. Additionally, the reduction in the removal efficiency may be because of slow diffusion from gas to the liquid phase as a result of low gas retention time in the second test as reported by [16]; rather than reaction limitation because Sublette and Sylvester [17] reported that microorganisms could metabolize H_2S within 1–2 s. Nonetheless, no significant changes in the elimination capacity of any of the biofilters were observed as a result of the imposed step changes, which indicates that the biofilters were operated below their critical H_2S mass loading.

3.3. Biofilter response to contaminant spike

Pulse experiments were performed to study the dynamic response of biofilters to peaks in contaminant concentration similar to what might occur in the case of a process malfunction. An H_2S spike of 615 ppmv was applied for half an hour after a steady inlet concentration of 370 ppmv had been applied for about 6 h (corresponding to an increase in the mass loading from 48.7 to 80.9 g m^{-3} h^{-1}) (Fig. 4). The concentration spike caused an immediate increase in the outlet concentration in all the three biofilters, resulting in decreased removal efficiency. The removal efficiency, monitored immediately after the pulse was stopped, dropped from $> 99.5\%$ to 97% for the compost and the mixture biofilter, while in hog fuel biofilter it dropped to 96% from an initial value of about 98%. The biofilters then performed at low removal rates for a few hours before the microorganisms started to re-acclimate and gradually the removal efficiency improved. The elimination efficiency rapidly recovered to its original valve for the hog fuel and the mixture biofilter within 1.5 h while it took about 2.5 h to reach its initial valve in case of the compost biofilter.

Surprisingly, in this test the hog fuel biofilter could not reach a removal efficiency of greater than 98%, for some unknown reasons. One possible reason might be a toxic effect of higher concentrations of H_2S on the resident microbial communities by altering the media buffering capacity, as reported by Chung et al. [18], because hog fuel biofilter had the lowest bed pH in comparison to compost and mixture biofilters (Fig. 5). Nutrient (nitrogen) limitation also may be a contributing factor for the lowest removal efficiency because hog fuel has a very low content of total nitrogen. Nevertheless, the recovery time was relatively short suggesting that the microorganisms present in the biofilter media may require an immediate re-acclimation period to adopt to moderate disturbances/spikes in H_2S mass loading.

