Technical and economical analysis of the conversion of a full-scale scrubber to a biotrickling filter for odor control

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Abstract The present paper evaluates the technical and economical feasibility of converting wet chemical scrubbers to biotrickling filters for H_2S control at the Orange County Sanitation District (OCSD), California. Results of 8 months of continuous operation of a biotrickling filter treating 16,000 $m^3\ h^{-1}$ of foul air are analyzed. The reactor was operated at a gas contact time of 1.6 to 2.2 seconds reaching H_2S elimination capacities up to 105-110 g $H_2S\ m^{-3}\ h^{-1}$, consistently maintaining outlet concentrations well below the regulatory limits (24 h average of 1 ppm_v) and demonstrating to be very robust against temporary changes. Also, a cost-benefit analysis of the conversion was performed. Savings from chemicals, energy and water usage compared to a chemical scrubber operated in parallel to the biotrickling filter throughout the project indicated that the payback time of the conversion was about 1.3 years. Cost savings ranged between US$ 40,000 per year, per scrubber. While the above number may be specific to OCSD conditions, the cost analysis suggests that there is a significant benefit of converting chemical scrubbers to biotrickling filters over a wide range of operating conditions.

Keywords Biotrickling filter, chemical scrubber conversion, cost-benefit analysis, hydrogen sulfide, operating costs, biotower.

Introduction

Presently, chemical scrubbing in packed-towers is leading the world market for odor control in publicly owned treatment works (POTWs). This is because chemical scrubbing is reliable and has the lowest cost of the chemical technologies for the treatment of foul air for applications over 50,000 $m^3\ h^{-1}$ (Card, 2001). However, wet scrubbing is expensive when operating and investment costs are compared to emerging biotreatment techniques such as biofiltration and biotrickling filtration (Jorio and Heitz, 1999; Devinny *et al.*, 1999). In the case of foul air treatment at POTWs, biotrickling filtration appears to be the most promising development, as it allows for very effective and compact reactors (Gabriel and Deshusses, 2003a). Biotrickling filters work in a similar manner to reactive chemical scrubbers except that the reaction is mediated by microorganisms. Foul or contaminated air is passed through a packed bed on which pollutant degrading bacteria are allowed to grow. An aqueous phase which contains essential inorganic nutrients is trickled over the packed bed, so that optimum conditions (pH, salt and nutrient concentration) can be maintained for the process culture. Biotrickling filters are increasingly used in industrial applications (Cox and Deshusses, 1998; Devinny *et al.*, 1999)

The advantage of any biological treatment over physicochemical techniques relies on savings obtained from operating costs. For example, yearly biofiltration operating costs are said to be around one-tenth of those of an absorption process (Jorio and Heitz, 1999). Gao *et al.* (2001) reported that the operating costs of a biofilter for H_2S removal were one-fourth of those of a wet chemical scrubber. They also found that costs were greatly influenced by the seasonal variation of loading rate due to temperature changes.

Water Science and Technology **Vol 50 No 4 pp 309–318** © IWA Publishing 2004

For equal equipment size, the capital costs of biotrickling filters are about the same or lower than those of chemical scrubbing since the design of both systems are very similar, with slightly more ancillary equipment for the chemical scrubber. In the particular case of H_2S, chemical scrubbing is effective at gas contact times as short as 1.3–2.5 seconds, thus small footprints are sufficient for treating large air streams. However, chemical scrubbing suffers from important drawbacks, such as generation of known air toxics such as halomethanes (WERF, 1996) and the requirement for hazardous and expensive chemicals, which pose serious health and safety concerns and is generally not considered in cost evaluations.

The case reported in the present paper evaluates the cost-benefit of the conversion of a chemical scrubber to a biotrickling filter. In this new development, the original gas contact time of 1.6 to 2.2 seconds was kept, and the biotrickling filter achieved similar or superior H_2S removal performance compared to the previously installed chemical scrubber (Gabriel and Deshusses, 2003a). Both the conversion costs of the chemical scrubber to a biotrickling filter and the operating costs of the reactor are evaluated.

