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Construction and Economics of a Pilot/Full-Scale Biological Trickling Filter Reactor for the Removal of Volatile Organic Compounds from Polluted Air

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ABSTRACT
The design and the construction of an actual 8.7-m^3 pilot/full-scale biotrickling filter for waste air treatment is described and compared with a previous conceptual scale-up of a laboratory reactor. The reactor construction costs are detailed and show that about one-half of the total reactor costs ($97,000 out of $178,000) was for personnel and engineering time, whereas ~20% was for monitoring and control equipment. A detailed treatment cost analysis demonstrated that, for an empty bed contact time of 90 sec, the overall treatment costs (including capital charges) were as low as $8.7/1000 m^3_{air} in the case where a nonchlorinated volatile organic compound (VOC) was treated, and $14/1000 m^3_{air} for chlorinated compounds such as CH_2Cl_2. Comparison of these costs with conventional air pollution control techniques demonstrates excellent perspectives for more field applications of biotrickling filters. As the specific costs of building and operating biotrickling filter reactors decrease with increasing size of the reactor, the cost benefit of biotrickling filtration is expected to increase for full technical-scale bioreactors.

IMPLICATIONS
With interest in biological techniques for air pollution control increasing, the true costs associated with the construction and operation of full-scale biological trickling filters are a fundamental criteria to evaluate the competitiveness of biotrickling filtration over more conventional air pollution control technologies. The present paper compares costs that were evaluated from a conceptual scale-up with actual numbers from the construction and operation of a pilot/full-scale biotrickling filter. The results are placed in a general perspective for the deployment of large biotrickling filters.

INTRODUCTION
Biological waste air treatment is an emerging technology that is gaining acceptance as environmental regulation is becoming increasingly stringent in the United States. The technique uses the ability of mesophilic mixed cultures of microorganisms to aerobically biodegrade absorbed pollutants. Two different types of gas-phase bioreactors can be distinguished.

Biofilters are reactors in which a humid polluted airstream is passed through a porous packed bed, usually compost, on which pollutant-degrading microbial cultures are naturally immobilized. Biofilters present a tremendous potential for air treatment. They have been implemented at full scale and have proven to be cost-effective.[1-3] However, the absence of a free liquid makes it sometimes difficult to control key environmental parameters such as pH and moisture content.[4-7]

Bioscrubbers are reactors in which a pollutant-containing waste airstream is contacted with a scrubbing solution. The most promising bioscrubber setup is the biotrickling filter, in which absorption and biodegradation of the pollutants is achieved in a single packed bed column reactor.[8] Biotrickling filters offer promise for the elimination of volatile organic compounds (VOCs) and chlorinated VOCs, odors, and reduced sulfur compounds.[9-13] At this time, only a few full-scale biotrickling filters have been implemented for industrial usage.[14,15] The main drawbacks of biotrickling filters are their higher costs than biofilters and possible clogging of the reactor over time by growing biomass.[8,16,17] Even so, biotrickling filters have sometimes proven superior to biofilters. The reason is that in biotrickling filters, environmental conditions can be better controlled.[8,10,12,13]

Because full-scale applications of biotrickling filters are still relatively rare, there is a lack of information on the true costs associated with the construction and operation of biotrickling filters at industrial scale. Recently, the comparative scale-up of two innovative reactor setups for biological waste air treatment was described.[13] The scale-up was essentially a design exercise using the results from a bench-scale biotrickling filter and three-phase airlift reactors to dimension technical-scale bioreactors. Both investment costs and operating costs were evaluated for the treatment of CH_2Cl_2-contaminated airstreams. The scale-up demonstrated that the investment costs were comparable and that the operating costs for the biotrickling filter were significantly lower than for the airlift reactor, essentially because of a lower water and electricity usage of the former bioreactor. For a 3-m^3 biotrickling filter, an investment of $184,000 was estimated and overall treatment costs were evaluated at $62/1000 m^3 of air treated.[13]

In the present paper, the actual design and construction of an 8.7-m^3 pilot/full-scale biotrickling filter are described and the real treatment costs are discussed. The design of the reactor was based on the same design criteria and principles described previously.[13] Actual investment and operating costs after 1 year of field operation are compared to those predicted previously.

REACTOR DESIGN AND FLOW SHEET

The dimensions of the bench-scale prototype, of the conceptual biotrickling filter, and of the reactor finally constructed are reported in Table 1. At the time of the concept prototype, a flow sheet was developed which served as a basis for treatment costs evaluation[13] and for actual reactor design. The conceptual flow sheet and that of the reactor that was actually built are compared in Figure 1. A CAD drawing and a picture of the constructed biotrickling filter are presented in Figures 2 and 3, respectively.

For the design of the actual bioreactor, further scale-up was needed. The same approach as in Zuber et al.[13] was applied to obtain reactor dimensions and air and water flow rates. A few modifications from the original design had to be performed. The original design included one column of ~7-m height with two packing sections on top of each other. Because of compliance with California's earthquake code, the bed height was split into two reactors through which the contaminated air flows in series. This and the fact that the skid-mounted reactor is equipped with wheels and a towing axle also made transportation of the reactor easier. This proved useful since the demonstration unit is being moved to various sites every 4–8 months. The result is a somewhat larger footprint (2.5 × 5.1 m) but a lower height (4 m).

