HYPERION TREATMENT PLANT (HTP)
H_2S REMOVAL TECHNOLOGIES TEST PROGRAM (CIP 2503)

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Gerald Hernandez, Group Manager, EED

new #
329520

BACKGROUND

The purpose of this testing program is to evaluate alternative scrubbing technologies for control of high concentrations of hydrogen sulfide (H_2H2Sat the Hyperion Treatment Plant's (HTP) Influent Sewer/Headworks Facility. This facility has encountered higher H_2S levels than was anticipated during the design of the odor control scrubbers. The scrubbers, originally designed for 40 ppmv, have been modified to treat 300 ppmv. However, the current scrubber technology in place at HTP is unable to handle this elevated sulfide load without significantly increased chemical dosages, and associated maintenance and operations problems. Knowledge gained from this testing program will be applied to odor control facilities throughout the plant to reduce chemical and maintenance costs.

WORK ACCOMPLISHED THIS PERIOD

Carbon Pilot Test

This test consists of a side-by-side comparison of Calgon's Centaur® carbon and standard, coconut-based carbon, with both treating the same foul air stream. The test units are polyethylene canisters, roughly the same size as a 55 gallon drum. Both units are treating approximately 250 cfm of foul air, with H_2S levels ranging between 20 ppmv and 160 ppmv.

After completing the first regeneration of Calgon's Centaur® Carbon on July 25, 1997, the ductwork was in need of repair. Repairs were made and the Centaur® pilot unit was put back on-line on August 7, 1997. As a result, there was a period of about two weeks between regeneration No. 1 and when the unit was put back on-line.

After the second regeneration, EED was contacted by Calgon to say that the test should be started over again with virgin Centaur®. Apparently, if the Centaur® carbon is exposed to oxygen after regeneration, the absorptive sites will be compromised. Thus, any data obtained after the first regeneration cannot be considered valid.

Calgon has recently developed a second generation of Centaur carbon which they call Centaur HP (for high performance). Calgon will be sending a new pilot unit which will prevent the carbon from being exposed to oxygen during or after regeneration.

Biological Trickling Filter Pilot Test

A method for the removal of hydrogen sulfide (H_2S) has been developed in which micro-organisms that are present in sewerage systems are used to biologically oxidize this compound. Called a biological trickling filter, or just biotrickling filter, this technology

utilizes a standard scrubber design with lava-rock media to treat hydrogen sulfide emissions. In pilot tests conducted by L.A. County Sanitation Districts (LACSD) (Morton, et. al.), concentrations of up to 120 ppmv have been treated with greater than 98% removal efficiency. The operating principle of the biotrickling filter is to develop a fixed-film biological growth of sulfur-oxidizing bacteria (principally thiobacilli) on packing media within a contactor column, through which foul air passes. Unlike biofilters, bio-trickling filters operate with a liquid flowing over the packing material which helps aid in mass transfer of a contaminant. Recirculating a solution allows essential nutrients or other compounds to be added to the liquid at any time and prevents dehydration of the biofilm. Contaminants are transferred to and degraded by the micro-organisms present in both the recirculating liquid and in the biofilm layer. Because the biotrickling filter does not require the addition of costly chemicals such as NaOCl and NaOH to operate, it has the potential to be an economical technology.

Two existing, standard chemical wet scrubbers were found at the now defunct Plant Influent Sewer Relocation (PISR) odor control facility near gate B. These scrubbers were relocated to the Influent Sewer/Headworks area and retrofitted for use as bio-trickling filter pilot units. The two units will be tested simultaneously using the exact same protocol, but each tower will have different bed media.

Biotrickling filters are intended to optimize the growth of sulfur-oxidizing bacteria (principally thiobacilli) which eliminate H_2S according to the following aerobic biological reaction:

$$H_2S + 2O_2 \xrightarrow{\text{sulfur oxidizing bacteria}} H_2SO_4$$

Because the by-product of biological H_2S oxidation is sulfuric acid, a portion of the recirculation solution must be blown-down periodically, otherwise acid concentration in the recirculation increases to the point that mass transfer of H_2S from the gaseous phase to the liquid phase is inhibited. However, the amount of dilute sulfuric acid waste that is blown down is minimal and can be easily neutralized by the alkalinity present in treated wastewater (HPE), which is slightly basic (pH≈8.0) and contains a small amount of organics which help to support the bacteria.

