# Performance of a Full-Scale Biotrickling Filter Treating H$_2$S at a Gas Contact Time of 1.6 to 2.2 Seconds

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*Emission of objectionable odors is a major problem for wastewater treatment and other processing facilities. Biological treatment is a promising alternative to conventional control methods, such as chemical scrubbing, but historically, biotreatment has always required significantly larger reactor volumes than chemical scrubbers.*

*In this paper, we present several aspects of the operation and performance of a chemical scrubber, retrofitted to operate as a biotrickling filter treating 16,000 m$^3$ h$^{-1}$ of foul air with the original gas contact time of 1.6 to 2.2 seconds. In continuous operation for more than a year, the biotrickling filter has shown stable performance and robust behavior for H$_2$S treatment, with pollutant removal performance comparable to using a chemical scrubber. Reclaimed water was used as a nutrient source for the process, and to maintain the pH in the biotrickling filter between 1.5 and 2.2. At a gas contact time of 1.6 seconds, H$_2$S removal was in excess of 95% for sustained inlet H$_2$S concentrations as high as 30 ppm$_v$. This corresponds to volumetric elimination rates of 95 to 105 g H$_2$S m$^{-3}$ h$^{-1}$. Efficiencies of about 90% were observed under transient conditions at 2.2 seconds gas contact time for inlet concentration peaks up to 60 ppm$_v$. The biotrickling filter also removed significant amounts of reduced sulfur compounds, ammonia, and volatile organic compounds present in traces in the air, which is important in practical applications.*

*Selected experiments, such as intermittent trickling operation and a one-month operation period at neutral pH, are also presented. Results indicate that the intermittent trickling operation does not have a significant effect on H$_2$S removal. However, when operated at neutral pH, biotrickling filter performance clearly decreased, probably due to an excessive chlorine supply to the reactor through the make-up water. The study demonstrates that biotrickling filters can replace chemical scrubbers as a safer, more economical technique for odor control.*

## INTRODUCTION

Biotrickling filters for air pollution control are bioreactors in which the contaminated air stream is passed through a packed bed on which pollutant-degrading organisms are immobilized as biofilms. The organisms degrade absorbed contaminants to harmless compounds [1]. In the case of H$_2$S control, autotrophic organisms oxidize sulfide to sulfate, using carbon dioxide as a growth source. For volatile organic compound (VOC) treatment, heterotrophic organisms utilize VOCs as carbon and energy sources.

Biotrickling filters have been shown to work well for the control of H$_2$S, reduced sulfur compounds (RSCs), and VOCs, either as sole pollutants or as complex gas mixtures [2-6]. However, in almost all previous cases, air contact times in biofilters or biotrickling filters have been in the range of 10 to 40 seconds [2-8]. Consequently, biotreatment always suffered from lower volumetric performance compared to conventional treatment methods that allow much shorter contact times. Chemical scrubbing is the most established of these conventional techniques for odor control worldwide, and is effective at gas contact times as short as 1.3 to 2 seconds [9]. However, chemical scrubbing has important drawbacks, such as high operating costs, generation of halomethanes that are known air toxics [10], and the need to use hazardous chemicals, which pose serious health and safety concerns.

Under these circumstances, there would be significant economical and safety benefits to converting chemical scrubbers to biotrickling filters, while keeping the same air contact time. Indeed, biotrickling filters are cheaper to operate than scrubbers, can potentially treat organic odors, and do not require the use of toxic and/or dangerous chemicals.