As shown in Figures 1 and 2, the contaminated air flows in series through the two reactors. The system uses a 3-hp regenerative blower (EG&G Rotron) to provide the air pressure. At the exit of the second tank, a knock-out pod (Solberg Manufacturing) was installed to reduce the losses of water from the reactor and prevent aerosol emissions. The water flow, provided by two parallel 5-hp centrifugal pumps (RS Corcoran), is in parallel. The bottoms of the two tanks are used for the control of pH and temperature (liquid height of ~0.4 m). A portion of water recycle is directed to the base of each tank (via pipe No. 12 on Figure 2) to provide adequate mixing of nutrients and caustic. A water-level observation tube is connected outside the tank wall to the base of the tank (below the water line) and above the water line. Float-level sensors inside the tube detect changes in water level. The nutrient and caustic are stored in large 0.75-m^3 tanks and supplied periodically on the pressure side of the water piping. GrowMore hydroponic premixed fertilizers were used for nutrient sources, and added by two diaphragm pumps. A concentrated nutrient solution containing 12/20/13 mass percentage of N/P/K, as well as 10% total of the trace elements Fe, Mg, Ca, Zn, Cu,

Table 1. Characteristics of the bench-scale, the conceptual, and the constructed biotrickling filter. The scale-up criteria for the latter two reactors was an inlet concentration of 2 g/m^3 of CH_2Cl_2 and a removal efficiency of 99.5%.[13]

	Bench-Scale[18]	Concept-Prototype[13]	Constructed Reactor
Biotrickling Filter Type	Gas and liquid in a counter-current contact	Cocurrent,[a] two bed layers on top of each other	Cocurrent,[a] two separate reactors in series
Packed Bed Volume (m^3)	7.6×10^{-3}	3.0	8.7
Reactor I.D. (m)	0.096	0.89	1.52
Packed Bed Height (m)	1.05	Two 2.4-m sections	Two 2.4-m sections
Air Flow Rate (m^3/hr)	0.5–3	100	350
EBRT[b] (sec)	9–55	108	90
Scrubbing Solution Tank Volume (m^3)	1×10^{-3} m^3 (separate tank)	0.05 in a separate tank and 0.2 m^3 (tank bottom)	0.75 m^3/tank (bottom of the tank)

[a]Flow direction can be switched; [b]EBRT is empty bed retention time.

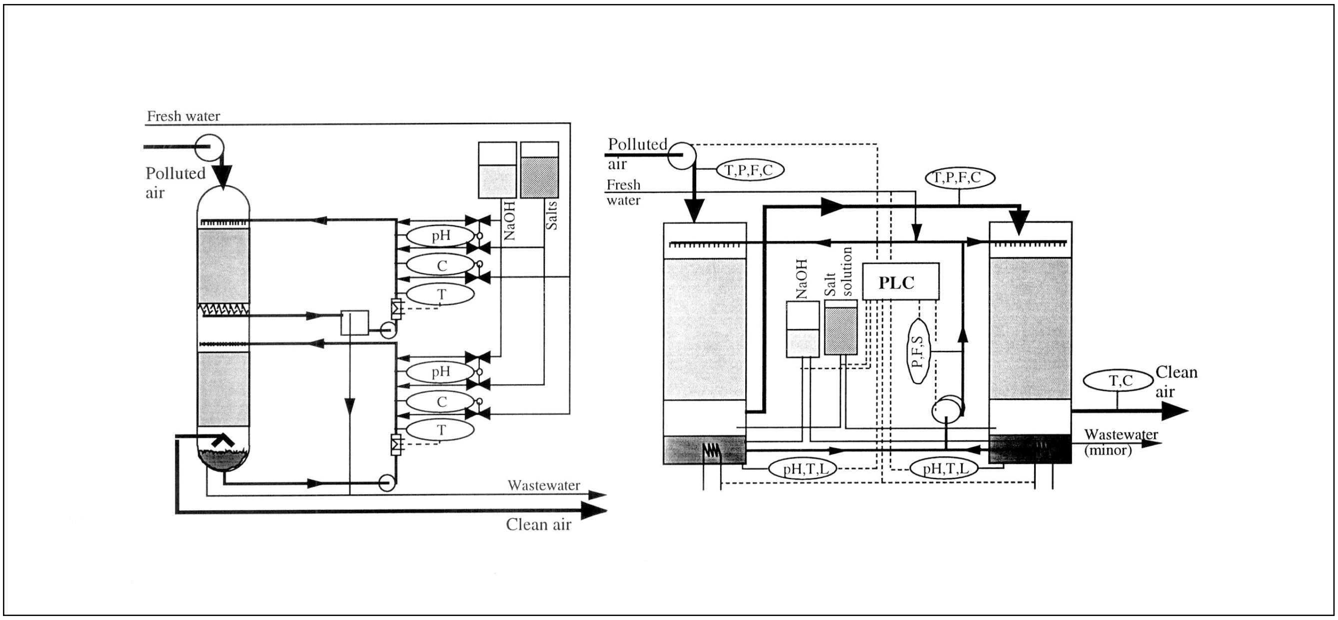

Figure 1. Flow sheet and control chart for the concept prototype (left)[13] and the constructed biotrickling filter (right). T: temperature; P: pressure; C: concentration; S: conductivity; L: level. Not all controls are shown.

