
Final Report

Conversion of a Wet Scrubber to a Biotrickling Filter at OCSD
Phase II Actual Conversion and Evaluation for H_2S Control

Work Period
May 2001 – September 2002

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February 2003

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EXECUTIVE SUMMARY

Orange County Sanitation District (OCSD) previously funded a study at UC Riverside to evaluate the feasibility of converting selected chemical scrubbers at OCSD to biological trickling filters. The results were very promising, and suggested that a number of scrubbers at either Plant 1 or Plant 2 could possibly be converted with significant cost and health and safety savings. Thus the objectives of Phase II were:

1. To refine the scrubber conversion procedure and costs to convert a scrubber.
2. To develop a monitoring protocol and apply it towards the evaluation of the biotrickling filter. This includes extended monitoring over time, and under a wide range of operating conditions.
3. To perform a detailed cost-benefit analysis of the converted scrubbers and to the extent possible to other scrubbers at OCSD.
4. To write a report with the findings and recommendations.

As the work progressed, 4 more scrubber were converted by OCSD personnel and additional objectives were identified which included:

5. Perform selected analyses on scrubbers I, Q, G, and J that were converted at Plant 2.
6. Perform selected experiments to understand the limits and performance of the biotrickling filters.

Overall, the project was extremely successful. The focus of the monitoring efforts was on biotrickling filter 10 which successfully treated 10,000 cfm of foul air for over 18 months keeping the original gas contact time of the scrubber of 1.6-2.3 seconds. Typical results are shown in Figures 1 through 4. Reclaimed water was used as nutrient source for the process and for maintaining the pH in the biotrickling filter between 1.5 and 2.2. Under these conditions, the biotrickling filter was able to successfully treat H_2S at rates comparable to those of chemical scrubbers. H_2S removal in biotrickling filter 10 was in excess of 98% for inlet H_2S concentrations as high as 30 to 50 ppmv. This corresponds to volumetric elimination rates of H_2S of 95 to 105 g H_2S m^{-3} h^{-1}. The performance of biotrickling filter I at Plant 2 was also very high.

Simultaneously to H_2S treatment, removal of 30-70% of odors, reduced sulfur compounds (RSCs), ammonia and volatile organic compounds (VOCs) and air toxics present in traces in the foul air was also observed (see Table 1).

H_2S treatment performance in biotrickling filters 10 and I was exceptionally high compared with other biofilters or biotrickling filters removing low concentration of H_2S, even at higher gas contact times. We determined that a combination of high pollutant mass transfer rate due to the special packing support that was used and optimum operating conditions (nutrient, pH, CO_2) was responsible for the unprecedented performance.

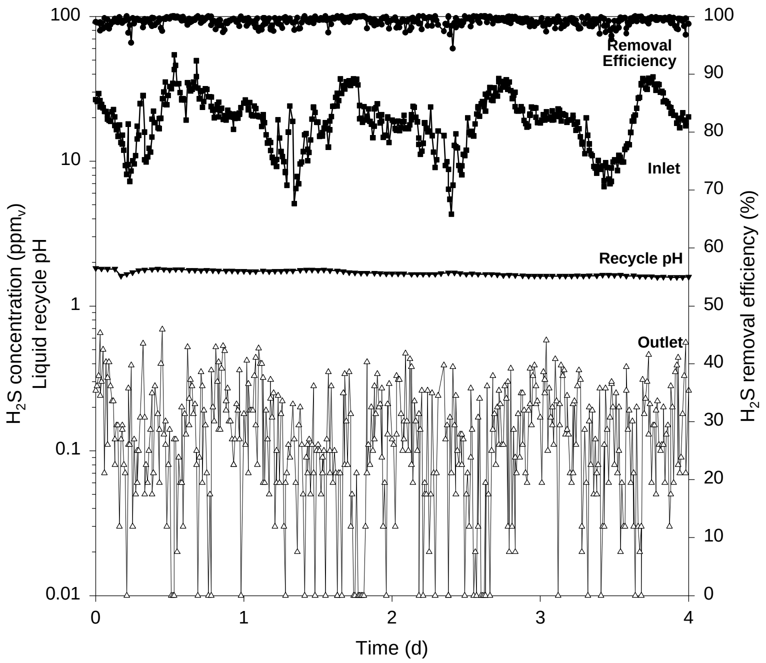

Figure 1. Typical H_2S removal in biotrickling filter 10. Time zero corresponds to 12:00 AM on September 5, 2001. Note the log scale for H_2S concentration. Also, non-detect (ND) by VAPEX is shown as 0.01 ppm_v.

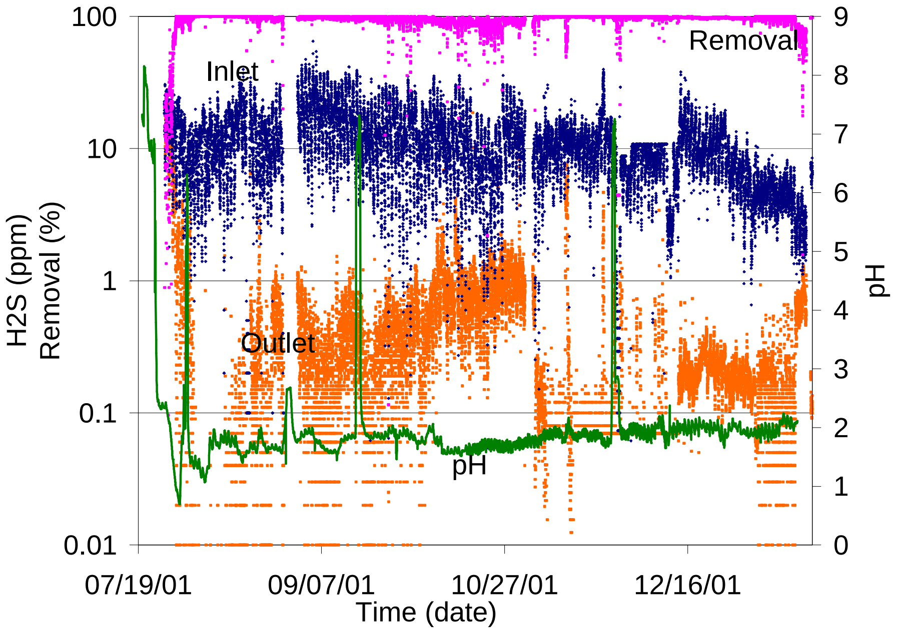

Figure 2. Long-term performance of biotrickling filter 10. H_2S removal efficiency, pH, inlet and outlet concentrations are shown. High pH events are either experiments or control system upsets.

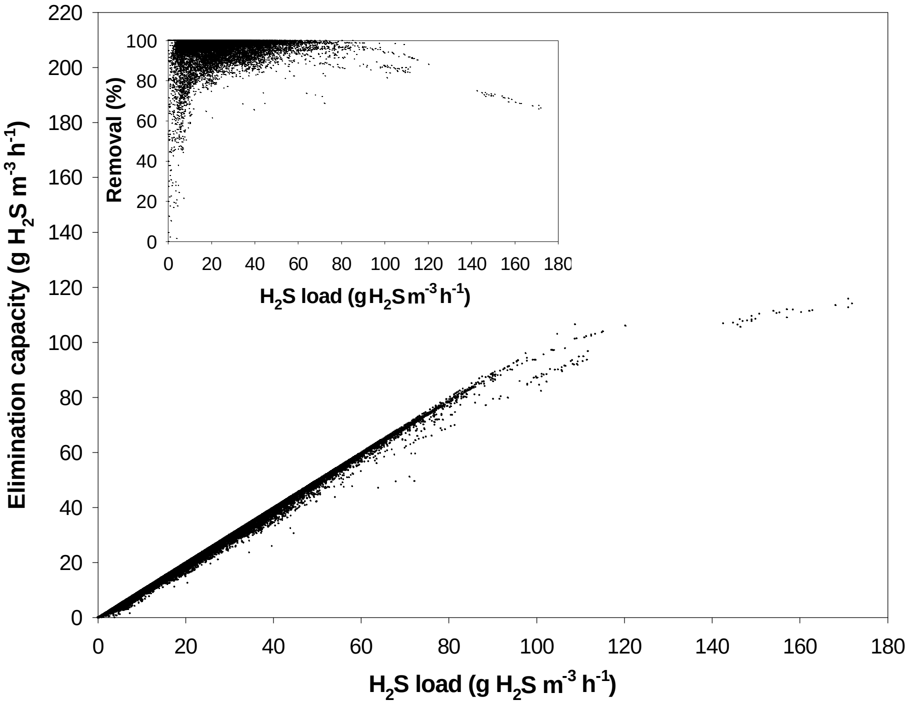

Figure 3. Elimination capacity of H_2S (= (concentration in-out)×air flow/bed volume) and removal efficiency versus inlet load (inset) in the biotrickling filter. Data include more than 8 months of continuous operation. Loadings above 110 g H_2S m^{-3} h^{-1} were achieved by spiking the inlet air with H_2S from a compressed gas cylinder.

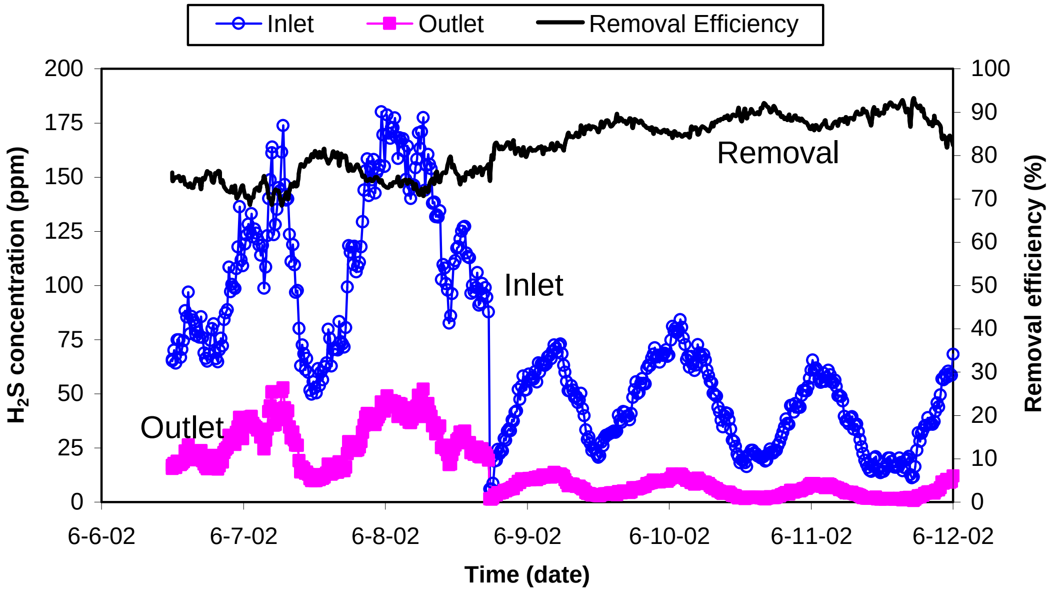

Figure 4. 6 days of typical H_2S removal in biotrickling filter I.

Table 1 Inlet concentrations and removal efficiencies of odor, VOCs and RSCs from biotrickling filter 10. Data are mean ± standard deviation, n=21 for RSCs, n=19 for VOCs, and n=9 for odor panels and are representative of about 8 months of operation at gas contact times between 1.6 and 3.4 seconds. D/T = dilution-to-threshold as measured by standard odor panel.

Compound	Inlet concentration, ppb_v	Removal efficiency, %
Carbonyl sulfide	67.2 ± 7.7	44 ± 11
Methyl mercaptan	192.5 ± 34.1	67 ± 11
Carbon disulfide	70.3 ± 20.5	35 ± 5
Methylene chloride	132 ± 93	36 ± 25
Chloroform	326 ± 263	30 ± 21
Benzene	147 ± 105	32 ± 21
TCE	16 ± 15	46 ± 28
PCE	224 ± 257	28 ± 20
Toluene	753 ± 2144	29 ± 14
Ethyl benzene	148 ± 221	41 ± 27
p and m-xylene	480 ± 852	41 ± 19
o-xylene	110 ± 210	44 ± 30
Odor	1980 ± 480 D/T	65 ±21

From the 18 month study, the following conclusions could be made.

1. The conversion of a chemical scrubber to a biotrickling filter is a relatively simple procedure. The costs associated with the conversion are mostly (~50%) associated with the purchase and shipping of the new packing that needs to be installed. For scrubber 10, the total estimated cost (i.e., parts and personnel) for the conversion by in-house personnel was about $21,000. The estimated cost of the conversion if performed by an outside contractor for that scrubber was about $50,000.
2. The scrubbers converted to biotrickling filters exhibited H_2S removal performance largely exceeding the predictions of Phase I. Sustained removal of H_2S with over 95% efficiency was achieved most of the time for biotrickling filter 10 at Plant 1, while biotrickling filter I at Plant 2, exposed to higher H_2S concentrations, exhibited high rate of H_2S degradation but partial removal. Biotrickling filter 10 had a maximum H_2S elimination capacity of about 105 g m^{-3} h^{-1}, while biotrickling filter I achieved elimination capacities over 250 g m^{-3} h^{-1} without reaching its maximum limit. These are truly unprecedented performances. We determined that the very high air velocity in the biotrickling filter contributed to high external H_2S mass transfer coefficients, thereby allowing such high H_2S removal rates to be achieved.
3. Stable and sustained H_2S removal was obtained at operating pHs of 1.8 to 2.2. Treatment at neutral pH was attempted but failed. However, the results were considered to be inconclusive, as the experiment was possibly affected by the excess free chlorine fed to the biotrickling filter during neutral pH operation.

4. Biotrickling filter 10 was subject to intense monitoring which revealed that it always met the AQMD discharge requirement (<1 ppm H_2S averaged over 24 h).
5. Removal of VOCs, RSCs and odors other than H_2S was not the primary objective of this phase of the study. Still, extended monitoring showed that these contaminants existed in traces (ppb levels) and that their removal ranged from about 30-70%, and was very variable. Removal of RSCs required about 2 months of acclimation.
6. The biotrickling filter exhibited a larger pressure drop (5-10" water column) than the former scrubbers. This is clearly because the new packing has a larger surface area, but is possibly also increased by packing compaction at the bottom of the bed. Testing structured foam is recommended.
7. The five biotrickling filters had less than 10 system upsets in 18 months of operation. In two or three instances, biotrickling filter 10 or I lost its H_2S removal efficiency. The most likely explanation was that overchlorinated plant water was fed and deactivated the biotrickling filter process culture. Another instance could be traced to acidic foam carryover from another scrubber. Thus, upsets were always due to a reason exterior to the biotrickling filtration process itself, suggesting that the process is stable and very reliable.
8. The biotrickling filters required little maintenance (although maintenance efforts were not quantitatively monitored). Their control was simple, and the biotrickling filter did not need any nutrients or chemicals other than plant water. This all contributes to a very positive cost-benefit outcome.
9. The biotrickling filter responded rapidly to changing conditions. Also, no marked effect on the performance could be found after periods of up to 48 hours' starvation.
10. A detailed cost-benefit analysis of converting scrubber 10 to a biotrickling filter revealed that conversion resulted in substantial savings. When compared directly to the parallel scrubber (scrubber 9), the savings amounted to $14,000 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. Another scenario considered the benefit of having biotrickling filter 10 over having no roughing treatment. In all these cases, total savings ranged from $40,000 to $70,000 per year. The benefits of not having chemicals on-site were not included, but are significant from a health and safety perspective. Overall, the cost-benefit analysis indicates that converting scrubbers is a highly beneficial innovation.

The study led to the following general recommendations.

1. Since biotrickling filtration proved very effective, reliable, and economically favorable, further conversions should be considered. In particular scrubbers 9 and H appear to be very good candidates. Also, biotrickling filters should be included in future odor control plans.

2. Operation of the biotrickling filters at pH lower than 1.5-1.8 is not recommended, since low pH can possibly damage the packing over time.
3. Low trickling rates are recommended as excess watering increases pressure drop and may affect removal.
4. Future biotrickling filters should include some system to neutralize chlorine in plant water prior to feeding to the biotrickling filter or an alarm if excessive levels are seen in plant water.

Further, for Phase III, the recommendations are:

5. Future conversion(s) should focus on testing a structured foam (i.e., cut-to-shape), as it may result in lower pressure drops and possibly even higher pollutant elimination capacities.
6. Another experiment at neutral pH should be conducted, with a chlorine neutralizer on the plant water feed.
7. The study of the effect of air residence time on RSCs, VOCs, and odor removal should be conducted over an extended period of time, so that multiple sampling over time under a wide range of conditions can be accomplished.
8. Phase III should focus on the many issues associated with residual odor as these are key for the implementation of biotrickling filters for second stage treatment.

1. BACKGROUND AND OBJECTIVES

Orange County Sanitation District (OCSD) had previously funded a study at UC Riverside which objective was to evaluate the feasibility of converting selected OCSD chemical scrubbers to biological trickling filters. The study addressed the technical feasibility of the conversion, and evaluated the cost-benefit of converting selected scrubbers at OCSD. The results were very promising, and suggested that a number of scrubbers at either Plant 1 or Plant 2 could possibly be converted (see detailed results in the final report of Phase I) with potential cost savings ranging from $5-50k per year per scrubber. One of the recommendations of the study was to convert a scrubber and study the actual conversion procedure, the treatment efficacy, and the cost-benefit of the conversion. In consultation with OCSD personnel, the objectives of a second phase were identified and tasks for Phase II were developed.

The objectives of this project were:

1. To refine the scrubber conversion procedure and costs to convert a scrubber.
2. To develop a monitoring protocol and apply it towards the evaluation of the biotrickling filter. This includes extended monitoring over time, and under a wide range of operating conditions.[1]
3. To perform a detailed cost-benefit analysis of the converted scrubbers and to the extent possible to other scrubbers at OCSD.
4. To write a report with the findings and recommendations.

As the work progressed, additional objectives were identified which included:

5. Perform selected analyses on scrubbers I, Q, G, and J that were converted at Plant 2.
6. Perform selected experiments to understand the limits and performance of the biotrickling filters.

Other activities by the UCR team also included helping in the development of a monitoring protocol for scrubbers to be converted at Plant 2, assist is reviewing plans for the new scrubber complex and input on the integration of biotrickling filters for H_2S and odor control.

The present report summarizes all the findings for Phase II. The report is organized as follows. In Chapter 2, the conversion procedure is presented. The monitoring and performance of the scrubbers that were converted is reported and discussed in Chapter 3. The cost-benefit analysis is discussed in Chapter 4, conclusions and recommendations are in Chapter 5, and additional information is provided in the appendices.

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[1] Note that the original objectives included a number of optimization procedures, but since the outlet concentrations of H_2S was almost always below discharge limit, process optimization efforts were reduced for lack of proper metrics that would indicate improvement of treatment performance. The efforts were redirected towards characterizing the biotrickling filtration process under selected conditions.

2. SCRUBBER CONVERSION PROCEDURE AND COSTS TO CONVERT A SCRUBBER

It was previously agreed that either scrubber 9 or 10 at Plant 1 would be converted. Scrubbers 9 and 10 are virtually identical and either one could be used for the project. There were subtle differences; the final choice between scrubber 9 and 10 required further evaluation. The main criteria included accessibility of the liquid recycle pumps, and differential pressure at the project initiation. Based on these, it was decided that scrubber 10 would be the first scrubber to be converted. Preparation and preliminary work for the conversion was in May-June 2001. Actual operation of the converted scrubber started July 20, 2001.

The major tasks and work performed for the conversion are described in this Section. The conversion followed the so-called 10 step procedure developed by the UCR team during Phase I of this project. Scrubber 10 was the first scrubber converted following review and evaluation of its characteristics with OCSD personnel. Note that several steps of the 10 conversion steps did not apply because of the specifics of the conversion considered. Also, in addition to what is described here, several supporting documents were developed, including a spreadsheet with a detailed protocol of the specific tasks to be performed, both for UCR work and non-UCR work (see Appendix 2).

2.1 Step 0: Preparation Work: Scrubber Isolation and Washing

Prior to actual conversion, scrubber 10 required some preparatory work consisting of the isolation and washing of the scrubber. This task was scheduled for the first and second days while foul air was passed through scrubber 9. Dampeners for scrubber 10 were closed. The work performed was as follows:

0.1 The fan for scrubber 10 was stopped and the stop button in the field panel was locked. For safety reasons the power source for the fan was locked temporarily

0.2 The inlet and outlet dampeners for scrubber 9 were opened. Afterwards the inlet and outlet dampeners for scrubber 10 were closed, avoiding foul air flow to scrubber 10

0.3 HCl line to scrubber 10 was closed and valves locked. This line is not used during the biotrickling filter operation. HCl will not be necessary during the scrubber decontamination.

0.4 Caustic injection line: The caustic pump was stopped and a lock was installed on the field panel button. Alarms were switched off from the plant SCADA system.

0.5 The scrubber and pipes were flushed with plant water until a neutral pH was reached. To wash the scrubber it was continuously fed plant water (flow rate ~ 15 gpm). Both recycle pumps were operated at the usual flow rate to ensure proper cleaning of pipes.

0.6 Subsequent to scrubber washing by UCR and OCSD personnel, the scrubber was decontaminated by a contractor (Water Systems Cleaning) using standard procedures. The contractor also removed the packing (see Section 2.3) and reinforced the packing support (see Section 2.4). The outside contractor provided the necessary materials, equipment and manpower to perform those tasks.

No action was necessary for the chlorine line because this line was closed and valves were already locked. This line was not used during biotrickling filter operation.

2.2 Step 1: Removal of Unnecessary Parts

It was recommended that for the first conversion, only a minimum number of changes would be done. Hence, most of the lines were kept as is to allow to return to scrubber operation should biotrickling filtration not be continued at the end of the project. Thus, the recycle pump and some associated piping were the only equipment that needed to be changed. Liquid recycle pump 302 was more accessible than liquid recycle pump 301. Thus pump 302 was replaced and pump 301 kept as is. Note that biotrickling filter operation at scrubber 10 only relied on a single pump (although a spare pump was purchased). The pump did not fail during the duration of the project. In the event of pump failure, a replacement pump can rapidly (within a day) be installed since the pump is a lightweight unit. Note that for conversion of scrubber I at Plant 2, the two pumps were replaced in order to avoid any downtime in the event of pump failure.

1.1 The recycle pump 301 was isolated from the surroundings by valve closures and alarm deactivation. Valves and power source for the pump were locked as required.

1.2 The recycle pump 302 was isolated from the surroundings by valve closures and alarm deactivation. Only the power source for the pump was temporary locked as required.

1.3 The plant and reclaimed water lines used to cool the pump were closed and valves locked. No cooling ring is necessary for the pump used for biotrickling filter operation.

1.4 The recycle pump 302 was disconnected from the recycle pipe and from the water cooling line (note there is a 0.5" water supply to the pump head for cooling purposes). The cooling line was capped.

1.5 The new pump was installed (see Section 2.7)

2.3 Step 2: Removal of Packing

Removal of old packing material by the outside contractor was accomplished by opening the manholes near the bottom of the bed and scooping material into large waste/trash bags. The material was analyzed to determine proper disposal of the packing. Note that the old packing was found to be completely fouled by chemical (presumably limestone) deposits, in spite of the fact that acid washing had been performed prior to removing the packing (see pictures in Appendix 1).

2.4 Step 3: Strengthening of Packing Support

Strengthening of the structural support for new packing material was thought to be required but it turned out that it was probably superfluous (the four scrubbers converted subsequently did not include strengthening the support). Water Systems Cleaning performed this task by installing a heavy duty reinforcement leg under the lower packing chamber grating. The pillar was made of Sch. 80 PVC pipe and was designed to support 5 tons. Prior to this task, technicians filled out a Confined Space Entry form in compliance with OSHA Regulations 1910.46 (Standards 29 CFR).

2.5 Step 4: Modification of the Liquid Distribution System

The liquid trickling rate for the biotrickling filter needed to be reduced to 20-30 gpm, a fraction of what is currently used in OCSD chemical scrubbers. The current distribution system is a typical liquid distributor with parting boxes and weir troughs. Discussions with the constructors (Paramount) confirmed that such liquid distribution was suitable for the biotrickling filter while providing a uniform water distribution. Thus, the liquid distribution system was not modified. Verification of the quality of the liquid distribution revealed that it was adequate.

2.6 Step 5: Modify the Mist Eliminator

There is a section of 1” Tripack packing at the top of the scrubber which served as a demister. It was said not to be very effective in removing fine liquid droplets from the outlet air stream under the present conditions, but since the potential for mist carry over from the biotrickling filter was low, the demister of scrubber 10 was not modified.

2.7 Step 6: Modify the Liquid Recycle Pump

The liquid recycle flow rate for the biotrickling was reduced to 20-30 gpm, a fraction of what was currently operated in the chemical scrubbers. A new liquid recycle pump of 0.5 hp, 3 phase motor, 230/460V electrical supply, with a polypropylene pump head was installed. The smaller pump required modifications in the piping to reduce the large liquid recycle pipe to the smaller pipe diameter fitting of the pump. (see pictures in appendix).

6.1 The recycle pump was mounted on the actual platform

6.2 The pump inlet and outlet were connected to the pipe. To do this, two piping assemblies attaching to the existing flanges and made of reductions from 6” to 1.5” and 4" to 1” for the inlet and outlet, respectively, were installed (see pictures in appendix)

6.3 An electrician from OCSD connected the pump to the power supply

6.4 Valves in the recycle line for the new pump were opened and the recycle pump was tested for leaks and proper operation.

2.8 Step 7: Modify the Inlet Air Ducts

This step did not apply for this conversion

2.9 Step 8: Installation of Secondary Effluent Supply

Secondary effluent was needed, since it serves as trickling liquid and a nutrient source and controls the pH. Plant water (slightly chlorinated secondary effluent) was already connected to scrubber 10, hence no change to the existing setup was made.

2.10 Step 9: Installation of the New Packing Material

New packing material was provided by M+W Zander (Germany). The purchase was through UCR and shipped via air freight. The packing was the same as used in Phase I, i.e, open pore polyurethane foam (ppi 10 = 10 pores per inch), 35 kg m^{-3} density and 40 mm cubes size were used. The interfacial area of this packing is said to be 600 m^2 m^{-3}. For 12 m^3 of packing the cost of the material was \$6400 plus shipping and customs costs of about \$4000 for a total of \$10,400.

For packing installation, the following procedure was followed. The packing is shipped in large bags under vacuum, and Zander recommended allowing the packing to expand and wetting the packing prior to installation inside the scrubber. This was done by dumping large amounts of packing on the ground and watering for about 5 minutes with plant water. A shovel was used to mix the packing and ensure proper wetting. The wet and expanded packing was then placed in large bags and poured into the scrubber via the manholes. The location of the upper manhole below the upper bed limiter made it difficult to completely fill the column. Subsequent conversions should consider removing the bed limiter so that filling the column with packing foam is easier. Note that as will be discussed later, one recommendation is to use a structured, cut-to-shape PU foam which installation will require entering the scrubber and arranging large cubes of foam in an ordered fashion.

2.11 Step 10: Modification of the Controls

Scrubber 10 already included remote monitoring and some degree of controls that were easily modified to accommodate biotrickling filter operation. The pH and pressure drop monitoring were maintained (pH probe needed recalibration). We also kept the existing low liquid level alarm and shutdown for the liquid recycle pump. Scrubber 10 includes H_2S monitoring using a VAPEX unit. Manual actuation of plant water supply valves was adequate to control the makeup water supply for nutrients and to control pH in the biotrickling filter.

The actual monitoring and control system was versatile enough to easily operate and control the biotrickling filter, so no modification other than deactivating selected control loops (pH, hypochlorite supply) and changing the pH setpoint was required.