Because of these benefits, the Orange County Sanitation District (OCSD) decided to look into the ap-
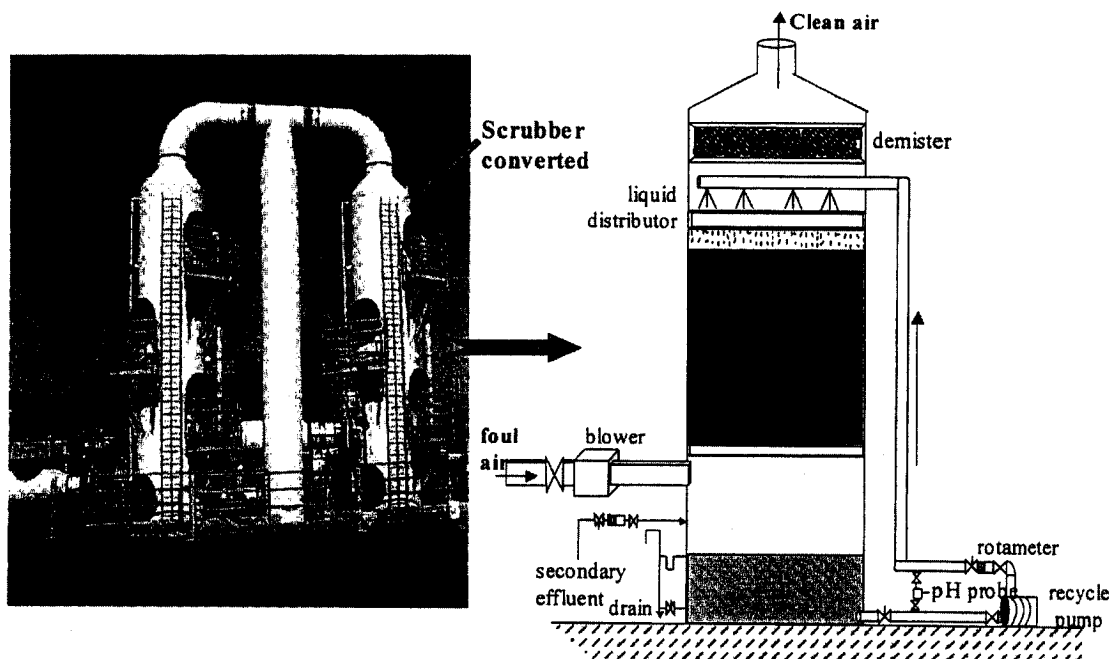
**Figure 1.** Picture of the headworks scrubbers at OCSD and schematic of the full-scale scrubber after conversion to a biotrickling filter (monitoring and controls not shown).

plicability of biofilters and biotrickling filters for odor emissions control more than a decade ago. OCSD provides wastewater treatment for 2.2 million residents in a densely populated 1,200 km² area of northern and central Orange County, California. Two years ago, OCSD started a formal Odor Characterization and Assessment Program to develop an Odor Control Master Plan.

One of the goals of this program was to address odor control needs by means of biological reactors. Research efforts were directed towards exploring the possibility of converting chemical scrubbers to biotrickling filters. This appeared feasible as both reactor types share very similar design and operational characteristics, and the cost-benefit of the conversion was deemed positive [11]. Details of the conversion procedure are discussed elsewhere [11, 12].

One of the key steps of the conversion is replacing the packing material, because the materials commonly used in chemical scrubbers (rings or other random dump plastic packing) do not have sufficient surface area to sustain a high biomass density. In addition, because biotrickling filters require a lower liquid trickling velocity than chemical scrubbers, the liquid recycle pump used for chemical scrubbers can be replaced by a smaller unit.

This paper presents and discusses the performance of the first scrubber converted to a biotrickling filter at OCSD. In addition, to assist in identifying operational limitations, the conversion team tested its response to sudden $H_2S$ load changes, operation under transient conditions, such as intermittent trickling operation, and long-term operation at neutral pH. The implications for future conversions are discussed.

### Biotrickling Filter Environment and Characteristics

OCSD operates two wastewater treatment plants, a 21,000 m³ day⁻¹ (80 MGD) facility called "Plant 1" located in Fountain Valley, and a 42,000 m³ day⁻¹ (160 MGD) facility ("Plant 2") located in Huntington Beach. The collection system contains approximately 600 km of trunk sewers, with 12 major drainage basins that discharge to the two treatment plants. The biotrickling filter under study was one of two almost identical trunkline scrubbers at the headworks complex of Plant 1 (Figure 1). Both scrubbers treat odorous air from the influent sewers trunklines, and from a screw pump enclosure, and act as first-stage roughing scrubbers to reduce $H_2S$ concentrations prior to further downstream treatment. Converting the chemical scrubber to a biotrickling filter did not alter the flowsheet or scrubber equipment, except for the modification to the packing and the liquid recycle pump (Table 1). According to the foam supplier (Zander, Germany), the packing material (4 cm cubes) is made of open pore polyurethane foam, with 10-15 pores per linear inch (PPI), and has a specific surface area of 600 m² m⁻³, a density of 35 kg m⁻³, and a porosity of 0.97. Foam packing is resistant to temperatures between -40° C and 100° C.

The scrubber construction includes a multi-beam gas-injected packing support and a U-type overflow pipe at a height of 1.37 m (4.5 feet) that defines a liquid reservoir volume at the bottom of the scrubber of 1.73 m³ (460 gal). To achieve an appropriate trickling velocity in the biotrickling filter, the existing 7 HP recycle pump of the chemical scrubber was replaced with a 0.5 HP pump (Ryan Herco, Anaheim, CA). This conversion