Material and methods

Headwork and Trunkline facilities description

The field work was performed at the Trunkline and Headworks complexes (Figure 1) at the Fountain Valley wastewater treatment plant, California, which is managed by Orange County Sanitation District (OCSD). The plant treats about 60 MGD (227,000 m^3 per day) of wastewater that enter the facility through the Trunkline, which has extensive foul air collection and treatment by chemical scrubbing.

The scrubber that was converted to a biotrickling filter, formerly named scrubber #10, treats odorous air from the influent sewers and from a sewage pump vent. The side-by-side configuration of the biotrickling filter with a parallel chemical scrubber (scrubber #9 in Figure 1) allowed for the direct comparison of the biological and chemical scrubbing processes. Trunkline scrubbers act as first-stage roughing scrubbers to reduce the H_2S concentration prior to further downstream treatment by the scrubbers located in the Headworks complex. In the past, both trunkline scrubbers were designed as counter-current, packed-tower scrubbers for caustic use, thus operated as absorption scrubbers.

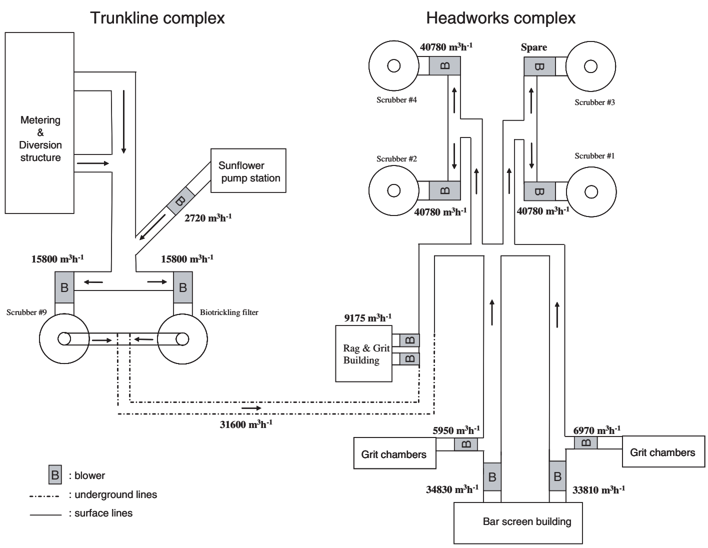

Figure 1 Schematic of the treatment system configuration in the Trunkline and Headworks complexes at OCSD wastewater treatment plant located in Fountain Valley. Arrows indicate foul airflow direction. Bold numbers indicate design airflows

Headworks scrubbers differ from the Trunkline scrubbers in that they include the addition of hydrogen peroxide for pollutants oxidation in order to improve removal efficiencies. All four Headworks scrubbers are single-stage, counter-current, packed-tower scrubbers. Typically, two or three scrubbers are operated, with the others serving as a standby. In order to facilitate the evaluation of the economical impact of the biotrickling filter in the downstream treatment, airflow from the Trunkline complex was redirected to feed only scrubbers #2 and #4 (Figure 1) during the time of the study.

Chemical scrubbers and biotrickling filter characteristics

Most of OCSD scrubbers are constructed following a similar design and the main differences among them are the foul air composition and the H_2S load they treat. Detailed characteristics of OCSD scrubbers' design can be found elsewhere (Gabriel and Deshusses, 2003b). In general, all chemical scrubbers are Fiberglass Reinforced Plastic (FPR) vessels with foul airflow to chemical scrubbers supplied by means of fixed speed or two-speed floor mounted FPR centrifugal blowers. All scrubbers have two recirculation pumps, one in operation and one in standby.

Table 1 shows the main characteristics of the reactors under evaluation and the elements to be considered in the economical evaluation of the chemical scrubbers and the biotrickling filter. In order to account for conversion benefits, its important to note that, prior to its conversion to a biotrickling filter, former scrubber #10 was exactly designed as described in Table 1 for scrubber #9. As a consequence, the lower power requirements for the liquid recycling and the absence of chemicals use and pumping will constitute the main operating costs savings of the conversion of the scrubber to a biotrickling filter.