ANALYSIS OF RESULTS

Modifications to existing towers have been completed and testing of the North bio-trickling filter (which contains lava rock) began on January 20, 1998. Figure 1 shows the start-up curve for the North biotrickling filter. 84% removal was reached in about 3 days, and 99.4% removal in about 8 days. Figure 2 shows performance after start-up. It should be noted that the contractor neglected to install the spray nozzles on these units. The fact that there was no nozzle did not seem to have much affect on performance. Nozzles were subsequently installed after this data was taken.

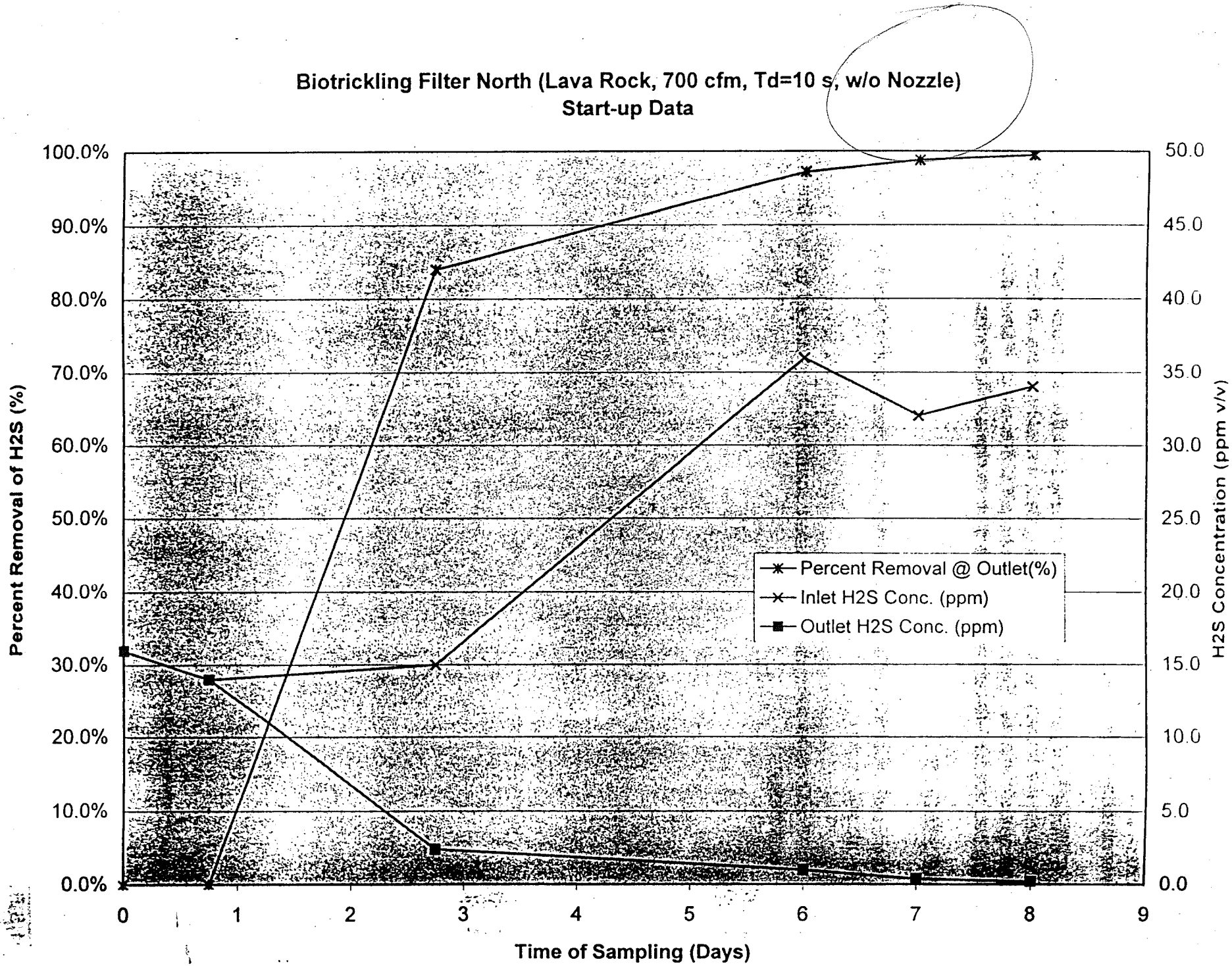
Sampling ports were installed at 1-foot intervals along the media bed (total bed depth = 7 feet). Figure 3 shows H_2S concentrations at each sample port and Figure 4 presents removal efficiencies at each sample port. As can be seen from this graph, a greater

percentage of H_2S is removed in the lower part of the tower as the test proceeded. This can better be seen in Figure 5. For this graph, bed height was placed on the Y-axis to get a more "physical" representation. 1/28 and 1/29 were the first two days after the unit had stabilized and was acheiving removal efficiencies above 99%. 2/11 and 2/13 are the most recent data points. This graph clearly shows that biological activity is migrating towards the lower portions of the bed.