**Table 1.** Full-scale biotrickling filter dimensions and operational characteristics.

| Characteristic | Value |
|---|---|
| Packing material | 4 cm cubes, open pore polyurethane foam (Zander, Germany) |
| Internal diameter | 1.8 m (6 feet) |
| Reactor height | 9.7 m (32 feet) |
| Bed height (nominal) | 3.7 m (12 feet) |
| EBRT (Empty Bed Retention Time) | 2 sec (1.6 - 2.2 s) |
| Liquid recycle rate | 77 L min$^{-1}$ |
| Liquid recycle flux | 1.82 m$^3$ m$^{-2}$ h$^{-1}$ |
| Water make-up rate | 7.5 L min$^{-1}$ |
| Type of water | Chlorinated secondary effluent |
| pH control | Manually, none other than by continuous make-up |
| pH recycle liquid | 1.5 - 2.3 (after acclimation) |
| Average inlet H$_2$S concentration | 5 - 10 ppm$_v$ (cold season) |
| | 15 - 35 ppm$_v$ (warm season) |
| Start-up time | ~9 days |

lowered the trickling rate to 77 L min$^{-1}$ (20 gpm), corresponding to a flux of 1.82 m$^3$ m$^{-2}$ h$^{-1}$. The foul airflow to the reactor is supplied by a fixed speed centrifugal blower, with a design flowrate of 16,300 m$^3$ h$^{-1}$ (9,600 cfm). At the bottom of the reactor, below the bed, is an air plenum of 2.1 m (7 feet) for air and make-up water feed. The liquid distribution system uses parting boxes and weir troughs, and is situated at 0.80 m (2.7 feet) above the top bed limiter. A mist eliminator, composed of a bed support plate, a demisting height of 0.45 m of 2" TriPack packing, and a second bed limiter, sits on top of the scrubber.

From an operational point of view, the biotrickling filter was not fed any inorganic nutrients. Instead, secondary effluent that had previously been characterized for nutrients, chlorine, and organic matter content, was used. From a conversion point of view, this was convenient because the former chemical scrubber was already piped with a secondary effluent line for make-up water supply. Also, pH and sulfate concentrations were both controlled by the continuous feed and purge of secondary effluent to the system. The pH in the biotrickling filter was allowed to drop to values between 1.5-2.3, and was maintained more than 90% of the time between these maximum and minimum values. Slow pH dynamics, due to the large recycle liquid volume, helped control pH fluctuations in the biotrickling filter during the day. No strict pH control, other than maintaining a constant make-up water flow around 7.5 L min$^{-1}$ (2 gpm), was necessary to operate the biotrickling filter during the entire period of operation, even under highly fluctuating H$_2$S inlet concentrations.

The biotrickling filter is a well-instrumented reactor in which main process variables can be monitored. Concentrations of H$_2$S were measured by online meters (Vapex Sentinel System, Quality Air Products, Inc. Ocoee, FL) with independent sensors connected to inlet and outlet reactor sampling ports. Also, an in-line pH sensor connected to the supervisory control and data acquisition (SCADA) system of the OSCD is used to monitor pH. The reactor includes a U-tube,

water-filled manometer to measure the pressure drop across the bed, and two online rotameters, one to measure water make-up supply and the other to measure the liquid recycle rate.

The on-line Vapex unit was configured to display H$_2$S inlet and outlet concentrations every 4 seconds, and to store the average of 12-minute segments. Online data were supplemented with grab sample measurements made with a Jerome 631X series meter (Arizona Instruments, Tempe, AZ) and with gas chromatography and sulfur compounds chemiluminescence detection. The latter method was also used to detect and measure other reduced sulfur compounds (carbonyl sulfide, sulfur dioxide, methyl mercaptan, ethyl mercaptan, dimethyl sulfide, carbon disulfide, n-Propylthiol, iso-Propylthiol, and dimethyl disulfide). VOCs were measured with a portable Scentograph Plus II gas chromatograph (Sentex Systems, Inc., Fairfield, NJ), with measurements corroborated by a certified lab (Calscience Environmental Laboratories Inc., Garden Grove, CA) using the EPA TO-14 method. Water samples from the liquid recycle and make-up water were analyzed for temperature, conductivity, carbon dioxide, ammonia, foul airflow, etc., with details described in Gabriel, et al. [12].