From an operational standpoint, chemicals additions to wet scrubbers are performed differently depending on the scrubber and the chemical added. Sodium hydroxide addition to wet scrubber #9 was regulated depending on the outlet H_2S concentration, measured by an on-line H_2S monitoring device (Vapex Sentinel, Vapex, FL) thus allowing caustic consumption to be optimized. Scrubber #4 has a Vapex unit on-line, but sodium hydroxide addition to this scrubber was performed based on the liquid recycle pH (setpoint usually set between 9 and 10) in order to make best use of hydrogen peroxide oxidation potential. Hydrogen peroxide is added to any of the Headworks scrubbers on a constant flow basis, which is manually adjusted by plant personnel.

Table 1 Summary of design characteristics of the biotrickling filter and chemical scrubbers under study at OCSD

	Scrubber #9	Scrubber #4	Biotrickling filter
Scrubber type	Pretreatment	End-of-pipe	Pretreatment
Air source	Influent sewer	Primary treatment	Influent sewer
Packed height (m)	3.7	4.6	3.7
Diameter (m)	1.8	2.7	1.8
Bed volume (m^3)	9.6	27	9.6
Packing	Random dump, plastic	Random dump, plastic	Open pore polyurethane foam. 40 mm cubes, random dump
Fan power (kW)	30	30	30
Recirculation pump (kW)	5.6	7.5	0.4
Caustic pump power (kW)	0.6	0.6	none
Hydrogen peroxide pump (kW)	none	0.03	none
Design air flow ($m^3 h^{-1}$)	15,800	40,780	15,800
Liquid recycle flow ($L min^{-1}$)	1650	2460	77
Make-up water flow ($L min^{-1}$)	76	30	7.7
Gas contact time (s)	2.2	2.4	2.2

In contrast, the biotrickling filter was not fed any chemicals. Instead, secondary effluent which had previously been characterized for nutrients, chlorine and organic matter content, was used as nutrient feed and trickling liquid. Using secondary effluent was convenient from a conversion point of view, since the former chemical scrubber was already piped with a secondary effluent line for make-up water supply. Also, the pH and sulfate concentrations were both controlled by the continuous feed and purge of secondary effluent to the system.

In order to more accurately calculate and compare the annual savings under different scenarios, the costs of H_2S treatment reported herein are based on the mass load ($L = C_{in} \times Q$) and the removal of a certain mass of pollutant ($E = (C_{in} - C_{out}) \times Q$) in the biotrickling filter or the chemical scrubbers where C_{in} and C_{out} are the H_2S inlet and outlet concentrations (g m^3), respectively, and Q is the air flow rate. The performance of the reactors is reported in terms of removal efficiency ($RE = (C_{in} - C_{out})/C_{in}$) and H_2S elimination (E). Note that elimination and loading are defined differently from the elimination capacity (EC) and loading usually used to report biofiltration performance studies. Here, since one evaluates actual mass of H_2S treated, no normalization by the bed volume is done and the elimination and loading are actual mass fluxes treated or loaded onto the systems.

Results and discussion

Conversion costs of the chemical scrubber

The feasibility of the conversion of any existing chemical scrubber depends on both the technical and the economical viability. However, a minimum and critical requirement for a chemical scrubber to make any retrofit viable from an economical point of view, is that the shell, packing support and most of the wetted parts need to be reused. A case-by-case study is necessary to determine conversion requirements and costs. When conversion is suitable, a general procedure for converting wet scrubbers as described in Gabriel *et al.* (2003b) may be followed. This was done for scrubber #10 and the costs were evaluated. From all the possible steps listed in the generic conversion procedure, only few were needed for the actual conversion of scrubber #10. Their actual costs are shown in Table 2.

For labor costs, skilled personnel (electrician, engineer) were considered at US$ 100 per hour while a field technician was charged at US$ 40 per hour. For parts cost, an inventory of current market prices was considered (year 2002). An additional preparation step to condition the scrubber for the conversion was included due to the large scale buildup in the packing. In addition, note that the removal of the old packing and the strengthening of the packed bed were performed by an outside contractor with a total cost of US$ 1465.