Mn, and S, was added with tap water to produce a feed of 0.7/1.2/0.8 g/L of N/P/K. Metering a 5% solution of NaOH served to control pH declines.

Since the unit was designed as an R&D tool, a sophisticated programmable logic controller (PLC) unit, programmed using Labview Software (National Instruments),

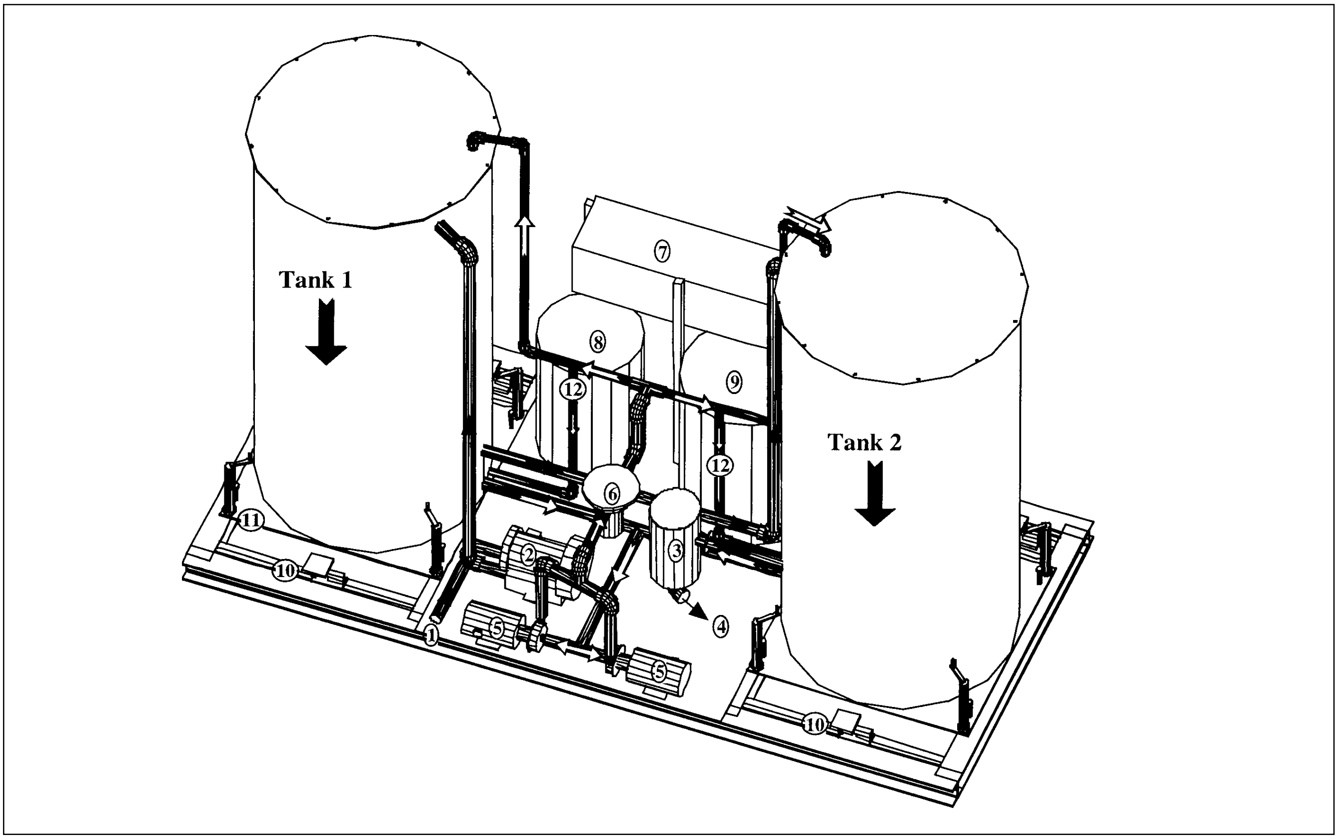

Figure 2. CAD drawing of the constructed biotrickling filter. Full arrows indicate airflow, open arrows indicate water flow. (1) Contaminated air inlet, (2) blower, (3) knockout pod, (4) outlet purified air, (5) water pumps, (6) strainer basket, (7) control box, (8) nutrient tank, (9) caustic tank, (10) sliding load cells (outside position), (11) jacks, and (12) water return to tank bottoms (for mixing).

Figure 3. The constructed biotrickling filter.

was developed to monitor and/or control important parameters. Inlet and outlet concentrations, air and water flow rate, pressure drop, temperature, and recycle water conductivity were continuously monitored. Nutrient and caustic addition, water addition and removal, and pH were monitored and controlled by the PLC. The PLC used on-off control logic to maintain the operating parameters of the reactor to within specified input limits. Specific construction materials and methods used to measure the operating parameters are listed in Tables 2 and 3, respectively.

A number of original features were included in the construction of the actual reactor. Each tank was placed on three load cells that allowed changes in biomass weight in the reactor to be monitored. Using load cells has proven successful for the monitoring and control of moisture content in biofilters.[2,5] In biotrickling filters, such a feature is more a research tool than a necessity. For industrial use, increase in pressure drop over the bed or decrease in removal performance are more useful indicators of biomass overgrowth. Nevertheless, load cells were allowed to monitor directly the changes in the amount of biomass present in the system.