**Microbial Counts and Activity Tests**

Grab samples of the polyurethane foam packing colonized with biomass were taken from the top layer of the reactor for microbial counts and activity tests. Biofilm attached to 15 cubes of foam was washed out by suspending it in three subsequent 500 mL aliquots of mineral medium [4]. Samples for both the microbial counts and substrate-induced oxygen uptake rate (OURs) measurements were the result of mixing the three fractions. The resulting suspension had a suspended solids concentration of 600 mg L$^{-1}$, as determined by dry weight. Microbial counts were performed by serial ten-fold dilutions of that cell suspension. Heterotrophic organisms were counted on plate count agar (Difco), and autotrophic sulfur oxidizers were counted on thiosulfate agar [13], as described by Cox and Deshusses [4]. Acidophilic and pH-neutral species were enumerated separately, preparing both
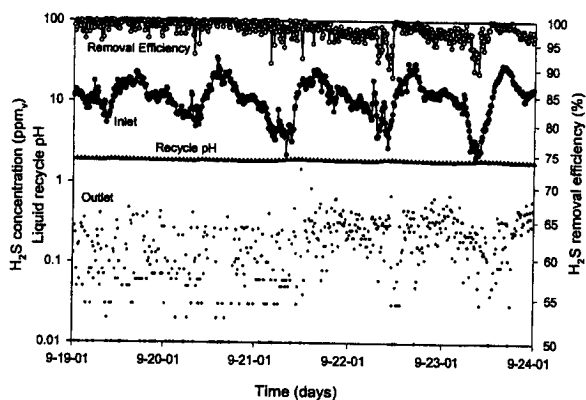
**Figure 2.** Typical $H_2S$ removal efficiency (o) and pH (▲) profile in the biotrickling filter under normal operating conditions. Note the log scale for inlet (●) and outlet (•) $H_2S$ concentrations.
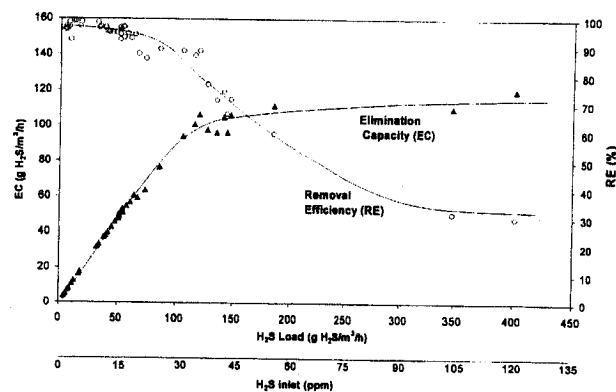


**Figure 3.** Elimination capacity [EC = (inlet-outlet concentration) x air flow/bed volume] and removal efficiency of $H_2S$ versus the inlet load (and corresponding $H_2S$ inlet concentrations) in the biotrickling filter during the spiking experiment.

media at either pH 4.5 and pH 7.0. Lower pH could not be tested as the medium would not set.

Oxygen uptake rate (OUR) measurements at different pH values between 1.7 and 8.5 were performed in a 2.5 mL custom-made vessel fitted with an oxygen electrode (YSI, Yellow Springs, OH) and initially saturated with air at 25° C. Inorganic carbon as carbonate was provided in each test by adding a concentrated stock of sodium carbonate to the suspended biofilm sample, so 800 mg $CO_3^{2-}$ $L^{-1}$ were present at the start of each test. Thereafter, the pH of aliquots of suspended biofilm samples was adjusted to the desired value with 6M HCl or 2M NaOH, and samples were immediately introduced in the vessel for endogenous OUR measurements. An initial concentration of 0.28 mM $Na_2S$ was introduced as substrate for total OUR determination. Sulfide-induced OUR was calculated by subtracting the endogenous OUR from the total OUR in each test. Tests were performed in triplicate at each pH tested.

## RESULTS AND DISCUSSION

### General Overview of Biotrickling Filter Performance

The concentration of $H_2S$ in the gases fed to the reactor fluctuated cyclically during normal operation with a typical repeating pattern. Figure 2 shows an example of this daily variation in the inlet $H_2S$ concentration profile, with low and high concentrations varying by up to a factor of 10 to 20. Independently of high inlet $H_2S$ fluctuations, outlet $H_2S$ concentrations were maintained well below 1 $ppm_v$, the allowable discharge limit for OCSD set by the South Coast Air Quality Management District (SCAQMD). This was the case most of the time when the biotrickling filter was in operation, demonstrating its very stable and robust operation. No sophisticated control system was needed to maintain the reactor pH. Even with the high daily variability in the inlet $H_2S$ concentration, a constant make-up water supply of 7.7 L $min^{-1}$ was sufficient to keep a stable hourly average pH in the liquid recycle of the biotrickling filter (See Figure 2). There-

fore, the same make-up water flow was maintained for year-round operation of the reactor. This means that reactor control and operation could be made simpler than that of chemical scrubbers, where the pH must be automatically controlled by caustic addition to ensure stable and economical operation.