In summary, the major conversion costs for scrubber #10 came from replacing the packing and installing a new liquid recycle pump. These are unavoidable costs, as it was previously found that Tripack, the former packing, was not suitable for biotrickling filtration, while an open pore polyurethane foam (M+W Zander, Germany) showed excellent results for H_2S removal (Gabriel *et al.*, 2004). 35% of materials cost for the installation of the new packing was due to airfreight shipping costs of the foam. Also, it was found that the liquid recycle flow rate for the biotrickling filter needed to be about ten times lower than this of

Table 2 Summary of cost of the conversion of chemical scrubber #10 to a biotrickling filter

Task	Labor (US$)	Parts (US$)	Total (US$)
Scrubber preparation	1,240	1,240	2,480
Removal of old packing	1,465	0	1,465
Liquid recycle pump replacement	2,140	2,782	4,922
Installation of the new packing	1,680	8,386	10,066
Modify controls	500	0	500
TOTAL	**7,025**	**12,408**	**19,433**

the chemical scrubber. Installing a lower capacity liquid recycle pump required re-piping of the recycle line due to the differences in the dimensions between the existing pipes, thus increasing the labor and materials cost required for this step. It should be noted that this conversion was experimental and considered only the minimum number of changes in order to allow returning to scrubber operation if biotrickling filtration was not to be continued at the end of the project. On the other hand, engineering costs included as labor costs during the current conversion may be diminished for routine conversions.

A cost of US$ 15,000 was considered as the minimum necessary for the conversion of any chemical scrubber based on the experience with scrubber #10. For other scrubbers, the cost will depend on the type and the actual construction of the chemical scrubber. Of particular relevance for the conversion are possible modifications of the liquid distribution system, modification of the mist eliminator, or modification of the inlet or outlet air ducts. These will all affect the economical viability of the conversion. Based on the results, it is estimated that the commercial cost, i.e., including indirect costs and profit, of such a conversion may be between US$45,000 and US$ 55,000.

Long-term performance of the biotrickling filter

Except for some initial low values, the airflow through the biotrickling filter was essentially constant, and the loading changes were a result of the fluctuations of inlet H_2S concentration. Figure 2 shows the biotrickling filter performance for the period under study. The results demonstrate the robustness of the system over a wide range of inlet loads, as the outlet concentration was maintained below 1 ppm_v, the discharge limit at OCSD.

The maximum elimination capacity at a gas contact times of 1.6 to 2.2 seconds was obtained at loadings around 105 g H_2S m^{-3} h^{-1} in a specific experiment where the inlet load to the biotrickling filter was spiked artificially with pure H_2S (Gabriel and Deshusses, 2003b). Significant removal of other reduced sulfur compounds, various trace volatile organics, and ammonia was observed (Gabriel and Deshusses, 2003a). Odor (as dilution-to-threshold) removal efficiency was on average 65% and correlated well with the removal of H_2S. A detailed discussion of the performance of the biotrickling filter can be found elsewhere (Gabriel and Deshusses, 2003a, b).

As shown in Figure 2, the pH in the biotrickling filter was allowed to drop to values

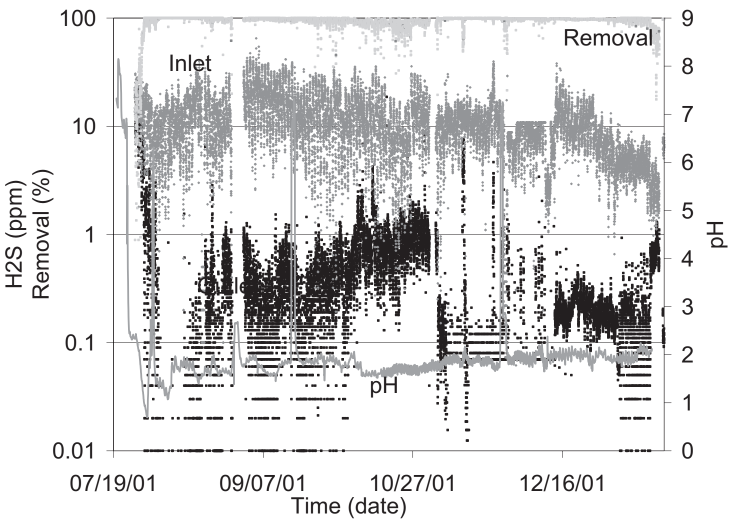

Figure 2 Performance of the biotrickling filter for 8 months of operation corresponding to the period under study between August 2001 and March 2002

