# Regular Transient Loading Response in a Vapor-Phase Flow-Direction-Switching Biofilter

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**Abstract:** The principal objective of this study was determination of the response of a laboratory-scale vapor-phase flow-direction-switching biofilter to loading changes associated with normal operations such as lunch breaks, overnight shutdowns, and single-shift operation of commercial and industrial facilities. Three regular transient loading cases were considered: (a) variable flow-reversal interval lenghts, (b) variable feed-on/off interval lengths, and (c) variable inlet concentration during a repeating feed-on/off cycle. Toluene was used as the model contaminant compound. The most significant findings of the study were: (1) Relative to unidirectional mode of operation, periodic flow reversal produced a more uniform distribution of reaction capacity along the length of the packed bed; (2) a 12 h flow reversal interval was sufficiently short to maintain the toluene-degrading microbial community in a near-fully active state throughout the unit whereas a 2 day flow reversal interval resulted in diminished removal rates in the first half of the bed and (3) Increasing off-period length resulted in greater penetration of contaminant into the bed and more uniform removal rates along the length of the bed. Information developed in this study should provide a more complete basis for establishing operating protocols and monitoring regulations for vapor-phase biofiltration systems.

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**CE Database subject headings:** Filtration; Biological treatment; Air pollution; Gas.

## Introduction

Biological treatment has become a commonly used method of reducing odors and other organic and inorganic contaminants from contaminated air streams, however, application of biological treatment has been limited by questions of process reliability. A major factor in process reliability is the ability of biological processes to respond to transient (varying) loadings. The focus of this research was to investigate the response of the most common type of vapor-phase biological treatment, biofilters, to transients resulting from regular flow-direction reversal, and cyclical feed-on/off operation. Regular flow reversal has been shown to increase reaction capacity in biofilter response to transient loadings (Kinney 1996; Song and Kinney 2000; Wright 2004; 2005; Wright et al., 2005.). Cyclical on/off operations result from temporary shut downs of manufacturing and commercial processes for periods typically ranging from seconds to days. When the contaminant feed stops microbial communities begin to enter a starvation survival mode of existence and, if the period is long enough, begin to die. Restarting the feed will result in temporarily reduced removal capacity as reactivation of the microbial communities takes time.

Most of the data reported in the literature on biofilter performance were the results of analysis of grab samples from systems operating at nominal steady state with contaminant concentration held constant. However, contaminant concentration is highly variable in most air streams. Correspondingly, off-gas characteristics from manufacturing and commercial operations will typically vary with time due to changes in processes, shut downs, shift changes, and spills. The performance of biofilters subject to transient loadings have been studied by a number of researchers (Al-Rayes et al. 2001; Campbell and Connor 1997; Damborsky et al. 1999; Deshusses 1995; Deshusses et al. 1995, 1996, 2001; Dirk-Faitakis and Allen 1998; Ergas et al. 1995a, b; Hodge and Devinney 1995; Irvine and Moe 2001; Kinney 1996; Kirchner et al. 1994; Leson and Winer 1991; Marek et al. 2000; Martin and Loehr 1996; Métris et al. 2001; Moe and Irvine 2001; Mysliwiec et al. 2001; Park and Kinney 2001; Parks and Loehr 1994; Schroeder et al. 2000; Schroeder 2002; Seed and Corsi 1994; Shi et al. 1995; Song and Kinney 2000, 2001; South Coast Air Quality Management District 1994; Tang et al. 1995; Tang and Hwang 1997; Tonga and Frisch 1993; Weber and Hartmans 1995; Woertz et al. 2001; Wright 2004; 2005; Wright et al. 1997, 2005). However, more information is needed because the relationship between transient loadings and biofilter response remains poorly understood (Deshusses 1995; Deshusses et al. 1996; Irvine and Moe 2001; Kinney 1996; Martin and Loehr 1996; Mysliwiec et al. 2001; Song and Kinney 2001; Tang et al. 1995; Tang and Hwang 1997; Schroeder et al. 2000; Schroeder 2002). In particular, more study is needed on biofilter response during extended periods of operation with repeating (cyclical) loading patterns, including regular feed-on/feed-off loading. In addition, more information on response within (along the length of) the packed bed

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is preferred to full-bed response (measured at the biofilter outlet), which is the response commonly reported. Observations of field installations (Ergas et al. 1995a; Wright et al. 1997), laboratory systems (Deshusses 1995; Deshusses et al. 1995, 2001), and industrial sources (South Coast Air Quality Management District 1994; Togna and Frisch 1993), result in the conclusion that adequate process monitoring and control of biofilter performance will require improved knowledge of transient loading response characteristics.

Transient loadings can be considered "regular" if they occur frequently on a repeating basis due to normal cycles in process operations, overnight and weekend closures, and scheduled maintenance activities. Regular transient loadings result from an intensification of work (e.g., higher rates of solvent use in a manufacturing process) and occur during changes in operation throughout an operating shift of manufacturing and commercial operations such as paint spraying, baking, coating, and chemical manufacture. "Irregular" transient loadings result from random or erratic events such as spills and unplanned shutdowns. Irregular transient loadings have been observed in emissions from wastewater treatment plants where relatively small diurnal transient loadings were overshadowed by occasional large spikes at intervals as long as several months (Ergas et al. 1995a).

### Transient Loading Response

The microbial population will adjust immediately to a sudden inlet concentration increase with increased mass removal rates. However, as the magnitude of the transient increases, measured as the ratio of peak-to-baseline concentration (or ratio of peak-to-mean concentration), the reaction capacity of the system can be exceeded and contaminants will penetrate deeper into the filter bed. A corresponding process exists with respect to downtime. When a unit is shut down for a period of time that is sufficiently long the microbial population begins to go do dormant. For short down periods deterioration in performance may not be measurable. However, as the downtime becomes longer reaction capacity is lost and increased penetration of contaminants will occur on start up (Deshusses et al. 1996; Kinney 1996; Marek et al. 2000; Martin and Loehr 1996; Park and Kinney 2001; Song and Kinney 2001; Tonga and Frisch 1993; Woertz et al. 2001; Wright 2005). In both cases, as concentration or downtime increase, a point will be reached where breakthrough occurs and untreated contaminants are emitted. If a step increase in contaminant concentration is sustained for an extended period of time, contaminant removal rates will increase in time as the population acclimates and grows. The process is slow and typically takes several days or weeks to complete (Parks and Loehr 1994; Seed and Corsi 1994; Tang et al. 1995). Following down periods the microbial population will re-acclimate and typically recover completely in a relatively short period of time, e.g., one or two days (Kirchner et al. 1994; Tang et al. 1995).