The biotrickling filter's $H_2S$ elimination capacity was well below its maximum achievable value most of the time because of the low loading to the biotrickling filter. Typically, $H_2S$ removal efficiencies were above 98%, with discharge levels well below 1 $ppm_v$ for inlet $H_2S$ concentrations as high as 30 $ppm_v$. In certain peak conditions, elimination capacities up to 100 g $H_2S$ $m^{-3}$ $h^{-1}$ were encountered. Further experiments were warranted to determine the maximum elimination capacity of $H_2S$ in the converted biotrickling filter. For this, a specific experiment was performed by artificially spiking the inlet air with pure $H_2S$ from a gas cylinder connected to the suction side of the biotrickling filter. Inlet $H_2S$ concentrations were increased incrementally up to 120 $ppm_v$ when the reactor was operating at 1.6 seconds empty bed retention time (EBRT). Figure 3 shows the elimination capacity and removal efficiency profiles for $H_2S$ during the experiment. At loadings up to 95 g $H_2S$ $m^{-3}$ $h^{-1}$, the system consistently degraded more than 90% of the influent $H_2S$. Above 95 g $H_2S$ $m^{-3}$ $h^{-1}$, $H_2S$ breakthrough occurred, while a quasi-zero order degradation regime was observed at loadings above 105 g $H_2S$ $m^{-3}$ $h^{-1}$. Such performance is exceptionally high compared with other biofilters or biotrickling filters removing low concentration of $H_2S$, even at higher gas contact times [3, 4, 7].

Simultaneous removal of RSCs, VOCs, and odor was also observed during normal operation (Table 2). Three out of nine RSCs analyzed were routinely detected in the inlet air. In case of RSCs and VOCs, we found high concentration spread at the inlet of the reactor, which led to a high variability in RSC and VOC removal. On average, at standard conditions (pH ~2, 1.6 seconds EBRT), RSC removal ranged between 15% and 40%, while VOC removal was around 30%.

**Table 2.** Average RSC, selected VOC, and odor removal in the biotrickling filter for an eight-month period of continuous operation between October 2001 and May 2002.

| Compound | Inlet concentration (ppb$_v$) | Removal Efficiency (%) |
|---|---|---|
| Carbonyl sulfide | 67 ± 8 | 44 ± 11 |
| Methyl mercaptan | 193 ± 34 | 67 ± 11 |
| Carbon disulfide | 70 ± 21 | 35 ± 5 |
| Methylene chloride | 132 ± 93 | 36 ± 25 |
| Toluene | 753 ± 214 | 26 ± 14 |
| m+p xylene | 480 ± 852 | 41 ± 18 |
| Odor | 1980 ± 480 D/T | 65 ±21 |
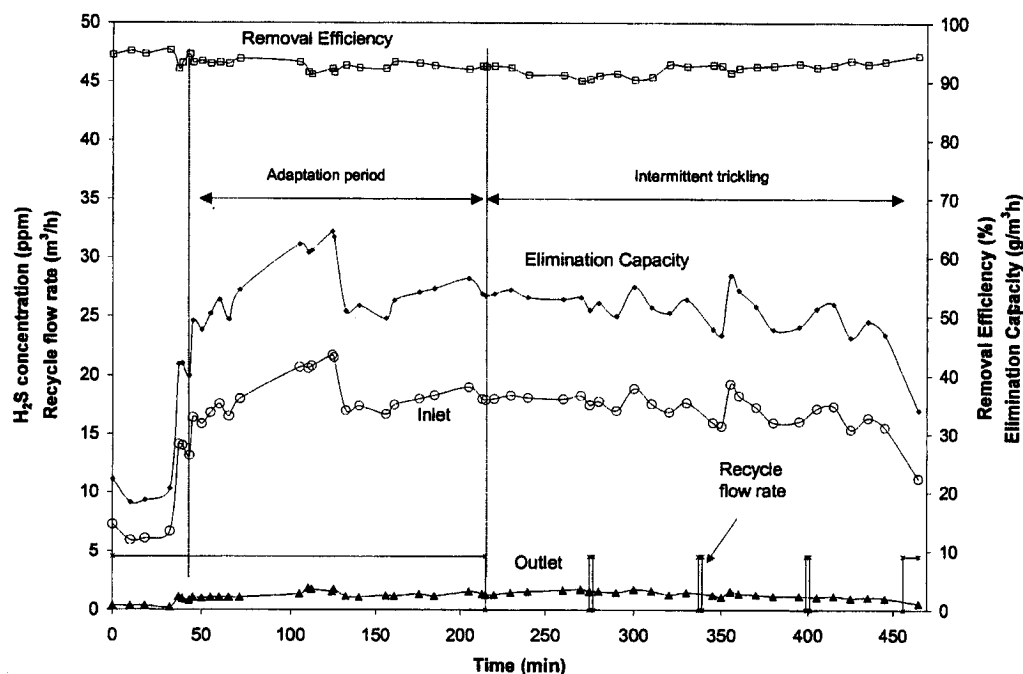


**Figure 4.** Performance of the biotrickling filter during intermittent trickling operation. The initial three hours shown is the adaptation period to the higher concentration of H$_2$S.