2.12 Special Requirements/Notes

1. OCSD contracted with Water Cleaning System for removing the packing and reinforcing the packing support (the final cost was below $2000)
2. OCSD provided a light duty crane and operator for removing the pump
3. OCSD provided an electrician to connect the new pump
4. OCSD arranged for storage space for the used packing
5. Tags and locks (cable ties) for switches and valves were provided
6. OCSD provided outstanding field personnel support on an as-needed basis during the conversion

2.13 Conversion Costs

The exact cost of the conversions was difficult to estimate because not all personnel time and efforts were accounted for. Still a good estimate of the cost is reported in the Cost-Benefits Chapter 4. A summary is given in this Section. One should stress that since this was a first conversion, there was more time dedicated to preparation work. Parts costs were modest as indicated below, with most of the material costs going towards the purchase and shipping of the packing. However, using a packing that had a proven track record was important for the project and it justified the higher cost. Custom made PU foam in the US would cost about the same as the purchase price below, however significant savings on the shipping costs would be accomplished.

Packing costs:	$6,400
Shipping/customs:	$4,000
Liquid recycle pumps:	$1,000
Fittings, flowmeters, miscellaneous:	$1,800
Removal of old packing (contractor):	$1,300
Grand total parts/contractor:	**$14,500**
Estimated labor	**$7,000**
Grand total	**$21,500**

(see more details in Chapter 4)

For further economic evaluation, one can estimate that the real cost of the conversion as performed by in-house personnel is in the range of $20,000 to $30,000. However, the work might be contracted out. Our best estimate is that an engineering service company would offer a “turnkey” conversion such as the one that was conducted on scrubber 10 for about $50k. That would include all preparation work, parts, conversion work and some O&M for startup and follow up.

2.14 Subsequent Conversions

Following the conversion of scrubber 10, Mike Larkin of OCSD directed the conversion of four scrubbers. UCR was not directly involved in the actual physical conversion, except for advice as needed. The conversions followed a similar procedure as the one listed above. The only difference is that some of the converted scrubbers use spray nozzles for liquid distribution. In those cases, the spray nozzles were replaced with smaller ones to accommodate the lower flowrate. The characteristics on the converted scrubbers is given in Table 2.1. No specific detail on the cost of the conversion was available.

Table 2.1 Summary of design parameters for the chemical scrubbers converted at OCSD.

Parameter	Scrubber 10	Scrubber I	Scrubber Q	Scrubber G	Scrubber J
Reactor location	Plant 1	Plant 2	Plant 2	Plant 2	Plant 2
Scrubber type	Pretreatment	Pretreatment	End-of-pipe	End-of-pipe	End-of-pipe
Air source	Influent sewer trunkline	Influent sewer trunkline	Primary treatment	DAFT off-gases[a]	Belt filter off-gases
Packed height (m)	3.9	3.3	3.3	3.1	4.9
Diameter (m)	2	2	3.3	2	3.3
Bed volume (m^3)	12	10	27.7	15	41.6
Liquid distributor	Parting box and weir troughs	Parting box and weir troughs	Nozzles	Nozzles	Parting box and weir troughs
Fan low / high speed (kW)	30 / Single speed fan	30 / Single speed fan	33 / 75	30 / Single speed fan	28 / Not available
Recirculation pump (kW)	5.6	2.2	11	15	7.5
Liquid recycle ($m^3 h^{-1}$)	99	79	136	168	150
Nominal air flow low / high ($m^3 h^{-1}$)	17,000 / Single speed fan	17,000 / Single speed fan	40,800 / 68,000	47,000	39,000 / Single speed fan
EBRT high / low (s)[b]	2.03 / Single speed fan	2 / Single speed fan	1.96 / 1.18	0.93 / Single speed fan	3.07 / Single speed fan
Average inlet H_2S (ppm_v)[c]	50	40-100	9	<10[d]	<7[d]
Average outlet H_2S (ppm_v) before conversion[c]	10	9	0.5	0.5	0

[a] Dissolved Air Flotation Thickeners. [b] EBRT = Empty Bed Retention Time = bed volume/air flow. [c] Estimated from on-line data and information collected during site visits. [d] Nuisance is mostly organic odors, not H_2S.

Conversion factors: to convert $m^3 h^{-1}$ to cfm divide by 1.7. To convert $m^3 h^{-1}$ to gpm multiply by 4.4.

3. PERFORMANCE OF THE CONVERTED SCRUBBERS

3.1 Characteristics of the Plant Water

Since the biotrickling filters were only receiving plant water as a source of nutrients, extensive characterization of the plant water was conducted on several occasion. Water samples from the liquid reservoir and two sources of make-up water were analyzed for ammonium, nitrate, nitrite, phosphate, sulfate, and organic matter content by means of Standard Methods (American Public Health Association, 1995). Chlorine was tested with a chlorine test kit in order to make sure that chlorine levels were below inhibitory levels of 3-5 ppm in the make-up water supplied to the biotrickling filter. Field measurements were performed for conductivity, dissolved oxygen, temperature, and carbon dioxide using specific probes connected to a portable datalogger (Vernier Software & Technology, OR). A total of 26 ions were measured by Inductively Coupled Plasma (ICP) technique in order to characterize micronutrients in both the make-up water supplied to the biotrickling filter and the liquid phase in the reactor.

Table 3.1 shows the averaged values and their standard deviations for the main parameters characterized between 7 to 12 different grab samples of both plant water and reclaimed at OCSD Plant 1. Other trace ions not shown in Table 3.1 such as Li^+, Al^{3+}, Ba^{2+}, Cu^{2+}, Fe^{3+}, Mn^{2+}, Zn^{2+} were found at levels between 50 and 10 mg m^{-3}. Grab samples analyzed from OCSD Plant 2 revealed similar results to those analyzed at Plant 1. Results on Table 3.1 revealed that both sources could be used as a nutrient source without any extra addition to sustain growth of Thiobacillus species. Plant water was preferred because of its higher nutrient content and minor free and combined chlorine presence. Although it remains to be proven, six months into the project, reclaimed water was used during plant water service failure which could have led to a possible inhibition of the biotrickling filtration process due to excessive chlorine levels. If such was the case, a simple neutralization cartridge for chlorine prior to feeding the biotrickling filter would probably suffice.

Table 3.1 Characteristics of water make-up sources available at Plant 1

Parameter	Units	Plant water Plant 1	Reclaimed water Plant 1
Sulfate	g m^{-3}	272 ± 119	176 ± 49
Nitrite	g N m^{-3}	0.5 ± 0.3	0.1 ± 0.06
Nitrate	g N m^{-3}	1.5 ± 0.6	1.3 ± 1.1
Phosphate	g m^{-3}	7.5 ± 1.9	6.5 ± 1.7
Ammonium	g N m^{-3}	16.7 ± 8.8	15.0 ±10.0
Free chlorine	g m^{-3}	0.8 ± 0.2	1.7 ± 0.7
Combined chlorine	g m^{-3}	1.6 ± 0.8	6.1 ± 3.3
Chemical oxygen demand (COD)	g m^{-3}	36 ± 17	29 ± 24
Biological oxygen demand (BOD_5)	g O_2 m^{-3}	16 ± 6	10 ± 3
Total organic carbon (TOC)	g C m^{-3}	18.5 ± 6.0	17.1 ± 4.3
Inorganic carbon (IC)	g C m^{-3}	58.4 ± 11.4	36.0 ± 12.1
Ca^{2+}	g m^{-3}	66.5 ± 11.9	53.6 ± 9.9
K^+	g m^{-3}	22.6 ± 6.1	15.3 ± 3.9
Mg^{2+}	g m^{-3}	32.5 ± 6.0	23.4 ± 7.2
Na^+	g m^{-3}	228.1 ± 58.4	185.8 ± 63.3
pH	--	7.6 ± 0.2	7.1 ± 0.1

3.2 Air Characteristics

The concentrations of H_2S in the off-gases of both Plant 1 and Plant 2 incoming sewers fluctuate cyclically (i.e, daily and seasonally) during normal operation. Figure 3.1 shows a high daily variation in the inlet H_2S concentration profile for trunkline biotrickling filters, and particularly for biotrickling filter 10 with a 7 fold difference between the maximum and the minimum. End-of-pipe biotrickling filter Q treats a mixture of the outlet air from biotrickling filter I plus air from the primary treatment of the facility. Temperature is very stable in the biotrickling filters and usually only fluctuates a few degrees around an average of 23-27 ^oC. (73-81 ^oF) (see Table 3.2)

No control system other than manual adjustment of make-up water flow rate was considered necessary for the converted scrubbers, which was later proved to be suitable for stable operation of the reactor. Even with such daily variability in the inlet concentration, the hourly average of pH measured in the liquid recycle of biotrickling filter 10 shows a very stable profile (Figure 3.1) when a constant make-up water supply of 7.7 L min^{-1} (2 gpm) is constantly fed. According to this, substantial simplification in the control of biotrickling filters can be accomplished compared to chemical scrubbers operation, where pH must be automatically controlled by chemical additives addition to assure stable reactor operation.

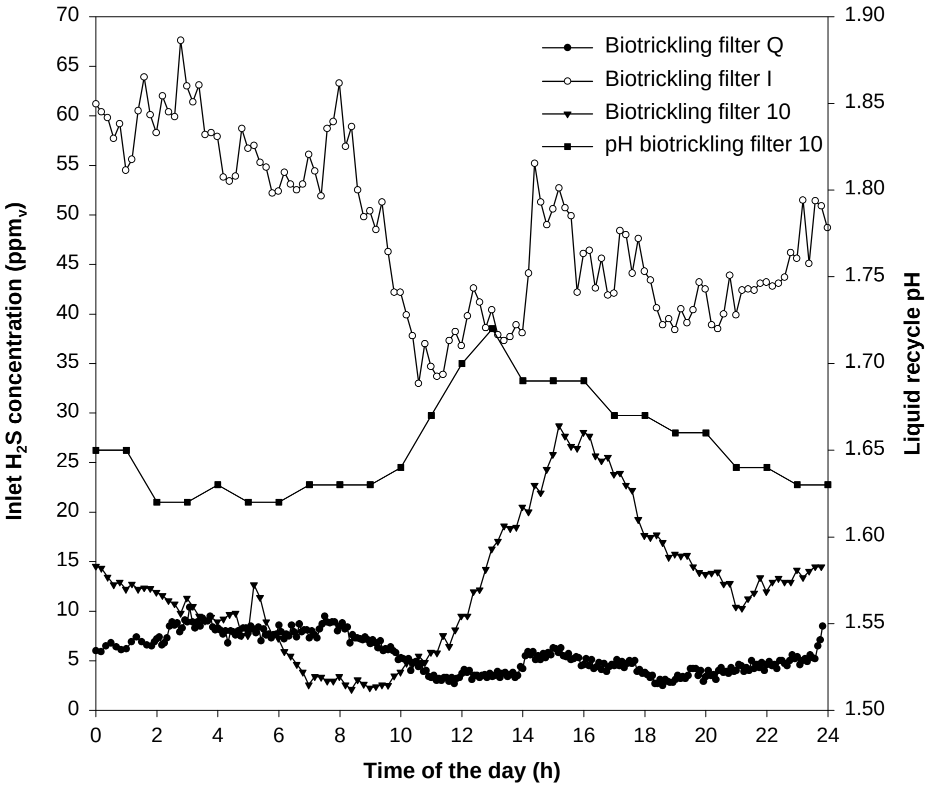


Figure 3.1 Hourly variations in H_2S inlet concentration profiles along the day for the scrubbers that were converted to biotrickling filters (scrubbers I, Q, and 10). Also shown is on-line measurements of pH in the biotrickling filter 10 after conversion. Inlet H_2S concentration for J and G are not shown since their H_2S concentration is always very low.

It is interesting to note that inlet carbon dioxide in foul air was found to have an average concentration of 4500 to 5000 ppm_v, i.e., much higher than the 600 ppm_v found in the air stream supplied to the pilot scale unit, during Phase I at UCR. Although not proven, the use of a more complete nutrient source and a higher amount of carbon dioxide (which is the source of carbon for the autotrophic organisms degrading H_2S) in the full-scale reactors may have been a factor for the high H_2S removal performance that was observed.

3.3 Startup of the Converted Biotrickling Filters

The startup of all converted biotrickling filters was performed in a similar way. Since scrubbers G and J are treating mostly low levels of odors which are difficult to quantify, and for which sampling was continuous, the discussion of the startup concentrates on the scrubbers that had on-line VAPEX for the continuous measurement of H_2S. These are scrubbers 10, I, and Q.

In each case, the bottom reservoir was filled with a mixture of plant water and return activated sludge from the plant to achieve a concentration of about 400 mg TSS L^{-1}. The liquid was then recycled over the bed for 24 hours without supply of neither foul air nor make-up water to promote cell attachment onto the packing. Then, the biotrickling filters were started up at the design foul air flow and water make-up supply of 7.7 L min^{-1}, 6.5 L min^{-1}, and 18 L min^{-1} for biotrickling filters 10, I, and Q, respectively. Because of different inlet conditions in each reactor, each one had a different startup.

Figure 3.2 shows the profile of H_2S removal efficiency and the pH in the recycle during the startup period for biotrickling filter 10. Despite some problems with the on-line H_2S meter device, the pH trend indicates that during the first three days, no noticeable H_2S biodegradation activity occurred in the biotrickling filter. The pH remained near neutral because of the continuous supply of secondary effluent to the reactor as nutrient source exceeded the rate of acid production. A sudden pH decrease took place the third day, which coincided with the first actual observation of H_2S removal.[#] Between day 3 and 7, moderate H_2S removal was observed, mostly during the part of the day where the inlet H_2S concentration was high. The opposite pattern (typical for breakthrough at high loadings) was observed during the following days, where the removal efficiency increased to reach 100 percent (day 9) mostly during low concentration hours. The early limitations in removal observed during the periods of low inlet concentration remain to be explained. After 15 days, the removal efficiency became virtually independent of the H_2S inlet concentration. We concluded that after that time, the biotrickling filters were acclimated.

It is interesting to observe the behavior of biotrickling filter 10 as a function of the pH in Figure 3.2. The pH constantly changed during the acclimation phase depending on the sulfide removal and sulfate production, but fluctuations of as much as 4 pH units in the recycle liquid did not affect the removal efficiency of the system, thus confirming that a more strict pH control was not necessary and that the system was quite resistant to short time pH swings. Once the reactor reached a quasi-steady state in terms of H_2S removal, no more adjustment of the water supply was necessary, as the pH of the system was stable with a continuous supply of 5.7 - 7.7 L min^{-1} (~2 gpm) of plant water.

[#] H_2S biodegradation results in 2 H^+ + SO_4^{--}, hence a decrease in the pH

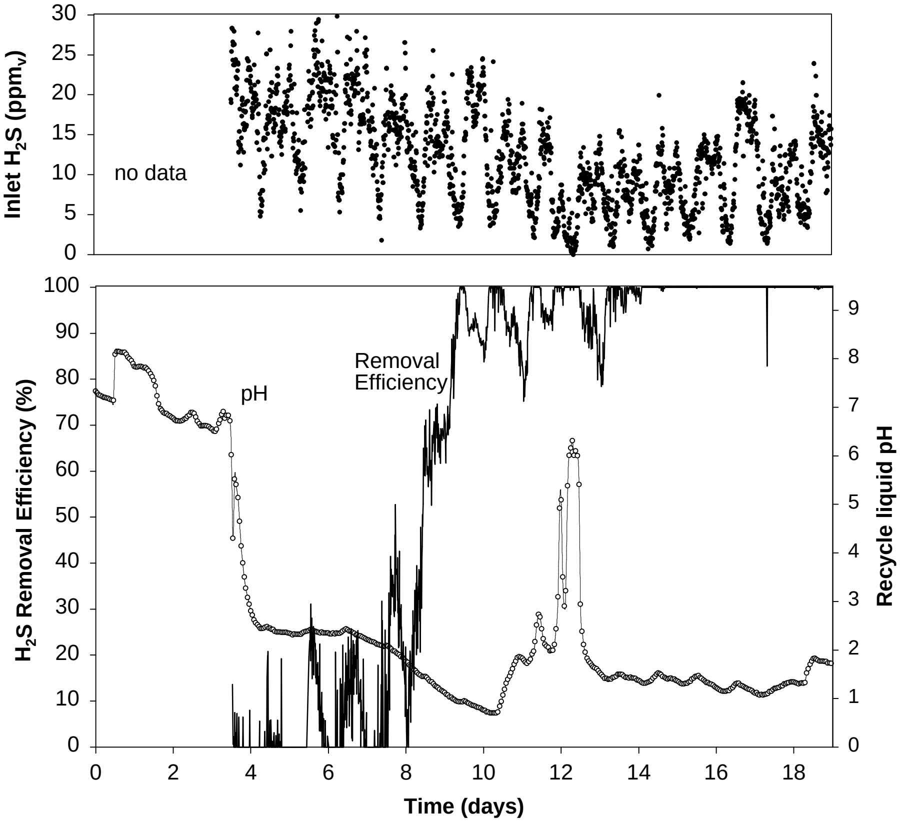


Figure 3.2 Performance of biotrickling filter 10 during the startup period. Top) Profile of H_2S inlet concentration to the biotrickling filter (12 minutes averaged data). Bottom) Removal efficiency (12 minutes averaged data) and pH (hourly averaged data).

The startup of biotrickling filter I is shown in Figure 3.3b. Examination of the Figure reveals that the behavior of biotrickling filter I was different from that of biotrickling filter 10, mainly because of the higher inlet H_2S load to this reactor, especially during the startup phase. Similarly to biotrickling filter 10, after 2 days of operation a gradual increase of the removal efficiency was observed until 99.7% removal was reached on day 14. During that period, averaged inlet load was 13 g H_2S m^{-3} h^{-1} to biotrickling filter I and 23.7 g H_2S m^{-3} h^{-1} to biotrickling filter 10. Over time, the load to biotrickling filter I was raised and the pattern of removal started to significantly differ from that of biotrickling filter 10 after two weeks of operation. The average removal efficiency of reactor I never reached more than 80%. This is clearly because the load (average value of 42 g H_2S m^{-3} h^{-1}) exceeded the treatment capability of the reactor at the time of the experiment. In any case, elimination capacity increased gradually between days 19 and 25 as a result of reactor adaptation to higher loads, which indicated that higher potential for H_2S treatment could be accomplished. The elimination capacity [$EC = (C_{in}-C_{out}) \times$ air flow/bed volume] vs. load curve for the first 30 days (startup phase) and one month after the startup phase is shown in Figure 3.4. The data illustrate that while relatively high elimination capacities were obtained, only partial removal was obtained in biotrickling filter I. Exact reasons for the difference between I and 10 have not been investigated.

For scrubber Q, the particular design of its overflow pipe made it necessary to have a higher water make-up supply in order to avoid emptying the sump of the reactor. That fact, coupled with a lower production of H+ as a result of a lower H_2S inlet concentration to the reactor, resulted in an average pH of 5.9 during the startup period. As shown in Figure 3.3a, operation at pH to some extent below neutrality did not affect H_2S removal efficiency, which was kept at a high percentage most of the time. Similarly, observations on scrubber Q confirmed that no strict pH control is necessary for the operation of H_2S removal biotrickling filters and that growth of H_2S-degrading populations are possible in a wide pH range (Islander et al., 1991; Chan and Suzuki, 1993).

The startup of biotrickling filter Q was different from that of biotrickling filter 10 or I because of the low concentration of H_2S at the inlet of the reactor, which probably caused a low biomass growth into the reactor. The time needed to reach a quasi steady-state removal efficiency (27 days) was almost twice the time required for highly loaded biotrickling filters 10 and I. Fluctuating removal efficiencies in the period between days 14 and 19 and the inability to treat H_2S spikes on days 12, 20 and 22 were directly related with a low inlet H_2S concentration. It suggests that special attention should be paid to the startup of biotrickling filters with low loadings. Extra nutrients and other possible measures to promote growth may be warranted.

A summary of the biotrickling filter performance for the month following the startup phase is listed in Table 3.2.

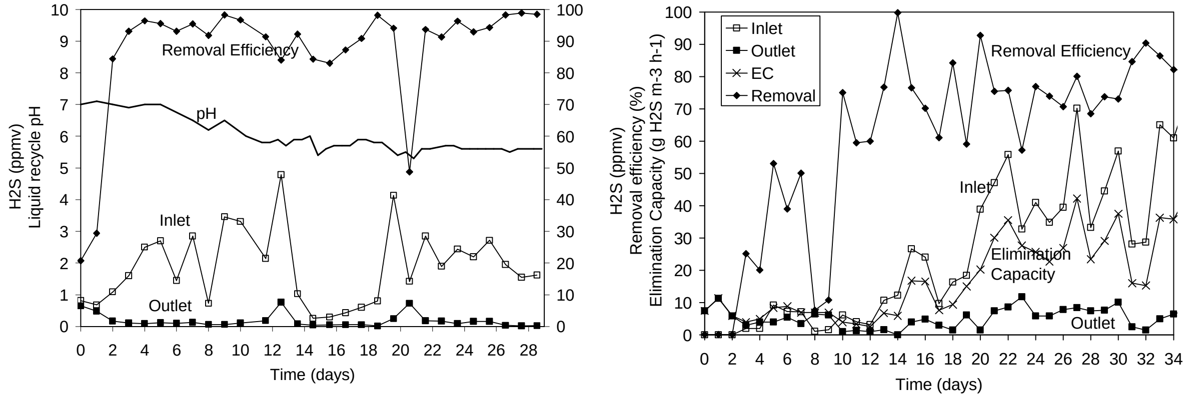


Figure 3.3 Performance of biotrickling filter Q (left) and biotrickling filter I (right) during startup.

Table 3.2 Operating conditions and summary of averaged performance for days 30 through 60 of the three biotrickling filters at OCSD treating significant H_2S concentrations. This table illustrates pseudo steady-state one month after startup.

Parameter		Units	Scrubber 10	Scrubber I	Scrubber Q
Packed height		m	3.14	3.05[a]	3.05[a]
Bed volume		m^3	8.17	8.02[a]	22.28[a]
Air flow[#]		$m^3\ h^{-1}$	10,245	12,100	12130
		cfm	6,050	7,150	7,150
Liquid recycle flow rate		$m^3\ h^{-1}$	4.5	4.5	12.7
		gpm	20	20	56
EBRT		sec	2.9	2.4	6.6
Water make-up flow		$m^3\ h^{-1}$	0.46	0.53	0.75
		gpm	2.0	2.3	3.3
pH		-	1.7	1.2	5.5
Temperature (liquid)		ºC	27.7	23.5	23.6
Pressure drop		cm water	23.2	27.3	3.5
Inlet H_2S	Max.	ppm_v	64.9	43.4	8.60
	Avg.		14.7	20.4	1.63
Outlet H_2S	Max.	ppm_v	6.5	11.83	3.00
	Avg.		0.2	4.7	0.25
H_2S elimination capacity	Max.	$g\ H_2S\ m^{-3}\ h^{-1}$	82.8	73.8	4.45
	Avg.		24.6	32.7	1.03
H_2S load	Max.	$g\ H_2S\ m^{-3}\ h^{-1}$	83.7	90.1	6.44
	Avg.		24.9	42.3	1.22
H_2S removal efficiency	Max.	%	99.9	99.3	99.9
	Avg.		98.5	78.2	86.4
Inlet RSCs concentration		ppb_v			
Carbonyl sulfide			57.7-142	192-321	< 30
Methyl mercaptan			96.8-250	261-361	< 44
Carbon disulfide			58.4-411	38.1-210	< 36
RSCs removal efficiency		%			
Carbonyl sulfide			0	4.6	n / a
Methyl mercaptan			44	13	n / a
Carbon disulfide			27	5	n / a

[a] Value at startup, bed volume could not be measured afterwards. [#] Air flow was increased subsequently

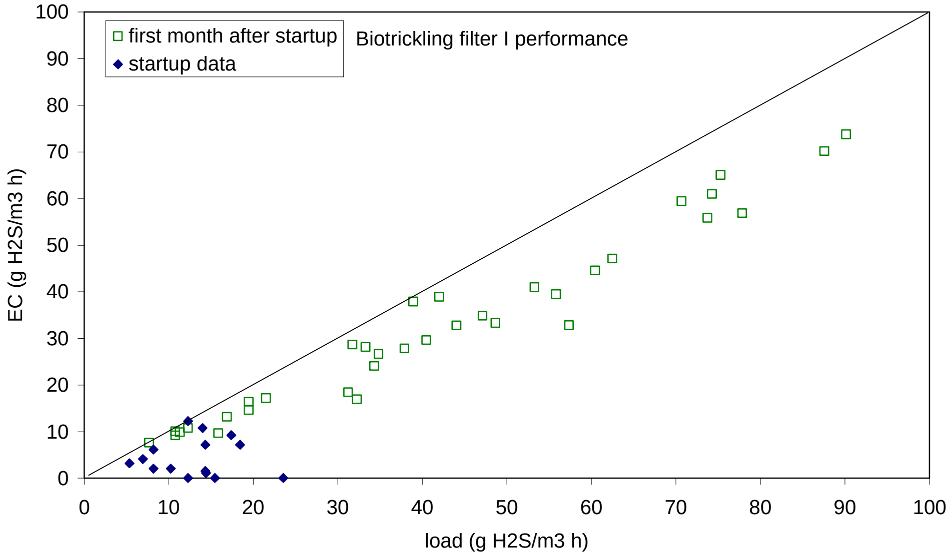


Figure 3.4 EC vs. load for biotrickling filter I (b) during startup and for the first month after startup. Note that the data plotted are from OCSD roundsheets because the VAPEX data were deemed unreliable at the time of the biotrickling filter startup.

3.4 Long-Term Performance of the Converted Biotrickling Filters - H_2S Removal

Typical H_2S removal in scrubber 10 is shown in Figure 3.5. The inlet concentrations of H_2S fluctuated daily between 5 and 40 ppm_v, while outlet concentrations were always maintained well below the 24 h averaged discharge limit of 1 ppm_v. As expected, concentrations of H_2S were lower during the winter months and higher during the summer months. A summary of the long term biotrickling filter performance and operating conditions is reported in Figure 3.6.

Overall, results in terms of H_2S removal were much better than predicted from the laboratory pilot tests of Phase I. The average H_2S removal efficiencies in biotrickling filter 10 were in excess of 98% for inlet loads of 25 g H_2S m^{-3} h^{-1}, while the average H_2S outlet concentration was always below the 1 ppm_v discharge limit and individual measurements seldom exceeded the discharge limit. This was particularly important for the two-stages treatment system made of biotrickling filters I and followed by Q, since the latter outlet stream discharges directly to the atmosphere. Still, for biotrickling filter Q, there are unresolved issues on residual odor after biotrickling filtration. The residual odor (see Section 3.5) was found to be highly variable, and often exceeding OCSD self imposed limit of 300 D/T. Understanding ways to achieve a lower odor discharge is part of the proposed research of Phase III.