As mentioned, the airflow was in series, downward through the two tanks. However, the connections between the stainless steel piping sections were made with flexible PVC tubing so that both the sequence of the tanks and the airflow direction could be switched if desired. This would allow an attempt at controlling biomass growth by starving part of the process culture either through directionally switching the airflow[19] or by alternating the sequence of the tanks in series.[20] Monitoring of the gaseous pollutant concentration was performed online using two SRI detectors in series: a dry electrolytic conductivity detector (DELCD) for monitoring chlorinated compounds and a flame-ionization detector (FID) to monitor HCs. Sampling was sequentially performed at the inlet, between the two tanks and at the outlet of the biotrickling filter. The plumbing of the sampling lines allowed periodic backflushing of the sampling lines with fresh air in order to avoid buildup of condensation in the sampling lines.

Table 2. Construction materials for the full-scale biotrickling filter.

Reactor Parts	Material
Reactor tanks	304 L stainless steel (12 gauge)
Skid	Steel
Air piping	304 L stainless steel, 8.1-cm i.d., in part flexible PVC with quick connect/disconnect
Water piping	Schedule 40 and 80 PVC 2.5- to 7.6-cm i.d.
Nutrient and caustic tanks	PE

Table 3. List of parameters monitored in the full-scale biotrickling filter.

Parameter to Be Measured	Type of Instrument
Air flow rate	Orifice plate (using differential pressure calculations)
Air phase concentration	FID/DELCD,[a] inlet between the tanks and outlet concentrations
Air pressure	Pressure gauges, three different locations
Air temperature	Thermocouples, three different locations
Tank weights	Load cells, three per tank
Water conductivity	Conductivity probe, one after the water pumps
Water flow rate	Paddlewheel flow sensors, in-line, one per tank
Water level indicators	Water float sensors, one for each high and low level, one for the level adjustment
pH	pH probes, one per tank
Water pressure	Pressure gauge, in-line on pressure side of pumps
Water temperature	Thermocouples, one in each tank

[a]Flame-ionization/dry electrolytic conductivity detector (for chlorinated compounds).

REACTOR PERFORMANCE

The pilot/full-scale biotrickling filter reactor was first set up at a fiberglass production facility to treat styrene-contaminated air, since no suitable test site could be found for CH_2Cl_2 treatment. Lower pollutant removal performance was expected since styrene is known to be much more difficult to biodegrade than CH_2Cl_2 is.[18,21] On average, styrene inlet concentrations ranged from 0.5 to 1 g/m^3. At the startup, the reactor was inoculated with activated sludge, and early performance monitoring of the reactor showed that styrene elimination capacity was 15 g/m^3/hr with 70% removal efficiency (Figure 4). As the system continued to operate, possible limitations were tested and eliminated to enhance reactor performance.[22] Nutrient supply was increased, reactor water temperature and pH were adjusted, and the organic loading was increased (days 45–63) to develop an active and effective biofilm. After such adjustments, elimination capacity increased to steady-state values of 24 g/m^3/hr (35 g/m^3/hr across the first tank in series), which is a high value for sustained styrene treatment under such concentrations and loading. Further experimental studies demonstrated that packing material with larger surface areas and a more definitive styrene degrading inoculum could possibly enhance the reactor performance even further.[22]

INVESTMENT COSTS EVALUATION

In the following section, investment costs estimated previously are compared with the actual costs. A key point that should be recognized is that the previously estimated costs were for a much smaller system (2.5-fold, see Table 1) than the system actually built. Nevertheless, the comparison highlights an interesting perspective about the real costs of constructing biotrickling filters for waste air treatment and the use of common design rules to estimate bioreactor costs. In Table 4, the estimated investment costs are compared to the actual investment costs, while the relative percentage of each expenditure is shown in Figure 5.

In general, during actual reactor design, efforts were directed toward minimizing all construction costs. As a result, in several instances, stainless steel was replaced by PVC, polypropylene, or PE, resulting in substantial cost savings but little impact on either the lifetime of the reactor or the expected pollutant removal performance. This is reflected, for example, in piping costs, which represent only 4% of the total reactor costs, while 20% of the basic investment was originally budgeted. The largest savings were achieved on the reactor columns. The difference can be explained by different stainless steels used (316 estimated vs. 304 used) and by the fact that estimated costs might have included a significant markup.

Splitting the bed into two smaller columns of a lesser structural complexity may also have contributed to some savings. Another important cost-saving measure was to replace the heat exchangers by simple immersion heaters. This also cut down on operating costs and avoided