Odor removal efficiencies around 65% were determined by odor panels, and were attributed mostly to H$_2$S removal. To improve residual odor reduction requires a better definition of the conditions needed to remove the other reduced sulfur compounds believed to be the main cause of residual odor.

**Intermittent Trickling Operation**

The biotrickling filter was tested for mass transfer limitations of the pollutant from the gas to the liquid and biofilm, as it had been reported as a factor influencing performance [14]. Possible liquid mass transfer limitations were tested by stopping the liquid trickling for repeated periods of 60 minutes to allow for complete water drainage from the bed. After each 60-minute period, water was trickled at the usual rate (77 L min$^{-1}$ liquid recycle flow, i.e., a flux of 1.82 m$^3$ m$^{-2}$ h$^{-1}$) for 2 minutes only to avoid inhibition by either an excessive accumulation of sulfate [3] or an excessive decrease of pH in the biofilm resulting from the continuous production of H+ and sulfate from

H$_2$S oxidation. In order to clearly detect any variation in H$_2$S outlet concentration directly related to the change in mass transfer characteristics when no water was being trickled, the inlet H$_2$S concentration was artificially spiked with pure H$_2$S from a gas cylinder to maintain an approximately constant inlet H$_2$S concentration of 17-18 ppm$_v$. As shown in Figure 4, an adaptation period of about 3 hours was included prior to the actual intermittent trickling experiment. This was included to minimize any interference due to changes in performance at higher inlet concentrations. Examination of H$_2$S data during the adaptation period shows that the outlet concentration followed relatively closely with the inlet concentration, while the inlet concentration was being adjusted. This suggests that pseudo steady-state was rapidly (i.e., within an hour) attained in the biotrickling filter.

During the actual ON/OFF trickling experiment, no significant change in H$_2$S removal performance was observed in any of the periods with or without trickling water. Following this experiment, another intermittent trickling experiment was conducted at a lower

**Table 3.** Microbial counts in a suspension of the biofilm from OCSD biotrickling filter at either pH 4.5 or 7.0.

| Heterotrophs (CFU mL$^{-1}$) | Sulfide oxidizers (CFU mL$^{-1}$) |
|---|---|
| pH=7.0 $(6.00 \pm 0.22) \times 10^7$ | $(4.65 \pm 0.66) \times 10^7$ |
| pH=4.5 $(1.27 \pm 0.11) \times 10^7$ | $(4.37 \pm 0.26) \times 10^7$ |

$H_2S$ inlet concentration so that the outlet concentration was around 1 ppm$_v$ $H_2S$. The rationale was that at lower concentrations, mass transfer could possibly be limiting, rather than the kinetic factors that limit performance at higher concentrations. The results (not shown) were similar to those of the experiment at a higher concentration. Thus, one can conclude that the water film over the biofilm did not limit the mass transfer of $H_2S$. These results were anticipated because the reactor conditions (i.e., high air linear velocity and relatively low biofilm and packing wetting) were very favorable for direct gas-biofilm pollutant mass transfer, minimizing the gas-liquid-biofilm path for pollutant mass transfer. It should be mentioned that the effect of intermittent trickling on odor, VOC, or RSC removal was not investigated. However, intermittent trickling had a positive effect on the pressure drop across the bed, reducing it by about 2 to 3 cm water column. Thus, intermittent trickling could provide a possible means for slightly reducing the operating cost of converted biotrickling filters.

### Effect of pH

It was suspected that the removal efficiency of VOCs in the biotrickling filter (around 30%) was limited by the low pH, which may have been inhibiting the growth of the heterotrophic biomass responsible for degrading the organic compounds. Further research to see whether operating the reactor at neutral pH could improve heterotrophic biomass growth and, therefore, increase VOC removal, was warranted. Several reports indicate that simultaneous removal of VOCs and $H_2S$ is feasible at near neutral pH [4] and different sulfur-oxidizers species have been found capable of degrading $H_2S$ at pH between 1.0 and 7.5 [15]. In addition, operating the biotrickling filter at pH ~7 for 24-hour periods did not significantly affect $H_2S$ removal at OCSD [12]. Hence, basic microbiological properties of the process culture were determined by plating and by OUR, and the biotrickling filter was operated at neutral pH to better investigate the influence of the pH on the $H_2S$ and VOC removal process.