between 1.5 and 2.3 and was maintained over 95% of the time between these maximum and minimum values. No strict pH control other than maintaining a constant make-up water flow around 7.7 L min^{-1} was necessary to operate the biotrickling filter during the entire period of operation, even under highly fluctuating H_2S inlet concentrations. More severe perturbations of the system, such as failure of the plant water chlorination resulting in ppm levels of free chlorine in plant water, or operation at neutral pH for over a week, resulted in a decrease of H_2S removal (Gabriel and Deshusses, 2003b).

Data assessment for operating costs calculation

Operating costs in each reactor were evaluated for a period of time of eight months, between August 2001 and March 2002. The costs associated with biotrickling filter operation are make-up water consumption and electricity corresponding to the blower and the recycle pump. The cost of chemical scrubbing must also include chemicals (sodium hydroxide and, if used, hydrogen peroxide) and the electricity corresponding to chemical pumps operation. The cost of chemicals (sodium hydroxide 25% at 0.47 US$/gallon; hydrogen peroxide at 1.86 US$/gallon), energy (0.07 US$/kWh) and water (43 US$/Mgallon) were calculated based on 2002 prices communicated by OCSD.

All cost analyses per scrubber were performed based on the total treatment cost in dollars, while comparison between scrubbers is based on the cost in dollars per mass of H_2S treated in each reactor in order to make cost calculations comparable. All cost calculations were performed on a monthly basis to take into account airflow changes in the reactors during the study and because of the changes in H_2S loading to the reactors. Seasonal fluctuations of H_2S concentrations were greater in the trunkline scrubber and in the biotrickling filter, because of the effect of temperature on H_2S production in the inlet sewer lines (Figure 2).

Monthly averages obtained from on-line H_2S sensors were used to calculate the amount of H_2S treated in each reactor. It was verified that straight averaging was equivalent (differences below 4%) to calculating the H_2S treated in each reactor based on time weighed average. Similarly, monthly averages were calculated for operational variables such as foul airflow and make-up water flow rate. Table 3 summarizes averaged monthly values for foul airflow measured for each scrubber, along with the difference between the inlet and the outlet concentrations of H_2S in the reactors. From this table, one can see that scrubber #4 is treating a much lower concentration of H_2S than #9 and the biotrickling filter, hence the lower mass of H_2S eliminated during the time considered.

Secondly, make-up water, energy and chemicals usage (if any) was calculated on a daily basis in order to obtain cumulative and instantaneous consumptions. Energy costs were calculated multiplying the time each electrical component of each reactor was in operation by

Table 3 Summary of monthly averaged airflow and H_2S from monitored data between August 01 and March 02.

Period	Foul airflow (m^3 h^{-1})			$C_{in} - C_{out}$ (ppm_v H_2S)		
	Biotrickling Filter	Scrubber #9	Scrubber #4	Biotrickling Filter	Scrubber #9	Scrubber #4
August	9,830	11,205	32,280	10.9	14.0	2.8
September	6,330	11,205	32,280	15.9	21.5	2.4
October	15,205	8,670	32,280	10.2	16.2	1.9
November	14,135	6,155	32,280	10.0	15.1	2.9
December	14,060	4,810	32,280	9.1	8.5	1.5
January	14,550	3,990	32,280	5.1	5.5	0.9
February	15,540	3,990	32,280	5.8	3.0	1.2
March	15,540	3,990	32,280	8.8	7.1	1.2

the cost of electricity and by the pump or blower power (Table 1). The run time for each electrical component was logged into the supervisory control and data acquisition (SCADA) system of the facility.

A steady flow of plant water was always used for operation of any of the reactors (Table 1). Water costs were calculated multiplying the time each reactor was in operation per month by the cost of secondary effluent and by the make-up water flow rate. Similarly, chemicals consumption in each scrubber was assessed multiplying the average flow delivered by each chemical metering pump to each scrubber, by the run time of each pump and by the cost of each chemical used.