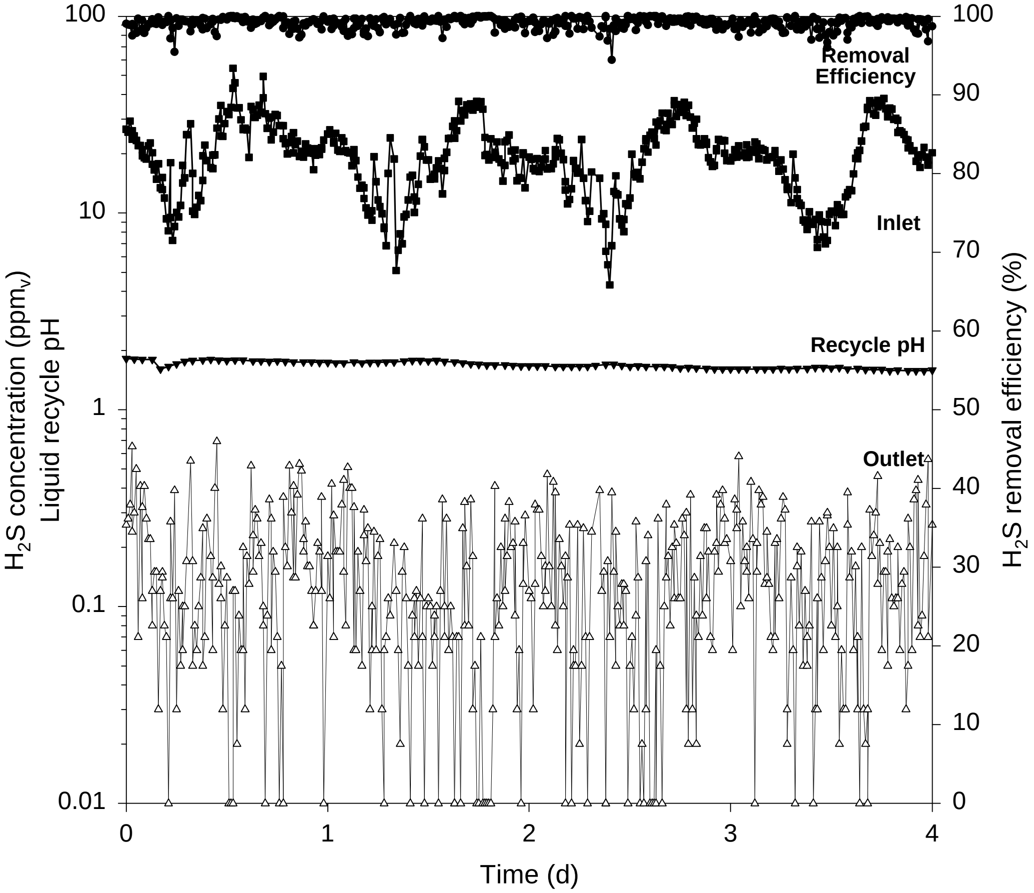


Figure 3.5 Typical H_2S removal in biotrickling filter 10. Time zero corresponds to 12:00 AM on September 5, 2001. Note the log scale for H_2S concentration. Also, non-detect (ND) by VAPEX is shown as 0.01 ppm_v.

The high performance in biotrickling filters 10 and I represents 5-20 times higher elimination capacities compared to other low odor removing systems (Smet et al., 1998). In addition, the biotrickling filters were able to deal with a variable inlet concentration, particularly for biotrickling filter 10, and maintained a relatively consistent discharge, usually below 1 ppmv even during peak hours. This is illustrated in the probability plots of Figure 3.7. Although the inlet concentration was highly fluctuating, the outlet was maintained well below the discharge limit level a high percentage of the time. The few outlet H_2S data above 1 ppm_v corresponded to transient periods of rapidly increasing H_2S inlet concentrations. The concentration distribution was clearly dependent on the ambient temperature, as temperature affected H_2S generation in the trunklines. In Figure 3.6b, we show that during the cold season, the reactor operated at lower H_2S inlet concentrations, which resulted in lower discharge concentrations a higher fraction of time. In both cases, however, the results of Figure 3.6 demonstrate the robustness of the system over a wide range of operating conditions.

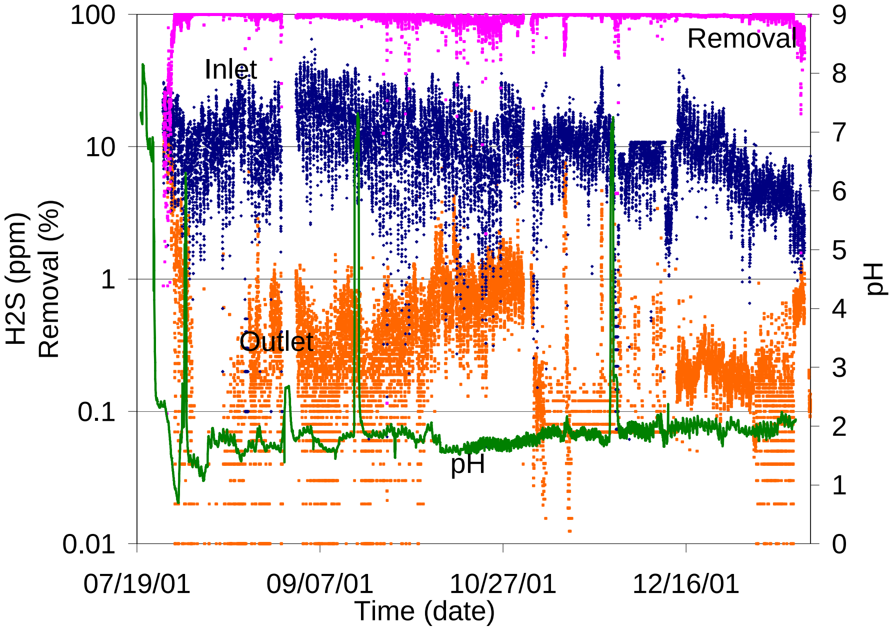


Figure 3.6 Long-term performance of biotrickling filter 10. H_2S removal efficiency, pH, inlet and outlet concentrations are shown. High pH events are either experiments or control system upsets. Data continue on next figure.

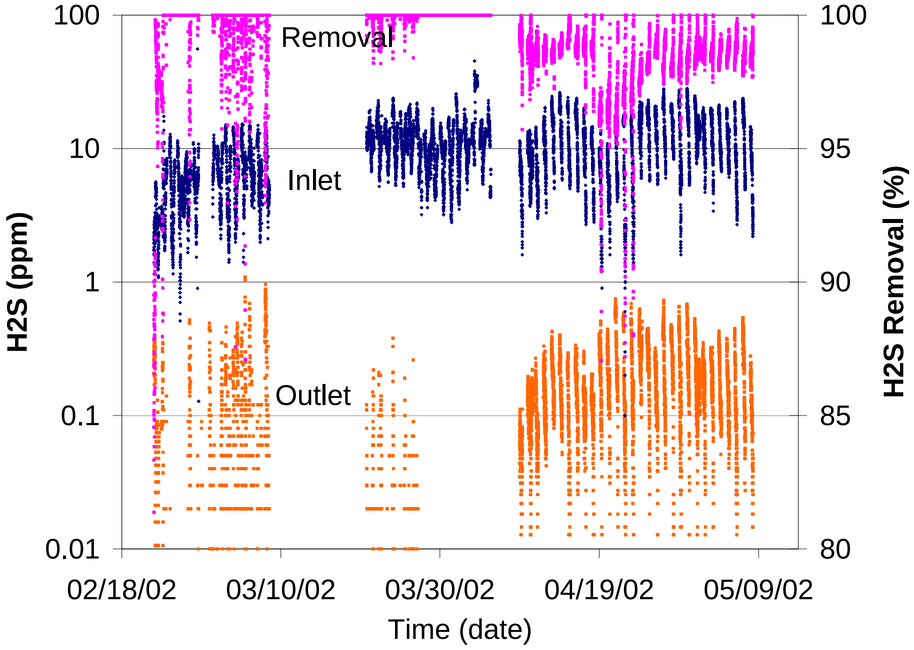


Figure 3.6 (cont.) Long-term performance of biotrickling filter 10. H_2S removal efficiency, inlet and outlet concentrations are shown. pH is not shown but fluctuated between 1.5 and 2.3, except during specific experiments.

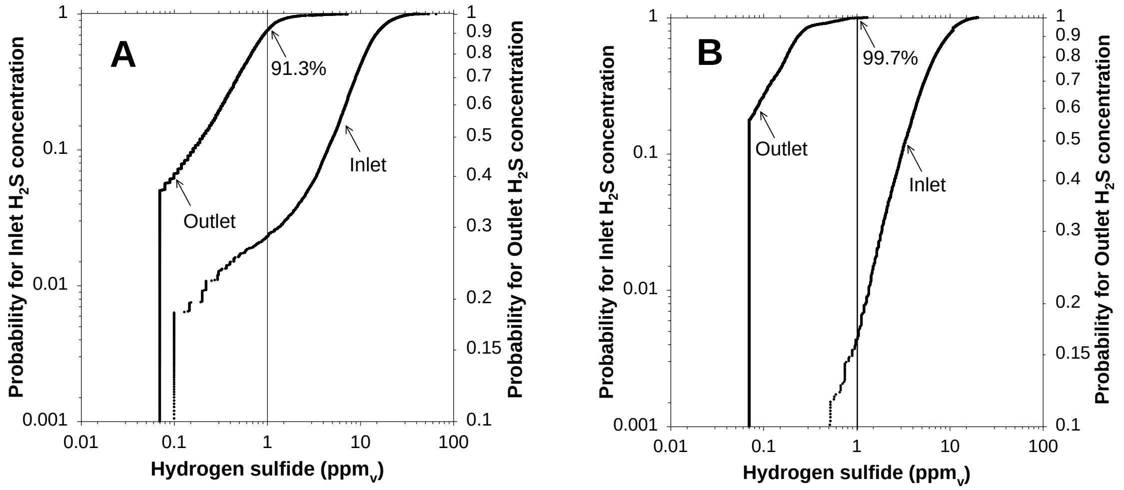


Figure 3.7 Normal probability plot of inlet and outlet H_2S concentrations from biotrickling filter 10 during routine operation of the reactor for all data acquired between August 8, 2001, and November 30, 2001 (A) and December 1, 2001, and March 31, 2002 (B). Vertical bar at 1 ppm$_v$ indicates the average discharge limit not to be exceeded for more than 24 consecutive hours. Note the different scales used for inlet and outlet probabilities.

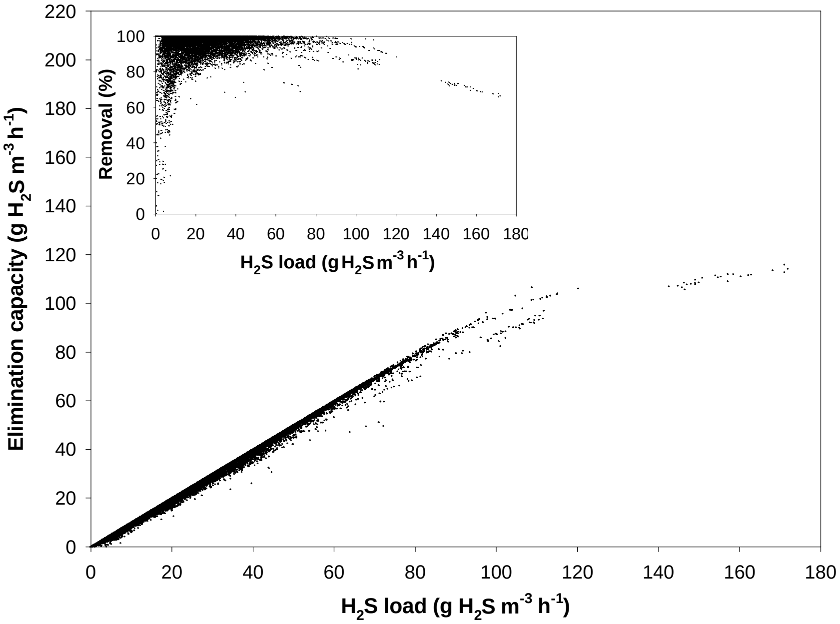


Figure 3.8 Elimination capacity of H_2S and removal efficiency versus inlet load (inset) in the biotrickling filter. Data include more than 8 months of continuous operation. Loadings above 110 g H_2S m^{-3} h^{-1} were achieved by spiking the inlet air with H_2S from a compressed gas cylinder.

Long term H_2S elimination capacity data are reported in Figure 3.8. As mentioned, the airflow in OCSD scrubbers was essentially constant, and the loading changes were a result of the fluctuations in H_2S inlet concentration. At loadings between 10 and 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}, breakthrough of H_2S occurred, while a quasi-zero order degradation regime was observed at loadings above 105 g H_2S m^{-3} h^{-1}, with removal efficiencies gradually decreasing to less than 80%. Removal efficiencies below 80% were also found at inlet loadings below 12 g H_2S m^{-3} h^{-1}, which corresponded to inlet H_2S concentrations below 3.5 ppm_v. However, the biotrickling filter effluent air was always in compliance. Overall, the H_2S removal performance obtained with biotrickling filter 10 is exceptionally high when compared with other biofilters or biotrickling filters removing low concentration of H_2S, usually even at higher gas contact times (Chung et al., 2000; Wu et al., 2001; Cox and Deshusses, 2002).

A side project conducted at UCR attempted to find an explanation to the higher than expected performances that were observed. The approach considered building a small differential biotrickling filter in which the air velocity could be modified (Kim and Deshusses, 2002). In summary, it was found that for a given set of operating conditions, the maximum elimination capacity of H_2S increased as the air velocity was increased. This is an extremely novel finding, and suggests that external (gas film) mass transfer limitation plays an important role in determining the rate at which H_2S is removed in conventional biotrickling filters. Indeed the biotrickling filters at OCSD are operated at a much high linear velocity than any previous biotrickling filter application. The air velocity is about 1.8 m s^{-1} for scrubber 10, compared to 0.05 m s^{-1} in a 1 m bed depth operated at 20 s Empty Bed Retention Time (EBRT). At this time, one can only speculate about why external mass transfer is so important in conventional biotrickling filter. H_2S degrading biotrickling filters have very thin biofilms (probably about 10-30 µm), and H_2S degrading bacteria appear to be extremely active (on a basis of H_2S degraded per g of biofilm). This creates a very large gradient of H_2S concentration in the biofilm, hence a very rapid mass transfer in the biofilm. Under these conditions, external mass transfer, which is usually fast compared to biofilm processes, becomes (in part) rate limiting, hence its greater importance here than in other biofiltration/biotrickling filtration studies. It is interesting to find that the specific activity of H_2S degrading organisms is very high. Presently, further experiments are conducted at UCR to elucidate the role of the CO_2 in air (H_2S degraders are autotrophic organisms utilizing CO_2 as carbon source), and the role of the trickling water composition, in particular pH and BOD on the biological kinetics of H_2S degradation.

Similarly to biotrickling filter 10, typical performance for biotrickling filter I and Q are reported in Figure 3.9 to 3.11. The data illustrate the specific points discussed in the previous section for these scrubbers, namely that biotrickling filter I achieved lower removal percentages, presumably because of higher loadings, but as shown in Figure 3.10, I was able to reach much higher and truly unprecedented H_2S elimination capacities, while Q was exposed to very low H_2S concentrations and always met low H_2S discharge requirements.

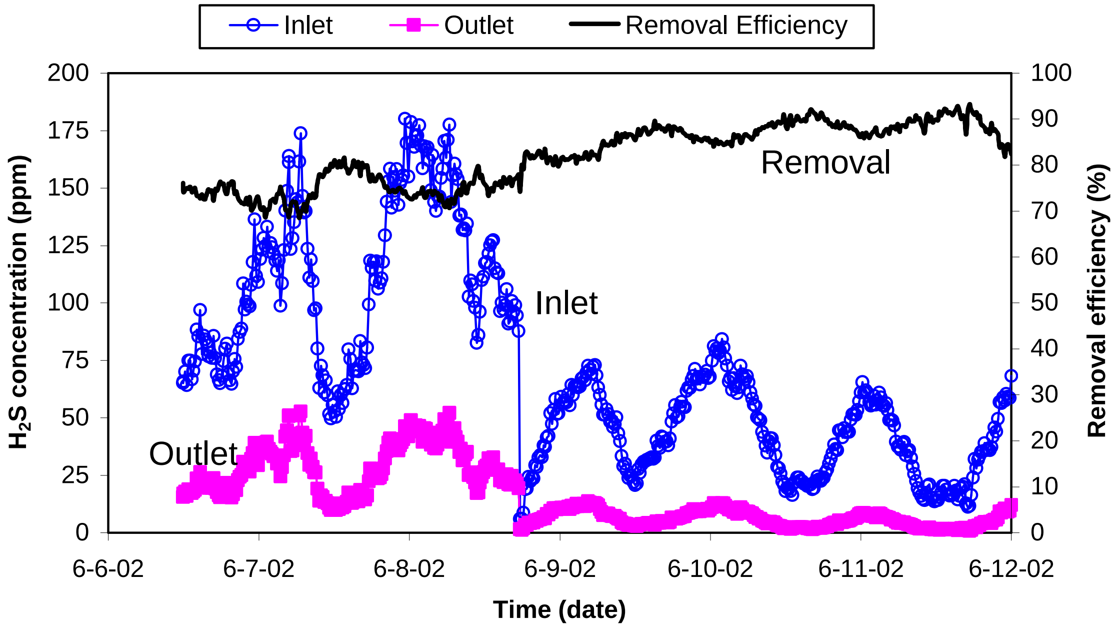


Figure 3.9 6 days of typical H_2S removal in biotrickling filter I. H_2S data are from VAPEX and are not necessarily accurately calibrated (shift late on June 9 may be due VAPEX adjustment).

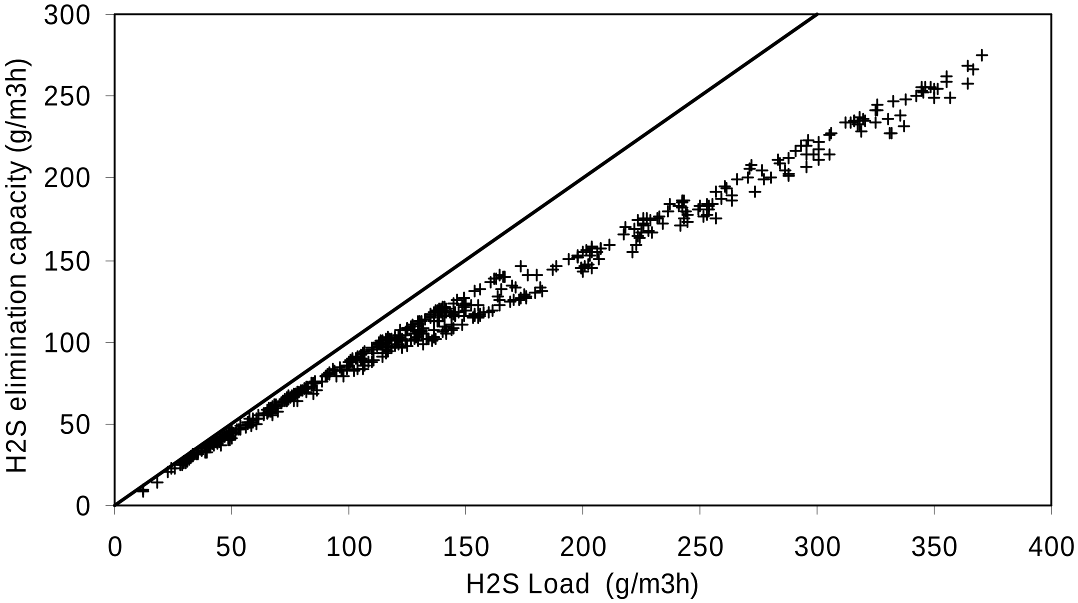


Figure 3.10 H_2S elimination capacity and load data for biotrickling filter I during the 6 days shown in Figure 3.9. The diagonal line of slope one represents the EC for 100% removal.

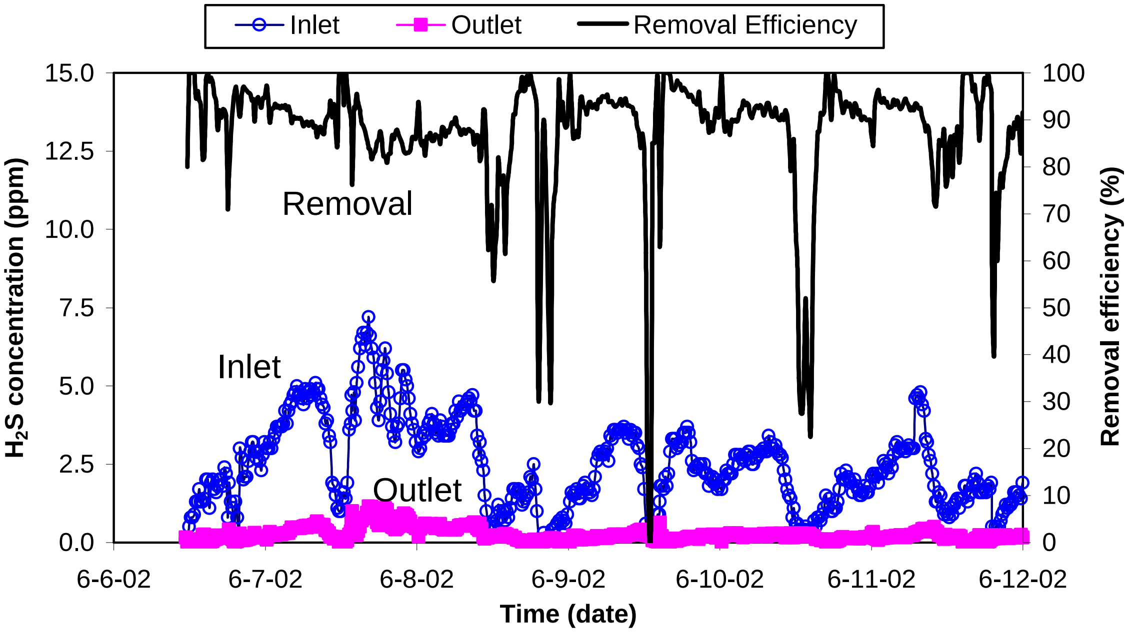


Figure 3.11 6 days of typical H_2S removal in biotrickling filter Q. H_2S data are from VAPEX and are not necessarily accurately calibrated. Note that transient low removal points corresponds to low or non-detect inlet concentrations.

3.5 Long-Term Performance of the Converted Biotrickling Filters - RSC, VOC and Odor Removal

While the focus of Phase II of the project was on H_2S removal, the removal of reduced sulfur compounds (RSCs) other than H_2S, of air toxics (VOCs) and odors was also measured. Analysis of the removal of RSCs, VOCs and odor proved to be a challenge, as sampling was not as frequent as H_2S sampling, concentrations were always extremely low and variable, and removal was only partial. In addition, for odor measurements, the analysis method (odor panel) relies on sample sniffing and subjective judgment and therefore it usually includes a large uncertainty. Results are summarized in Table 3.3 and the following can be concluded:

- Concentrations or RSC and VOCs were very low (ppb range) while odor concentrations were relatively high (values as high as 7000 D/T were sometimes measured in the inlet air).
- Partial removal of most compounds was achieved. The removal is impressive, if one considers that the air contact time is in the order of 2 seconds.
- Data for VOC were highly variable. It was not unusual to find higher concentrations in the outlet than in the inlet. This is due both to the variability of VOC inlet concentrations during the day, and due to analytical uncertainties.
- Odor concentrations measured by dilution to threshold had an extreme variability over time and between inlet and outlet values. This is both because of the measurement method and because of odor makeup and emission variations.
- In almost all cases, residual odor existed which suggested that further treatment was required or that improvement of actual treatment performance was necessary. Residual odor was also observed when H_2S outlet concentrations were very low, suggesting that

compounds other than H_2S, presumably RSCs, were in great part responsible for residual odor. Further investigations on the makeup of residual odors, and on means to improve treatment of residual odors will be performed in Phase III. (see also Section 3.7.6 for more data on RSC removal as a function of EBRT).

Table 1 Inlet concentrations and removal efficiencies of odor, VOCs and RSCs from biotrickling filter 10. Data are mean ± standard deviation, n=21 for RSCs, n=19 for VOCs, and n=9 for odor panels and are representative from about 8 months of operation at gas contact times between 1.6 and 3.4 seconds. D/T = dilution-to-threshold as measured by standard odor panel.

Compound	Inlet concentration, ppb_v	Removal efficiency, %
Carbonyl sulfide	67.2 ± 7.7	44 ± 11
Methyl mercaptan	192.5 ± 34.1	67 ± 11
Carbon disulfide	70.3 ± 20.5	35 ± 5
Methylene chloride	132 ± 93	36 ± 25
Chloroform	326 ± 263	30 ± 21
Benzene	147 ± 105	32 ± 21
TCE	16 ± 15	46 ± 28
PCE	224 ± 257	28 ± 20
Toluene	753 ± 2144	29 ± 14
Ethyl benzene	148 ± 221	41 ± 27
p and m-xylene	480 ± 852	41 ± 19
o-xylene	110 ± 210	44 ± 30
Odor	1980 ± 480 D/T	65 ±21

3.6 Pressure Drop in the Converted Biotrickling Filters

An important factor for the determination of the cost of treatment is the pressure drop of the biotrickling filter. If maintained properly, i.e., acid washed regularly and operated with a tight control of the pH, chemical scrubbers usually have a relatively low pressure drop, e.g., 2-5 cm of water column (1-2”). This was not necessarily the case in scrubbers at OCSD as the packing of the chemical scrubbers showed significant fouling by limestone (see picture of fouled packing in Appendix). With the foam packing, higher pressure drops compared to clean well-maintained scrubbers were experienced and further investigations were required. In Figure 3.12, the pressure drop per unit of length is reported as a function of the linear gas velocity for all converted scrubbers. Based on theories for flow in porous media, a quadratic relationship is expected. However, the results show a relatively linear trend. It is unclear why such a difference occurred (it may simply be the range o f the velocities tested); the discrepancy is not a matter of serious concern.

The question of whether pressure drop was increased due to packing compaction at the bottom of the column is worthy of investigation. In scrubber 10, the bed lost a significant height due to compaction in the weeks after starting the system. We observed qualitatively that bed compaction was proportional to the trickling rate most probably because high tricking rates result in a higher dynamic hold-up, hence a larger weight on the packing causing more compaction. Very high trickling liquid velocities should therefore be avoided as they cause higher pressure drops and result in no improvement of H_2S removal. An interesting observation after the first intermittent trickling experiment was that the bed expanded from the lower trickling rate, resulting in a 3-4” decrease in pressure drop (see Figure 3.25, further). As discussed further, intermittent trickling may be a means to reduce pressure drop, hence treatment costs.

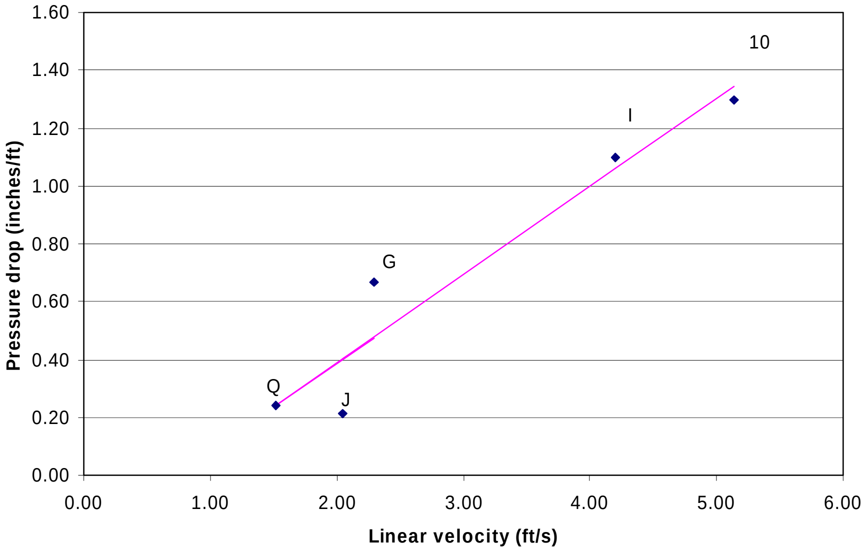


Figure 3.12 Pressure drop in the converted scrubbers as a function of the gas linear velocity.

After discussion with Zander/Juergen Loy (Germany), the provider of the foam, the use of larger foam cubes, cut-to-shape to completely fill any void was discussed. The pros and cons of each packings are listed in Table 3.4. Our recommendation is to test the cut-to-shape packing in an upcoming conversion (e.g., scrubber 9 and/or scrubber H), as it appears that the advantages outweigh the disadvantages.

Table 3.4 Comparison of random dump and cut-to-shape open pore PU foam bed characteristics.

	4 × 4 × 4 cm cubes, random dump	40 × 40 × 40 cm cubes, cut-to-shape
Ease of installation	Easy, random dump	Requires cutting to exactly fit the column. Requires confined-space entry to position the foam.
Volume of packing required	Final bed contains lots of air gaps. 100% use of the packing.	Waste due to cutting. About 25-30% more than actual bed volume is required. Final bed contains no air gaps.
Compaction	Likely at the bottom of the column.	Unlikely. Note that special care is required for the arrangement of the packing at the location of the air distribution system at the bottom of the column.
Effect on H_2S removal performance	Cut-to-shape system is expected to have higher performance as the bed contains a large volume of packing (i.e., less air voids). However, attention should be paid to avoid any wall effect and air channeling as these will have a negative effect on H_2S removal.	
Effect on pressure drop	Arguments about decrease/increase of pressure drop can be made either way. • Pressure drop may decrease in the cut-to-shape system as packing compaction will be much lower. • Pressure drop may increase in the cut-to-shape system as the packing is more dense and does not contain all the gaps that the random dump bed has. The end result will depend on the importance of the above two effects.	