The limitations on transient loading response are important because (1) many desirable applications for biofilters will be at operations having transient loadings (e.g., enterprises with variable processing rates and operating on one or two shifts per day and/or closing on the weekends), and (2) appropriate performance monitoring requirements should reflect actual operating characteristics. Emission standards are usually based on the expectation that contaminant mass exiting the biofilter will be limited to a prescribed value during a specified period of time, or that it will not occur at any time. However, transient loadings, such as those that occur upon start-up following weekend closures, are common and they can result in elevated levels of contaminant passing through biofilters (untreated) for short periods of time on a regular basis. As a result, monitoring programs that rely on periodic grab samples obtained during steady-state operation can underestimate the quantity of contaminant discharged from the unit. Currently available models cannot be used to predict transient loading response with great accuracy because adequate characterization of the microbial population is not possible at this time (Mysliwiec et al. 2001). Therefore, a significant need exists to develop greater understanding of the relationship between transient loadings and biofilter response and to develop operating strategies to manage transient loadings and minimize contaminant breakthrough.

### Sorption

Sorption/desorption effects are typically minor in mature biofilters treating compounds with low to moderate solubility in water, (Al-Rayes et al. 2001; Campbell and Connor 1997), particularly when rigid/pelletized inorganic packing materials are used (Woertz et al. 2001). In contrast, sorption/desorption can be significant upon start-up (or restart following extended down periods), when the contaminant is highly soluble (Al-Rayes et al. 2001; Campbell and Connor 1997; Deshusses et al. 1995), or when the packing has high organic matter content (Hodge and Divinney 1995; Marek et al. 2000; Martin and Loehr 1996; Tang et al. 1995; Tang and Hwang 1997; Weber and Hartmans 1995).

### Flow-Direction Switching

Maintaining a more uniform microbial population throughout the column by alternating the direction of flow has been shown to provide high levels of reaction capacity along a greater fraction of the column's length. The additional reaction capacity results from increasing the microbial population density in the downstream half of the bed and maintaining that population in an active state. Early evidence that alternating flow direction approach would be successful was provided in experiments by Kinney (1996) who moved the inlet point from the first section to the second section of a four-section biofilter. Contaminant removal rates in the second section increased immediately. However, response in the third and fourth sections of the biofilter were poor, as would be expected if microbial population densities were low and the cells were relatively inactive. Song and Kinney (2000) extended this work and demonstrated that both biomass and biomass activity decreased along the length of a unidirectional flow biofilter and were maintained relatively constant in a flow directional switching (FDS) biofilter. Wright (2004; 2005) and Wright et al. (2005) found that reaction capacity nearly doubled and breakthrough of untreated contaminant was eliminated or reduced during transient loading events as a result of periodic flow-direction switching.

Reversing the direction of flow in a biofilter is not a difficult process in laboratory-scale systems and it might be feasible in full-scale systems. The most significant unknown in the application of flow reversal to control transient loadings is the operational time that should be used before flow reversal. Beyond some threshold length of time, the longer the interval between flow reversals the greater the temporary loss of bacterial activity and removal capacity in the first half of the bed following flow reversal and the the longer it takes to recover the lost activity and removal capacity. The time between flow reversals must be short enough to maintain a majority of the population in the column in an active state. The optimum time between flow reversals will be a function of the type of microorganisms involved. Song and

**Table 1.** Operation Parameters for Regular Transient Loading Scenarios

| Parameter | Cycle period length (h)[a] | | | |
|---|---|---|---|---|
| | 4 | 8 | 16 | 32 |
| Peak-to-mean-loading-ratio 2 | | | | |
| Period duration | | | | |
| • Feed interval (hours): | 2 | 4 | 8 | — |
| • Off interval (hours): | 2 | 4 | 8 | — |
| Peak-to-mean-loading-ratio 8 | | | | |
| Period duration | | | | |
| • Feed interval (hours): | — | 1 | 2 | 4 |
| • Off interval (hours): | — | 7 | 14 | 28 |

[a]Cycle period length = sum of feed-on and feed-off periods.

Kinney (2001), studying 1, 3, and 7 day flow direction switching frequencies, reported that a 3 day flow reversal period provided the best overall performance, balancing reduced reacclimation times provided by frequent switching against long-term stability provided by longer switching periods. In addition it was reported that the 3 day switching frequency produced the largest elimination capacity.

### Research Objectives

The primary objectives of this study were to determine the relationship between regular contaminant loading pattern and response in a flow-direction switching biofilter. Three loading cases were considered.