Sulfide-induced OUR measurements of pH-adjusted samples at different pH values (See Figure 5), using biomass from the biotrickling filter showed maximum activities at low and near-neutral pHs, indicating that two different types of microorganisms capable of degrading sulfide coexisted and were active in the biotrickling filter. In addition, similar activity values were obtained at either pH 2 and 7.5 to 8.5. This indicates that, provided the removal of $H_2S$ in the biotrickling filter is kinetically limited, similar performance is expected under either low or near neutral pH conditions. Interest-
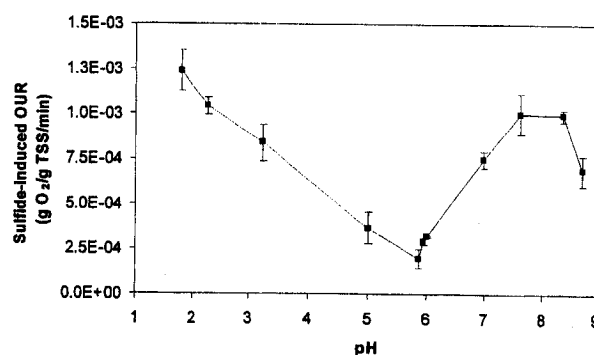


**Figure 5.** Specific sulfide-induced OUR profile as a function of pH determined with biomass from the OCSD biotrickling filter.

ingly, minimal sulfide biodegradation activity was found at pH between 5 and 6.

Although microbial activity was markedly different at pH 4.5 and pH 7 (Figure 5), microbial counts reported in Table 3 indicate that the concentration of sulfide-oxidizers in the OCSD biofilm was independent of pH. Microbial counts also revealed that neutral pH was more favorable for heterotrophic biomass growth, confirming the potential benefit of operating the full-scale biotrickling filter at near neutral pH. Therefore, subsequent to this experiment, the operating pH in the biotrickling filter was set to 7.5 to 8 by increasing the make-up water supply from 7.7 to 39 L min$^{-1}$.

Figure 6 shows the monitored variables and the removal efficiency observed during the operation of the biotrickling filter at near-neutral pH. For a period of 40 hours after the pH increase, the outlet $H_2S$ concentration remained at previous discharge levels indicating no positive or negative effect on removal, but after that, lower $H_2S$ removal efficiencies (50 to 60%) were observed. On day 18 the reactor was re-inoculated with concentrated sludge from the wastewater treatment plant in an attempt to promote biodiversity, but this had no effect. The $H_2S$ removal efficiency remained steady at around 50%. The biotrickling filter progressively lost its efficiency, reaching $H_2S$ removal rates as low as 5% on day 36. At that point, the operation was returned to low pH by cutting the make-up water. Immediately, $H_2S$ removal resumed when the pH decreased below 3, and removal efficiencies reached the usual values of 90+% one week after pH reached a value of 2. The same behavior was found for RSCs and VOCs, for which removal efficiencies dropped to 0-5% while the biotrickling filter was operated at neutral pH, and quickly returned to previous values after the biotrickling filter reached its low pH set-point.
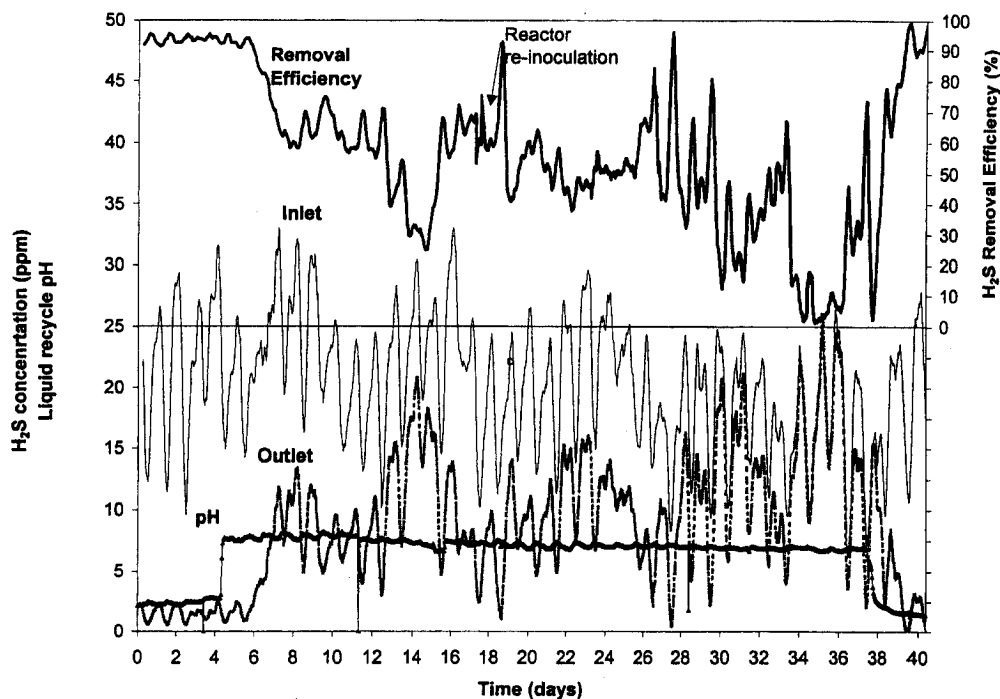
**Figure 6.** Long-term performance of the biotrickling filter at near neutral pH. Inlet $H_2S$ concentration, outlet $H_2S$ concentration, and removal efficiency profiles are presented as moving averages of 6 hours data collected at 12-minute intervals. Day 0 corresponds to 12:00 am on July 6, 2002. Water make-up increased on Day 4 and was cut back on Day 36.