3.7 Specific Experiments

Throughout the study, specific experiments were conducted in order to better characterize the systems and increase the general understanding of the behavior of the converted scrubbers, or to possibly increase the removal of reduced sulfur compounds or of odor. The results of the most meaningful experiments are reported in the next Sections. The focus of most of these experiments was on biotrickling filter 10.

3.7.1 H_2S spiking

In order to determine the maximum elimination capacity of H_2S in the converted biotrickling filter, 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 raised up to 120 ppm_v when the reactor was operating at 1.6 seconds EBRT. The experiment was conducted over a few days with each concentration maintained for several hours to ensure steady-state. Figure 3.13 shows the elimination capacity and removal efficiency profiles for H_2S over a wide range of loadings (corresponding to different inlet concentrations). 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}, breakthrough of H_2S occurred, while a quasi-zero order degradation regime was observed at loadings above 105 g H_2S m^{-3} h^{-1}. Comparison of the data of Figure 3.13 with long-term transient data (See Figure 3.8 discussed earlier) reveals that the two graphs are essentially identical. This indicates that the biotrickling filter rapidly reached steady-state during this experiment and that no significant differences existed between the performance during regular operation and during spiking H_2S.

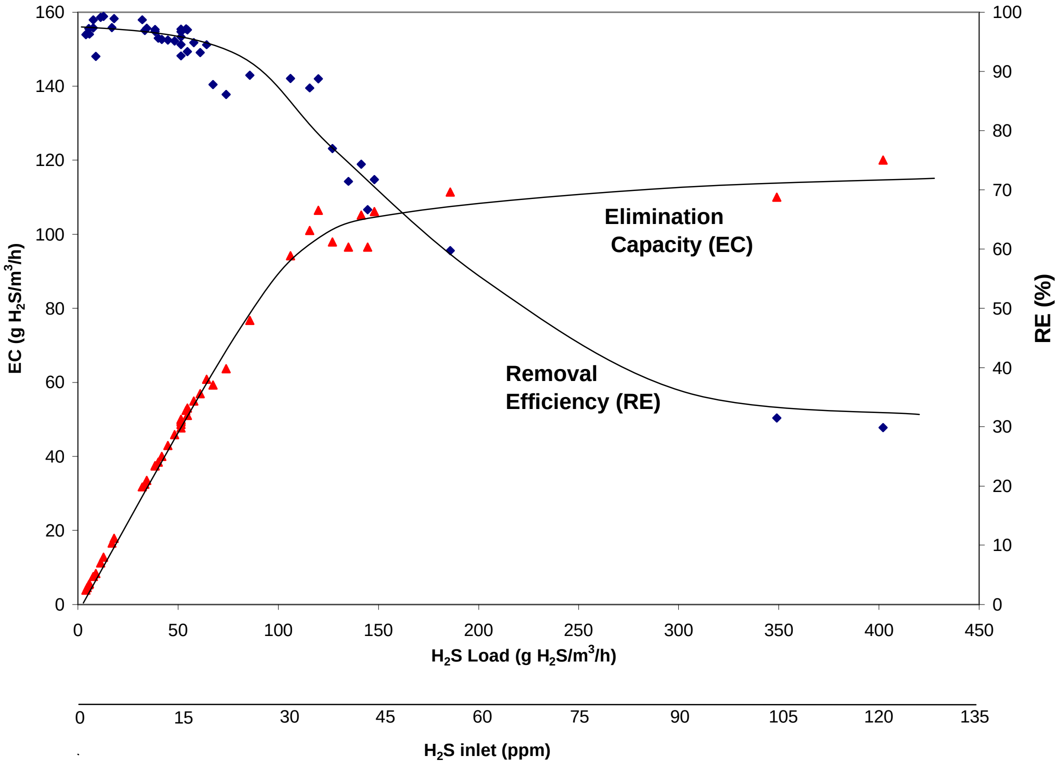


Figure 3.13 H_2S elimination capacity vs. loading during the H_2S spiking experiment.

As mentioned in Section 3.4, the observed performance is exceptionally high compared with other biofilters or biotrickling filters removing low concentration of H_2S, even at higher gas contact times (Smet et al., 1998; Cox and Deshusses, 2002; Koe and Yang, 2000). Those studies, usually reach H_2S elimination capacities of about 20-30 g m^{-3} h^{-1}, at much higher H_2S concentration and longer gas contact time. Koe and Yang's (2000) reports are probably the closest to OCSD conditions, but they only achieved partial H_2S removal at contact times of 5 s or more, and H_2S inlet concentration lower than 20 ppm (see Figure 3.13b for excerpts from Koe and Yang's results). This is markedly lower than observed at OCSD.

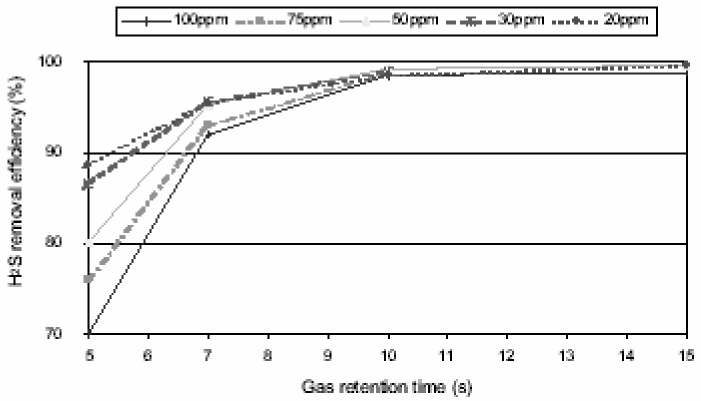


Figure 3 The performance of the BTF under high H_2S loading conditions in the presence of sewage off-gas

Figure 3.13b Performance of Koe and Yang's biotrickling filter (from Koe and Yang, 2000).

3.7.2 Effect of intermittent trickling and effect of a sudden change in concentration

The effect of trickling the recycle liquid intermittently was investigated. Intermittent trickling reduces the liquid film over the biofilm and may improve mass transfer. A positive effect was obtained during Phase I with the TriPack packing, while no improvement was observed with the Zander foam. Still, further experiments in the field were warranted. Biotrickling filter 10 was used for this purpose. The experimental protocol and conditions were as follows:

- In an earlier experiment, we found that the bed height was fluctuating depending on the wetting resulting in unwanted air flow changes. Thus, to expand the bed the day before the start, intermittent trickling (2 min ON/30 & 60 min OFF) was conducted for 5 hours. However the bed did not expand. The reasons are unclear but the constant bed height suggest that airflow did not significantly change during the experiment.
- The inlet H_2S concentration was about 30 ppm (by spiking with pure H_2S). It was important to have a residual of H_2S in the outlet so that if any improvement would occur during the experiment, it could be observed.
- The liquid recycle rate was set to 20 gpm. Continuous recycle was kept for 3 hours prior to intermittent trickling operation in order to reach a pseudo-steady state.
- Average temperature: 23.1 ^oC (73 ^oF)
- pH: 2.1
- Foul airflow rate: 15,700 m^3 h^{-1} (9250 cfm)
- Pressure drop: 10.3" water column while trickling water
  9.8" water column without trickling water
- Water make-up: 0.45 m^3 h^{-1} (2.0 gpm)
- Bed volume: 6.69 m^3 (all the time)
- EBRT: 1.54 sec
- The actual experiment lasted 10 hours, and consisted of repeated 2 min ON and 60 minutes OFF cycles for the liquid recycle pump. Note that a mathematical model of the pH change within the biofilm during intermittent trickling was used to verify that the pH would not reach inhibitory levels during the 60 minute OFF period.

The results are shown in Figure 3.14. The first phase of the experiment shows the adaptation of the biotrickling filter to the higher concentration, as H_2S was spiked at a higher level in order to establish a residual H_2S in the outlet. Examination of Figure 3.14 reveals that the outlet concentration followed relatively closely the changes in the inlet, while the inlet concentration was being adjusted. This suggests that pseudo steady-states are rapidly attained in the biotrickling filter (within an hour). During the actual ON/OFF trickling experiment, the inlet was maintained at a relatively constant concentration. As shown in Figure 3.14, no significant change in the outlet concentration could be detected suggesting that intermittent trickling does not result in any performance improvement.

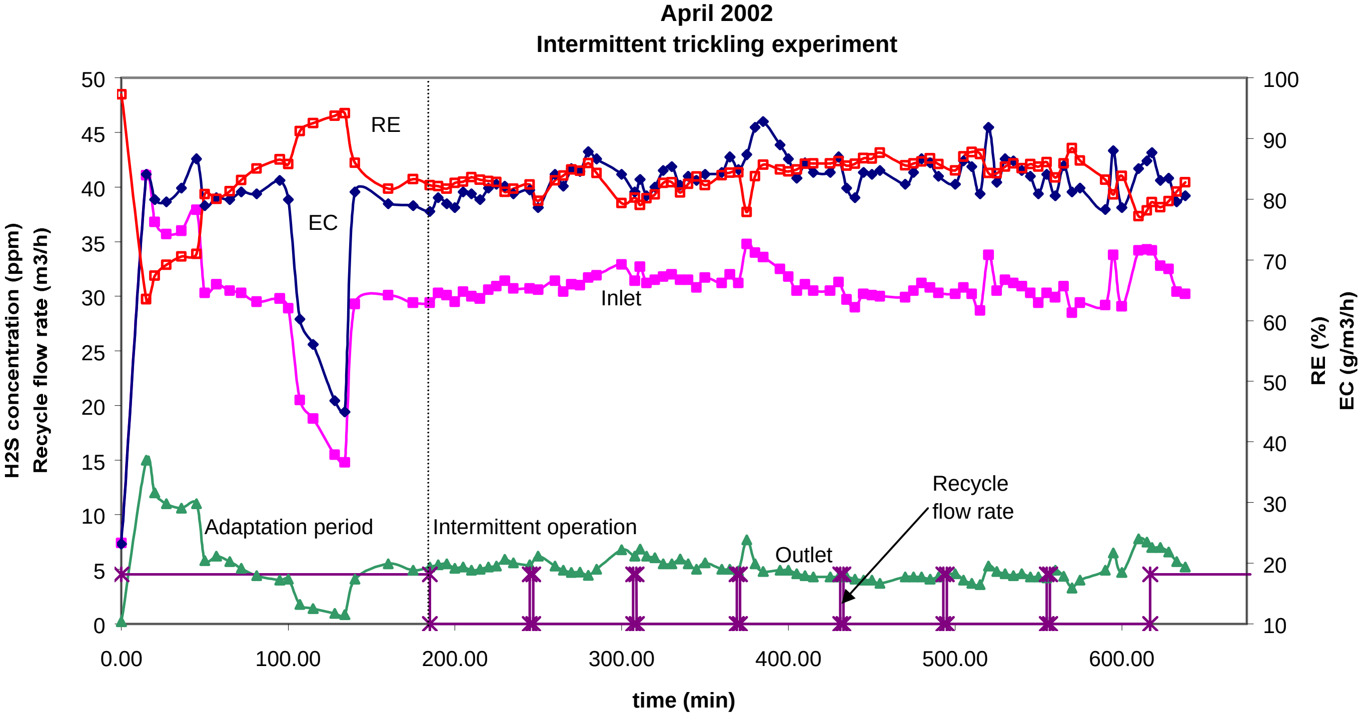


Figure 3.14 Performance of biotrickling filter 10 during the intermittent trickling experiment. 7 cycles of 2 min ON and 60 minutes OFF with the recycle pump were conducted.

Another intermittent trickling experiment was conducted at a lower inlet concentration so that the outlet concentration was around 1 ppm H_2S. The rationale was that at lower concentrations, mass transfer would possibly be limiting, rather than kinetic limitations at higher concentrations. The results shown in Figures 3.15-16 were relatively similar to those of the experiment at a higher concentration. The transient phase after spiking H_2S was relatively short (1-2 hours) and a new steady-state was rapidly reached. During intermittent trickling, there appears to be a slight improvement in the performance during cycles #2 and #3, however, we do not believe that the improvement was significant. The difference may rather be the result of slightly fluctuating inlet conditions.

In conclusion, intermittent trickling does not improve nor is detrimental to H_2S removal. The effect on odor, VOC, or RSC removal was not investigated. It should be mentioned that intermittent trickling had a positive effect on the pressure drop across the bed, reducing it by about 1”. This and the saving of operating the pump only part of the time would provide a possible means for slightly reducing the operating cost of the biotrickling filter.

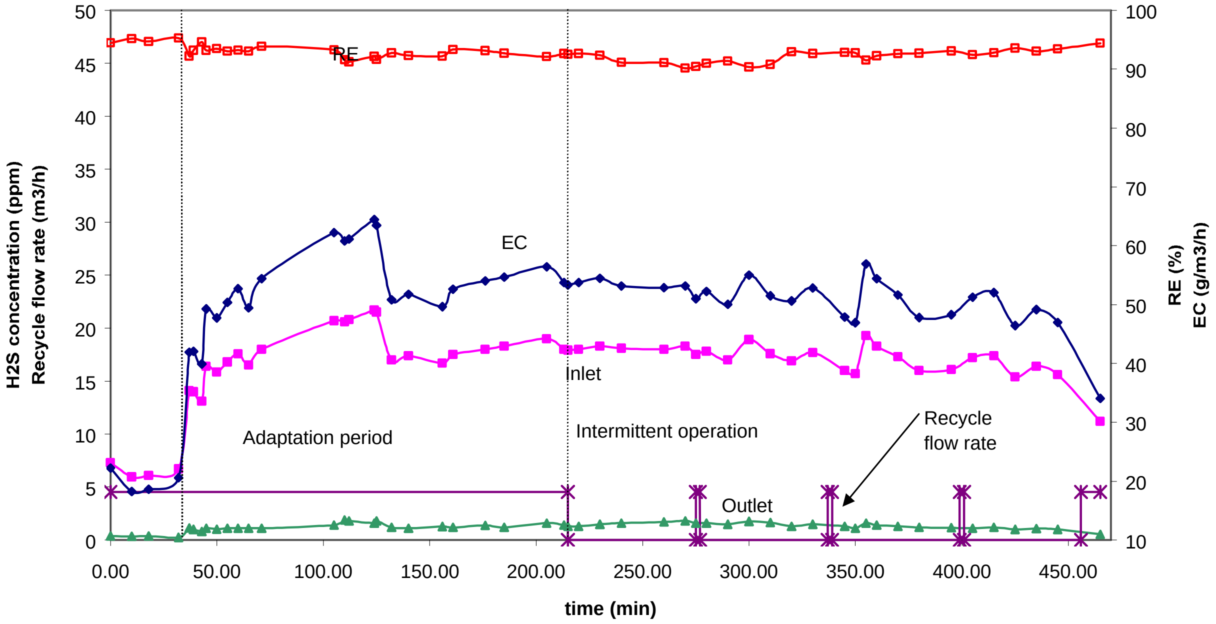


Figure 3.15 Performance of biotrickling filter 10 during the second intermittent trickling experiment conducted at a lower inlet H_2S concentration. Four 2 min ON/60 minutes OFF cycles were conducted.

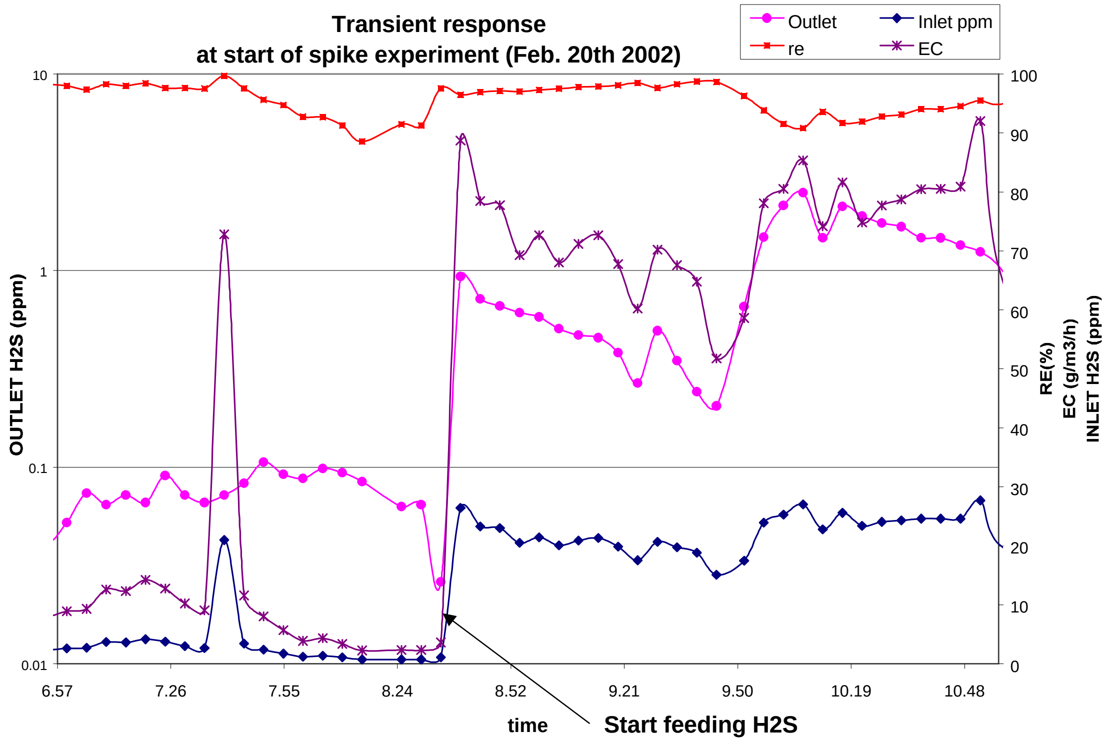


Figure 3.16 Performance of biotrickling filter 10 during the preparation of the second intermittent trickling experiment conducted at a lower inlet H_2S concentration. The transient response to a sudden change in inlet concentration is shown. The data suggest that new steady-states are rapidly achieved.

3.7.3 H_2S concentration profile along the bed height

In many instances, sampling the pollutant along the height of the bed provides useful information on the local H_2S elimination rate. Hence, sampling of H_2S directly in the bed along the height was performed under different inlet H_2S concentrations (2 to 42 ppm) on different days. Illustration of the experimental setup are shown in Figure 3.17 and conditions were as follows:

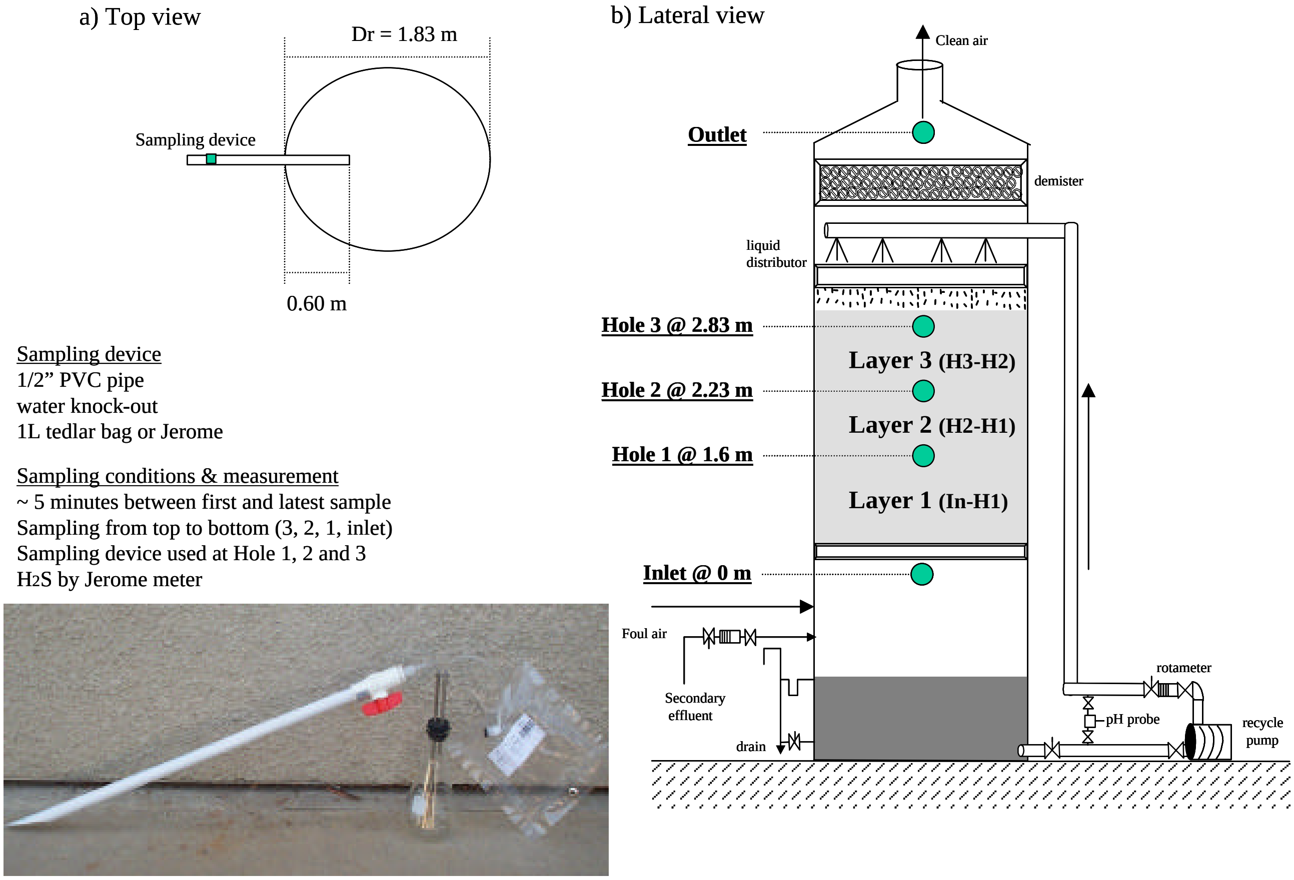
- The bed height was approximately constant between first measurement (Dec 12, 2001) and the last one (April 3, 2002). For calculations a constant bed volume of 6.69 m^3 was used.
- The airflow was approximately constant (between 15,600 and 14,400 $m^3 h^{-1}$, i.e., 9200-8500 cfm) so that all measurements were done under similar conditions (EBRT ~ 1.6 sec).
- Intermediate height sampling ports were drilled on the side of biotrickling filter 10. With inlet and outlet, this makes 5 points along the height. Note that usually, it is not recommended to sample within a bed, as local concentrations may not be representative of average cross-sectional concentrations because of channeling or local dead volumes. In the laboratory, reactors are usually built with bed segments, with sampling performed in the air plenums between the segments. This was obviously not possible here.
- The sampling period was 5 minutes using a combination of the VAPEX system (for inlet and outlet) and the Jerome meter. The time was short enough to assume that concentration profiles remained constant.
- The measurements at concentrations above 10 ppm inlet concentrations were performed while feeding artificially H_2S.

The results of the several H_2S concentration profiles and elimination capacities for the different segments delimited by the sampling ports are reported in Figures 3.18-19. The results show that under non-limiting conditions,[#] between 77% and 90% of the total removal of H_2S is achieved in the first segment. That section of the bed had a highest activity for H_2S elimination. This is not only because it was exposed to the highest concentrations, but rather because this segment probably had higher amount of biomass. This fact is illustrated in Figure 3.20 were the elimination capacity of the various segments is reported as a function of the loading to the particular segment.

Next, the concentration/removal data for all segments were used in order to define the combined effect of bed height and inlet concentration on the removal of H_2S. The results are shown as contour plot in Figure 3.21 and are useful for the evaluation of the applicability of biotrickling filters for the treatment of H_2S under various bed height/inlet concentrations. Note that at low inlet concentration, only partial removal is achieved. This is the result of both the fact that the process becomes diffusion limited at low concentration, and of an analytical artifact caused by the Vapex unit which rarely reads a zero concentration. Still such calculation allows to determine that about 96% removal efficiency would be achieved at 1 sec EBRT while feeding 8 ppm H_2S, or that a biotrickling filter of half the size of biotrickling filter 10 would be enough for 80% removal efficiency when feeding 18 ppm inlet concentration at 17,000 $m^3 h^{-1}$ (10,000 cfm), i.e., operating at a EBRT of 1 sec.

[#] Non-limiting conditions means that the outlet concentration of a given segment is not close to non-detect. This corresponded to inlet concentrations of at least 15 ppm (see Figure 3.18)

Similar attempts were made to determine VOC concentration profiles. These failed because of fluctuations of VOC concentrations over time, and the relatively low removal percentages resulting in irregular profiles that made no physical sense.



Sampling device
1/2” PVC pipe
water knock-out
1L tedlar bag or Jerome

Sampling conditions & measurement
~ 5 minutes between first and latest sample
Sampling from top to bottom (3, 2, 1, inlet)
Sampling device used at Hole 1, 2 and 3
H_2S by Jerome meter

Figure 3.17 Schematic of the experimental protocol for the determination of the H_2S concentration profile along the bed height.

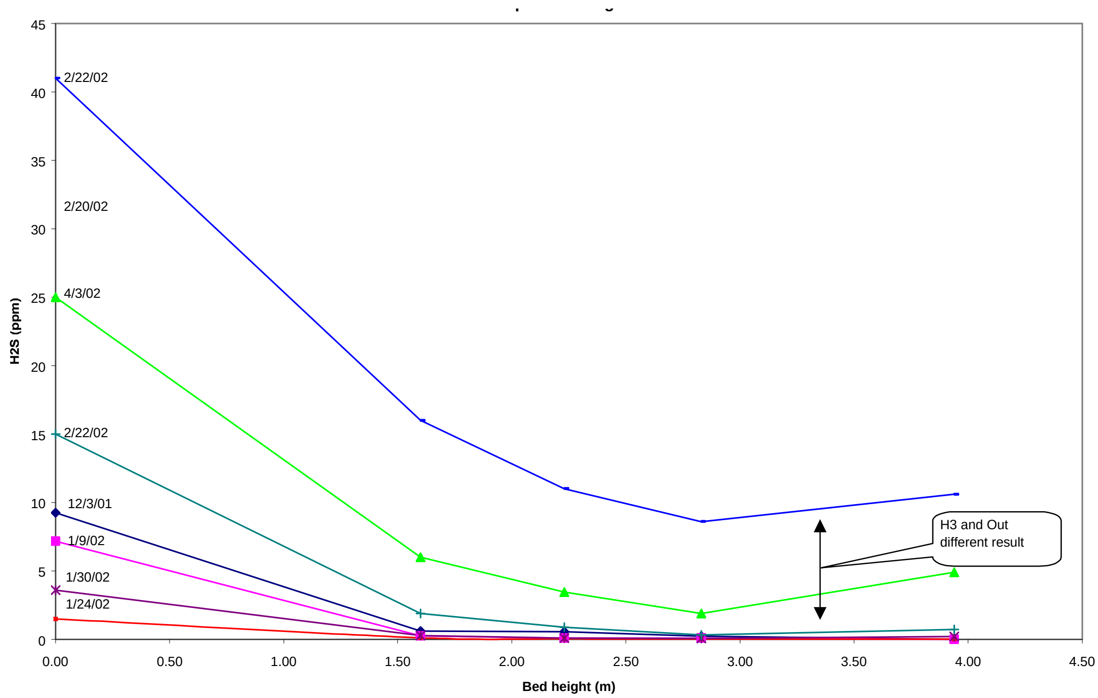


Figure 3.18 H_2S concentration profiles along the bed height.