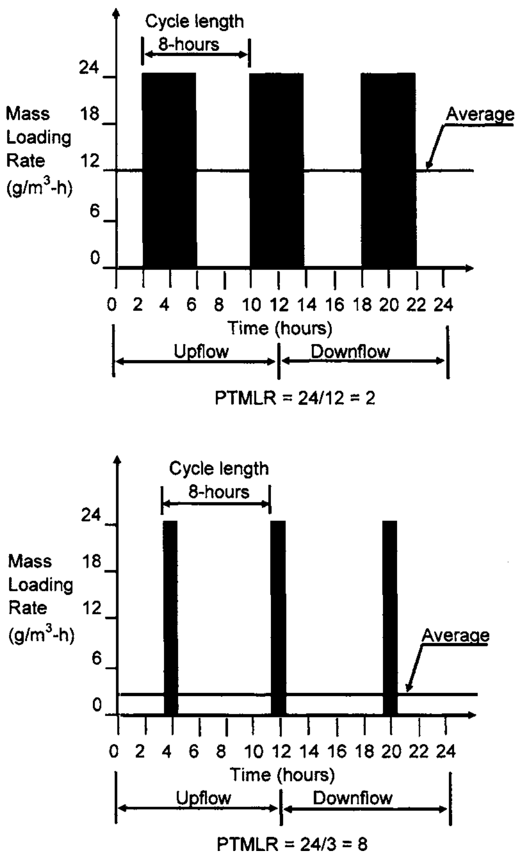


**Fig. 1.** Illustration of two cases of regular transient loading patterns with 8 h cycle lengths superimposed on a flow-direction switching interval of 12 h. The top pane represents a peak-to-mean-loading-ratio (PTMLR) value of 2 (4-h-on/4-h-off) and the bottom panel represents a PTMLR value of 8 (1-h-on/7-h-off).

1. Variable flow-reversal interval length;
2. Variable feed-on/feed-off interval lengths; and
3. Variable inlet concentration during a regular feed-on/off loading pattern.

Biofilter response was assessed by monitoring toluene vapor concentration at several points along the length the packed beds. Toluene was used as a model contaminant because it is a common solvent with widespread use in industry and is a component of gasoline, water-based paints, and many other commercial products. Fractional removal of toluene in a given segment of the bed was determined by subtracting the toluene concentration value measured at the downstream end of the segment from the value measured at upstream end of the segment. Volumetric flowrate was held constant throughout all of the experiments.

## Materials and Methods

### Experimental Apparatus

The biofilter column was constructed of 15 cm-inner-diameter stainless steel pipe consisting of four 25-cm-long media bed sections in series separated by 5-cm-deep plenums for sampling. The packing media was 0.64-cm-diameter rigid mineral (extruded diatomaceous earth) cylindrical pellets (Celite R-635, Janus Scientific Inc., Fairfield, Calif.). An air-stream containing toluene vapor and nutrient aerosol was conveyed to the inlet of the FDS biofilter column (top or bottom depending on the cycle phase) using a double solenoid, four-way, five-port valve and electronic controller. A more complete description of the experimental apparatus, nutrient solution, and air-stream sampling and analysis have been described previously (Wright 2004, 2005; Wright et al. 2005), except, in this study, only one FDS biofilter was used, new media was used at startup, and the feed apparatus did not include a humidifier or aerosol reduction device.

### Biofilter Startup and Operation

The FDS biofilter operated with a nominal air-stream flux of 1 $m^3/m^2$ min, empty-bed contact time of 1 min and media bed temperature of 23°C. The FDS biofilter operated on a 12 h FDS interval length throughout the study with the exception of the FDS Interval Length experiment in which the period was extended to 24 and 48 h (see paragraph below). Nutrient solution was recirculated through the packing when performance in the inlet region of the bed deteriorated significantly. Pressure drop across the bed was measured five times during the study period and values ranged from 0.1 to 0.4 in. of water column.

#### Flow-Direction Switching Interval Length

The relationship between FDS interval lengths and removal rates was investigated by measuring toluene removal in the packed bed after steady-state response was achieved. The experiment was conducted with constant loading at a nominal inlet concentration ($C_0$) of 107 $ppm_v$ and a FDS interval length value of 12 h. Inlet $C_0$ values varied over an approximate range of 30 ppm due to slight irregularities in the syringe pump movement with time. The experiment was repeated using a FDS interval length of 24 and of 48 h.

#### Regular On/Off Transient Loading

Cyclical feed-on/off transient loading experiments were conducted to investigate the impact of variable values of cycle length,

**Table 2.** Timeline for Segments (Runs) of the Study

| Segment of the study | Run 1 | Run 2 | Run 3 | Run 4 |
|---|---|---|---|---|
| Elapsed time (days) since startup of the biofilter | 116 | 172 | 264 | 324 |

average loading rate, and $C_0$ on biofilter response. Cycle length was the sum of feed-on and feed-off period lengths. Average loading rate was expressed as "peak-to-mean-loading-ratio" (PTMLR), the ratio of nominal loading rate during feed-on periods to nominal average loading rate over the cycle period. Air, toluene vapor, and nutrient aerosol were passed through the biofilter during the "feed-on" periods. Toluene feed was discontinued during "feed-off" periods whereas air and nutrient aerosol flow was continued. For each regular transient-loading experiment, gas-stream samples were collected at the same point in time within the FDS interval each day.

Biofilter response to variable cycle lengths were investigated using PTMLR values of 2 and 8 and a nominal $C_0$ value of 107 $ppm_v$. Operation parameters for the experimental scenarios are given in Table 1. For the PTMLR value of 2, cycle period lengths of 4, 8, and 16 h were used. For the PTMLR value of 8, cycle period lengths of 8, 16, and 32 h were used. In a separate set of experiments, biofilter response to variable inlet concentration during a PTMLR 8 regular 1-h-on/7-h-off loading pattern was investigated. In these experiments $C_0$ values used were 107, 214, and 428 $ppm_v$ and the corresponding nominal average loading rate values were 3.0, 6.1, and 12.2 $g/m^3$ h, respectively. A hypothetical illustration of regular transient loading is provided in Fig. 1 for a cycle length of 8 h and PTMLR values of 2 (top) and 8 (bottom).

The loading patterns are regular when considering the biofilter as a whole. However, inspection of Fig. 1 reveals that the loading pattern is not strictly regular within each loading cycle when considering each end of the flow-direction-switching biofilter separately. For example, in the case of PTMLR 2 with an 8 h cycle length, the loading pattern as experienced by the bottom end of the biofilter beginning with the end of the previous (upflow) feeding cycle (Fig. 1, top, 12th hour) is 14-h-off/4-h-on/4-h-off/2-h-on/ and then repeats. In the case of PTMLR 8 (Fig. 1, bottom), the loading pattern is 15.5-h-off/1-h-on/7-h-off/0.5-h-on / then it repeats. When the phrase "regular transient loading" is used in this study reference is to the loading pattern as experienced by the biofilter as a whole.