Figure 6 shows how pressure drop has increased as the bio-mass increases. Ways to minimize pressure losses are being investigated, including more uniform-sized lava rock and other types of media. Figure 7 shows the pH of the sump. It should be noted that this variataion has not had an appreciable effect on removal efficiencies.

FUTURE STUDIES

- The South biotrickling filter will be started. The South unit is filled with small, dump-in, plastic packing.
- Modifications to an existing pilot-sized scrubber are planned to test the Lo-Cat chnology.


Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)
Start-up Data
Percent Removal of H2S (%)
H2S Concentration (ppm v/v)
Time of Sampling (Days)
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
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0
1
2
3
4
5
6
7
8
9
Percent Removal @ Outlet(%)
Inlet H2S Conc. (ppm)
Outlet H2S Conc. (ppm)

Post-it® Fax Note 7671	Date 5/19/97	# of pages ▶ 3
To Patty Jones	From Larry Hsu	
Co./Dept. AQMD	Co. EED	
Phone # 310 677 5263	Phone # 310 514 3373	
Fax # 310 677 5117	Fax #	

ION

File: 2503 - 8 - 12

Purpose: Discussion of Biotrickling Filter Pilot Test with APC Operations

Meeting Date: May 19, 1997 @ 10 a.m.

Location: Headworks Odor Control Area

Notes by: Larry Hsu

Attendees:
Jerry Hernandez, EED
Larry Hsu, EED
Steve Johnson, EED
Zafar Kassai, AQMG
Russell Johnson, APC Operations
Bill Conley, SE Construction

This meeting was held to address the concerns of APC Operators regarding the 2503 - H2S Removal Technologies Test Program: Biotrickling Filter Pilot Test.

It was agreed by all present that construction & testing could proceed (pending Marcia Smith's approval) on the Biotrickling Filter towers under the following conditions:

1. Monthly acid washing will necessitate that the Contractor cease work & leave the area. Acid washing could take a period of 2 hours and occur monthly for each packed tower. Bill Conley agreed that this would not be a problem as long as he is given advance notice as to when acid washings are to occur. Russell Johnson will give a copy of the acid washing schedule to all interested parties. Russell agreed to notify the Contractor via Zafar if APC Operations are to deviate from the provided acid washing schedule.

2. Russell Johnson was concerned that too many projects were occurring simultaneously. It was agreed that this would not be a problem if APC Operation's responsibilities on these projects are kept to a minimum.

3. Bill Conley & Russell Johnson agreed that the area east of the northern scrubber, between the two duct support pads would be a satisfactory lay down area for the biotrickling filter work. Please refer to the attached drawing.

4. It was agreed that the H2O2 (hydrogen peroxide) tank and the two, 1 foot diameter towers could remain at their present location at the NW corner of the Headworks odor control containment area.

5. Russell Johnson noted that the shower/eyewash on the H2O2 tank skid should be covered up, since it is out of service. AQMG agreed to cover up the shower/eyewash.

6. Bill Conley agreed to keep the access way (west of the containment area) clear for plant access.

Attachments

Cc: Gary Moore, EED
Doug Sereno, EED
John Saldin, EED
Wilson Elias, EED
Patty Jacobs, AQMG
Mike Noguchi, AQMG
Marcia Smith, APC Operations

FORM GEN 160 (Rev 8-80)

CITY OF LOS ANGELES

INTER-DEPARTMENTAL CORRESPONDENCE

Date: July 9, 1998

To: Distribution

From: Steve Johnson SCJ

File: HTP-2503-3-2

Subject: **H_2S REMOVAL TECHNOLOGIES TEST PROGRAM - PROJECT 2503 BIOTRICKLING FILTER PILOT TEST MODIFICATIONS/ADDITIONS TO TEST PROTOCOL**

On June 16, 1998, a meeting was held to discuss the latest results from the biotrickling filter pilot test. The following modifications/additions to the test protocol resulted from this meeting (all other relevent sections of the original protocol to remain in effect):

Biotrickling Filter Units (2) @ 4-1/2' Diameter

- Both Units: replace existing recirculation pumps with larger capacity pumps (max. system capacity: 40 gpm). Pump recirculation lines to be installed to accommodate a wide range of recirculation rates, allowing the pumps to run at the most efficient point. Existing recirculation pumps to be moved to skid unit (skid unit described below).
- North Unit: lava rock will be removed and sent to screening facility for classification. Lava rock greater than 3/4" to be returned to unit for analysis of effects on pressure drop. A sample of lava rock to be sent to a lab to perform a bioassay.
- South Unit: existing 1" Jaeger plastic packing will be replaced with engineered plastic packing from Lantec.