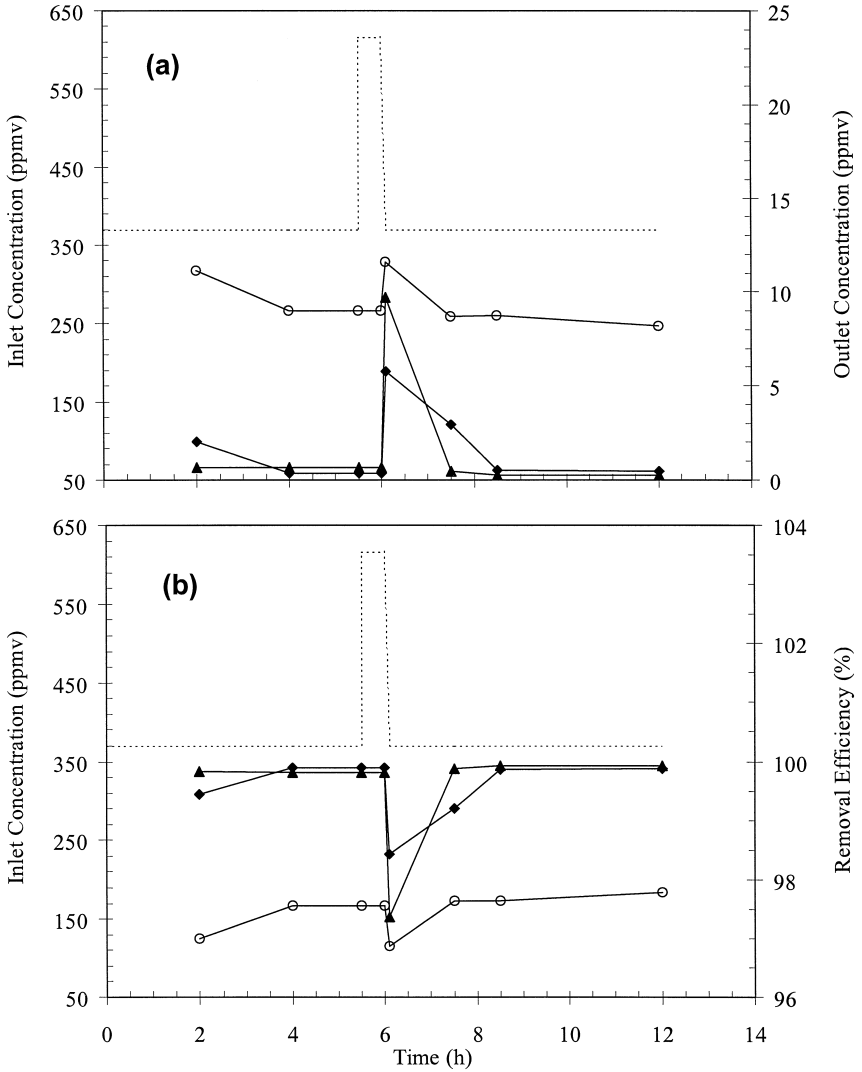

Fig. 4. Transient response of biofilters to H_2S concentration spike ($L_s = 60$ m h^{-1}). --- H_2S inlet concentration; ♦ Compost biofilter; ○ Hog fuel biofilter; ▲ Mixture biofilter outlet concentrations in (a) and H_2S removal efficiencies in (b).

3.4. Biofilter re-acclimation

Re-acclimation tests were conducted to examine the response of previously acclimated biofilters to starvation periods, to evaluate whether the biofiltration process can with stand such situations and to determine the time needed to recover full efficiency. Starvation included both the ‘idle phase’ when there was no airflow through the biofilter bed and the ‘no-contaminant-loading phase’ when only water saturated air was flowing

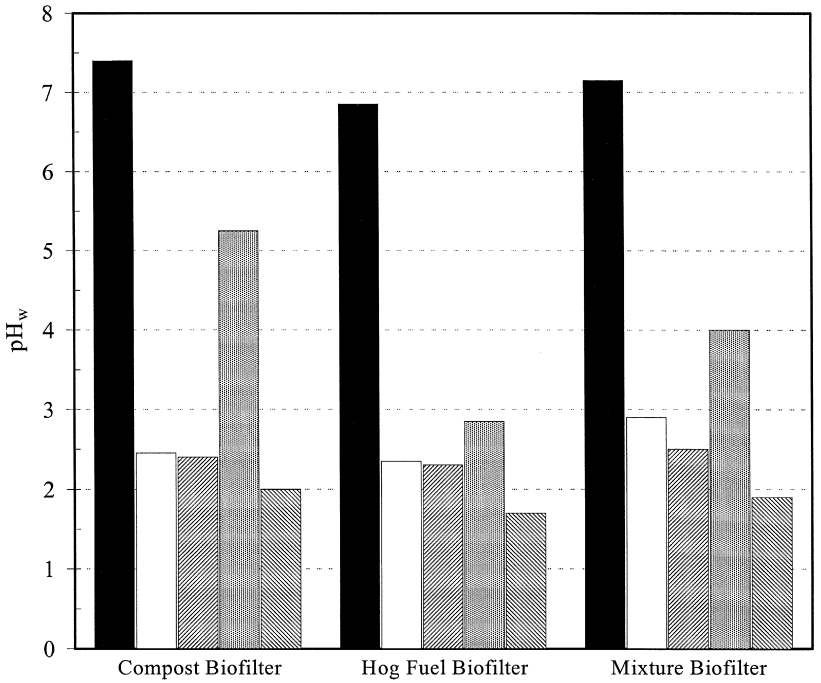

Fig. 5. Biofilter media and leachate pH. ■ Initial pH; □ Final pH (Ist stage); (right diagonal-filled square) Final pH (2nd stage); (dot-filled square) Final pH (3rd stage); (left diagonal-filled square) Leachate pH.

through the biofilter. As with initial acclimation, re-acclimation was considered to have been achieved when 99% removal was attained. Two periods of idle phase (3 and 7 days) and a period of no-contaminant-loading phase (3 days) were selected, however a summer vacation allowed the examination of an idle phase of 3 months. These periods were chosen to closely represent the real world periods of non-operation, such as 2 to 3 day weekends, and a 7 day period that could occur during mill shutdowns and process upsets.