The low performance of the biotrickling filter during neutral pH operation appeared contradictory to the results obtained from the OUR determinations and the microbial counts. Although we don't have a firm explanation for the reduced performance, speculation is that removal efficiencies were reduced by process culture inhibition in the reactor because more chlorine was supplied to the biotrickling filter via the make-up water. This explanation is consistent with a higher accumulation of detached biomass observed at the bottom of the sump during neutral pH operation, indicating that significant sloughing of the biofilm from the packing occurred. Unfortunately, chlorine concentrations in the recycle liquid were not monitored during the experiment. The free chlorine concentration in the make-up water remained constant at 1-2 ppm, but the chlorine loading to the reactor was 5 to 10 times higher because of the higher make-up water feed rate.

An unrelated observation is consistent with the hypothesis that chlorine affected the process. During the project, there was one instance in which the biotrickling filter suddenly stopped removing $H_2S$. Interestingly, it coincided with a failure of the plant water chlorination system, resulting in levels estimated at 10 ppm in plant water, possibly causing the inactivation of the process culture. Altogether, the chlorine effect could explain why VOC removal, theoretically favored at neutral pH, also ceased during neutral pH operation, and why the system recovered immediately after low pH operation was resumed. In any case, further investigation is required to confirm the above hypothesis, or determine other possible explanations.

**Economic Analysis**

A detailed cost-benefit analysis was conducted based on eight months of scrubber and biotrickling filter operation. Only the major findings are presented here. The cost of the materials to convert the chemical scrubber was about $22,000. It should be mentioned that this was the first conversion, and included only the minimum necessary changes to allow for returning to scrubber operation if biotrickling filtration was not continued at the end of the project. The conversion, if performed by a contractor, would cost $40,000 to $60,000. On the other hand, a cost evaluation of the scrubber operated in parallel with the biotrickling filter indicated that the chemical costs associated with the treatment of $H_2S$ were in the range of $11 per kg of $H_2S$ removed for the parallel chemical scrubber, and $51 per kg of $H_2S$ removed for the post-treatment chemical scrubber. Because the biotrickling filter removed over 3,000 kg of $H_2S$ per year, the savings in chemical costs are expected to exceed $30,000 per year, demonstrating that biotrickling filtration is much more cost-effective than chemical scrubbing.

**CONCLUSIONS**

The results presented and discussed in this paper show that, even under highly fluctuating $H_2S$ inlet concentrations, the chemical scrubber converted to a biotrickling filter proved to be very robust for sustained $H_2S$, reduced sulfur compound, and VOC treatment. The biotrickling filter was able to consistently maintain outlet $H_2S$ concentrations well below the regulatory limits of 1 $ppm_v$. This is unique for a sys-

tem operated at gas contact times between 1.6 and 2.2 seconds, i.e., markedly lower than what was previously thought of as the lower limit for gas-phase bioreactors. Further, the biotrickling filter demonstrated its capability to effectively treat inlet $H_2S$ concentrations up to 60 $ppm_v$, and reach elimination capacities of 105 to 110 g $H_2S$ m$^{-3}$ h$^{-1}$. This performance level has never been achieved before at such a low gas contact time in a biotrickling filter.

Of course, at very high velocity, the challenge is to successfully remove $H_2S$ concentrations below the regulated discharge limits. This was accomplished in the present project for relatively low inlet $H_2S$ concentrations (in the range of 2-5 $ppm_v$), and under transient conditions up to inlet $H_2S$ concentrations well above 60 $ppm_v$. No significant changes in performance were found by operating the reactor under intermittent trickling conditions, although long-term operation at neutral pH was found to be quite inefficient. The true reason for this low performance is not known, but we suspect it to be linked to the free chlorine supplied with the make-up water used for the pH control. Further research is being conducted to address pH effect, and to improve RSC and VOC removal in the biotrickling filter. From an economic perspective, converting a chemical scrubber to a biotrickling filter results in important savings, mainly due to the elimination of chemical costs. This suggests that such conversions will become more widespread in the near future.

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