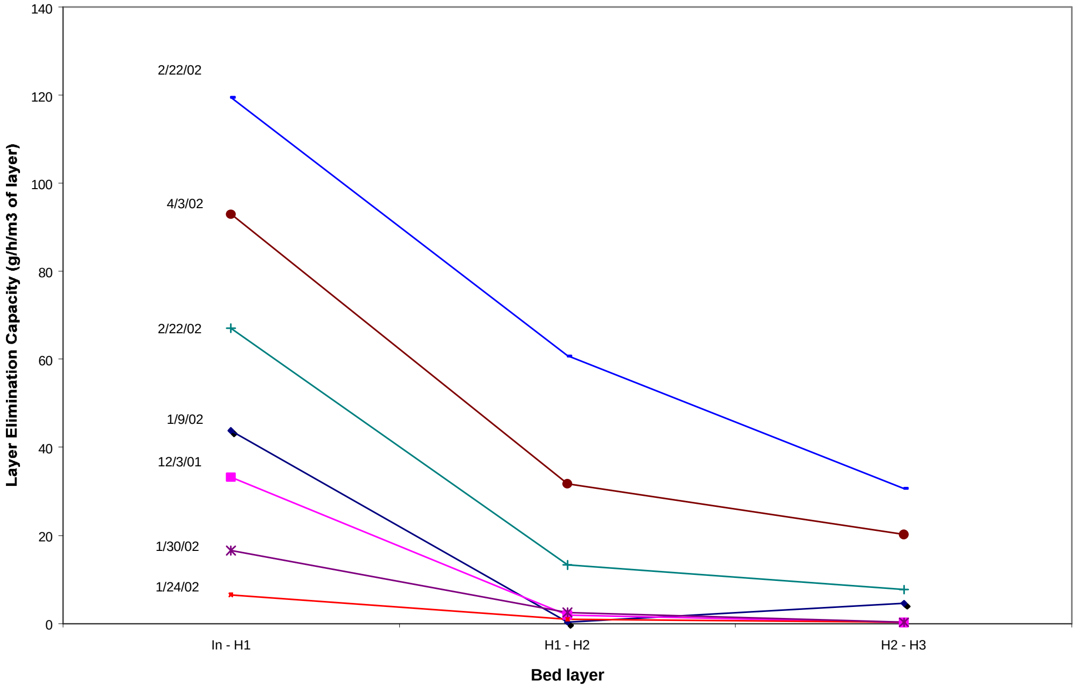


Figure 3.19 H_2S elimination capacity in the different sections along the bed height. The local elimination capacity is calculated using the concentration profile data.

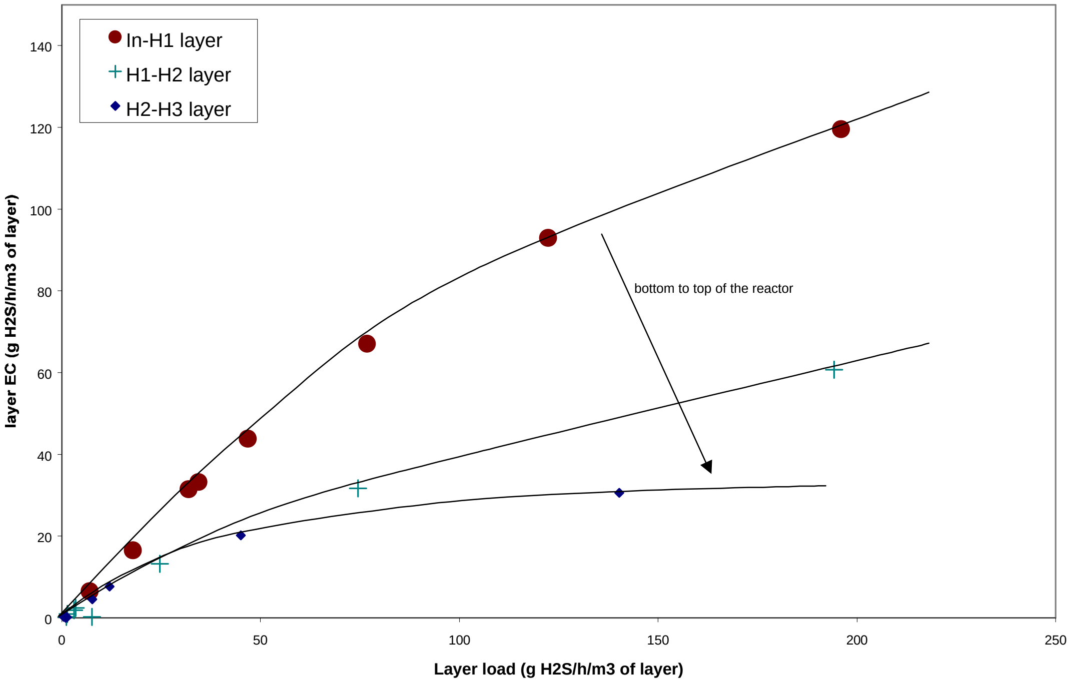


Figure 3.20 H_2S elimination capacity vs. load for the different sections of the bed showing a higher activity at the air inlet port.

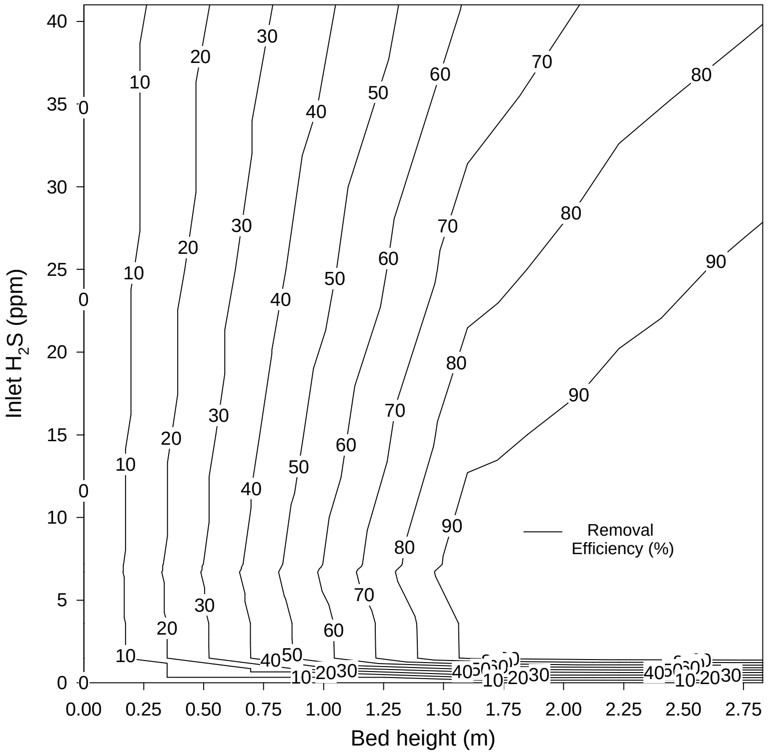


Figure 3.21 Contour plot of computed H_2S removal efficiency along the bed height and as a function of the H_2S inlet concentration. The graph is computed from the different concentration profile data for an gas velocity of 1.8 m s^{-1}, and is only valid for that air velocity.

3.7.4 System response after a starvation period

Any biotrickling filter may need to be stopped for several days for maintenance or in the event of system upset. We found that there was no impact on the performance of the biotrickling filter when subjected to a few hours of down time (data not shown). Also we also found that when the H_2S inlet concentration was changed stepwise, less than 4 hours were needed before reaching a new steady-state (see Section 3.7.2). When the blower of biotrickling filter 10 was stopped for two days between 8/29/01 and 8/31/01 while the bearings were being replaced, the effect of a longer-term starvation period on the biotrickling filter performance was investigated. While the blower was stopped, the make-up water supply was turned off to avoid an increase in the pH due to a dilution of the liquid in the reservoir. Liquid trickling was maintained during that period. The impact of starvation was assessed by observing the removal efficiency and the outlet concentration when the system was resumed. Figure 3.22 shows that the daily average H_2S removal efficiency increased gradually day after day, and required 4 to 5 days to increase from 96.7% to 98.7%. It should be stressed that the maximum allowed discharge concentration of 1 ppm of H_2S was never exceeded during reactor restart. The results of this experiment demonstrate the robustness and the stability of the system, suggesting that the effect of starvation of 48 hours or less is minimal.

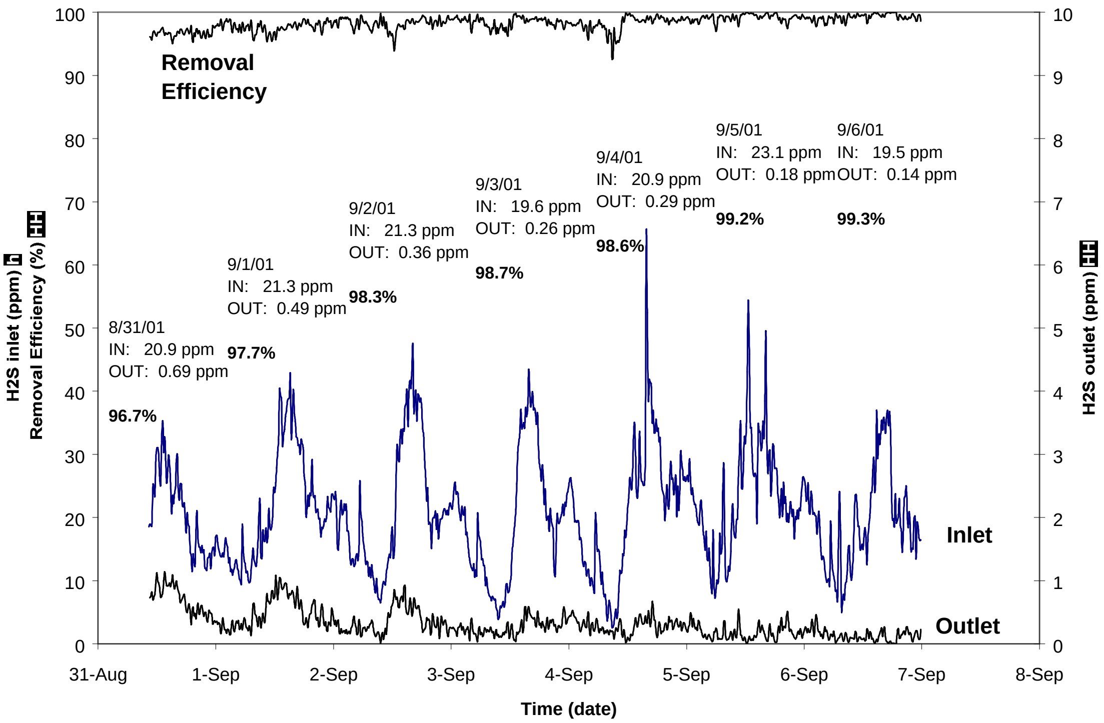


Figure 3.22 Daily averaged values for the inlet and outlet concentrations, and removal efficiency after restarting biotrickling filter 10 after two days without foul air.

3.7.5 Effect of pH: short and long term exposure to neutral pH

Short Term Exposure

Since the biotrickling filters degrading H_2S were routinely operated at low pH, the question of the effect of short term pH change, or a pH shock was raised. In order to assess that effect, the water make-up supply to biotrickling filter 10 was increased from 2 gpm to 20 gpm (starting 10:00 AM, September 16th, 2001) for a period of 33 hours. Note that as will be discussed for the long term pH effect, the increase in water makeup was later suspected to have a detrimental effect because of the larger free chlorine supply to the system, and its possible inhibitory effect on the process culture. In the present experiment, one may speculate that such toxic effect of chlorine could possibly be neglected because of the short duration of the experiment.

The removal efficiency of the biotrickling filter was compared before, during and after the sudden pH increase considering a 48 hours period for each phase as shown in Figure 3.23. Because of the highly variable inlet load to the reactor, average performance could not be directly compared. Instead, the data was sorted to match pairs of identical inlet H_2S concentrations and a paired t-test was conducted on individual removal efficiencies. The "before" pH increase period was tested against the "during" and the "during" period was tested against the "after" pH increase.

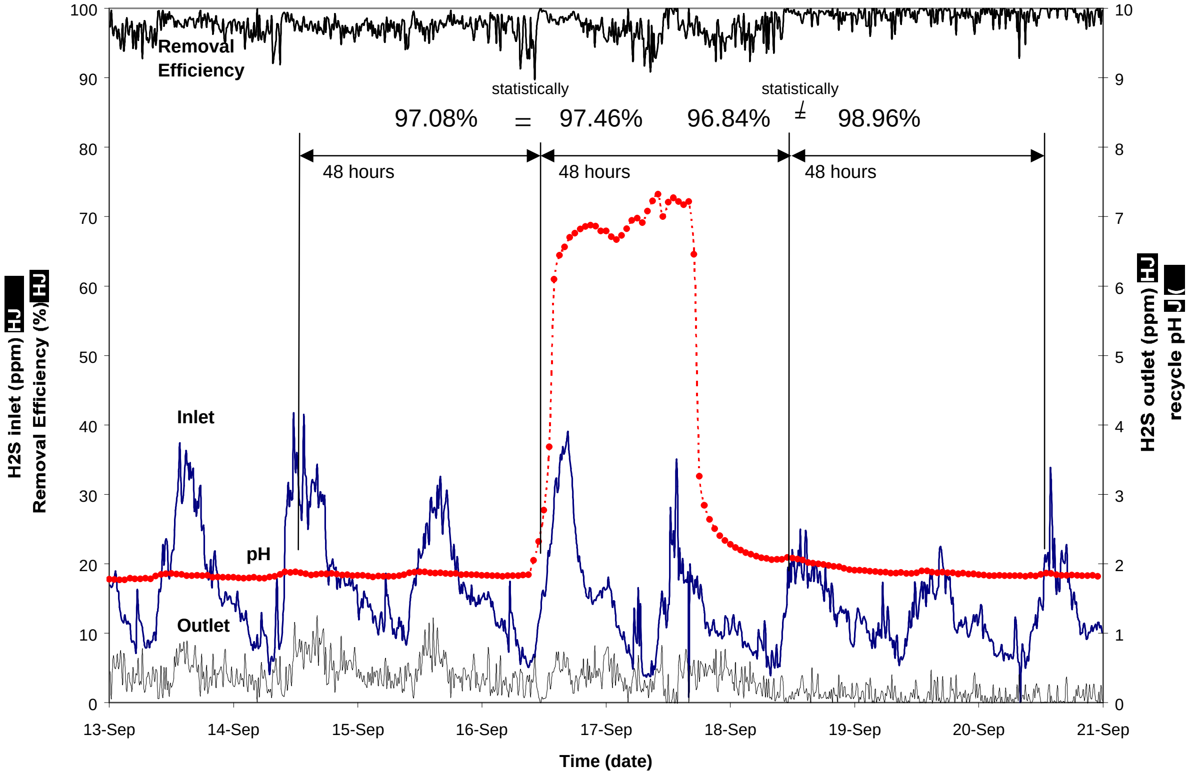


Figure 3.23 Performance of biotrickling filter 10 before, during and after a short incursion in to neutral pH. Percentages shown correspond to the resulting average of the data that were selected for match with the neighboring period ("during" has two values depending on the data that paired with "before" or with "after".

The results of the statistical tests revealed that the removal efficiencies before and during the pH change were not greatly different from each other, while the removal after the pH change was different (at the 99% level) from previous data. While the improvement in performance (96.84% vs. 98.96%) may seem small, it represents a significant increase in terms of number of transfer units in the biotrickling filter. This means that for difficult applications, or when a converted biotrickling filter is discharging H_2S concentrations that are close to the regulatory limit, optimizing the operating conditions through successive refinement of parameters such as pH, trickling rate, water makeup or any other parameter that is believed to influence performance may be warranted. More experiments of this type, and longer term experiments (see below) are necessary to fully understand the complex relationship between operating pH and H_2S, RSCs and VOCs removal in order to optimize performance.

Long Term Effect

After several months of operation at pH ranging from 1-2, and H_2S removal over 90-99%, the pH was increased to near neutral. The rationale for the experiment was that neutral pH could increase VOC and RSC removal, while based on the short term incursion at high pH, no specific effect on H_2S removal was expected. Hence, the plant water feed to the scrubber was increased to about 20 gpm and the performance of the system was monitored. The results in terms of H_2S removal are shown in Figure 3.24. They show that the biotrickling filter performance slowly collapsed, with close to no removal of H_2S about a month after the change in the pH setpoint. Interestingly, the removal of VOC and RSC also decreased from about 30-50% to about 0-5% during neutral pH operation; the biotrickling filter had unexpectedly lost most of its biological activity. Examination of the liquid in the sump revealed that a large amount of biomass had detached from the packing. Under the growing concerns of the plant operators and because of the increase of chemical usage in the post-treatment scrubbers 1-4, it was decided to return biotrickling filter 10 to a low pH and hopefully restore the good H_2S, VOC, and RSC removal performances. Indeed, effective treatment was rapidly re-established as shown in Figure 3.24.

A firm explanation as to why the reactor performance collapsed could not be found. It was first hypothesized that immediately after the pH was increased, it reached high values (possibly up to 8-8.5), which may have killed or inactivated the process culture. We believe that if this had been the case, the culture would have recovered within the duration of the experiment. A more plausible explanation is that during the high pH experiment, the added load of chlorine (a few ppm, but at a 10 fold supply rate) may have inactivated the process culture. Unfortunately, chlorine was not monitored during the experiment. However, an unrelated observation is consistent with this hypothesis. During the project, there were two instances where a biotrickling filter suddenly stopped removing H_2S. At least in one case, this loss of performance 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.

Consequently, it is recommended a new experiment at neutral pH be conducted during Phase III, and that the plant water be dechlorinated prior to feeding to the biotrickling filter during the experiment. Further, installing either a chlorine monitoring system or a dechlorination system on the feed of future biotrickling filters should be considered.

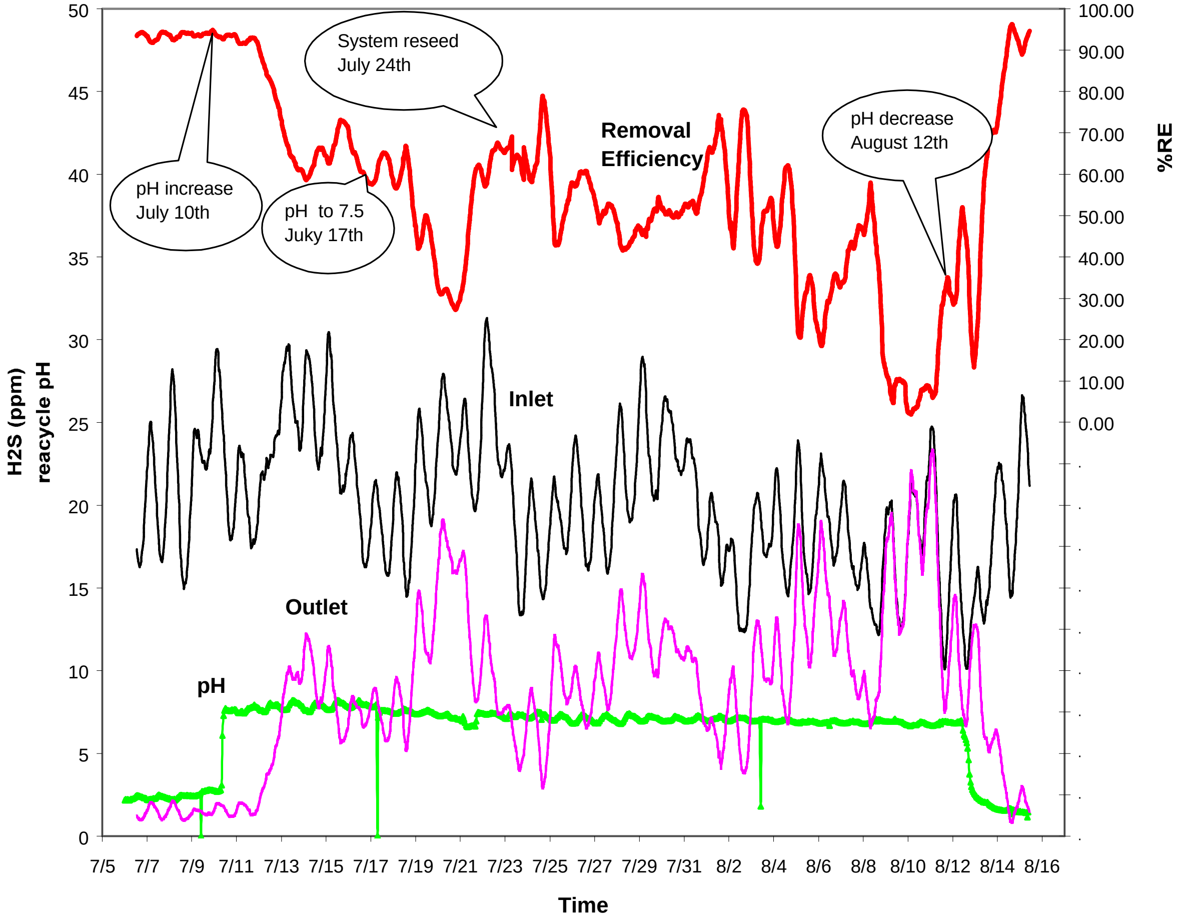


Figure 3.24 Overview of the experiment on the long-term effect of pH.

3.7.6 Effect of EBRT

During the project, the effect of gas contact time (EBRT) on the removal of H_2S and on the removal of reduced sulfur compounds was investigated. The task was complicated by several factors including the highly variable inlet concentrations, the variability in bed height, the difficulty in measuring large air flows accurately, and the fact that the biotrickling filter air flow rate could not necessarily be changed as dictated by an optimum experimental design, as it still required to fulfill its treatment functions. Still a large amount of data was available for H_2S, and about 30-50 analyses for RSCs. A summary of the timeline of the data used for the analysis and of the actual operating conditions is shown in Figure 3.25.

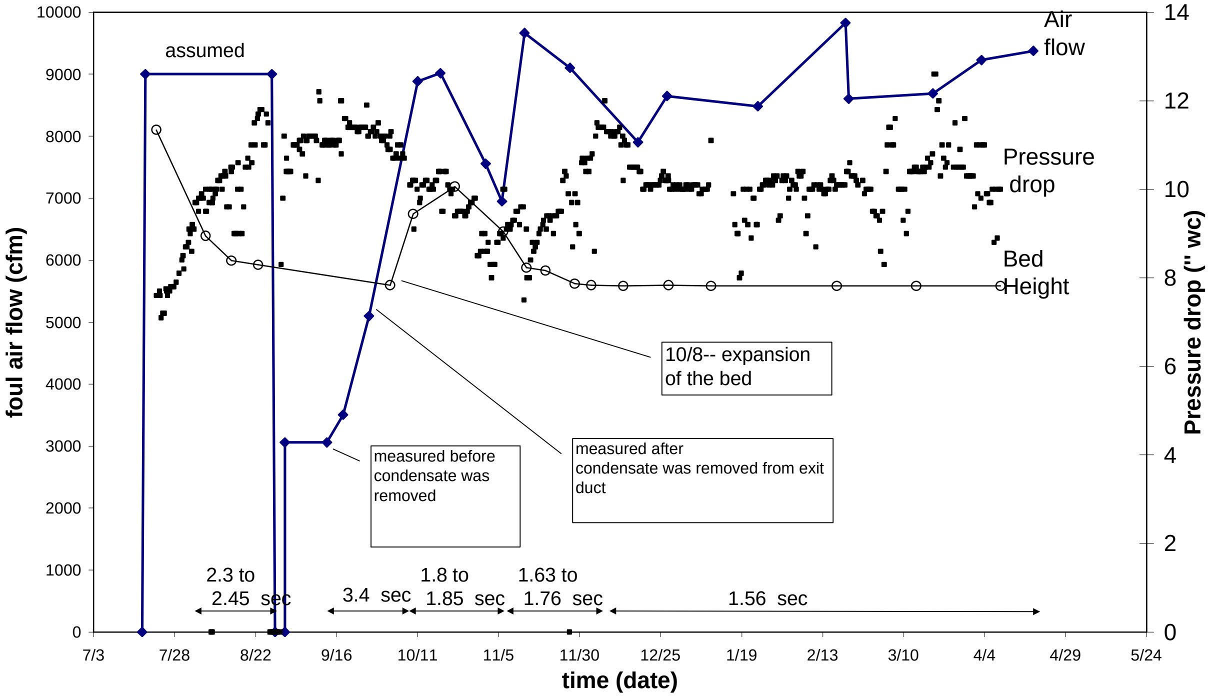


Figure 3.25 Overview of air flow and bed height data during Phase II. Pressure drop is shown for information and reveals that it correlates with bed height. Selected data at different air flowrates were used for side-by-side comparison.

As far as H_2S removal is concerned, a summary of the data is listed in Table 3.5 and results are plotted in Figure 3.26. The data are from long-term operation and were selected such that their inlet concentrations would match, i.e., enabling direct comparison. The error bars on Figure 3.26 representing the standard deviations are relatively large because of the fluctuating inlet conditions. Analysis of the data revealed that the removal at the different EBRT was not significantly different, which is a direct consequence of the large standard deviations observed. However, analysis indicated that system was much more sensitive to concentration changes at low EBRTs.

Table 3.5 Numerical data for the analysis of the effect of EBRT on H_2S removal.

Data points (~ duration)	**EBRT (s)**	**Load (g H_2S m^{-3} h^{-1})**	**Inlet (ppm)**	**H_2S Removal (%)**
2147 (18 days)	4.47	20.6 ± 9.4	18.6 ± 8.5	98.1 ± 1.6
2353 (20 days)	3.39	18.5 ± 9.9	12.7 ± 6.7	96.0 ± 6.2
921 (8 days)	2.44	22.0 ± 10.1	10.8 ± 5.0	99.9 ± 0.7
951 (8 days)	2.35	26.8 ± 16.5	12.7 ± 7.8	98.5 ± 3.2
655 (5.5 days)	2.27	24.3 ± 12.2	11.1 ± 5.6	96.9 ± 5.7
1548 (13 days)[a]	1.85	28.6 ± 16.2	10.7 ± 6.1	89.8 ± 7.5
1226 (10 days)[a]	1.81	29.2 ± 16.7	10.7 ± 6.1	87.8 ± 8.1
845 (7 days)	1.76	29.8 ± 9.9	10.6 ± 3.5	97.3 ± 8.0
831 (7 days)	1.67	31.7 ± 8.5	10.7 ± 2.9	98.4 ± 4.8
889 (7 days)	1.63	32.8 ± 2.8	10.8 ± 6.9	95.4 ± 12.4
12856 (107 days)[b]	*1.56*	*23.1 ± 14.2*	*7.3 ± 4.5*	*97.3 ± 5.7*

[a] Data for 1.85 and 1.81 s EBRT are just after the first intermittent trickling experiment in October 2001 (see Figure 3.25). A temporary low removal efficiency was observed until the bed height recovered again due to settling *[b]Not plotted on Figure 3.26*

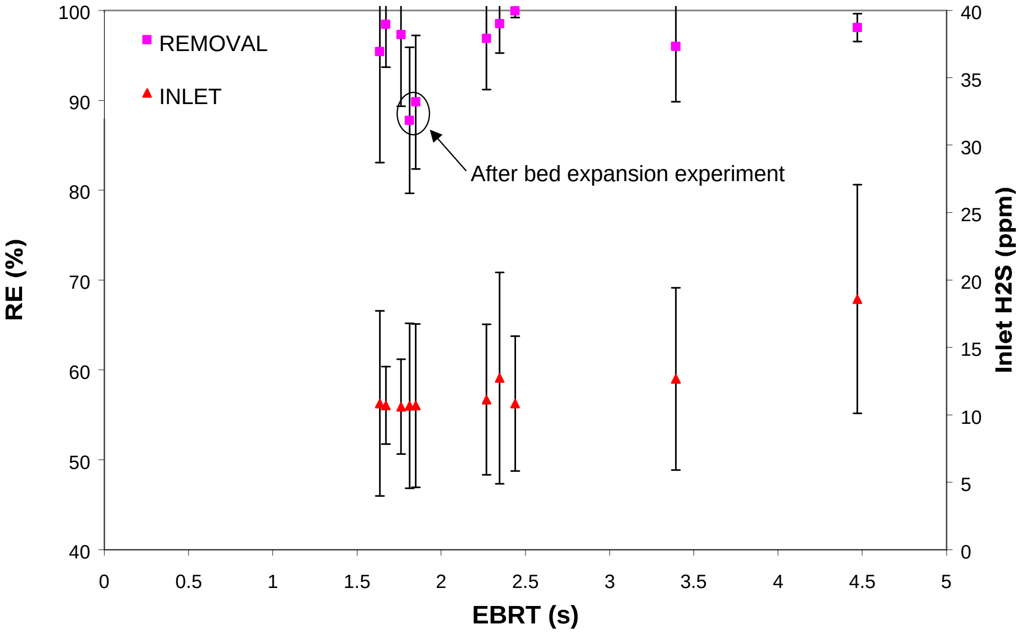


Figure 3.26 Effect of EBRT on H_2S removal. Data with similar inlet concentrations were selected from the pool of long-term data. Inlet concentrations are shown for quality control.