## Results and Discussion

The biofilter was operated with constant loading (107 $ppm_v$) in FDS mode for 115 days prior to conducting the regular transient loading experiments. During that time modifications were made to improve system reliability and control. A timeline for segments

**Table 3.** Initial Conditions, Period Durations, and Other Parameters for the Feed-On/Feed-Off Regular Transient Loading Experiments

| Transient loading parameter | Cycle period length (h)[a] | | | |
|---|---|---|---|---|
| | 4 | 8 | 16 | 32 |
| **Peak-to-mean-loading-ratio 2** | | | | |
| Period duration | | | | |
| • Feed interval (hours): | 2 | 4 | 8 | — |
| • Off interval (hours): | 2 | 4 | 8 | — |
| • Transient state (days)[b]: | 11 | 11 | 19 | — |
| • Experiment (days): | 18 | 14 | 27 | — |
| Initial condition[c]: | CF 2 | PTMLR 2/CP 4 | CF 3 | — |
| At start of first feed interval, elapsed time since | | | | |
| • startup of biofilter (days): | 181 | 201 | 216 | — |
| • last nutrient recirculation (days) | 63 | 84 | 99 | |
| • flow direction switch (hours) | 1.0 | 2.2 | 0.17 | — |
| Flow direction during sampling | up | up | up | — |
| **Peak-to-mean-loading-ratio 8** | | | | |
| Period duration | | | | |
| • Feed interval (hours): | — | 1 | 2 | 4 |
| • Off interval (hours): | — | 7 | 14 | 28 |
| • Transient state (days)[b]: | — | 15 | 8 | 9 |
| • Experiment (days): | — | 21 | 12 | 17 |
| Initial condition[c]: | — | CF 4 | CF 1 | PTMLR 8/ CP 16 |
| At start of first feed interval, elapsed time since: | | | | |
| • start-up of biofilter (days): | — | 122 | 134 | 147 |
| • last nutrient recirculation (days) | — | 5.7 | 18 | 31 |
| • flow direction switch (hours) | — | 3.33 | 2.83 | 1.83 |
| Flow direction during sampling | — | up | up | up |

[a]Cycle period length = sum of feed-on and feed-off periods.

[b]Transient state = time required to achieve pseudo-steady-state biofilter response.

[c]Initial condition = loading condition prior to the start of the experimental run; CF X refers to continuous feed, run X; PTMLR X refers to peak to mean loading ratio, value X; and CP X refers to cycle period, length X.

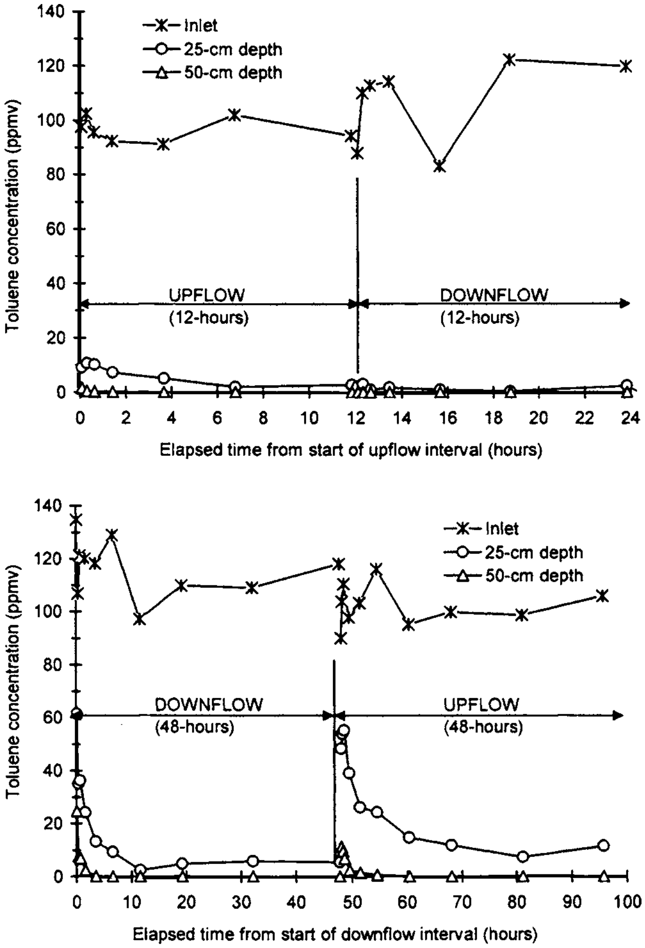


**Fig. 2.** Concentration profiles for constant loading with flow-direction switching interval lengths of (top) 0.5 days and (bottom) 2 days. Note that 50 cm is the midpoint depth of the unit and that breakthrough did not occur.

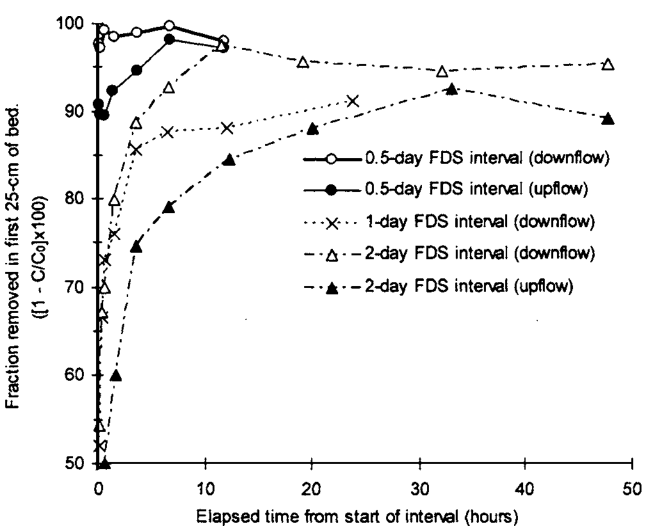


**Fig. 3.** Fraction removed (%) in the first 25 cm of the bed for constant loading with flow-direction switching (FDS) interval lengths of 0.5, 1, and 2 days. Response data for the 1 day FDS upflow interval was not collected. Elapsed times of operation following a nutrient recirculation procedure for the 0.5, 1, and 2 day FDS interval lengths were 3, 18, and 8 days, respectively. The nominal feed concentration was 107 ppm$_v$.