Operating costs and analysis of the biotrickling filter and chemical scrubbers #9 and #4

Table 4 summarizes the major operating costs during the period considered for each one of the three reactors. It does not includes the average cost of make-up water ($3.5, $34, and $15 per month, for the biotrickling filter, scrubber 9, and scrubber 4, respectively) since they are negligible compared to the other operating costs. On an average basis, 99% of energy costs in the biotrickling filter, and 78% and 84% for chemical scrubbers 4 and 9, respectively, are due to electrical power requirements for the blower. Since pressure drop through the packed-bed has an effect on efficient blower operation, energy costs in the biotrickling filter will be affected by proper blower operation. This suggests that further investigations into the effect of packing size and the effect of trickling rate are warranted, as they may reduce energy costs. Similarly, energy cost represents 64% and 38% of total operation costs in chemical scrubbers 9 and 4, respectively.

The average monthly costs from Table 4 were used to estimate yearly operating cost assuming that the 8 months of operation were representative of a full year of operation. In doing so, some uncertainty is introduced. Overall, we estimated that, assuming a surge in H_2S concentration in May-July, chemical costs for scrubber 4 would not exceed $40,000 per year, i.e., within 20% of our above estimates.

Since the amount of pollutant degraded in each reactor was different, comparison of costs must be performed once data is normalized based on the amount of H_2S treated. Results indicate that total operating costs of the biotrickling filter were around $18,000 per year. In the case of scrubber 9 and scrubber 4, total operating costs were $32,800 and $56,700, respectively, with the higher costs due mainly to the larger amount of chemicals consumed. On the basis of mass of H_2S removed, the average total treatment costs were $13.2/kg ($0/kg for chemicals) in the biotrickling filter, $32/kg ($11/kg for chemicals) in scrubber 9, and $84/kg ($51/kg for chemicals) in scrubber 4. These values fit in the wide range of operating costs reported for packed-bed, caustic-only chemical scrubbers of $2 to

Table 4 Monthly consumption of energy and chemicals and treatment capacity during the period under study. (Totals are rounded numbers)

Period	Biotrickling filter Energy (US$)	Biotrickling filter H_2S treated (Kg)	Scrubber #9 Energy (US$)	Scrubber #9 Chemicals (US$)	Scrubber #9 H_2S treated (Kg)	Scrubber #4 Energy (US$)	Scrubber #4 Chemicals (US$)	Scrubber #4 H_2S treated (Kg)
August	1408	97.9	1497	1006	128.7	1513	2975	65.6
September	1522	99.5	1729	1342	229.5	1907	2828	94.5
October	1574	159.4	1852	897	143.8	1586	2229	41.6
November	1406	129.0	1724	709	88.5	1842	2504	95.4
December	1570	131.0	1729	814	39.0	1932	2170	48.8
January	1560	74.7	1841	912	22.5	1972	2829	32.7
February	1419	82.5	1548	819	10.4	1780	3255	34.0
March	1566	139.2	1848	1262	29.0	1972	4391	39.5
Yearly	**18,000**	**1370**	**20,700**	**11,600**	**1040**	**21,800**	**34,800**	**680**

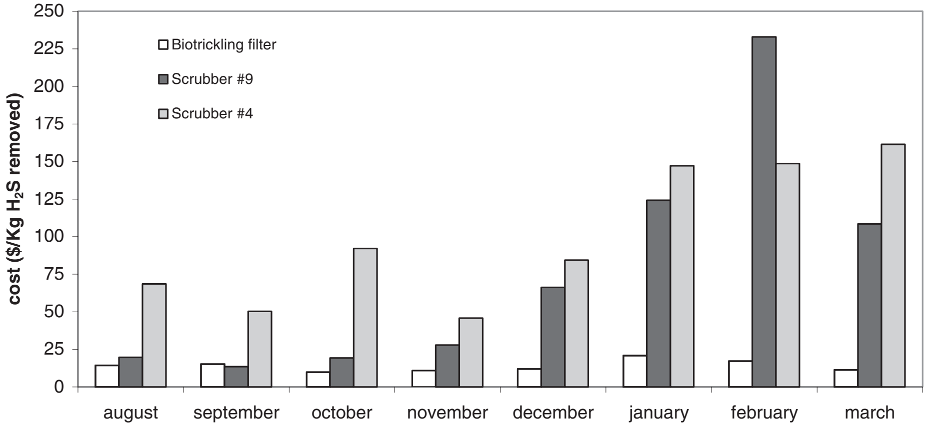

Figure 3 Monthly operating cost of each reactor under study based on the mass of H_2S removed