3.4.1. Re-acclimation after idle phase

In the first experiment the biofilters were left idle for a week, after which the system was restarted under the same conditions pertaining prior to the interruption. At the end of this period, the H_2S mass loading was re-started at about 45 g m^{-3} h^{-1} (corresponding to C_{in} of 340 ppmv and L_s of 60 m h^{-1}). Fig. 6 shows the restart-up time course for the three biofilters after a 7 day starvation period. All the three biofilters rapidly recovered their initial removal efficiency of 99% within 25–30 h. The recovery pattern was almost same in all the three biofilters; however, the mixture biofilter showed the lowest removal efficiency after restart-up. Although H_2S removal efficiencies were low in the initial hours after the restart, some biodegradation took place immediately after the process was restarted, indicating that the H_2S degrading microorganisms already existed in the biofilters, but they were not quite active because of 7 days of starvation.

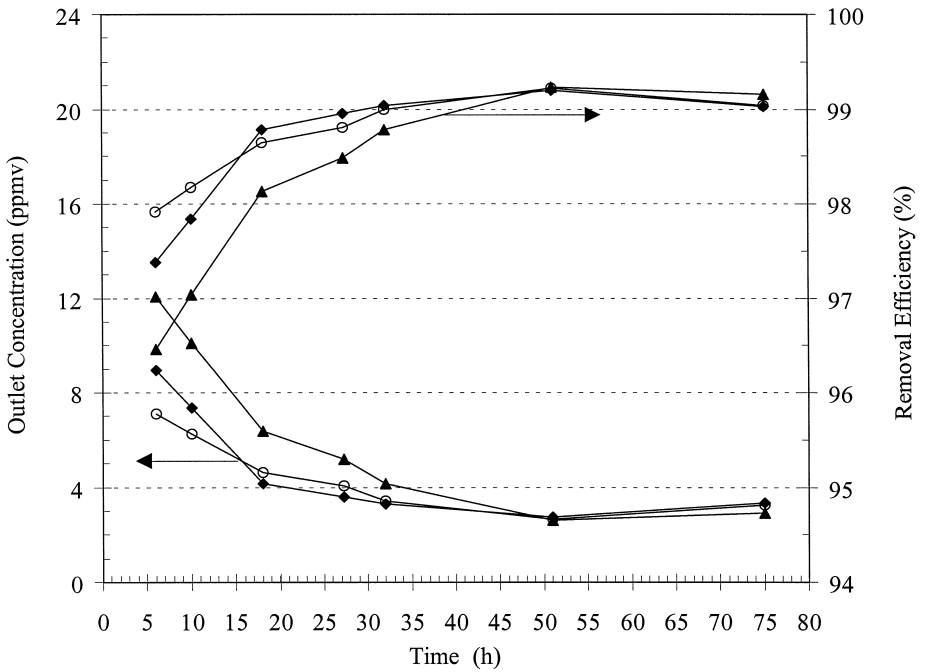

Fig. 6. Biofilter restart-up time course after 7 days of idle phase ($L_s = 60$ m h^{-1}, $C_{in} = 340$ ppmv). ♦ Compost biofilter; ○ Hog fuel biofilter; ▲ Mixture biofilter outlet concentrations and H_2S removal efficiencies.

This eventually led to a much shorter re-acclimation time as compared to the initial acclimation periods of 10–12 days for biofilters treating H_2S reported in the literature [19,20].