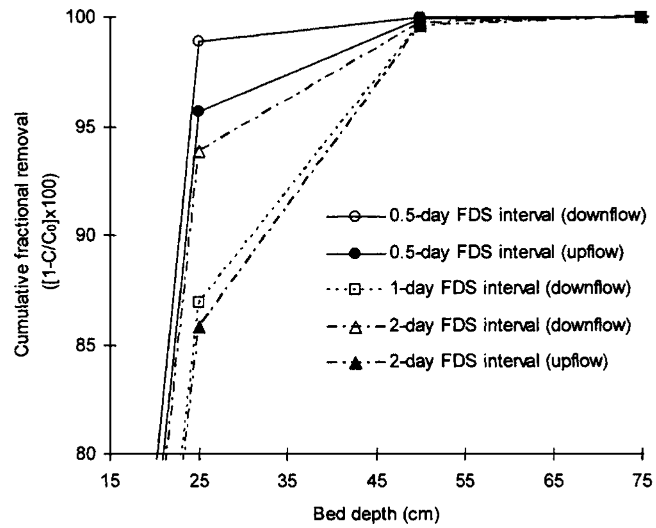


**Fig. 4.** Constant loading response as a function of bed depth for variable flow-direction switching (FDS) interval lengths based on weighted mean values over the interval. Note that the vertical (cumulative fractional removal) scale begins at 80%.

of the study (shown as Runs 1–4) is provided in Table 2. Each "run" began with several days of constant loading followed by transient loading experiments. The variation of feed-on/feed-off interval length experiments were conducted during Runs 1–3 and further details of those experiments, including initial conditions, transient loading period durations, and other parameters are provided in Table 3. The variable inlet concentration with regular feed-on/off loading experiments and the variable flow-reversal interval length experiments were conducted during Run 4. Results are discussed in the following.

### *Variation of Flow-Reversal Interval Length*

Biofilter response to variation of FDS interval length after several (6 to 12) days of operation at the stated FDS interval length with constant loading at a nominal $C_0$ value of 107 ppm$_v$ are presented

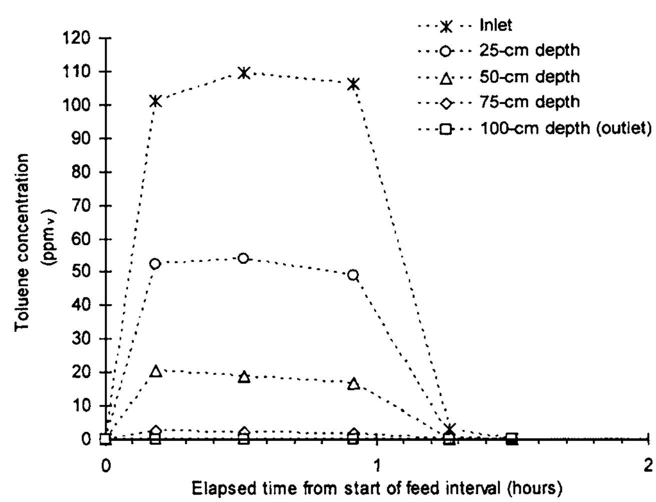


**Fig. 5.** Pseudo-steady-state response of the 12 h flow-direction switching biofilter to a 1-h-on/7-h-off regular transient loading pattern during a feed interval (note: the feed interval was followed by 7 h of no feed and then the pattern repeated)

in Figs. 2–4. Toluene concentration at the inlet, 25, and 50 cm depths of the bed over consecutive up and down flow direction intervals are presented in Fig. 2, top and bottom, for FDS interval lengths of 0.5 and 2 days, respectively. The fraction of inlet toluene concentration removed in the first 25 cm of the bed over time is given in Fig. 3 for FDS interval lengths of 0.5, 1, and 2 days. Data collection for the 0.5, 1, and 2 day FDS interval characterization was initiated 3.5, 18, 8 days after the unit was regenerated with nutrient solution, respectively. Response profiles as a function of bed depth are presented in Fig. 4. Data markers are weighted average response values over the flow switching interval.

Although the feed concentrations and loading rates were relatively low, total biofilter response was excellent (complete removal in the first-half of the bed) for all operating cases (upflow, downflow, and variable FDS interval length) and the impact of transient loading on biofilter response was apparent only in the inlet region of the bed. A direct comparison between upflow and downflow responses can be made because consecutive data sets were taken over a single upflow-downflow cycle. Differences in response between downflow and upflow mode of operation following the flow-direction switch is believed to be an artifact resulting from differences in moisture content, temperature, or pH at each end of the biofilter bed (Mysliwiec 2001). When the unit was in downflow mode a 0.5 day flow reversal interval was sufficiently short to maintain the toluene-degrading microbial community in a fully active state and a 2 day switching interval was long enough to negatively impact performance in the first-half of the bed for approximately a 10 h period. When in upflow mode there was a minor impact in the first half of the bed for a 0.5 day switching interval and a deeper/longer (30 h) impact for the 2 day FDS interval, as can be seen in Figs. 2 and 3. Note that the 1 day FDS interval performance was little different than the 2 day FDS interval. The 1 day interval experiment was conducted 18 days after a nutrient recirculation procedure whereas the 2 day interval experiment was conducted only 8 days after nutrient recirculation. During the 2 day interval experiment the first 25 cm of the bed was probably experiencing some channeling due to nonuniform moisture distribution or clogging, factors that may have decreased removals. Cumulative fractional removals as a function of bed depth can be found in Fig. 4 for variable FDS interval lengths based on weighted mean values over the upflow and dowflow intervals. Overall fractional removals averaged 97 and 90% in the first 25 cm of the bed for the 0.5 and 2 day FDS interval lengths, respectively.