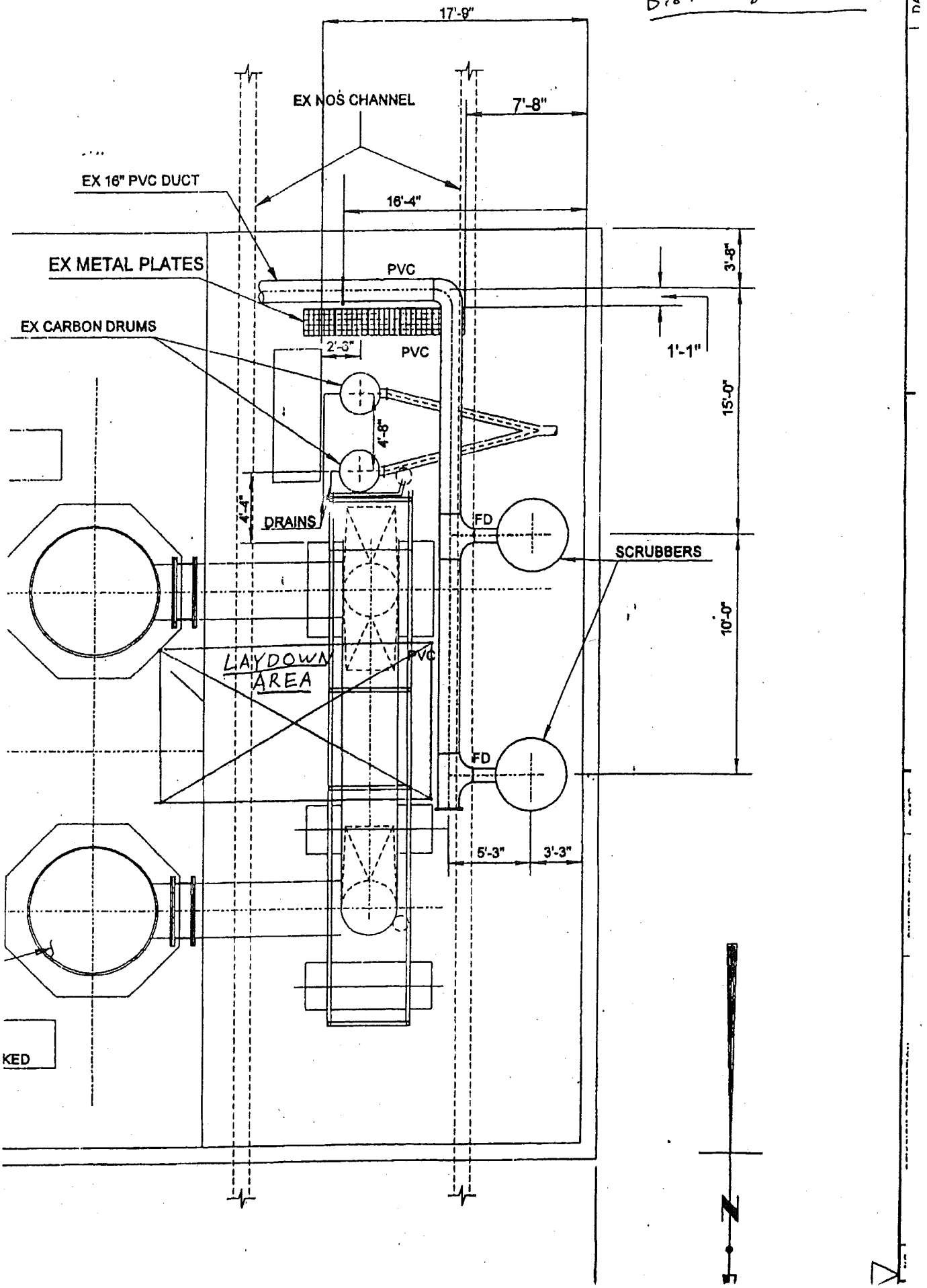
Skid Mounted Biotrickling Filter Units (2) @ 1-foot Diameter