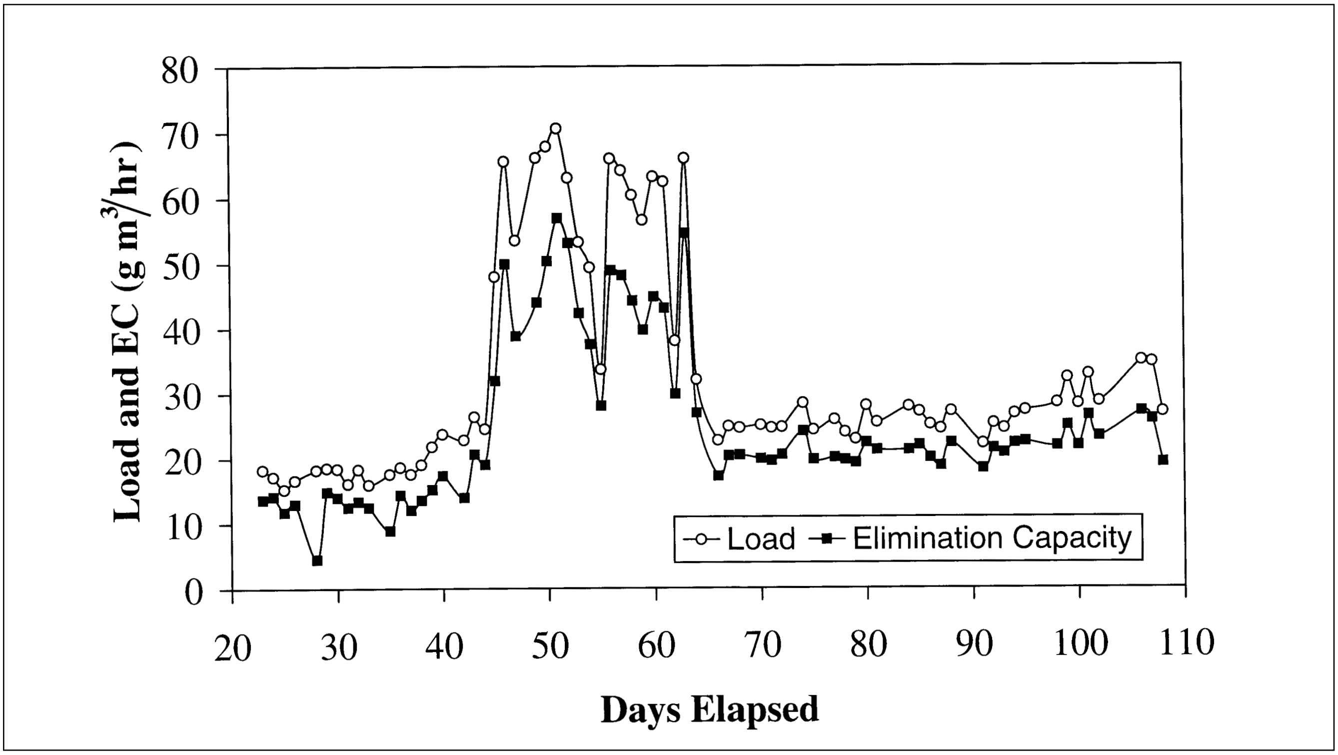

Figure 4. Load and elimination capacity over the course of the experiment for the pilot-scale biotrickling filter reactor treating styrene. [Load = inlet concentration × air flow rate/bed volume; elimination capacity = (inlet-outlet concentration) × air flow rate/bed volume].

Table 4. Comparison of estimated and actual investment costs for the biotrickling filter.

Description of the Cost (US$)	Concept Reactor Estimated Costs[13]			Actual Reactor Total Actual Costs
Basic Investment				
Column (stainless steel)	72,000			14,400
Packing	16,200[a]			12,000[b]
Blower for the airflow	5500			1800
Two water pumps (trickling flow)	2500			2900
Tank in the upper loop	1200			none
Tank for NaOH	2800[c]			300[d]
Tank for the mineral nutrients	100[d]			300[d]
Two heat exchangers	15,600			1300[e]
Secondary Cost		**Subtotals by Categories**		**Totals**
Monitoring and controls (12% of the basic investment)	13,900	**Total Monitoring and Controls**		30,000
		Computer	1300	
		Metering pumps, meters, electrodes, and transducers	12,100	
		Data acquisition	6000	
		Load cells	3600[f]	
		FID/DELCD detectors	7000	
Piping (20% of the basic investment)	23,100			7600
Insulation (7% of the basic investment)	8100			none
Building (20% of the basic investment)	23,100	**Total Building**		9500
		Skid and various structural	5100	
	none	Installation of wheels	4400[f]	
Engineering Costs		**Subtotals by Categories**		**Totals**
Total Engineering Costs	none[g]	**Total Engineering Costs**		97,400
		Design	53,200	
		Construction	31,700	
		Testing	12,500	
Grand Total: Reactor Cost	$184,100		$177,500	
Specific Reactor Cost/m^3 of Filter Bed	$61,367/m^3		$20,402/m^3	

[a]Sulzer Mellapak 350Y; [b]Actual packing was provided for free, value reported is for plastic (random or inexpensive structured) packing; [c]Stainless steel; [d]PE; [e]Immersion heaters were used instead of heat exchangers; [f]Useful for R&D unit, not required otherwise; [g]Engineering costs were lumped into other costs.

the need for a steam supply. Immersion heaters are also more reliable than heat exchangers, and in the case of the biotrickling filter, are less subject to fouling and upset by biomass. If the primary costs for the actual system were overestimated in the conceptual design, an opposite trend was noticed for the secondary costs, in particular for the monitoring, control, and electrical devices expenses (see Table 4). These costs constituted a large fraction of the actual reactor costs.

On the positive side, contrary to most of the other expenses, monitoring and control costs are fairly independent of reactor size. Hence, their proportion to the total reactor costs will decrease when increasing the size of the unit. Their unusually high value also reflects the fact that the constructed unit is extremely well instrumented so that effective data collection could be performed. A number of features, such as load cells, dual detectors, or complex PLC, would not be included in a technical unit. As far as building costs are concerned, they were only about one-third of the original estimate, even with the expensive installation of wheels and the skid construction. Again, a technical unit would not include these features, which would positively affect the overall costs.