Significant levels of reaction capacity existed at both ends of the FDS biofilter (shown in Figs. 2–4) and this favorably distinguishes FDS biofilters from conventional unidirectional biofilters which typically have minimal levels of reaction capacity in the second half of their beds (Ergas et al. 1994; Kinney 1996; Song and Kinney 2001; Wright 2004, 2005; Wright et al. 2005). The results of this study support conclusions reached by Song and Kinney (2001) that relative to unidirectional mode of operation, periodic flow reversal produced a more uniform distribution of reaction capacity along the length of the packed bed. In the work by Song and Kinney, the effect of flow direction switching interval length on the distribution of biomass and toluene degrading activity was investigated for interval lengths of 1, 3, and 7 days after 23, 34, and 44 days of operation, respectively. In general, biofilter fractional removals reported here are greater than in work by Song and Kinney, probably because the experiments of this study were done at an earlier stage in the biofilter's run and the inlet concentration was approximately half that used in the experiments by Song and Kinney. Other relevant results from the work by Song and Kinney include (1) no apparent lag (reacclimation/reactivation) period following direction switches for 1 day switching intervals (same as observed in this study for the 0.5 day interval), (2) the existence of a lag (reacclimation) period for 3 and 7 day switching intervals (same as observed in this study for the 1 and 2 day intervals), and (3) performance in the inlet region diminished with time of operation.

### *Variation of Feed-On/Feed-Off Interval Length*

Pseudo-steady-state biofilter response to 1-h-on/7-h-off regular transient loading (peak-to-mean-loading-ratio value of 8 and cycle length of 8 h) is shown in Fig. 5. The FDS biofilter operated with a 12 h FDS interval length throughout the regualr feed-on/off transient loading experiments and sampling was done when the unit was in upflow mode. The "steady-state" response was achieved 16 days after initiation of the loading pattern. A summary of initial conditions and feed-on/off, transient state, experiment period durations, and other parameters for these experiments is provided in Table 3. A comparison of Fig. 2 (top) and Fig. 5 reveals that regular transient loading brought about a loss of removal efficiency in the first 75 cm of the bed when compared to constant-feed loading. For example, on the average, greater than 97% of the inlet toluene was removed in the first 25 cm of the bed for constant loading [Fig. 2 (top)] whereas only 50% of the toluene was removed in the first 25 cm of the bed when the loading pattern was switched to 1-h-on/7-h-off regular transient loading and held there until steady-state response was achieved (Fig. 5). However, the 100 cm depth responses were similar (i.e., complete removal in both cases). This comparison demonstrates the ability of the microbial community to adapt to changes in loading conditions and the importance of having excess bed depth to accommodate shifts in cell population away from the inlet when transient loadings occur.

A summary of pseudo-steady-state (PSS) fractional removal profiles through the length of the bed is shown in Fig. 6. Values of mass loading and removal by column section and removal efficiency by column section are given in Table 4. Each of the PSS transient loading fractional removal values (markers) shown in Fig. 6 are averages of the response observed in the three final feed intervals of the experiment. Average response values for each feed interval were determined by integration of the area under the response curve (e.g., Fig. 5) and dividing the result by the length of the feed interval. As indicated in Fig. 6, reaction activity was concentrated near the inlet end of the column where the profile slope is greatest during continuous feed loading. In general, as off-period length and PTMLR increased, the fraction of toluene removed in the inlet region(s) decreased, the extent of toluene penetration into the packing increased, and removal became more uniform along the length of the bed. It is hypothesized that the shift of biofilm growth deeper in the bed occurred because an increasing fraction of the microbial population shifted their metabolism toward dormancy as off-time increased, which resulted in contaminant penetrating deeper into the bed when feeding resumed. The presence of elevated contaminant concentrations deeper in the bed, which would have diminished with time during the feed interval as upstream microorganisms recovered from dormancy, supported biofilm growth in that region. Therefore relative to constant feed operation, discontinuous loading produced a more dispersed biofilm along the length of the bed. A similar shifting of removal activity away from the inlet is observed for increased biofilter runtime as clogging, channeling, or nutrient