In the second test the biofilters were restarted after a period of 3 months during which there was no airflow through the biofilters at all. The operating conditions after the restart were same as before the break. The re-acclimation was started with the addition of H_2S mass loading at about 50 g m^{-3} h^{-1} (corresponding to C_{in} of 379 ppmv and L_s of 60 m h^{-1}). The biofilter re-acclimation is presented in Fig. 7. Here the biofilters showed a mixed pattern of recovery. Initially after the re-start the removal efficiency increased for first 24 h probably due to adsorption on the filter media, and then started declining up to 47 h in case of hog fuel and the mixture biofilters while even further up to 71 h for the compost biofilter. After 71 h the performance of compost and the mixture biofilters increased steadily reaching an elimination efficiency of 99% by 122 h. The elimination efficiency of the hog fuel biofilter decreased further after 71 h reaching approximately 97% by 122 h. After 122 h the removal efficiency for the compost and the mixture biofilter remained stable at around 99% while the hog fuel biofilter performance improved and reached 98% by 142 h. This re-confirmed the situation of toxicity of higher H_2S concentrations on the microbial populations resident in the hog fuel biofilter as observed in the earlier test with the biofilter response to H_2S concentra-

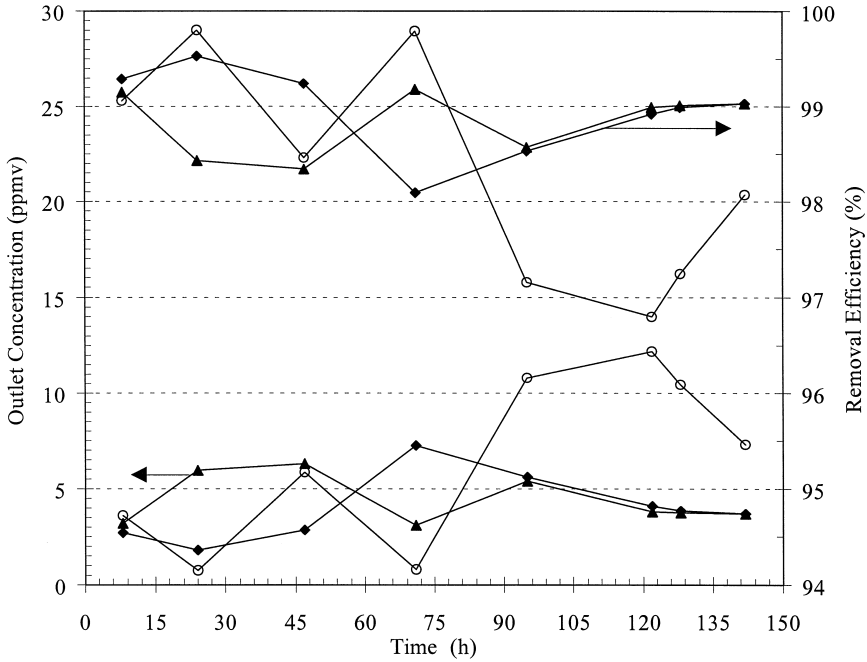

Fig. 7. Biofilter restart-up time course after 3 months of idle phase ($L_s = 60$ m h^{-1}, $C_{in} = 379$ ppmv). ◆ Compost biofilter; ○ Hog fuel biofilter; ▲ Mixture biofilter outlet concentrations and H_2S removal efficiencies.

tion spike. The test could not be continued further, because an H_2S gas cylinder was not available at the time. Nevertheless, the re-acclimation, although taking longer than for the 7 days starvation period, confirmed the earlier results of Martin and Loehr [9], and was significantly short as compared to the initial acclimation times reported by Degorce-Dumas et al. [19] and Furusawa et al. [20] mainly because biodegradation had already occurred during the sorption phase with immediate and efficient biodegradation restoration.