Engineering time expenses were estimated at an average rate of about $43/hr. Although it was not always possible to distinguish between amounts of time dedicated to various aspects of the project, an approximate distribution between the design phase, the construction phase, and the testing phase was performed and the numbers reported in Table 4. Clearly, these costs are important and reflect the fact that the reactor was designed and constructed from scratch. Much time and effort were dedicated to material selection. For the construction of subsequent

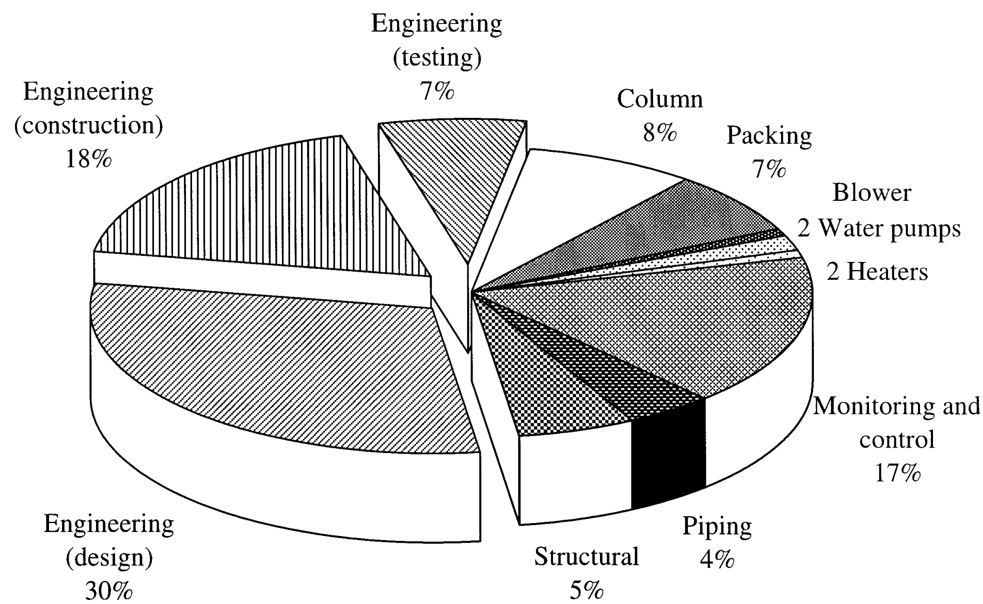

Figure 5. Distribution of the costs for the construction of pilot/full-scale biotrickling filter.

reactors of lesser complexity, the length of all phases will be considerably reduced. While doing so, significant savings are expected ($42,000 on engineering, $10,000 on controls, and $5,000 on building). Hence, a good estimate of the cost of a technical unit, without the sophistication of the present biotrickling filter, is about $120,000. This was the amount used in the following section to determine the overall operating costs.

From a commercial point of view, the importance of the engineering costs in the overall bill suggests that construction of a biotrickling filter reactor as modular units is probably more cost-effective than a custom design. This will drastically reduce the engineering time, simplify the construction phase, and provide more flexibility on the customer side. The dimensioning is then reduced to the determination of the type and number of modules required for a particular application. This practice is already commonly used by several biofilter vendors.

OVERALL TREATMENT COSTS EVALUATION

Using the price of chemicals and energy listed in Table 5, the treatment expenses estimated previously[13] are compared with the actual treatment costs in Table 6. The operating expenses of Table 6 were normalized per 1000 m^3 of waste air treated to allow for comparison since the size of the conceptual and the constructed reactors are different. They consider a reactor life of 10 years; hence, capital charges of 10% of the reactor cost per year were added to the variable charges. For the constructed biotrickling filter, a reactor cost of $120,000 was used since it is more representative of a technical unit than our R&D unit (see previous section).

Two scenarios are considered for the actual costs. Case 1 is for nonchlorinated VOC treatment (i.e., minor pH change during treatment), hence low water, caustic, and nutrient usage, and the use of one recycle pump only and a minimal heating requirement. This case represents probably the lowest possible costs achievable with this particular unit. Case 2 considers the high rate of CH_2Cl_2 removal, hence a much larger water supply to keep the chloride ions below 100 mM (inhibitory concentration), dual pump operation, and substantially higher heating. This case represents the upper limit of the treatment costs for this unit. While normalizing costs per unit of volume of air treated is common practice, one should keep in mind that the air flow rate [or empty bed residence time (EBRT)] through the biotrickling filter can be varied. This will obviously affect the normalized treatment cost, but will also change the pollutant

Table 5. Estimated and actual variable costs used for the calculation of the operating costs in Table 6.

Category	Previously Used[13]	Actual Values
Tap water ($/$m^3$)	2.73	1.32[a]
Wastewater (industrial) ($/$m^3$)	2.02	n/a
Mineral salts ($/kg)	9.5[b]	1.7[c]
NaOH ($/kg)	0.95	1.32
Electricity ($/kWh)	0.10	0.05
Steam at 3 bar ($/kg)	0.026	none
Personnel ($/hr)	60	40

[a]Combined water and sewage cost; [b]Technical grade chemicals; [c]Premix fertilizers.