A similar analysis was performed for RSCs. Only carbonyl sulfide (COS), methyl mercaptan (MM) and carbon disulfide (CS_2) were routinely detected. Because of the fluctuations in the inlet concentration of RSCs, only few data points are available at similar inlet concentration. These are reported in Table 3.6 and plotted in Figure 3.27. They show that the lower the air contact time, the lower the removal efficiency (for COS and MM only), but data may not be representative as there were only 1-2 analyses per EBRT above 1.6 seconds and 17 analyses at 1.6 seconds EBRT.

Table 3.6 Numerical data for the analysis of the effect of EBRT on RSC removal. Note the discrepancy between the number of samples at 1.56 s EBRT and the other EBRTs.

Compound	**EBRT (s) / (number of data)**	**Load ($g\ H_2S\ m^{-3}\ h^{-1}$)**	**Inlet (ppb)**	**RE (%)**
Carbonyl sulfide	4.47 (1)	0.149	76.1	60.6
	3.39 (1)	0.169	65.7	43.2
	1.85 (1)	0.327	69.3	35.4
	1.81 (2)	0.327	68.0	25.1
	1.76 (1)	0.218	44.0	8.0
	1.67 (2)	0.289	55.4	9.5
	1.56 (17)	0.313	55.5	11.2
Methyl Mercaptan	3.39 (2)	0.442	220	75.3
	1.85 (1)	0.667	181	54.9
	1.81 (1)	0.566	150	62.9
	1.76 (1)	0.384	99	48.5
	1.67 (2)	0.538	132	50.9
	1.56 (13)	0.329	73	26.3
Carbon Disulfide	3.39 (2)	0.174	53.5	32.1
	1.85 (1)	0.558	93.2	36.8
	1.81 (1)	0.495	81.1	34.5
	1.76 (1)	0.716	114.0	9.6
	1.56 (14)	0.591	79.0	13.5

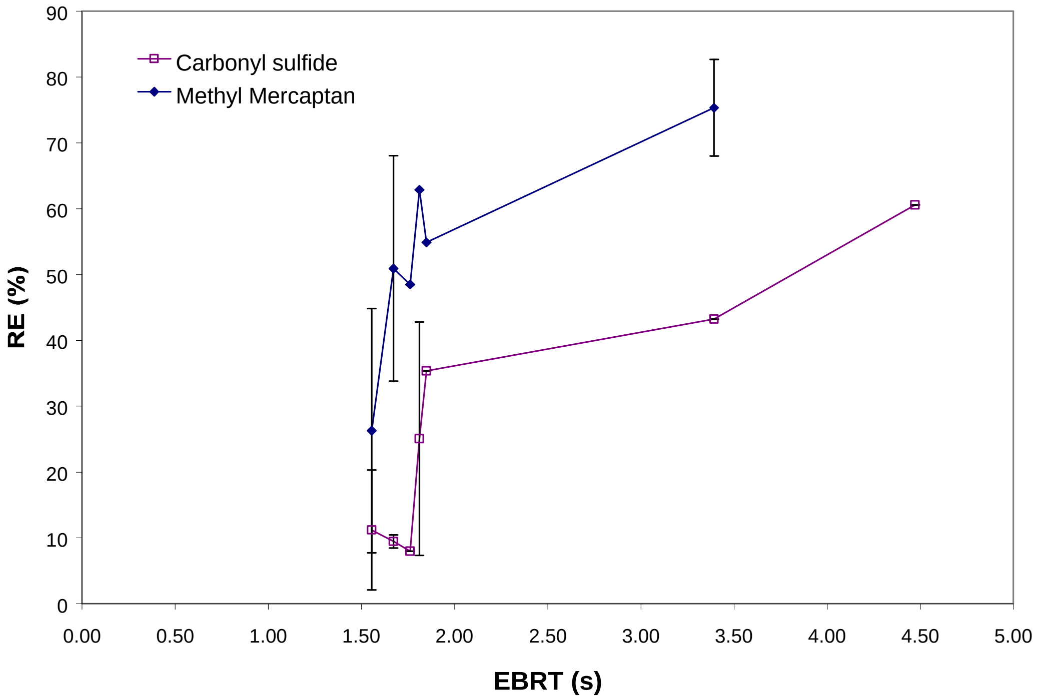


Figure 3.27 Effect of EBRT on RSCs removal. Data with similar inlet concentrations were selected from the pool of long-term data (30-50 analyzes). Note that data may not be representative as there were only 1-2 analyses per EBRT above 1.6 seconds and 17 analyses at 1.6 seconds EBRT.

Overall, the results of the analysis of the performance at different EBRTs based on long term data highlighted the fact that more controlled experiments were needed. Hence, an experiment was conducted were the inlet dampener opening was used to modify the air flow and the removal of H_2S and RSCs at different EBRTs was determined. EBRTs of about 1.6, 2.1 and 6.8 seconds were tested for durations of 4 hours each. The experiment lasted over 2 days. There was a total of 4, 7 and 8 samples taken at 1.6, 2.1 and 6.8 seconds, respectively. The results are reported in Figures 3.28 (dampener opening calibration), 3.29 (removal of RSC), 3.30 (removal of H_2S) and 3.31 (inlet concentration for quality control). Unfortunately, because of the inlet variability inherent to all experiments with the field biotrickling filter, some grab samples had outlet concentrations that exceeded the inlet value. Further, in the case of H_2S, the effect of the fluctuating inlet concentration was larger than the effect of EBRT (see Figure 3.30) making any quantitative conclusion impossible. Our recommendation is that for H_2S, the results of the long-term performance discussed earlier (see Figure 3.26) are more representative. Still, the results present interesting trends for RSC as reported in Figure 3.29. They indicate that a clear improvement is obtained at longer EBRTs, particularly for methyl mercaptan. The improvement is less significant for the other RSCs. These results should however be taken with great care, in particular we caution against using them in a quantitative manner for biotrickling filter design, as the number of sample replicates was low due to analytical constraints.

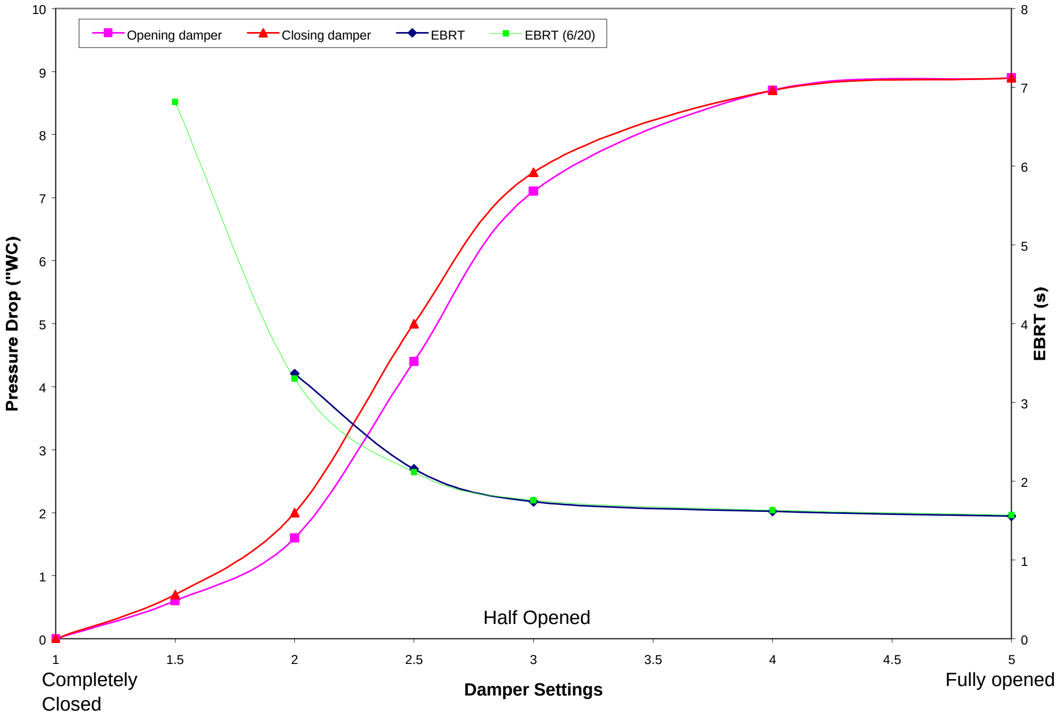


Figure 3.28 Calibration of air flow vs. dampener opening.

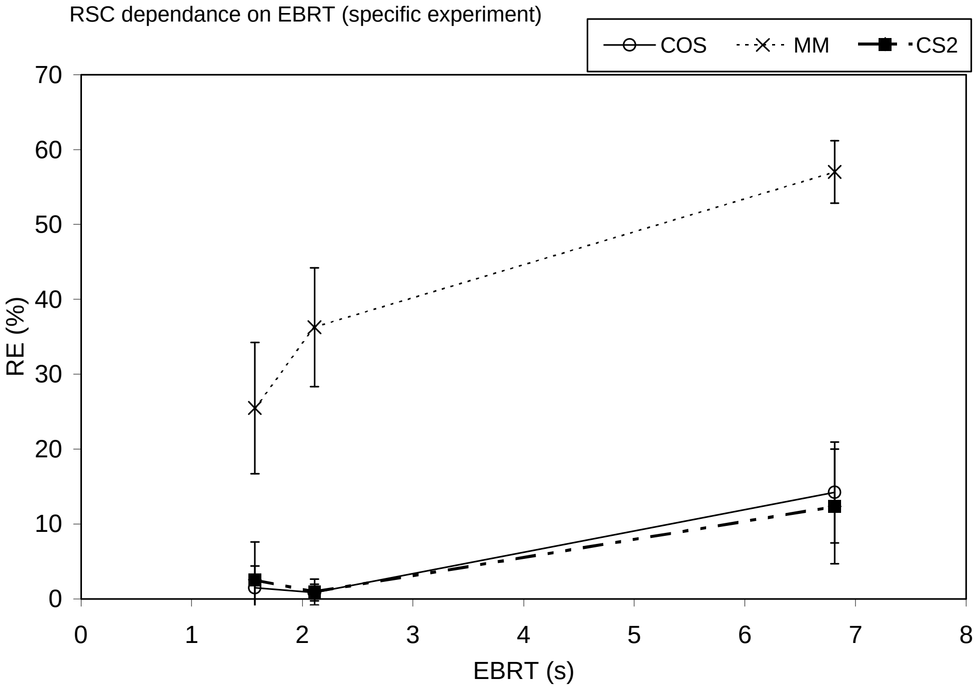


Figure 3.29 Effect of EBRT on RSC removal. Data is from the short-term experiment where the dampener opening was varied.

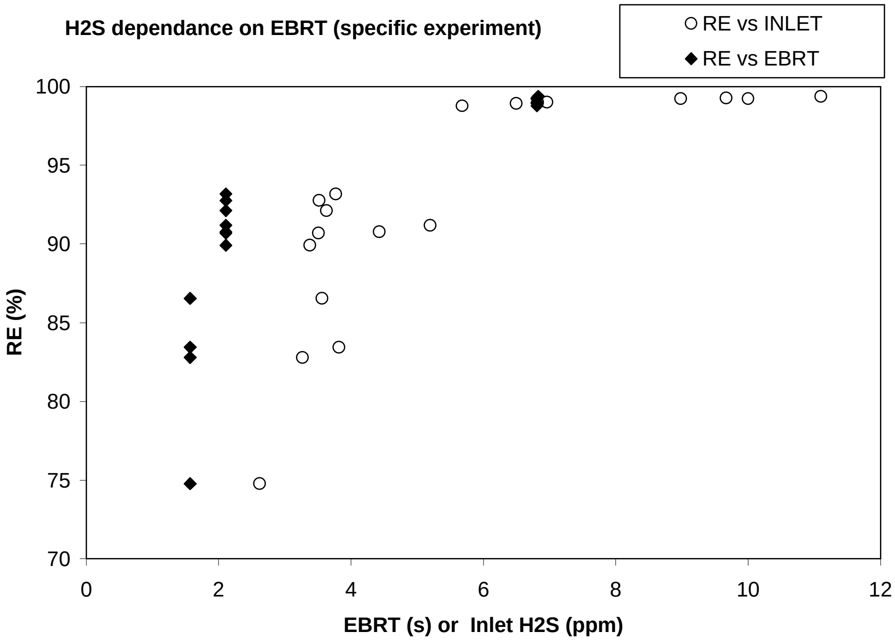


Figure 3.30 Effect of EBRT on H_2S removal. Data is from the short-term experiment where the dampener opening was varied. As shown, the inlet H_2S concentration varied significantly making any conclusion about the relationship between removal and EBRT impossible.

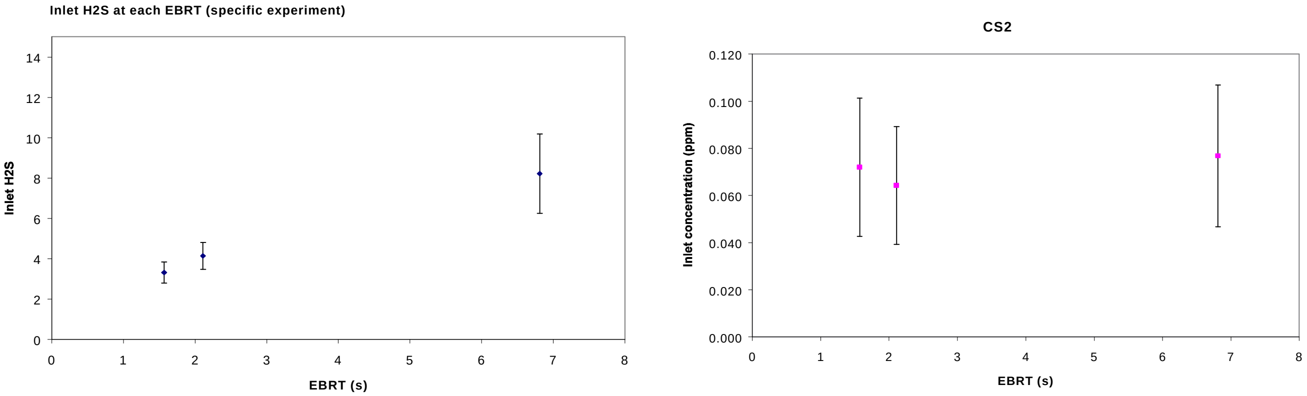


Figure 3.31 Inlet concentration of H_2S or CS_2 during the experiment. H_2S was not constant while CS_2 remained approximately constant.

3.8 Overall Assessment of the Operation of the Converted Scrubbers

Overall, the biotrickling filters -especially biotrickling filter 10- were found to be very stable, providing sustained H_2S treatment over time. The required maintenance was low and the biotrickling filter systems were running all the time, except when ancillary equipment such as the blowers needed service. During the project, there were a few instances where H_2S treatment performance was significantly reduced. When a cause for the loss of treatment performance could be found, it was never the biotrickling filtration process that was defective, but rather the result of ancillary equipment failure which affected the biology of the biotrickling filter. Examples include excess chlorine supply after failure of the plant water chlorination system, or suction of acid into the biotrickling filter after an acid wash on the parallel scrubber caused acidic foam to back-flow into the air ducting. Hence, the biotrickling filtration process itself can be qualified as very stable and reliable. Avoiding failure of ancillary equipment will be key for future biotrickling filter application at OCSD.

Evaluation of one year of operation of biotrickling filter #10 reveals that the biotrickling filter successfully treated H_2S at rates comparable to those of chemical scrubbers. H_2S removal was often in excess of 98% for inlet H_2S concentrations as high as 30 to 50 ppm_v. This corresponds to volumetric elimination rates of H_2S of 95 to 105 g H_2S m^{-3} h^{-1} which is exceptionally high compared with other biofilters or biotrickling filters removing low concentration of H2S, even at higher gas contact times (Smet et al. 1998; Koe and Yang 2000; and Cox and Deshusses 2002). Biotrickling filter I exhibited higher H_2S removal rates, though at partial H_2S removal.

4. COST-BENEFITS ANALYSIS

4.1 Introduction

The cost analysis for the conversion of chemical scrubber 10 to a biotrickling filter is divided into 2 main parts: the evaluation of conversion costs of the chemical scrubber and the operating costs analysis. The configuration of OCSD Trunkline-Headworks complexes allowed us to perform the cost-benefit analysis under two different scenarios: First a cost comparison of a chemical scrubber operated in parallel with a biotrickling filter, in which the economical impact of the biotrickling filter on the downstream chemical scrubbers was evaluated. Second, we compared the costs-benefits of having the biotrickling filter versus having no biotrickling filter upstream.

4.1.1 Headwork and trunkline facilities description

In order to better understand the relationship between treatment performance and costs, the scrubber/biotrickling filter environment is first described. The economical analysis was performed on the Trunkline and Headworks complexes (Figure 4.1) at Plant 1. The trunklines have extensive foul air collection, and treatment by chemical scrubbing. In addition, dosage of hydrogen peroxide and ferrous chloride is performed in the trunklines to reduce odor formation. The cost of this chemical addition was not considered in the economical analysis. The side-by-side configuration of biotrickling filter 10 with chemical scrubber 9 allowed for the direct comparison of the biological and chemical scrubbing processes. Trunkline scrubbers act as first-stage roughing scrubbers to reduce odor, which is mostly H_2S, prior to further treatment downstream by the scrubbers 1 through 4 located at the Headworks complex. In the past, both trunkline scrubbers were designed as countercurrent, packed-tower scrubbers for caustic (sodium hydroxide) use, thus operated as H_2S absorption only scrubbers, but they were often operated with water only without caustic addition or even taken off-line to save power and chemical costs when incoming H_2S and odors loads were low. In order to allow for a direct economical comparison of chemical scrubber 9 and biotrickling filter 10, scrubber 9 was operated as designed during the complete duration of the study, i.e., with controlled sodium hydroxide metering to the reactor.

Headworks scrubbers differ from the Trunkline scrubbers in that they include the addition of hydrogen peroxide for pollutant oxidation in order to improve removal efficiencies. All four Headworks scrubbers are single-stage, counter-current, packed-tower scrubbers that treat on average a total of about 72,000 cfm. Typically, three scrubbers are operated, with the others serving as a standby, depending on the incoming load to the complex. Air coming in the complex may be either distributed equally among chemical scrubbers or may be preferably redirected to one or more target scrubbers. Thus, in order to facilitate the evaluation of the economical impact of the biotrickling filter on the downstream treatment, airflow from the Trunkline complex was redirected to feed only scrubbers 2 and 4 (Figure 4.1) during the time of the study.

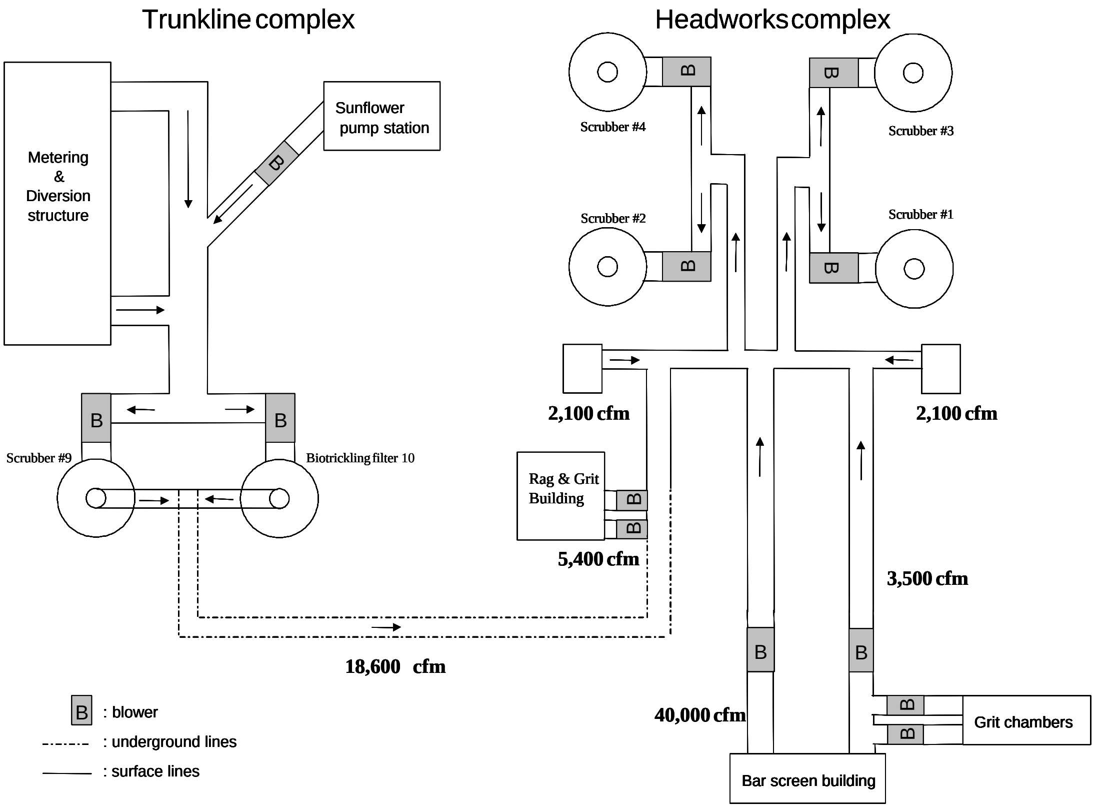


Figure 4.1. Schematic of the treatment system configuration in the Trunkline and Headworks complexes at OCSD Plant 1. Arrows indicate foul airflow direction. Bold numbers indicate design airflows.

Table 4.1 shows the main characteristics of the scrubbers and biotrickling filter included in the cost-benefit analysis. It is important to note that prior to its conversion to a biotrickling filter, scrubber 10 was operating in an identical manner to scrubber 9. Therefore, differences in power requirements and chemical usage between these two reactors will be the main focus of the cost comparison.

Table 4.1. - 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 (ft)	12	15	12
Diameter (ft)	6	9	6
Bed volume (ft^3)	340	954	340
Fan power (HP)	40	40	40
Recirculation pump (HP)	7.5	10	0.5
Caustic pump power (HP)	0.75	0.75	n/a
Hydrogen peroxide pump (HP)	n/a	0.04	n/a
Design air flow (cfm)	9300	24000	9300
Liquid recycle flow (gpm)	435	650	20
Make-up water flow (gpm)	20	8	2
Design EBRT (s)[a]	2.2	2.4	2.2

[a] Empty Bed Retention Time = bed volume/air flow

Note that operational parameters from Table 4.1 such as airflow and make-up water flow will differ from actual reactor operation. Thus, specific measurements and monitoring were performed to evaluate operating costs. From an operational standpoint, chemicals addition to wet scrubbers is performed differently depending on the scrubber and the chemical added. Sodium hydroxide addition to scrubber 9 was regulated depending on the outlet H_2S concentration, measured by an on-line H_2S monitoring device (Vapex Sentinel, Vapex, FL). Although scrubber 4 has a Vapex unit on-line, sodium hydroxide addition to scrubber 4 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 in a constant flow basis manually adjusted by plant personnel.

4.1.2 Definitions

Biological trickling filter operation and chemical scrubbers at the Trunkline and Headworks complexes were extensively monitored in order to ensure their performance and to evaluate the cost-benefit of the conversion. In order to more accurately calculate and compare the annual savings under different scenarios, costs of H_2S treatment reported are based on the mass loading (*L*) and the elimination of a certain mass of pollutant (*E*) in the biotrickling filter or the chemical scrubbers. Efficiency of the reactors is reported in terms of removal efficiency (RE). These terms are defined in Equations 1 to 3, where C_{in} and C_{out} are the H_2S inlet and outlet concentrations expressed in g m^{-3} (to convert ppm to g m^{-3}, multiply ppm by 0.00137), respectively, and Q is the air flow rate in m^3 h^{-1} (to convert cfm to m^3 h^{-1} multiply by 1.7).

H_2S Elimination $E = (C_{in} - C_{out}) \times Q$ ($g\ h^{-1}$) (Equation 4.1)

Removal efficiency $RE = (C_{in} - C_{out}) / C_{in}$ (%) (Equation 4.2)

Loading $L = C_{in} \times Q$ ($g\ h^{-1}$) (Equation 4.1)

Note that elimination and loading are defined differently than the elimination capacity (EC) and loading used in performance studies (Chapter 3), as the latter are normalized by the volume of the bed. Here, since one has to evaluate actual mass of H_2S treated, no normalization is done and the elimination and loading are actual mass fluxes treated or loaded onto the system.

4.2 Conversion Costs of the Chemical Scrubber

A detailed description of the conversion costs based on the 10-step procedure is presented in Tables 4.2 to 4.6. Note that only those steps that had actual costs are shown (see Chapter 2 for a detailed description of actual steps and conversion procedure). For labor costs, skilled personnel (electrician, engineer) were considered at a fully burdened rate $100 per hour while a field technician was charged at $40 per hour. For parts cost, some purchased by UCR and some by OCSD, an inventory of current market prices was considered. An additional step as a preparation step to condition the scrubber for the conversion was added to the 10-step protocol due to the large scale buildup in the packing. In addition, note that steps 2 and 3 corresponding to the removal of the old packing and the strengthening of the packed bed support are not detailed in a particular Table 4 since both were performed by an outside contractor (Water Systems Cleaning) with a total cost of $1465. This cost is included in Table 4.7 that summarizes the associated costs for each task and the total costs needed for the conversion of chemical scrubber 10.

Table 4.2 details the costs required for the preparation step. Note that scrubber isolation includes 8 hours labor for an engineer in order to consider the analysis performed by OCSD and UCR personnel of the pipe lines to close to isolate the scrubber for the operation as a biotrickling filter (caustic, pump cooling ring, etc.). The scrubber was also acid washed twice with hydrochloric acid prior to the conversion. Whether it was really needed is unknown. A cost of $620 per acid wash was considered according to the Phase I report .

Table 4.2 Labor and parts costs for scrubber preparation.

STEP 0: Scrubber preparation			
Person-hours of labor per scrubber for			**Total**
- Acid washing	8h, at	40$/h, =	320
- Scrubber isolation	8h, at	100$/h, =	800
- Scrubber isolation	3h, at	40$/h, =	120
Materials			
- Hydrochloric acid:	2wash	620$/wash	1240
TOTAL LABOR STEP 0			**$ 1240**
TOTAL MATERIALS STEP 0			**$ 1240**
TOTAL STEP 0			**$ 2480**

In Table 4.3, the costs for the removal of the old liquid recycle pump are listed together with 3 hours of engineering labor that were dedicated to the analysis performed by UCR and OCSD personnel to disconnect the appropriate safety alarms such as a low liquid level sump alarm installed on the scrubber .

Table 4.3 **– Labor and parts costs for removal of unnecessary parts of the scrubber.**

STEP 1: Removal of unnecessary parts			
Person-hours of labor per scrubber for			**Total**
- Alarms disconnection	3h, at	100$/h, =	300
- Liquid recycle pump removal	3h, at	40$/h, =	120
Materials			
- Cap ¼" for recycle pump cooling pipe	1cap	7$/cap	7
TOTAL LABOR STEP 1			**$ 420**
TOTAL MATERIALS STEP 1			**$ 7**
TOTAL STEP 1			**$ 427**

Table 4.4 details costs for the installation of the new liquid recycle pump. Note that a backup pump was also purchased but not installed. Material used for all re-piping was CPVC Schedule 80 plastic 1-1/2” nominal diameter except when indicated.