\$280 per kg of H_2S removed (EPA, 1996; Card, 2001; Witherspoon, 2002). As expected, the second stage scrubber #4 exhibited higher operating costs due to a higher chemical usage compared to the first stage scrubber #9. The percentage of the chemicals cost *vs.* total operating cost was as high as 60% for scrubber 4 compared to 35% for scrubber 9.

The above values are averages, but a high seasonal variability of the treatment costs per mass of H_2S removed was found over the time of the study for the chemical scrubbers, whereas the treatment cost in the biotrickling filter was relatively constant (Figure 3). It is worth stressing that direct comparison of the specific treatment for a given month in Figure 3 should be undertaken with care, as the masses treated in each reactor were not necessarily the same. Therefore, the costs per kg of H_2S treated were reported in Figure 4 as a function of the amount of H_2S treated.

Since the cost plotted in Figure 4 include blower costs, it is logical to find that the specific treatment costs in the biotrickling filter increase at low loadings since this is the only cost for the biotrickling filter. However, in all cases the costs of the biotrickling filter are much lower than those of chemical scrubbing. The inset in Figure 4 shows the cost of chemicals only. The inset highlights that the efficiency of chemical scrubbing decreases as the

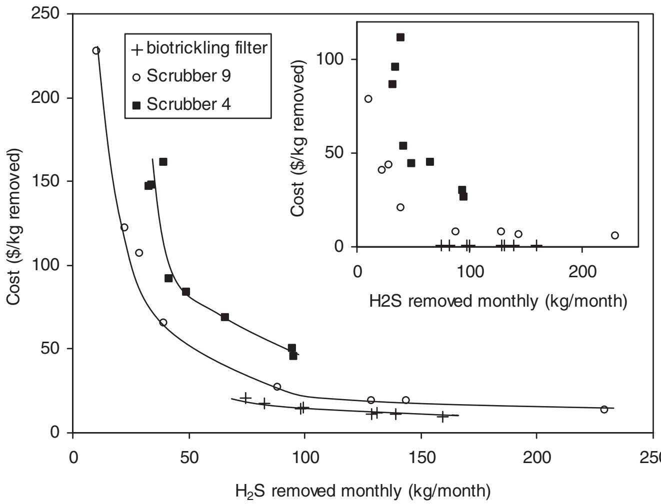

Figure 4 Total operating cost per kg of H_2S removed as a function of the mass of H_2S removed in each reactor. The inset shows the costs of chemicals only

concentration of H_2S decreases. If costs are reported per thousands of cubic meters of air treated (data not shown), scrubber 9 becomes the most expensive scrubber, whereas scrubber 4 and the biotrickling filter have approximately the same costs. But as indicated earlier, scrubber 4 is treating about twice the flow of the biotrickling filter, and much lower concentrations. Hence, direct comparison of cost per volume of air treated is not necessarily warranted.

Cost-benefit analysis of the conversion of scrubber 10 to a biotrickling filter

A cost-benefit analysis of the conversion of scrubber 10 must take into account operation of the Trunkline and Headworks complexes during the period under study. Since the load to each reactor changed during the project (thereby affecting treatment costs), the most realistic scenario is a direct comparison of chemical scrubber 9 versus the biotrickling filter operating simultaneously and comparing the average operating cost directly from the data in Table 4 and Figures 3 and 4. Further, the impact of the biotrickling filter upstream of chemical scrubber 4 should be taken into account as the H_2S that was treated in the biotrickling filter did not need to be treated downstream in scrubber 4.