3.4.2. Re-acclimation after no-contaminant-loading phase

The biofilters were restarted under the same conditions as before, after a no-contaminant-loading phase of 3 days. The re-acclimation was started with the addition of H_2S mass loading at about 49 g m^{-3} h^{-1} (corresponding to C_{in} of 370 ppmv and L_s of 60 m h^{-1}). The results are summarized in Fig. 8. The re-acclimation pattern was similar to one after the idle phase, however the biofilters started with a removal efficiency of around 98%. The elimination efficiency increased almost linearly in case of the compost and the mixture biofilter reaching $> 99\%$ within 17 h. However, in case of the hog fuel biofilter the removal efficiency further dropped to about 96%. 25 h after restart-up the H_2S destruction efficiency was almost constant and $> 99\%$ for the compost and the mixture biofilter, while it reached about 97.5% in case of the hog fuel biofilter by 42 h. Once again the hog fuel biofilter could not achieve a removal efficiency of greater than

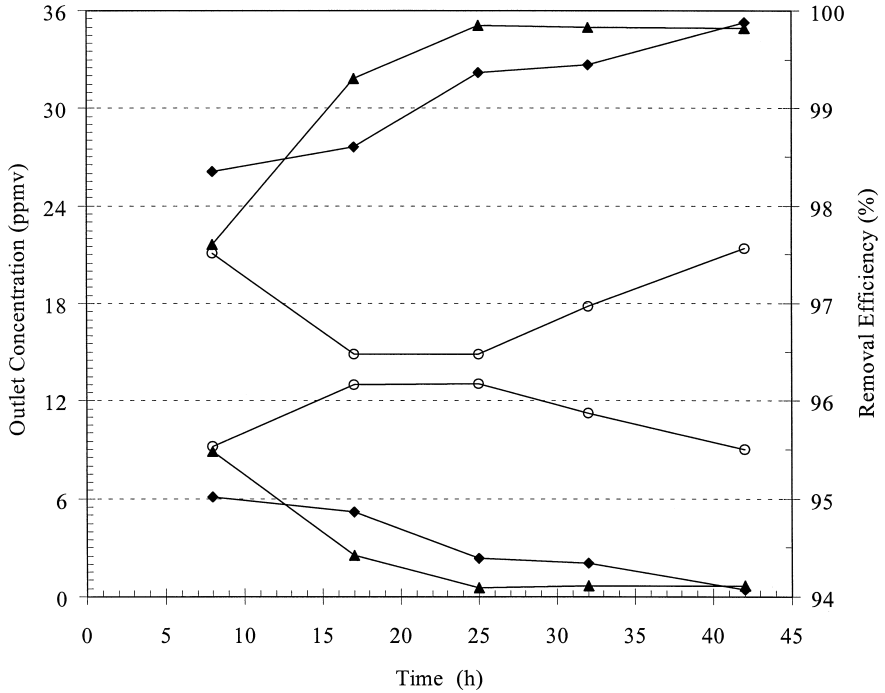

Fig. 8. Biofilter restart-up time course after 3 days of no-contaminant-loading phase ($L_s = 60$ m h^{-1}, $C_{in} = 370$ ppmv). ♦ Compost biofilter; ○ Hog fuel biofilter; ▲ Mixture biofilter outlet concentrations and H_2S removal efficiencies.

98% even after 42 h of restart-up time, confirming the microbial toxicity of higher concentrations of H_2S. It may be noted that these tests were conducted after 6 months of continuous operation of the biofilters treating H_2S. Nevertheless, the re-acclimation time was much shorter, about half of the restart-up time after the 7 day idle phase, justifying the results of Martin and Loehr [9] that re-acclimation measured by achieving desirable removal efficiency is achieved significantly faster if humidified air containing no contaminant is passed through the biofilter rather than letting the biofilter stagnate with no air flow.

4. Conclusions

Step changes both in H_2S concentration and the waste airflow rate demonstrated that the biofilters acclimatized rapidly to the new operating conditions. The compost and hog fuel biofilters were found to respond more rapidly to fluctuating mass loading as compared to the mixture biofilter that exhibited short term breakthroughs at each increment in mass loading. During transient state operation the sorption capacity of the filter material played an important role to peak shave the concentration loads. In most

cases about 2–8 h were needed after the step changes by the biofilters to recover to initial removal capacity. This is similar to the findings of Deshusses et al. [2,3] for ketones in compost based biofilters.