Table 4.4 Labor and parts costs for installation of the new liquid recycle pump.

STEP 6: Modify liquid recycle pump			
Person-hours of labor per scrubber for			**Total**
- Pump selection / redesign	14h, at	100$/h, =	1400
- Electrical job & re-piping	8h, at	40$/h, =	320
Materials			
- Liquid recycle pump	1Units	507$/unit =	507
- One backup pump	1Units	507$/unit =	507
- Rotameter	1Units	210$/unit =	210
- Flange 6" (Van Stone)	1Units	127$/unit =	127
- Flange 4" (Van Stone)	1Units	75$/unit =	75
- Reducer bushing 6x3"	1Units	93$/unit =	93
- Reducer bushing 4x3"	1Units	43$/unit =	43
- Reducer bushing 3x2"	2Units	39$/unit =	78
- Reducer bushing 2x1-1/2"	2Units	39$/unit =	78
- Elbow 90	8Units	15$/unit =	120
- Elbow 45	1Units	18$/unit =	18
- Tee	2Units	22$/unit =	44
- Ball valves (Viton ring)	3Units	139$/unit =	417
- Male adapter	2Units	17$/unit =	34
- Straight pipe (20 m)	4Ft	6.40$/ft =	25.6
- Union (Viton ring)	5Units	36$/unit =	180
- Nipples	1Units	10$/unit =	10
- Pipe supports (16 ft FPR channel + clamps + fittings)	1Units	115$/unit =	115.4
- Pump cover	1Units	5$/unit =	5
- Heat starter & rewiring	1Ft	80$/ft =	80
- Primer (CPVC, 1 Qt can)	0.5Can	13$/can=	6.25
- Pipe cement (CPVC, 1 Qt can)	0.5Can	17$/can=	8.5
TOTAL LABOR STEP 6			**$ 1720**
TOTAL MATERIALS STEP 6			**$ 2,782**
TOTAL STEP 6			**$ 4,502**

Table 4.5 details costs for the installation of the new packing material, performed by UCR personnel by randomly dumping the packing material into the scrubber. Four UCR persons (considered as low-tech personnel due to the type of work involved) were needed to install the packing. This took a total time of 8 hours, including 1 hour planning and instruction per person.

Table 4.5 Labor and parts costs for installation of the new packing material.

STEP 9: Installation of New Packing Material			
Person-hours of labor per scrubber for			**Total**
- Skilled technician/engineering	4h, at	100$/h, =	400
- Packing installation	32h, at	40$/h, =	1280
Materials			
- Packing material			$ 6,400
- Shipping/transportation costs/customs			$ 4,000
TOTAL LABOR STEP 9			**$ 1680**
TOTAL MATERIALS STEP 9			**$ 10,400**
TOTAL STEP 9			**$ 12,080**

Table 4.6 details costs for the modification of the controls of the scrubber in order to operate as a biotrickling filter. Personnel costs are mainly associated with the analysis of the operating conditions of the biotrickling filter and deactivation of the certain control loops, since no pH control or chemical feed was necessary for biotrickling filter operation.

Table 4.6 Labor and parts costs for the modification of the controls of the scrubber-biotrickling filter.

STEP 10: Modification of the controls			
Person-hours of labor per scrubber for			**Total**
- Skilled technician/engineering	4h, at	100$/h, =	400
- Switching of scrubber controls	2.5h, at	40$/h, =	100
TOTAL LABOR STEP 10		**$**	**500**
TOTAL MATERIALS STEP 10		**$**	**0**
TOTAL STEP 10		**$**	**500**

Table 4.7 summarizes the costs of chemical scrubber 10 conversion. Note that Step 1 and Step 6 costs are lumped together because all are associated with the replacement of the liquid recycle pump. In summary, the larger cost came from the new packing purchase. Note that the cost of installing a smaller liquid recycle pump and the required re-piping is relatively modest and it pays for itself (in energy costs) in about one year.

Table 4.7 Summary of cost of the conversion of chemical scrubber 10 to a biotrickling filter.

Task	**Labor ($)**	**Parts ($)**	**Total ($)**
Scrubber preparation (Step 0)	1240	1240	2480
Removal of old packing (Step 2&3)	1460	0	1460
Liquid recycle pump replacement (Step 1&6)	2140	2790	4930
Installation of the new packing (Step 9)	1680	10,400	12080
Modify controls (Step 10)	500	0	500
TOTAL	**$7,025**	**$14,430**	**$21,450**

It should be noted that this first conversion was experimental and therefore it 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. Thus, no more than the minimum number of modification were performed in the instrumentation and controls of the chemical scrubber, and most of the unnecessary parts such as pipes, scrubber backup recycle pump and pumps for chemicals feeding were kept in place. On the other hand, engineering costs included in Tables 4.2 to 4.7 as labor costs for the current conversion were higher because of the novelty of the work, and may be reduced for routine conversions.

4.3 Economical Assessment, Operating Costs and Benefits

4.3.1 Data

Operating costs for each reactor were evaluated for a period of eight months, between August 2001 and March 2002, in order to acquire enough data under different operating and environmental conditions. The costs associated with biotrickling filter operation are make-up water consumption and electricity. The cost of chemical scrubbing must also include chemicals (sodium hydroxide or sodium hydroxide and hydrogen peroxide) and the electricity corresponding to chemical pumps operation. The cost of chemicals, energy and water were calculated based on the prices communicated by OCSD (2002) and compiled in Table 4.9. Secondary effluent price was based on the FY 2001-02 cost for treating wastewater at OCSD.

Table 4.8 Summary and type of costs for the biotrickling filter and chemical scrubbers under study.

	Scrubber 9	Scrubber 4	Biotrickling filter 10
Blower	Electrical	Electrical	Electrical
Recycle pump	Electrical	Electrical	Electrical
Caustic pump	Electrical	Electrical	None
Hydrogen peroxide pump	None	Electrical	None
Sodium hydroxide	Chemical	Chemical	None
Hydrogen peroxide	None	Chemical	None
Make-up water	Water	Water	Water

Note that chemical scrubbers require HCL for cleaning (acid washes) while biotrickling filters do not require cleaning. In absence of an official preventive maintenance schedule for scrubbers 4 and 9, these costs were not included in the study.

Table 4.9 Prices of chemicals, energy and water at OCSD.

Item	Purchased unit	Price ($)
Sodium hydroxide 25%	$/gallon	0.47
Hydrogen peroxide 50%	$/gallon	1.86
Electricity	$/kWh	0.07
Water	$/Mgallon	43

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. Cost calculations were performed on a monthly basis to take into account airflow changes in the reactors during the study and because of the changing H_2S loading to the reactors, particularly to the Trunkline scrubbers, which fluctuated seasonally because of the effect of temperature on H_2S production in the inlet sewer lines (Figure 4.2).

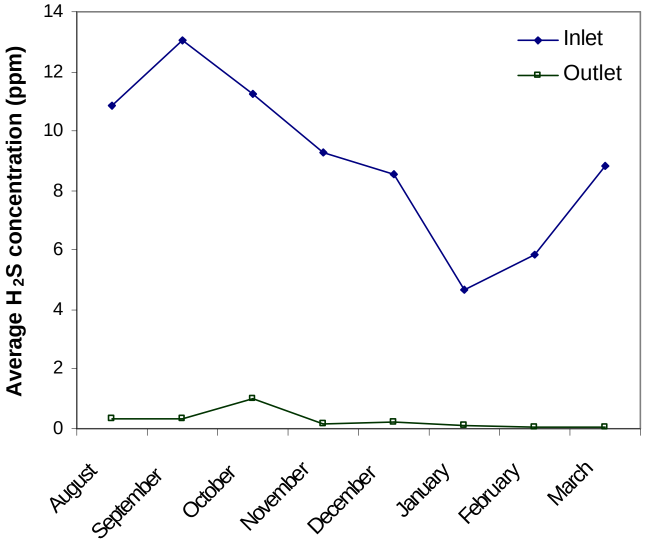


Figure 4.2 - Seasonal variation between August 2001 and March 2002 of monthly average H_2S inlet and outlet concentrations for biotrickling filter 10.

First, to calculate the amount of H_2S treated in each reactor, data from Vapex units and airflow measurements were used, when available, to calculate H_2S elimination following Equation 4.1. In the case of scrubber 4, Vapex data were not available for several periods of time. Instead, off-line measurements collected by plant operators twice per day were used. Two calculations methods for the elimination were compared as follows:

1) Based on data averages: given that one inlet and one outlet H_2S datum is obtained from on-line Vapex unit every 12 minutes, all data collected per day was averaged daily and then all daily averages were averaged per month to come up with a monthly averaged value for the inlet and outlet H_2S for each reactor. Averages were similarly applied for twice-a-day off-line data. As an example, Figure 4.3 shows the fluctuation in the H_2S concentration in the biotrickling filter. The use of daily average as inlet and outlet H_2S for the whole day is representative since sampling is usually performed at regular intervals. (Uneven frequency sampling would result in giving different weight to the various samples).

2) Based on data integration (=time-averaged): inlet and outlet H_2S load data is integrated along the time to get the real mass of H_2S that enters and exits the reactor, which is more accurate and allows for irregular sampling frequency, but is considerably more time consuming because of data gaps from Vapex units. Also, in case of improper Vapex functioning, when off-line data was used, this method can lead to large uncertainties.

Both calculation methods were compared for part of the biotrickling filter data in order to ensure that using the averaged data was roughly equivalent to data integration. Table 4.10 shows that no significant difference exists using both methods, consequently averages were used for further calculation.

Table 4.10 Comparison of calculation method for determination of H_2S Elimination.

Method to calculate Elimination	August	November	February
Daily + Monthly averages	97.90	128.95	82.51
Numerical integration	98.3	124.52	86.1
Difference (%)	-0.4	+3.4	-4.4

Similarly, monthly averages were calculated for operating variables such as foul airflow and make-up water flow rate, even if the sampling frequency was much lower. Daily make-up water flow rate was obtained from OCSD round-sheets collected twice per day. Airflow measurements were performed at different frequencies for each reactor: one measurement for scrubber 4 (June 2002), 9 measurements for scrubber 9, and 14 measurements for biotrickling filter 10 between October 2001 and April 2002. Airflow measurements were performed with a Pitot Tube using the 3-D and 2-D traverse methods. Table 4.11 summarizes averaged monthly values for foul airflow measured for each scrubber along with the amount of H_2S removed and the difference between the inlet and the outlet concentration to the reactors. It can already been seen that scrubber 4 is treating a much lower concentration of H_2S than 9 and 10, hence the lower mass of H_2S eliminated within the time considered.

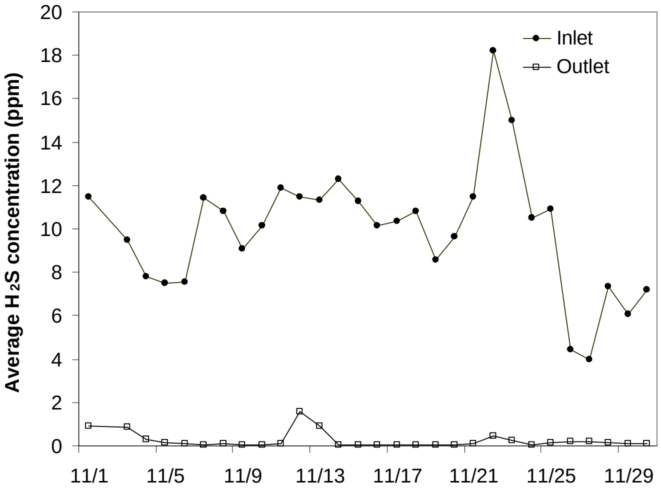


Figure 4.3 Fluctuations of average daily H_2S inlet and outlet concentrations to the biotrickling filter (average method, November 2001).

Table 4.11 Summary of monthly averaged airflow and H_2S from monitored data between August 01 and March 02.

Parameter	Reactor	August	September	October	November	December	January	February	March
Foul airflow (cfm)	BTF 10	5785	3724	8950	8319	8275	8566	9145	9145
	9	6595	6595	5102	3623	2830	2347	2347	2347
	4	19000	19000	19000	19000	19000	19000	19000	19000
C_{in} - C_{out} (ppm H_2S)	BTF 10	10.9	15.9	10.2	10.0	9.1	5.1	5.8	8.8
	9	14.0	21.5	16.2	15.1	8.5	5.5	3.0	7.1
	4	2.8	2.4	1.9	2.9	1.5	0.9	1.2	1.2
Amount of H_2S removed (kg H_2S/month)	BTF 10	97.90	99.48	159.38	128.95	130.95	74.72	82.51	139.20
	9	128.69	229.51	143.78	88.46	38.96	22.46	10.44	29.02
	4	65.63	94.50	41.55	95.43	48.81	32.72	33.98	39.52

Following the determination of the mass of H_2S treated in scrubbers 4 and 9 and in the biotrickling filter 10, make-up water, energy and chemical consumption were calculated on a daily basis in order to obtain cumulative and instantaneous consumption rates. As before, the data were averaged on a monthly basis for easy comparisons. Energy costs were calculated multiplying the time each mechanical element of each reactor was in operation per month (Table 4.12) by the cost of electricity (Table 4.9) and by the pump or blower power (Table 4.1). It should be stressed that in the absence of specific information on the actual amperage used by the blower as a function of the pressure drop in each reactor, the nominal power of the blower was used instead of the actual electrical power usage. This introduces some uncertainties that require further definition. Run time for each one of the mechanical elements was logged into the SCADA system of the facility and reported as total daily and total monthly operation times. Note that the biotrickling filter systematically achieved very high time of operation per month indicating the high reliability of the process.

Table 4.12 Run time of each mechanical element with electrical consumption.

Parameter	Reactor	August	September	October	November	December	January	February	March
Blower	BTF 10	665.0	719.8	744.8	665.1	742.5	737.8	671.0	741.4
	9	595.4	692.4	744.3	692.9	695.0	739.8	634.8	742.6
	4	535.8	720.0	600.2	695.5	743.1	744.0	671.7	743.9
Liquid recycle pump	BTF 10	738.8	720.0	731.7	668.7	742.6	737.2	671.4	704.7
	9	603.3	694.5	745.0	695.6	693.4	739.9	635.2	738.1
	4	720.0	720.0	599.0	695.5	671.7	744.0	671.7	743.7
Caustic pump	9	454.4	281.9	158.2	125.1	170.9	160.9	144.4	222.7
	4	443.1	687.9	486.0	666.9	741.3	737.4	671.1	743.8
H_2O_2 pump	4	535.8	720.0	600.2	695.5	743.1	744.0	671.7	743.9

In the biotrickling filter, plant water is mainly used to control the pH and for nutrients feeding, while make-up water is supplied to chemical scrubbers at a higher rate in order to have the scrubbing solution purged. In any case, a steady flow of plant water was always used for operation of any of the reactors. Water costs were calculated multiplying the time each reactor was in operation per month (considered as the running time logged for the blower in Table 4.12) by the cost of secondary effluent (Table 4.9) and by the monthly average of make-up water flow rate, the latter recorded twice per day by plant operators in the round sheets (Table 4.13).

Table 4.13 Monthly averaged make-up water flow rate per reactor.

Parameter	Reactor	August	September	October	November	December	January	February	March
Make-up water flow rate (gpm)	BTF 10	2	2	2	2	2	2	2	2
	9	20	20	20	20	20	20	20	20
	4	8	8	8	10	9	8	8	7

Similarly, chemicals consumption in each scrubber was assessed multiplying the average flow delivered by each chemical metering pump to each scrubber (considering the pump output set by the plant operator and recorded twice per day in round sheets) by the run time of each pump (Table 4.12) and by the cost of each chemical used (Table 4.9). In case of caustic pumps, logged data in the SCADA system was used to calculate the pump run time. We found a high discrepancy between caustic pump running time data logged in the Vapex unit for scrubber 9 and the pump running time data logged in the SCADA system (Table 4.12). Thus, data were double-checked against the caustic consumption based on the monitoring of the level in the caustic tank that serves the Trunkline and Headworks complexes. Individual consumption for scrubber 9 was calculated taking into account the number of chemical scrubbers in operation (2 or 3 in the Headworks complex). Close agreement was found between the caustic consumed calculated from the SCADA running time and the consumption calculated from the tank level monitoring. Consequently, data from the SCADA was chosen for all further calculations.

Table 4.14 Volume of caustic consumed per month at scrubber 9 as a function of data source for calculation.

Basis for NaOH usage calculation	August (gallons)	September (gallons)	October (gallons)	November (gallons)	December (gallons)
Vapex logged data	208	1057	1593	766	444
SCADA logged data	2130	2842	1898	1501	1723
Round sheets NaOH tank level	2940	2700	1817	1785	1665

In the case of hydrogen peroxide, since data was not logged into the SCADA system, flow recorded twice a day by plant operators in the round sheets was used to calculate total monthly usage (Table 4.15). Table 4.15 also summarizes chemical consumption for each chemical and all scrubbers. A ratio of 0.2-0.5 for hydrogen peroxide/caustic usage was found in scrubber 4.

Table 4.15 Amount of chemicals consumed per month in scrubbers 4 and 9.

Chemical for scrubber #	August	September	October	November	December	January	February	March
H_2O_2 (gal.) scrubber 4	669	812	646	896	745	733	777	794
NaOH (gal.) scrubber #4	2587	2792	1566	1785	1661	3104	3721	6171
NaOH (gal.) scrubber #9	2130	2842	1898	1501	1723	1931	1733	2672

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

Table 4.16 summarizes the major operating costs during the period considered for each one of the three reactors. Table 4.16 does not includes monthly average make-up water cost of $3.5, $34, and $15 for the biotrickling filter, scrubber 9, and scrubber 4, respectively, since they are negligible compared with other operating costs. On an average basis, 98.7% 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 case of biotrickling filtration will be affected by proper blower operation. This suggests that further investigations into the effect of packing size (random dump vs. cut-to-shape, see Section 3.6) and the effect of trickling rate (see Section 3.7.2) 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.

Table 4.16 Monthly consumption energy and chemicals and treatment capability in the chemical scrubbers and in the biotrickling filter during the period under study.

	Biotrickling filter		Scrubber 9			Scrubber 4		
Month	Energy ($)	H_2S treated (kg)	Energy ($)	Chemicals ($)	H_2S treated (kg)	Energy ($)	Chemicals ($)	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 total estimated	18036	1370	20699	11642	1037	21757	34779	678

The average monthly costs from Table 4.16 were used to calculate 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. We believe that the uncertainty is small for the following reasons. Examination of the costs in Table 4.16 reveals that the monthly energy costs are nearly constant for all reactors. The monthly chemical costs for scrubbers 4 and 9 are also nearly constant, while the amount of H_2S treated in scrubber 9 decreased steadily over the course of the study, possibly as a result of the decrease in air flow through that scrubber and the poor performance due to fouling. The amount of H_2S treated in scrubber 4 varied over time, with lows during the cold season, which correlated with higher chemical usage. 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. In our view this is acceptable, in light of the variability in scrubber operation and performance. Thus, using the 8 month period for the cost-benefit is representative of one year of operation.

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 case of scrubber

9 and scrubber 4, total operating costs were $32,770 and $56,710, respectively, with the higher costs due mainly to the larger amount of chemicals consumed.

Based on the mass of H_2S removed, the average total treatment costs and chemical-only treatment costs in the biotrickling filter and scrubbers 4 and 9 were as follows:

- Biotrickling filter: total treatment costs $13.2/kg Chemicals only: $0/kg
- Scrubber 9: total treatment costs $32/kg Chemicals only: $11/kg
- Scrubber 4: total treatment costs $84/kg Chemicals only: $51/kg

These values fit in the wide range of operating costs reported for packed-bed, caustic-only chemical scrubbers of $2 to $280 per kg of H_2S removed (Card, 2001; Whitherspoon *et al.* , 2002; EPA, 1996). As expected, the second stage scrubber (number 4) exhibited higher operating costs due to a higher chemical usage compared to the first stage scrubber (number 9). The percentage of the chemicals cost vs. total operating cost was as high as 60% for scrubber 4 compared to 36% 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 4.4). It is worth stressing that direct comparison of the specific treatment for a given month in Figure 4.4 should be exerted with care, as the mass treated in each reactor were not the same. Therefore, the costs per kg of H_2S treated was reported as a function of the amount of H_2S treated in Figure 4.5. Even if inlet loads for the three reactors do not completely overlap, a similar, but offset trend is found for scrubber 9 and 4, with scrubber 4 being the most expensive, as already discussed. Since the cost plotted in Figure 4.5 include blower costs, it is logical to find that the specific treatment costs in the biotrickling filter increase at low loadings, however, in all cases the costs of the biotrickling filter are much lower than those of chemical scrubbing. Chemical-only costs for scrubbers 4 and 9 are shown in Figure 4.6 where it is clear that chemical usage per mass of H_2S removed is increased as the H_2S loading to the scrubbers is reduced.

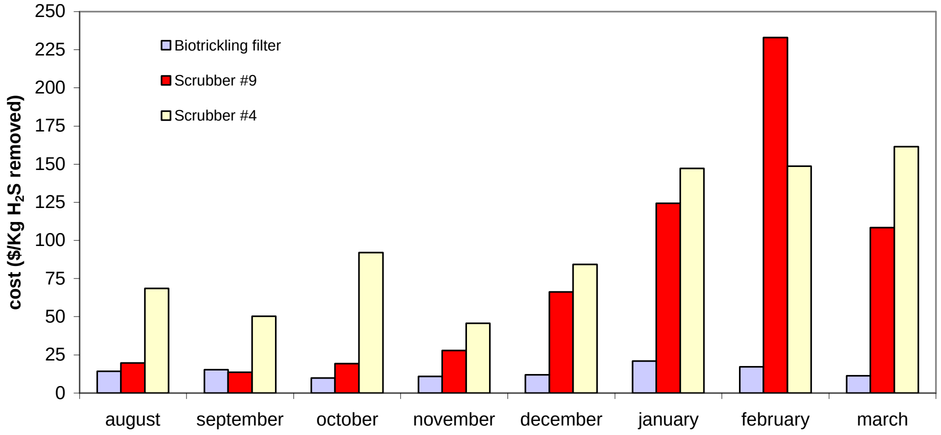


Figure 4.4 Monthly specific treatment cost of each reactor during the study.

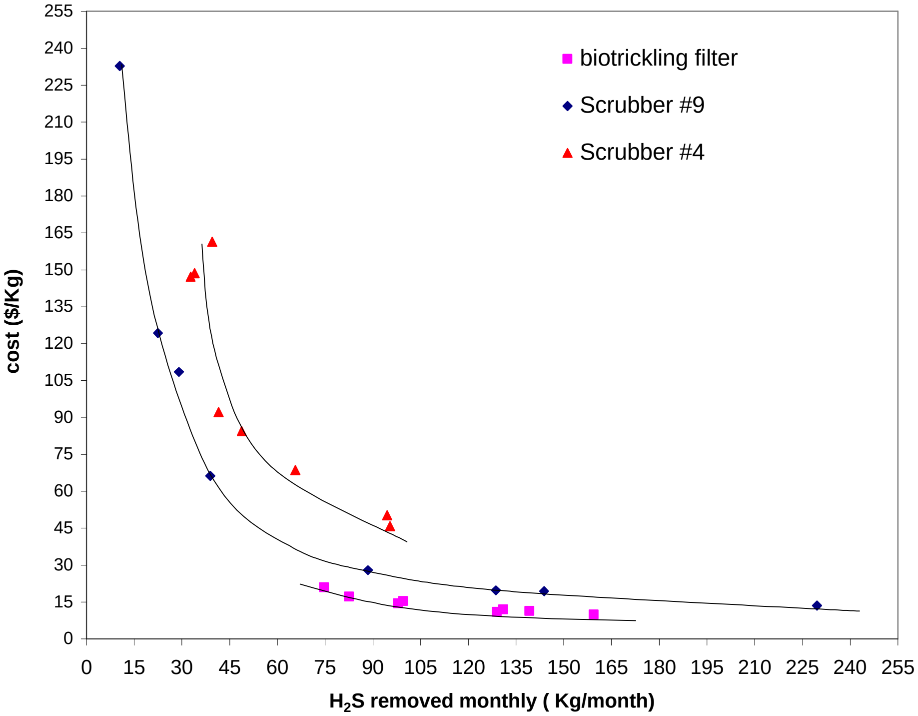


Figure 4.5 Specific treatment cost (chemicals + energy) per kg of H_2S removed as a function of the mass of H_2S removed in each reactor.

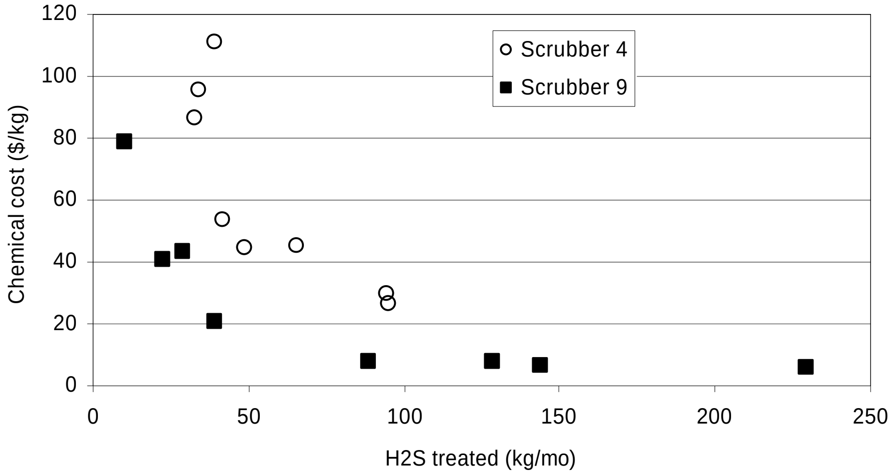


Figure 4.6 Specific treatment cost (chemicals-only) per kg of H_2S removed as a function of the mass of H_2S removed in each reactor. Here, the costs associated with the pumping of the chemicals has been neglected. Note that the monthly average H_2S treated is 57 kg and 86 kg for scrubbers 4 and 9 respectively.

4.3.3 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 4.16 and Figures 4.5-4.6. Further the impact of the biotrickling filter upstream of chemical scrubber 4 should be taken into account as all the H_2S that was treated in the biotrickling filter is H_2S that did not require treatment in scrubber 4.

Another approach for cost-benefit determination may consider the fact that before the conversion of chemical scrubber 10 to a biotrickling filter, both scrubbers 9 and 10 were not operated as scrubbers, except during peak H_2S emission in summer. Rather, foul air from the trunklines was passing through directly to the Headworks complex (scrubbers 1-4). This allows a second scenario to be defined for cost-benefit analysis, consisting of having a biotrickling filter upstream of a chemical scrubber compared to having all H_2S treated downstream. This analysis is discussed later in the present report.

Thus, cost-benefit analysis was performed first by direct comparison of chemical scrubbers 9 and 4 and biotrickling filter operation 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 4.16. Direct savings (scrubber 9 vs. biotrickling filter 10) in chemicals are about $1000 per month. The numbers of Table 4.16 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 4.16 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 treatment in scrubbers 1-4. Linear extrapolation to 1 year of these savings from excess H_2Sremoved in the biotrickling filter as shown in Table 4.16 indicates that these savings per year would be $29,000 (note that this supplemental amount of chemicals would be consumed by the four scrubbers 1-4 of the headwork complex). Thus, the total estimated yearly savings of the conversion are $14,300 + $29,200 = **$43,500**.

Table 4.16 Costs savings analysis of having biotrickling filter 10 compared to scrubber 9.