Thus, a cost-benefit analysis was performed first by direct comparison of chemical scrubbers 9 and 4 and biotrickling filter costs, taking into account the cost of the conversion of the chemical scrubber 10 to a biotrickling filter. Details of the total monthly savings in chemicals, energy and total operation costs savings between scrubber 9 and the biotrickling filter are shown in Table 5. Direct savings (scrubber 9 vs. biotrickling filter 10) in chemicals are about \$1000 per month. The numbers of Table 5 extrapolated to one year of operation result in direct savings of \$14,700 per year by having reactor 10 as a biotrickling filter instead of a chemical scrubber. 80% of these total savings are due to chemical savings.

Since the biotrickling filter outperformed scrubber 9, Table 5 also takes into account the cost of post-treatment of the difference between biotrickling filter 10 and scrubber 9, by multiplying the excess H_2S treated in 10, by the treatment cost (chemicals only, since the air flow in scrubber 4 is unchanged) per mass for H_2S treated in scrubbers 4. Linear extrapolation to 1 year of these savings from excess H_2S removed in the biotrickling filter as shown in Table 5 indicates that these savings per year would be \$29,000 per year. This is the additional amount of chemicals that would be consumed by the four downstream scrubbers 1-4 of the headwork complex. Thus, the total estimated yearly savings of the conversion were \$43,700.

Savings obtained from chemicals, energy and water usage reduction only from scrubber 9 indicate that the payback time for scrubber 10 conversion was about 1.5 years assuming a

Table 5 Cost savings analysis of having biotrickling filter 10 compared to scrubber 9 (all costs in US\$, numbers not rounded, all digits shown). Items: A= chemicals saved BTF vs #9 (\$/month); B = electricity saved BTF vs #9 (\$/month); C= total direct savings BTF vs #9 (\$), (C =A + B); D = excess H_2S removed in BTF vs #9 (kg H_2S/month); E = chemical savings in #4 from excess H_2S removed in BTF (\$), (E = C × \$51/kg); F = total savings per month BTF compared with #9 (\$), (F = A + B + E).

Item	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	Sum 8 months	Extrapol. 1 year
A	1,006	1,342	897	709	814	912	819	1,262		
B	89	207	278	318	160	281	161	282		
C	**1,095**	**1,549**	**1,175**	**1,027**	**974**	**1,193**	**980**	**1,544**	**9,537**	**14,306**
D	0	0	16	40	92	52	72	110		
E	0	0	816	2,040	4,692	2,652	3,672	5,610	19,482	29,223
F	**1,095**	**1,549**	**1,991**	**3,067**	**5,666**	**3,845**	**4,652**	**7,154**	**29,019**	**43,529**

cost for the conversion cost of $21,500 (in-house conversion, direct costs only). If chemical savings from scrubber 4 are included (see Table 5), the payback time for the conversion is reduced to less than 6 months. This clearly demonstrates the high economical viability of converting a trunkline chemical scrubber to a biotrickling filter. It must be stressed that the savings resulting from acid washes for chemical scrubbers ($600–$4,000 per year per scrubber, assuming one to six acid washes per year) or reductions in insurance costs, accidents or risks due to chemicals on-site were not included, although they can be significant.

Conclusions

A detailed cost-benefit analysis of converting a roughing chemical scrubber to a biotrickling filter revealed that scrubber conversion resulted in substantial savings. When compared directly to the parallel chemical scrubber #9, the savings amounted to $14,700 per year, mostly from reduced chemicals use. Since the biotrickling filter outperformed the chemical scrubber, the cost-benefit analysis also considered the expense associated with the post-treatment of the untreated fraction of H_2S from the chemical scrubber #9. In this case, the savings amounted to about $43,000. It is challenging to generalize the numbers presented above to other scrubber conversions. On the one hand, the converted scrubber at OCSD was exposed to relatively high concentrations of H_2S, which probably increased the absolute cost savings, compared to chemical scrubbing. On the other hand, the scrubbers at OCSD are operated under relatively tight control, with careful metering of the chemicals to avoid over-dosage. Hence, scrubbers elsewhere may have a higher chemical consumption and the savings using a biotrickling filter may be even more important than those reported here. A case-to-case evaluation will of course be required.

Acknowledgments

The authors would like to thank OCSD for project funding and OCSD personnel, in particular Jeff Brown, and plant operators for their outstanding and continuous support of the field operation.

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