Table 6. Estimated and actual operating costs normalized for 1000 m^3 of air treated.

Category	Previously Estimated[13] ($/1000 m^3 of air treated)		Actual Case 1: (Low Cost) ($/1000 m^3 of air treated)		Actual Case 2: (Upper End Cost) ($/1000 m^3 of air treated)	
	Subtotals	Totals	Subtotals	Totals	Subtotals	Totals
Tap water		3.55		0.05[a]		0.62
Wastewater (industrial)		2.62		–		–
Mineral salts		4.17		0.58		1.74
NaOH		1.78		0.01		2.48
Electricity		2.65		1.35		2.49
Blower	0.25		0.59		0.59	
Pumps	0.66		0.40		0.80	
Heater	1.74[b]		0.21		0.95	
Miscellaneous	–		0.15		0.15	
Personnel		26.30[c]		2.81[d]		2.81[d]
Total operating costs		41.1		4.80		10.14
Capital charges[e]		21.0		3.91		3.91
Total treatment costs/1000 m^3		62.1		8.71		14.05

[a]Sewer discharge included in tap water; [b]Steam; [c]384 hr/year; [d]220 hr/year; [e]Capital yearly charges at 10% of reactor cost (for the actual reactor, the reactor cost of $120,000 was used; see text for justification).

removal. Hence, this phenomenon should be fully taken into account when comparing various biological reactors for waste air treatment. In both cases, the design value (EBRT ~90 sec), which was relatively high, was used for the calculation. A lower EBRT will decrease specific costs substantially.

The results shown in Table 6 demonstrate that the real costs were much lower than estimated previously. The reasons are that high expenses were projected but did not occur (in particular, water and personnel; cheap fertilizers were used instead of technical purity chemicals) and that increasing the size of the actual unit and the air flow rate significantly reduced the specific treatment costs. Figure 6 compares the respective distribution of the treatment costs. As a whole, the numbers in Table 6 and Figure 6 show that the greatest differences were observed in specific water usage and maintenance. Scaling biotrickling filters further up is expected to reduce even more specific maintenance costs.

In the case of chlorinated VOC treatment, the price of the caustic needed to neutralize acids produced in the reactor by biological activity accounts for 17% of the total operating costs. Clearly, caustic usage is a linear function of the amount of chlorinated VOCs degraded. Because near-neutral pH needs to be maintained in the reactor, not much flexibility exists as far as reducing these costs. When integrating biotrickling filtration in an industrial setup, one should consider the generation of alkaline wastes elsewhere, which could be used in the biotrickling filter while reducing both biotrickling filtration and alkali neutralization costs.

Neither nutrient nor electricity consumption were optimized during the first year of field operation. However, both present a significant potential for cost reduction. For example, in spite of its higher capital cost, the use of a variable speed blower might prove advantageous. As pressure drop increases over time due to biomass buildup, the blower speed can be adjusted so that the air flow rate remains constant while energy consumption is minimized. Also, the two-pump design for the recycle liquid, in addition to the flexibility and the redundancy, allows one to operate the system with one pump only during low treatment periods. It has even been recently proposed that intermittent trickling might be advantageous, not only to the process economics, but sometimes also to the overall pollutant removal performance.[14,23] Such a proposal needs to be seriously considered. With the present biotrickling filter, the versatility of the PLC will allow such intermittent trickling to be easily implemented.

In all cases, the capital charges were a significant part (25–45%) of the total treatment expenses, showing the importance of careful design and material selection in order to minimize capital expenditures. This suggests that overdimensioning biotrickling filters to allow for starvation or nutrient limitation, that is, inefficient use of the entire reactor volume, in order to control biomass growth might be a very expensive solution. Other means to control biomass, such as chemical or mechanical biomass removal or packed bed backflushing, should probably be preferred.[16,17] It also suggests that retrofitting existing scrubbers to accommodate for biotrickling filter operation might

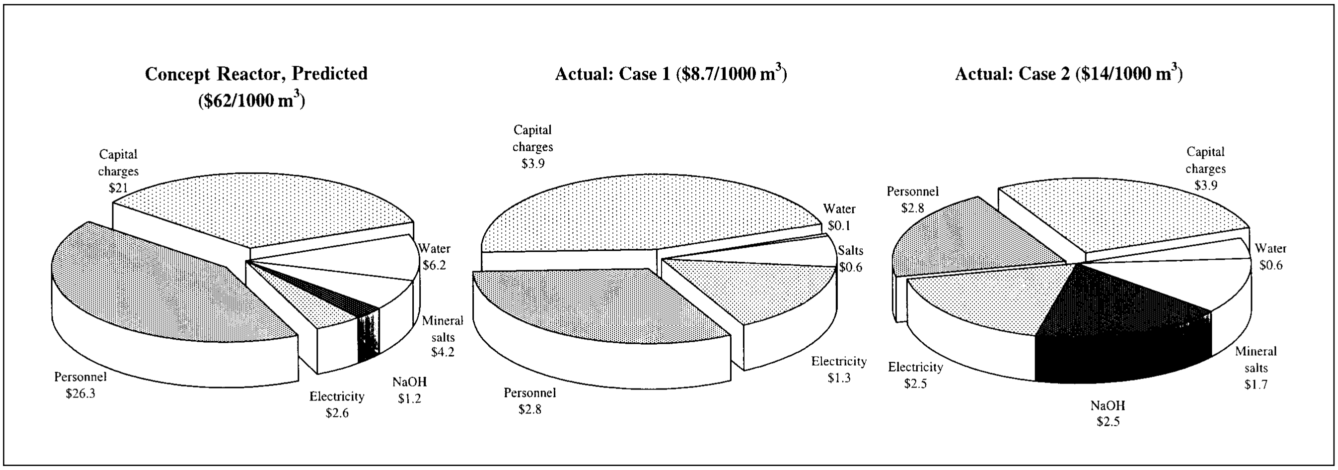

Figure 6. Distribution of the treatment costs for the actual pilot/full-scale biotrickling filter.

be a worthwhile solution, especially when biotrickling filters are to replace traditional water or chemical scrubbers.