Item	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**March**	**Sum 8 months**	**Extrapol. 1 year**
Chemicals saved in the BTF vs. #9 ($/month) (A)	1006	1342	897	709	814	912	819	1262		
Electricity saved in the BTF vs. #9 ($/month) (B)	89	207	278	318	160	281	161	282		
Total direct savings BTF vs. #9 ($) =(A)+(B)	**1095**	**1549**	**1175**	**1027**	**974**	**1193**	**980**	**1544**	**9537**	**14306**
Excess H2S removed in BTF vs. #9 (kg H2S/month) (C)	0	0	16	40	92	52	72	110		
Chemical savings in #4 from excess H2S removed in BTF ($) = C × $51/kg = (D)	0	0	816	2040	4692	2652	3672	5610	19482	29223
Total savings per month BTF compared to #9 ($) = (A)+(B)+(D)	**1095**	**1549**	**1991**	**3067**	**5666**	**3845**	**4652**	**7154**	**29019**	**43529**

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 cost for the conversion cost of $21,500 (in-house conversion, direct costs only). In addition, it should be stressed that there is a significant benefit for not having chemicals on-site or ancillary costs such as acid washes. These have not been included in the calculations, although the former benefit is expected to be of great significance (see report of Phase I). If chemical savings from scrubber 4 are included (see Table 4.16), 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.

A second possible approach for cost-benefit evaluation is to compare having the biotrickling filter and calculate savings for scrubber 4 operation compared to having no treatment in the biotrickling filter. In this hypothetical case, the amount of H_2S removed in the biotrickling filter must be directly treated in scrubbers 1-4, i.e. a total of 1370 kg H_2S per year. Since operating costs of scrubbers 1-4 depend on the amount of H_2S removed, a range of savings is established depending on how the calculation is performed. If the average yearly cost of $51 per kg H_2S removed is considered (again, only chemical costs are taken, since the blower energy costs should not be counted twice), the yearly savings of having a biotrickling filter vs. having nothing would be about $70,000. As discussed for Figure 4.5, this is probably overestimated since the additional load to scrubbers 1-4 would reduce the specific costs. The additional 1370 kg H_2S to be treated mean around 114 kg H_2S per month to be split between the several scrubbers of the headworks complex. Assuming that this is split into three scrubbers, the additional monthly loading per scrubbers would be 38 kg. According to Figure 4.5, the chemical-only cost would be reduced from \$51 to \$32/kg for the entire complex of scrubbers, i.e., from \$84 to \$65 for the total costs. Hence, the estimated savings are calculated as follows:

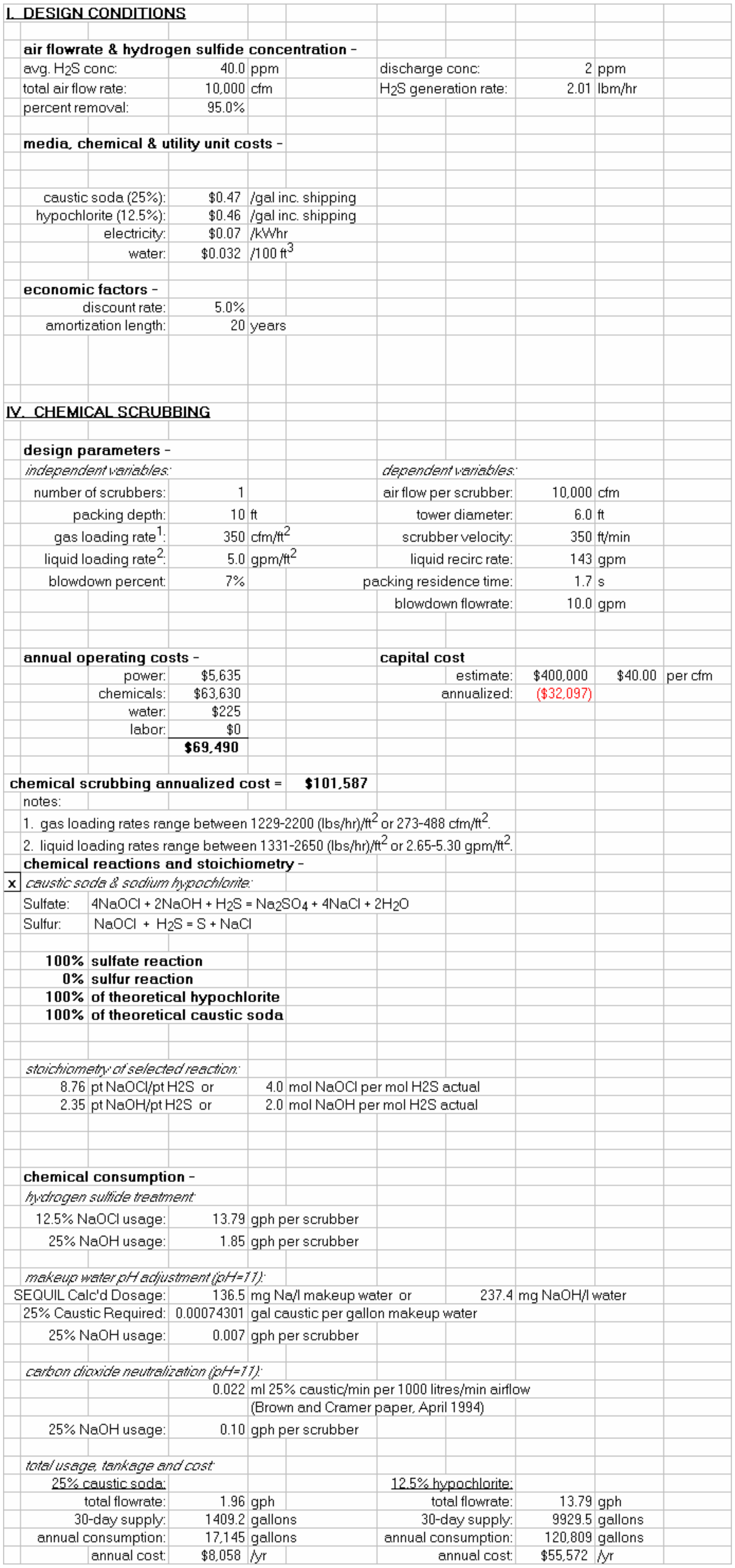
- With biotrickling filter. The complex treats about 678 kg × 3 scrubbers = 2034 kg yearly in the presence of the biotrickling filter. Thus the total costs assuming 3 scrubbers in operation is 2034 × \$84 = \$171,000.

- Without biotrickling filter. The complex would treat about 678 × 3 + 1370 = 3404 kg yearly in absence of the biotrickling filter; the total costs assuming 3 scrubbers in operation is 3404 × \$65 = \$221,000.

Following this method, the estimated savings of having the biotrickling filter compared to no roughing treatment are about \$50,000 per year.

In any of the cases considered, the cost-benefit of scrubber 10 conversion to a biotrickling filter ranges between \$40,000 and \$70,000 per year. As mentioned before, the savings resulting from acid washes for chemical scrubbers (\$600-4000 per year per scrubber, assuming low maintenance of one acid wash per year, up to high maintenance of bi-monthly acid washes) or reductions in insurance costs, accidents or risks due to chemicals on-site were not included. In summary, all results point to the high economical viability of the conversion.

A detailed analysis of the cost benefits of the conversion of scrubbers I and Q has not been performed, because of the lack of the necessary data. Some engineering calculations are presented for information below. They are based on the stoichiometry of H_2S oxidation using hypochlorite, calculated using the spreadsheet shown in Figure 4.7. The spreadsheet is a courtesy of Philip Wolstenholme (Brown & Caldwell) and allows for setting partial consumption of caustic or hypochlorite (see category called % of xyz reaction). Selected values are reported in Table 4.17. They are comparable to our initial guess, based on the fact that biotrickling filter I performs extremely well at concentrations higher than biotrickling filter 10, that savings for I and J are about 30-50% higher than those calculated for biotrickling filter 10. The cost-benefit of the conversion of Q, J, and G require further investigation.



I. DESIGN CONDITIONS							
air flowrate & hydrogen sulfide concentration -							
avg. H_2S conc:	40.0	ppm	discharge conc:	2	ppm		
total air flow rate:	10,000	cfm	H_2S generation rate:	2.01	lbm/hr		
percent removal:	95.0%						
media, chemical & utility unit costs -							
caustic soda (25%):	$0.47	/gal inc. shipping					
hypochlorite (12.5%):	$0.46	/gal inc. shipping					
electricity:	$0.07	/kWhr					
water:	$0.032	/100 ft^3					
economic factors -							
discount rate:	5.0%						
amortization length:	20	years					
IV. CHEMICAL SCRUBBING							
design parameters -							
independent variables:			*dependent variables:*				
number of scrubbers:	1		air flow per scrubber:	10,000	cfm		
packing depth:	10	ft	tower diameter:	6.0	ft		
gas loading rate[1]:	350	cfm/ft^2	scrubber velocity:	350	ft/min		
liquid loading rate[2]:	5.0	gpm/ft^2	liquid recirc rate:	143	gpm		
blowdown percent:	7%		packing residence time:	1.7	s		
			blowdown flowrate:	10.0	gpm		
annual operating costs -			**capital cost**				
power:	$5,635		estimate:	$400,000		$40.00	per cfm
chemicals:	$63,630		annualized:	($32,097)			
water:	$225						
labor:	$0						
	$69,490						
chemical scrubbing annualized cost =	**$101,587**						
notes:							
1. gas loading rates range between 1229-2200 (lbs/hr)/ft^2 or 273-488 cfm/ft^2.							
2. liquid loading rates range between 1331-2650 (lbs/hr)/ft^2 or 2.65-5.30 gpm/ft^2.							
chemical reactions and stoichiometry -							
☒ *caustic soda & sodium hypochlorite:*							
Sulfate:	$4NaOCl + 2NaOH + H_2S = Na_2SO_4 + 4NaCl + 2H_2O$						
Sulfur:	$NaOCl + H_2S = S + NaCl$						
100%	**sulfate reaction**						
0%	**sulfur reaction**						
100%	**of theoretical hypochlorite**						
100%	**of theoretical caustic soda**						
stoichiometry of selected reaction:							
8.76	pt NaOCl/pt H2S or	4.0	mol NaOCl per mol H2S actual				
2.35	pt NaOH/pt H2S or	2.0	mol NaOH per mol H2S actual				
chemical consumption -							
hydrogen sulfide treatment:							
12.5% NaOCl usage:	13.79	gph per scrubber					
25% NaOH usage:	1.85	gph per scrubber					
makeup water pH adjustment (pH=11):							
SEQUIL Calc'd Dosage:	136.5	mg Na/l makeup water or		237.4	mg NaOH/l water		
25% Caustic Required:	0.00074301	gal caustic per gallon makeup water					
25% NaOH usage:	0.007	gph per scrubber					
carbon dioxide neutralization (pH=11):							
	0.022	ml 25% caustic/min per 1000 litres/min airflow					
		(Brown and Cramer paper, April 1994)					
25% NaOH usage:	0.10	gph per scrubber					
total usage, tankage and cost:							
25% caustic soda:			12.5% hypochlorite:				
total flowrate:	1.96	gph	total flowrate:	13.79	gph		
30-day supply:	1409.2	gallons	30-day supply:	9929.5	gallons		
annual consumption:	17,145	gallons	annual consumption:	120,809	gallons		
annual cost:	$8,058	/yr	annual cost:	$55,572	/yr		

Figure 4.7 Spreadsheet model for the calculation of the costs of chemical scrubbing (courtesy of Philip Wolstenholme; Brown & Caldwell). The spreadsheet allows for setting partial consumption of caustic or hypochlorite (see category called % xyz reaction). It was used to generate the values reported in Table 4.17. The section dealing with capital costs and power cost should be disregarded. Labor costs were set to zero on purpose. Our impression is that the required caustic is greatly underestimated (see also Table 4.17).

Table 4.17 Spreadsheet generated results for chemical consumption for scrubber I or J based on stoichiometric assumptions. Note that our impression is that the required caustic is greatly underestimated using this method(probably because it neglects or underestimate the amount of caustic used up by CO_2 absorption). Values in bold indicate conditions close to scrubber I and J.

Average H_2S inlet (ppm)	% sulfate reaction	% of theoretical hypochlorite	% of theoretical caustic soda	Annual caustic consumption (ga/yr)	**Annual caustic annual cost ($/yr)**	Annual hypochl. consumption (ga/yr)	**Annual hypochl. cost ($/yr)**	**Annual chemical costs ($/yr)**
10	100%	100%	100%	4,984	$2,342	30,202	$13,893	$16,235
20	100%	100%	100%	9,038	$4,248	60,404	$27,786	$32,034
40	**100%**	**100%**	**100%**	**17,145**	**$8,058**	**120,809**	**$55,572**	**$63,630**
80	**100%**	**100%**	**100%**	**33,361**	**$15,680**	**241,617**	**$111,144**	**$126,824**
40	100%	75%	100%	17,145	$8,058	90,606	$41,679	$49,737
40	100%	50%	100%	17,145	$8,058	60,404	$27,786	$35,844
40	100%	0%	100%	17,145	$8,058	0	$0	$8,058

5. CONCLUSIONS AND RECOMMENDATIONS

Overall, the project was extremely successful and the following conclusions could be made.

1. The conversion of a chemical scrubber to a biotrickling filter is a relatively simple procedure. The costs associated with the conversion are mostly (~50%) associated with the purchase and shipping of the new packing that needs to be installed. For scrubber 10, the total estimated cost (i.e., parts and personnel) for the conversion by in-house personnel was about $21,000. The estimated cost of the conversion if performed by an outside contractor for that scrubber was about $50,000.
2. The scrubbers converted to biotrickling filters exhibited H_2S removal performance largely exceeding the predictions of Phase I. Sustained removal of H_2S with over 95% efficiency was achieved most of the time for biotrickling filter 10 at Plant 1, while biotrickling filter I at Plant 2, exposed to higher H_2S concentrations, exhibited high rate of H_2S degradation but partial removal. Biotrickling filter 10 had a maximum H_2S elimination capacity of about 105 g m^{-3} h^{-1}, while biotrickling filter I achieved elimination capacities over 250 g m^{-3} h^{-1} without reaching its maximum limit. These are truly unprecedented performances. We determined that the very high air velocity in the biotrickling filter contributed to high external H_2S mass transfer coefficients, thereby allowing such high H_2S removal rates to be achieved.
3. Stable and sustained H_2S removal was obtained at operating pHs of 1.8 to 2.2. Treatment at neutral pH was attempted but failed. However, the results were considered to be inconclusive, as the experiment was possibly affected by the excess free chlorine fed to the biotrickling filter during neutral pH operation.
4. Biotrickling filter 10 was subject to intense monitoring which revealed that it always met the AQMD discharge requirement (<1 ppm H_2S averaged over 24 h).
5. Removal of VOCs, RSCs and odors other than H_2S was not the primary objective of this phase of the study. Still, extended monitoring showed that these contaminants existed in traces (ppb levels) and that their removal ranged from about 30-70%, and was very variable. Removal of RSCs required about 2 months of acclimation.
6. The biotrickling filter exhibited a larger pressure drop (5-10” water column) than the former scrubbers. This is clearly because the new packing has a larger surface area, but is possibly also increased by packing compaction at the bottom of the bed. Testing structured foam is recommended.
7. The five biotrickling filters had less than 10 system upsets in 18 months of operation. In two or three instances, biotrickling filter 10 or I lost its H_2S removal efficiency. The most likely explanation was that overchlorinated plant water was fed and deactivated the biotrickling filter process culture. Another instance could be traced to acidic foam carryover from another scrubber. Thus, upsets were always due to a reason exterior to the biotrickling filtration process itself, suggesting that the process is stable and very reliable.
8. The biotrickling filters required little maintenance (although maintenance efforts were not quantitatively monitored). Their control was simple, and the biotrickling filter did not need

any nutrients or chemicals other than plant water. This all contributes to a very positive cost-benefit outcome.

9. The biotrickling filter responded rapidly to changing conditions. Also, no marked effect on the performance could be found after periods of up to 48 hours' starvation.
10. A detailed cost-benefit analysis of converting scrubber 10 to a biotrickling filter revealed that conversion resulted in substantial savings. When compared directly to the parallel scrubber (scrubber 9), the savings amounted to $14,000 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. Another scenario considered the benefit of having biotrickling filter 10 over having no roughing treatment. In all these cases, total savings ranged from $40,000 to $70,000 per year. The benefits of not having chemicals on-site were not included, but are significant from a health and safety perspective. Overall, the cost-benefit analysis indicates that converting scrubbers is a highly beneficial innovation.

The study led to the following general recommendations.

1. Since biotrickling filtration proved very effective, reliable, and economically favorable, further conversions should be considered. In particular scrubbers 9 and H appear to be very good candidates. Also, biotrickling filters should be included in future odor control plans.
2. Operation of the biotrickling filters at pH lower than 1.5-1.8 is not recommended, since low pH can possibly damage the packing over time.
3. Low trickling rates are recommended as excess watering increases pressure drop and may affect removal.
4. Future biotrickling filters should include some system to neutralize chlorine in plant water prior to feeding to the biotrickling filter or an alarm if excessive levels are seen in plant water.

Further, for Phase III, the recommendations are:

5. Future conversion(s) should focus on testing a structured foam (i.e., cut-to-shape), as it may result in lower pressure drops and possibly even higher pollutant elimination capacities.
6. Another experiment at neutral pH should be conducted, with a chlorine neutralizer on the plant water feed.
7. The study of the effect of EBRT on RSCs, VOCs, and odor removal should be conducted over an extended period of time, so that multiple sampling over time under a wide range of conditions can be accomplished.
8. Phase III should focus on the many issues associated with residual odor as these are key for the implementation of biotrickling filters for second stage treatment.

6. ACKNOWLEDGMENTS

The authors would like to thank OCSD personnel, in particular Jeff Brown, and Plant Operators at Plant 1 and Plant 2 for their truly outstanding and continuous support of the field operation.

The assistance of Dario Araya, UCR Undergraduate Student for the field experiments and laboratory analyses was also appreciated.

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APPENDIX 1. PICTURES

Scrubber 9 (left) and biotrickling filter 10 (right) at Plant 1

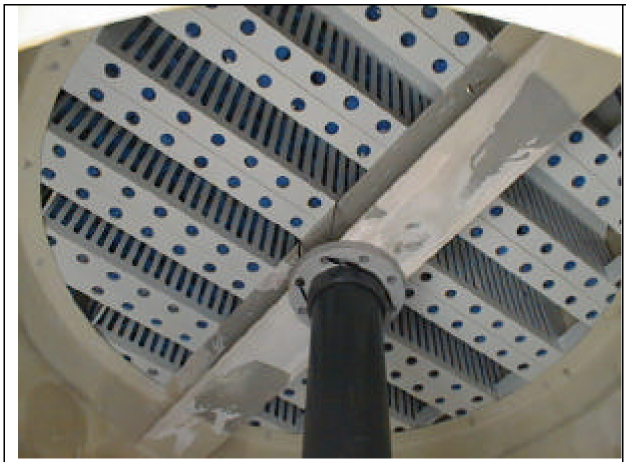
Vapex H_2S monitoring system.

Installation of the packing. The packing (open pore polyurethane foam) shipped under vacuum to save space is expanded and wetted prior to dumping in the scrubber.

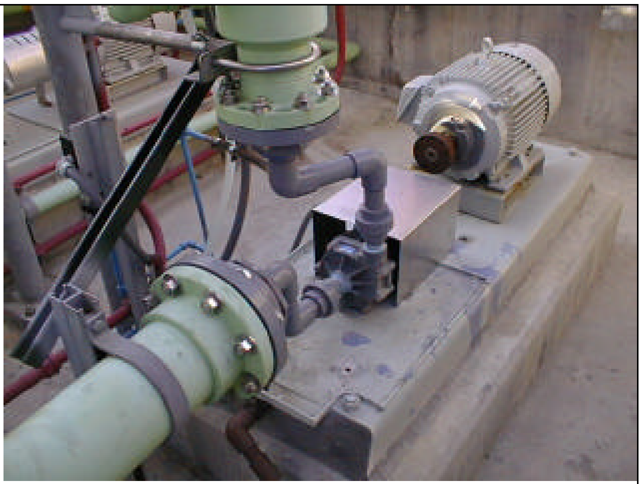
Dumping of the foam packing into the scrubber.

The foam packing (partly) installed into the vessel.

The heavily fouled TriPack packing removed from scrubber 10. New TriPack is on the right. An acid wash had been done on scrubber 10 prior to removing the packing but was not successful in removing all the scale deposits.



Reinforcement of the packing support in biotrickling filter 10. Subsequent conversions did not include such a reinforcement.



Because trickling rate is much lower in biotrickling filters, a smaller recycle pump (shown under protective cover) was installed on biotrickling filter 10. The larger pump is shown in the back.

Biotrickling filter I at Plant 2 which treats very high H_2S concentrations (roughing biotrickling filter).

North Complex at Plant 2. The second scrubber from the left is biotrickling filter Q which treats part of the air from biotrickling filter I.

 Biotrickling filter J at Plant 2 which treats mostly odors.	 Recycle pump for biotrickling filter G. The former pump is on the right, smaller pump installed on the left.

APPENDIX 2DETAILS OF CONVERSION WORK PERFORMED AND SCHEDULE (SCRUBBER 10)

Step 0: Preparation work: Scrubber isolation and washing

					Day 1 was 5/17/01
Task	**Task name**	**Description**	**Performed**	**Date**	**Remarks**
0.1	fan stop	stop fan and lock panel selector	OCSD	5/14/2001	Fan was stopped prior beginning. Tag and lock added by OCSD
0.2	damper closure	Open outlet and inlet butterfly valves for #10 and close them for #9	OCSD	5/14/2001	Tag and cable tie added by OCSD
0.2	damper closure	ensure no foul air entrance to the scrubber	OCSD	5/24/2001	H2S concentration checked prior WSC entrance to the scrubber
0.3	Chlorine line closure	close and lock valves in the Chlorine feed line	OCSD	5/22/2001	Tagged prior beginning. New tag and cable tie added
0.4	Stop caustic injection	stop caustic pump and lock panel selector	OCSD	5/16/2001	tag and lock added in the panel selector by OCSD
0.4	Stop caustic injection	Ball valves 305 & 305C closed & locked	OCSD	5/16/2001	Tag and cable tie added by OCSD
0.5	acid washing	30% HCl used. Both recycle pumps operated during washing	OCSD	16 to 18	Begin on 5/16/01. Finished on 5/18/01
0.5	HCl line closure	close and lock valves in the HCl feed line	OCSD	5/22/2001	After scrubber acid washing
0.6	scrubber washing	close and lock valve in the chlorine recycle line	OCSD	5/22/2001	Valve closed prior beginning. Tag and cable tie added by OCSD
0.6	scrubber washing	reclaimed water used. Both recycle pumps operated during washing	OCSD	5/21/2001	pH=6.6 reached
0.6	scrubber washing	second acid wash	OCSD	5/22/2001	ph=7 reached
0.6	scrubber washing	stop recycle pumps 301. Lock panel and field selectors	OCSD	5/22/2001	tag and lock added by OCSD
0.6	scrubber washing	stop recycle pumps 302. Lock panel and field selectors	OCSD	5/22/2001	tag and lock added by OCSD
0.6	scrubber washing	close and lock ball valves in the reclaimed water feed line	OCSD	5/22/2001	tag and cable tie added by OCSD
0.6	scrubber washing	close and lock ball valves in the plant water feed line	OCSD	5/22/2001	tag and cable tie added by OCSD
0.7	scrubber decontamination	Water Systems Cleaning (high pressure water washing)	Contractor	5/25/2001	
0.8	vapex isolation	Vapex unit locking	OCSD	5/14/2001	tag and cable tie added by OCSD

Step 1: Removal of unnecessary parts

Task	**Task name**	**Description**	**Performed**	**Day**	**Remarks**
1.1	Recycle (stdby) pump isolation	close diaphragm valve 10IDV301	OCSD	5/18/2001	
1.1	Recycle pump isolation	lock diaphragm valve 10IDV301	OCSD	5/18/2001	tag and lock added by OCSD
1.1	Recycle pump isolation	close diaphragm valve 10IBV301A	OCSD	5/18/2001	security
1.1	Recycle pump isolation	lock diaphragm valve 10IBV301A	OCSD	5/18/2001	tag and lock added by OCSD
1.1	Recycle pump isolation	lock pump 301 power source	OCSD	5/18/2001	tag and lock added by OCSD
1.2	Recycle pump (removed) isolatio	close diaphragm valve 10IDV302	OCSD	5/18/2001	
1.2	Recycle pump isolation	close diaphragm valve 10IBV302A	OCSD	5/18/2001	tag and lock added by OCSD
1.2	Recycle pump isolation	lock pump 302 power source	OCSD	5/18/2001	security
1.2	Recycle pump isolation	close ball valve 10IBV302A	OCSD	5/18/2001	tag and lock added by OCSD
1.2	Recycle pump isolation	close ball valve 10IBV302B	OCSD	5/18/2001	tag and lock added by OCSD
1.2	Pump cool ring closure	close ball valve 10IBV318B	OCSD	5/18/2001	tag and lock added by OCSD
1.2	Pump cool ring closure	close ball valve 10IBV319B	OCSD	5/18/2001	tag and lock added by OCSD
1.2	Pump cool ring closure	close ball valve 10IBV302	OCSD	5/18/2001	
1.2	Pump cool ring closure	1/4" cap added cooling ring pipe	OCSD	5/27/2001	Cap necessary to avoid pump off alarm to be triggered
1.2	Pump cool ring closure	lock ball valve 10IBV302	OCSD	5/18/2001	
1.3	Pump extraction	disconnect motor	OCSD	5/18/2001	
1.3	Pump extraction	disconnect cool ring 1/2" duct	OCSD	5/18/2001	
1.3	Pump extraction	disconnect suction from 6" duct	OCSD	5/18/2001	
1.3	Pump extraction	disconnect discharge from 4" duct	OCSD	5/18/2001	
1.3	Pump extraction	unscrew support	OCSD	5/18/2001	
1.3	Pump extraction	extract pump from ditch with a crane	OCSD	5/18/2001	pump storage at OCSD required

Step 2: Removal of packing

Task	Task name	Description	Performed	Date	Remarks
2.1	packing removal	Water Systems Cleaning	Contractor	5/24/2001	storage at OCSD required
2.2	water reservoir drainage	Water Systems Cleaning	Contractor	5/22/2001	

Step 3: Strengthening of packing support

Task	Task name	Description	Performed	Date	Remarks
3.1	Install box beams	Water Systems Cleaning	Contractor	5/25/2001	6" pipe Sch. 80 CPVC pipe used as a support pillar

Step 4: Modification of the Liquid Distribution system

Not necessary to change the actual liquid distribution system

Step 5: Modification of the Demister

Not necessary to change the actual mist eliminator

Step 6: Recycle Pump change

Task	Task name	Description	Performed	Day	Remarks
6.1	Pump electrical connection	Connection of the pump to the in field PLC	OCSD	6/22/2001	
6.2	Repiping	Suction port (6" pipe-1-1/2" port)	OCSD	6/19/2001	
6.2	Repiping	Discharge port (4" pipe-1-1/2" port)	OCSD	6/19/2001	
6.2	Repiping	Structural support installation	OCSD	6/26/2001	
6.2	Pump cool ring closure	1/4" cap added cooling ring pipe	OCSD	5/29/2001	Cap necessary to avoid pump off alarm to be triggered
6.2	Repiping	Rotameter installation	OCSD	September	Must have been done from the beginning
6.4	Recycle pump testing	open diaphragm valve 10IDV302	OCSD	5/29/2001	
6.4	Recycle pump testing	open diaphragm valve 10IBV302A	OCSD	5/29/2001	
6.4	Recycle pump testing	unlock pump 302 power source	OCSD	5/29/2001	
6.4	Recycle pump testing	reservoir fill up	OCSD	5/29/2001	
6.4	Recycle pump testing	start recycle pump (Selector 10IHS302B)	OCSD	5/29/2001	

Step 7: Modify the inlet air ducts

Not necessary to modify ducts

Step 8: Installation of secondary effluent supply

Not necessary, Plant water & Reclaimeed Water available

Step 9: Installation of the new packing material

Task	Task name	Description	Performed	Date	Remarks
9.2	Packing installation	Main volume of packing dumped into the reactor	UCR	7/13/2001	
9.2	Packing installation	Top of bed filled from upper manhole	UCR	7/14/2001	

Step 10: Modification of the controls

Actual controls are enough for biotrickling filter control