H_2S pulses to the biofilters showed that when H_2S was pulsed, degradation rates were reduced initially in all the three biofilters for few hours until the microorganisms started to adapt to the new environment. Then the removal efficiency gradually increased and reached the initial level prevalent before the concentration spike. This demonstrated that at extremely high concentrations, H_2S self inhibited its biodegradation, as also reported by Chung et al. [18]. The biofilters took about 1.5–2.5 h to reach the original removal capacity after the H_2S pulse was stopped.

The biofilters were found to be capable of withstanding different periods of starvation with rapid recovery to full performance when starvation ceased. Longer periods of idle phase required longer periods of re-acclimation. Additionally, a no-contaminant-loading phase experienced a shorter restart-up time as compared to idle periods of non-use. Moreover, early removal efficiency was lower after the idle phase than after the starvation period with no-contaminant-loading. The re-acclimation time (5 days) for the biological activity after the longest starvation period of 3 months was much shorter than the literature reported [19,20] initial start-up period of 10–12 days, and the biofilters reached their maximum efficiency after 120 h. The hog fuel biofilter was identified as less efficient than compost and the mixture biofilter in recovering to original removal capacity after different periods of starvation.

Acknowledgements

The authors would like to acknowledge the financial support from the Science Council of British Columbia (SCBC) and the Pulp and Paper Research Institute of Canada (PAPRICAN). The authors also express their gratitude to Barbara Buchanan of PAPRICAN for her continued assistance in gas analysis during the research.

References

[1] R.J. Abumaizer, E.H. Smith, W. Kocher, J. Environ. Eng. 123 (1997) 606.
[2] M.A. Deshusses, G. Hamer, I.J. Dunn, Biotechnol. Bioeng. 49 (1996) 587.
[3] M.A. Deshusses, J. Environ. Eng. 123 (1997) 563.
[4] A.H. Wani, R.M.R. Branion, A.K. Lau, J. Environ. Sci. Health 32A (1997) 2027.
[5] G.A. Sorial, F.L. Smith, M.T. Suidan, P. Biswas, R.C. Brenner, J. Hazard. Mater. 53 (1997) 19.
[6] Y. Yang, E.R. Allen, J. Air Waste Manage. Assoc. 44 (1994) 1315.
[7] T.S. Webester, J.S. Devinny, E.M. Torres, S.S. Basrai, Environ. Prog. 15 (1996) 141.
[8] R.L. Morton, R.C. Caballero, Proc. 90th Annual Meet. and Exhibition of Air and Waste Manage. Assoc., Toronto, (June 8–13, 1997) Paper # 97-WP71B.04.
[9] F.J. Martin, R.C. Loehr, J. Air Waste Manage. Assoc. 46 (1996) 539.
[10] H.M. Tang, S.J. Hwang, S.C. Hwang, Hazard. Waste Hazard. Mater. 12 (1995) 207.
[11] M. Mohseni, D.G. Allen, Proc. 90th Annual Meet. and Exhibition of Air and Waste Manage. Assoc., Toronto (June 8–13, 1997) Paper # 97-WP71B.04.

[12] M.J. Gibson, L. Otten, Proc. 90th Annual Meet. and Exhibition of Air and Waste Manage. Assoc., Toronto (June 8–13, 1997) Paper # 97-WA71A.03.
[13] Y. Yang, E.R. Allen, J. Air Waste Manage. Assoc. 44 (1994) 863.
[14] A.H. Wani, R.M.R. Branion, A.K. Lau, Submitted to J. Air and Waste Manage. Assoc. 1997.
[15] Environment Canada, Reference Method EPS1/RM/6, January 1992.
[16] Y.C. Chung, C. Huang, C.P. Tseng, J. Biotechnol. 52 (1996) 31.
[17] K.L. Sublette, N.D. Sylvester, Biotechnol. Bioeng. 29 (1987) 249.
[18] Y.C. Chung, C. Huang, C.F. Li, J. Environ. Sci. Health 32A (1997) 1435.
[19] J.R. Degorce-Dumas, S. Kowal, P. Le Cloirec, Can. J. Microbiol. 43 (1997) 264.
[20] N. Furusawa, I. Togashi, M. Hirai, M. Shoda, H. Kubota, J. Ferment. Technol. 62 (1984) 589.