Direct comparison of the actual treatment costs ($8.7–$14/1000 m^3) obtained for the biotrickling filter with those of competing technologies is difficult because the treatment costs are strongly affected by the specifics of each application. The treatment costs are particularly sensitive to the air flow rate, the concentration and nature of the pollutant, and the emission pattern (steady concentration vs. frequent variations or weekend shutdown). In a first approximation, it is possible to use the numbers from Table 6 (Cases 1 and 2) and adjust them for the other expenses associated with competing technologies. Adsorption onto granular activated carbon (GAC) or thermal incineration does not require water, mineral salts, NaOH, water pump, or heater electricity. Hence, these costs are removed and GAC usage or natural gas costs are added to the numbers of Table 6.

For direct comparison with Cases 1 and 2, a VOC concentration of 0.1 and 2 g/m^3, respectively, was assumed. For the calculation of treatment costs of adsorption onto GAC, it was assumed that capital expenses would be ~30% cheaper than those of the biotrickling filter. A cost of $9/kg for the GAC (including regeneration) was used in the calculation, and adsorption of 0.3-kg VOC/kg GAC was assumed.[24-26] The resulting total treatment costs for GAC adsorption are $9.3 and $66/1000 m^3 of air treated for Cases 1 and 2, respectively. This is significantly higher than the estimated costs ($8.7 and $14, respectively) of biotrickling filtration reported in Table 6.

For thermal oxidation techniques, capital expenses will be ~30% higher than for the biotrickling filter,[24,25,27] and additional heating or fuel costs are estimated to be $1–$5/1000 m^3 of air treated depending both on the type of oxidizer (catalytic or thermal, with or without heat recovery) and the specific energy costs.[24,25,27] Thus, the total treatment cost for oxidation techniques amounts to about $9.6–$13.6/1000 m^3 of air, irrespective of Cases 1 or 2. This is relatively similar to the biotrickling filtration costs in Table 6, and further problem definition would be required to more accurately calculate the specific treatment costs. In any case, biotrickling filtration appears to be quite competitive and, as mentioned earlier, the treatment costs will decrease with increasing reactor size.

A thorough cost analysis by Menig et al. showed that biofiltration of airstreams ranging from 10,000 to 60,000 m^3/hr was 55–65% cheaper than regenerative catalytic oxidation.[25,28] Based on our experience with the pilot/full-scale biotrickling filter, our estimation for the investment costs of a 500-m^3 biotrickling filter is approximately $1.5–$4 million with yearly operating costs ranging from $150,000 to $300,000. Such a reactor could treat 10,000–150,000 m^3/hr of contaminated air, depending on the pollutant treated and the required removal efficiency. The total yearly treatment costs (including capital charges) would range from $450,000 to $700,000, and the specific treatment costs would range from $0.3 to $4.0/1000 m^3 of waste air treated. Comparison of these costs with those reported for the actual 8.7-m^3 reactor and the above estimated GAC costs or energy costs only in oxidation systems shows that the competitiveness of biotrickling filtration greatly increases with increasing waste air flow rate and with increasing reactor size.

CONCLUSIONS

The design and construction of a biological trickling filter for air pollution control was presented and discussed. A comparison was made between a previously published[13] reactor design and theoretical cost estimate and the actual design, construction, and operation of the reactor. The analysis of the construction expenses revealed that the actual cost for the 8.7-m^3 pilot/full-scale reactor was about $180,000. About one-half of this amount was for personnel associated with the design, construction, and testing of the reactor, while the other half was for materials. The relatively high cost (per volume unit) reflected the fact the reactor was a small demonstration unit and included sophisticated equipment that would not be included in an industrial biotrickling filter reactor.

Details of the operational costs demonstrated that they were highly application-dependent. While treatment of easily degradable compounds in this particular trickling filter was about \$8.7/1000 m^3 of air treated, the treatment costs for either chlorinated compounds or for reduced sulfur compounds was significantly increased by the higher water usage and the requirement for alkali to control the pH (\$14/1000 m^3 air). Still, treatment costs are below those of conventional techniques. A brief analysis of the treatment costs further showed that the competitiveness of biological air pollution control greatly increases as the size of the reactor increases, and much lower treatment costs were projected for large industrial-scale biotrickling filters. Interestingly, the capital charges over the 10-year reactor life constituted a major part (25–45%) of the total treatment costs. This suggests that a careful design and material selection should be performed to minimize capital expenses. It also suggests that much research effort should be directed toward optimization of pollutant elimination in biotrickling filters so that the smallest possible reactors can be constructed.

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