**Table 4.** Mass loading, mass removal, and removal efficiency by column section

| Loading parameters | | | | | Mass loading (g/h m³) | | | | Mass removal (g/h m³) | | | | Removal efficiency: As a percentage of inlet concentration to section | | | | Removal efficiency: As a percentage of inlet concentration to biofilter | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Time (hs) | | | Section | | | | Section | | | | Section | | | | Section | | | | |
| $C_0$ (ppm) | PTMLR | Cycle | Feed | No-feed | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | Total |
| 107 | 1 | Continuous Feed Run 3 | | | 94.6 | 2.44 | 0.15 | 0.01 | 92.2 | 2.29 | 0.15 | 0.01 | 97.4 | 93.8 | 96.7 | 100.0 | 97.4 | 2.4 | 0.2 | 0.0 | 100.0 |
| 107 | 2 | 4 | 2 | 2 | 96.8 | 33.7 | 6.9 | 0.09 | 63.2 | 26.8 | 6.8 | 0.09 | 65.2 | 79.6 | 98.7 | 97.4 | 65.1 | 27.8 | 7.0 | 0.1 | 100.0 |
| 107 | 2 | 8 | 4 | 4 | 94.3 | 40.3 | 4.8 | 0.02 | 54.0 | 35.5 | 4.8 | 0.01 | 57.2 | 88.1 | 99.7 | 41.3 | 57.7 | 37.1 | 5.2 | 0.0 | 100.0 |
| 107 | 2 | 16 | 8 | 8 | 95.5 | 46.7 | 5.3 | 0.46 | 48.8 | 41.3 | 4.9 | 0.42 | 51.1 | 88.6 | 91.3 | 90.3 | 51.4 | 43.1 | 5.1 | 0.4 | 100.0 |
| 107 | 8 | 8 | 1 | 7 | 96.7 | 47.0 | 17.9 | 2.41 | 49.7 | 29.1 | 15.5 | 2.38 | 51.4 | 61.9 | 86.5 | 99.0 | 51.4 | 30.1 | 16.0 | 2.5 | 100.0 |
| 107 | 8 | 16 | 2 | 14 | 92.3 | 50.7 | 20.9 | 3.61 | 41.6 | 29.8 | 17.3 | 3.48 | 45.1 | 58.8 | 82.8 | 96.6 | 45.1 | 32.3 | 18.7 | 3.7 | 99.9 |
| 107 | 8 | 32 | 4 | 28 | 86.8 | 53.5 | 22.1 | 3.24 | 33.3 | 31.4 | 18.9 | 3.04 | 38.3 | 58.7 | 85.4 | 94.1 | 38.3 | 36.2 | 21.7 | 3.5 | 99.8 |
| 107 | 8 | 8 | 1 | 7 | 96.7 | 47.0 | 17.9 | 2.41 | 49.7 | 29.1 | 15.5 | 2.38 | 51.4 | 61.9 | 86.5 | 99.0 | 51.4 | 30.1 | 16.0 | 2.5 | 100.0 |
| 214 | 8 | 8 | 1 | 7 | 183.4 | 97.1 | 1.77 | 0.02 | 86.3 | 95.3 | 1.75 | 0.02 | 47.1 | 98.2 | 98.9 | 86.0 | 47.1 | 52.0 | 1.0 | 0.0 | 100.0 |
| 428 | 8 | 8 | 1 | 7 | 381.3 | 243.7 | 23.3 | 0.02 | 137.6 | 220.4 | 23.3 | 0.02 | 36.1 | 90.4 | 99.9 | 100.0 | 36.4 | 57.7 | 5.9 | 0.0 | 100.0 |

limitation negatively affect bed performance, however, in the case of discontinuous feeding, the condition of the bed near the inlet remains good.

Some researchers have suggested that regular transient loading, including that provided by flow-direction switching, conditions the (or selects for a) microbial population that can respond better to transient loading than biofilters that are not subject to regular transient loading (Campbell and Connor 1997; Damborsky et al. 1999; Ergras 1995a; Irvine and Moe 2001; Moe and Irvine 2001; Song and Kinney 2000, 2001; Woertz et al. 2001; Wright 2005). Flow directional switching operation incorporates the advantages believed to accrue from feast/famine operation of microbial processes and improved mass transfer characteristics of biofilms that are uniformly distributed (dispersed) throughout the length of the packed bed (Wright 2005). Furthermore, FDS appears to produce greater long-term operational stability, as seen in the work of Song and Kinney (2001) and Wright (2005). The reason(s) for improved long-term stability appear to include a delay in the onset of biomass clogging as biomass is distributed more uniformly across the length of the bed when the unit is operated in FDS mode. Additional benefits of FDS operation may include better control of moisture and pH within the bed, which would be expected to reduce drying-induced channeling and pH upsets.

### *Variable Inlet Concentration during a Regular Feed-On/Off Loading Pattern*

Response to changes in $C_0$ during regular transient loading is shown in Fig. 7. The flow-direction switching biofilter was initially brought to mature condition with constant loading and a nominal $C_0$ value of 107 ppm$_v$. At time "0" the operation was changed to 1-h-on/7-h-off and this loading pattern was maintained for the remainder of the experiment. On day 22 the inlet toluene concentration was increased to 214 ppm$_v$ and on day 44 the concentration was again doubled to 428 ppm$_v$. The ability of the biofilter to immediately increase reaction rates when subjected to sudden increases in $C_0$ can be seen on days 22 and 44 when $C_0$ was doubled to 214 ppm$_v$ and then again to 428 ppm$_v$ and the rate of contaminant mass removed in the first column section in-

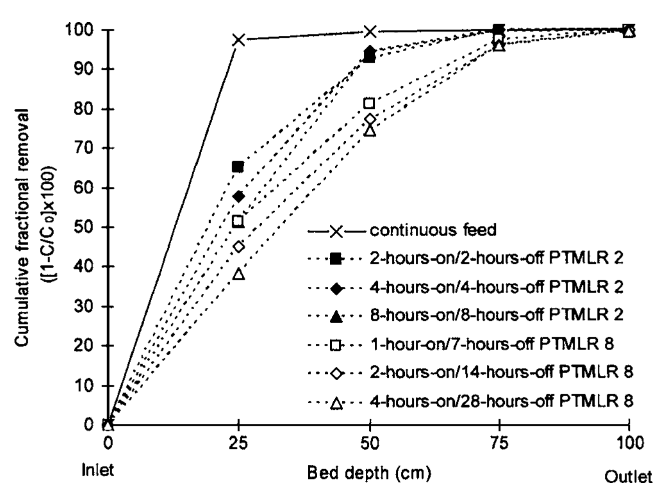


**Fig. 6.** Summary of the 12 h flow-direction switching biofilter pseudo-steady-state response (% removed) to regular transient loadings as a function of bed depth. The nominal feed concentration was 107 ppm$_v$.

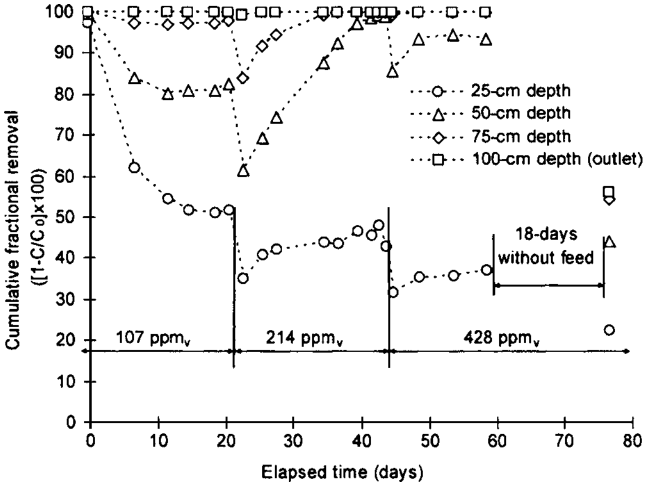


**Fig. 7.** Response (cumulative percent removal) of the 12 h flow-direction switching biofilter to variation of $C_0$ during a 1-h-on/7-h-off regular transient loading pattern

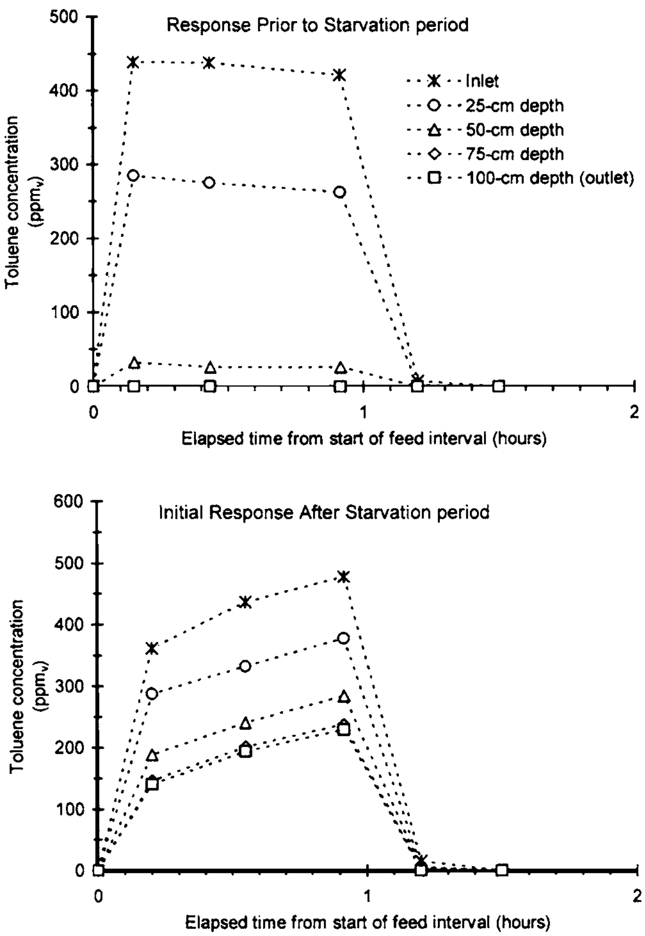


**Fig. 8.** (Top) Response (concentration profiles) of the 12 h flow-direction switching biofilter during the last feed interval prior to initiating an 18 day starvation period and (bottom) the response during the first feed following the starvation period. The biofilter was operating on a 1-h-on/7-h-off regular transient loading pattern at 428 ppm$_v$ toluene concentration.

creased from 49.7 to 86.3 and 137.6 g/h m$^3$, respectively (see Table 4 for the complete set of data). Because mass removal rates increased with increases in $C_0$, the biofilter was diffusion (substrate) limited rather than kinetically limited for the range of $C_0$ used in this study. Removal rates generally increased in the days following step increases, which is consistent with observation made by others for conventional unidirectional-flow biofilters (e.g., Tang et al. 1995). Although it is reasonable to assume that the effects of toluene sorption and desorption within the packed bed during and following transient loading events were small (as discussed previously), sorption/desorption effects were not characterized in this study.

Biofilter resilience can be seen in Figs. 7 and 8 when the unit was subjected to 18 days without contaminant or air feed (beginning on Day 59). The microbial population in the flow-direction switching biofilter retained a significant level of toluene degrading capacity during the shutdown period and was able to remove over 56% of $C_0$ during the first feed interval following the starvation period (Day 77). The first two biofilter sections (i.e., the first half of the bed) removed approximately 23% of the inlet toluene concentration each, whereas the third and fourth sections removed only approximately 10 and 2%, respectively. Published data on biofilters subjected to extended shutdown periods (longer than two weeks) are very limited and further investigation of this subject is needed.

## Conclusions

When transient loadings occur in biofilters the reaction capacity or the mass transfer capacity of the inlet region may be exceeded. In such cases higher concentrations of contaminants are carried deeper into the bed and, in some cases, pass through the unit untreated. Using a directionally switching mode of operation results in greater removal rates in the downstream bed sections and greater capacity to respond to transient loadings (Kinney 1996; Song and Kinney 2000; Wright 2004, 2005; Wright et al. 2005). The principal objective of this study was determination of the response of a vapor-phase flow-direction-switching biofilter to regular transient loadings. Outcomes of the study include:

1. Relative to unidirectional mode of operation, periodic flow reversal produced a more uniform distribution of reaction capacity along the length of the packed bed.
2. A 12 h flow reversal interval was sufficiently short to maintain the toluene-degrading microbial population in a fully active state.
3. A 2 day flow reversal interval resulted in diminished removal rates in the first half of the bed for up to 30 h following the flow direction switch.
4. Increasing off-period length in a cyclic feed-on/feed-off transient loading pattern resulted in (a) greater penetration of toluene into the bed as toluene removal rates in the inlet region of the packed bed decreased and (b) more uniform removal rates along the length of the bed.
5. Complete removal of contaminant was observed for a 4-h-on/28-h-off cyclic loading pattern. This result indicates that a properly maintained biofilter can perform satisfactorily (no contaminant breakthrough) following evening and 2 d weekend closures at commercial or industrial sites. Downtimes exceeding approximately 2 d could probably be managed by providing short periods of supplemental feeding during the closure period.

Development of operating strategies to minimize breakthrough should allow more extensive application of vapor-phase biofiltration technology. Moreover, information developed in this study should provide a more complete basis for establishing monitoring regulations for vapor-phase biofiltration systems.

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