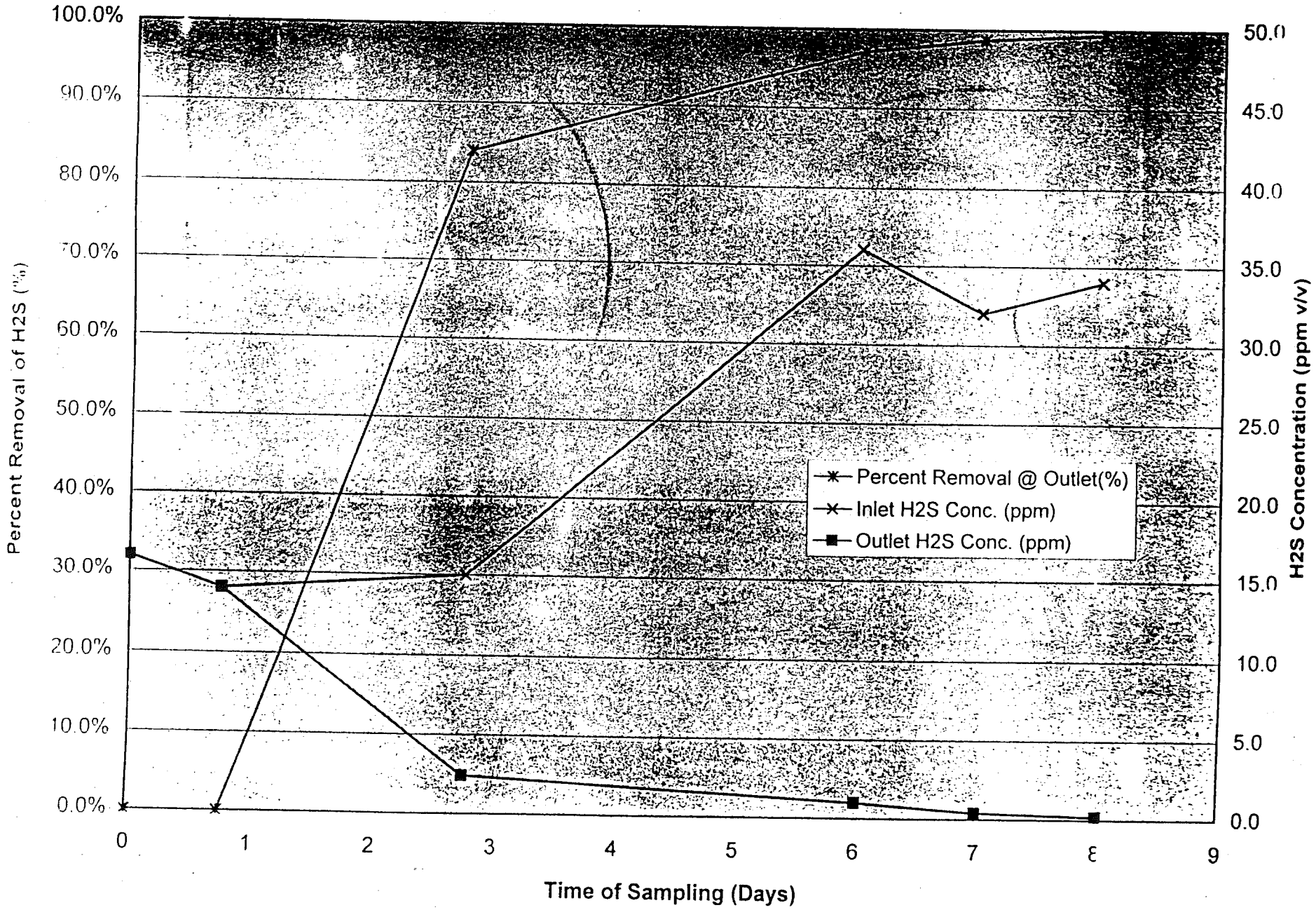
- Unit No. 1: one gallon of waste activated sludge (WAS) to be added to the recirculation fluid daily (this will serve as the make-up water). More WAS may be added daily depending on removal efficiency and the results of pH tests. 1" Jaeger plastic packing will be utilized as the media.
- Unit No. 2: Foamglas® "saddles" to be utilized for media, with HPE as make-up.

Distribution:
T. Haug
J. Hernandez
D. Sereno
[redacted]

L:\2503\CO\RPT\PROTOCOL.MOD

Biotrickling Filter test




Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)
Start-up Data
Percent Removal of H2S (%)
H2S Concentration (ppm v/v)
Time of Sampling (Days)
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
1
2
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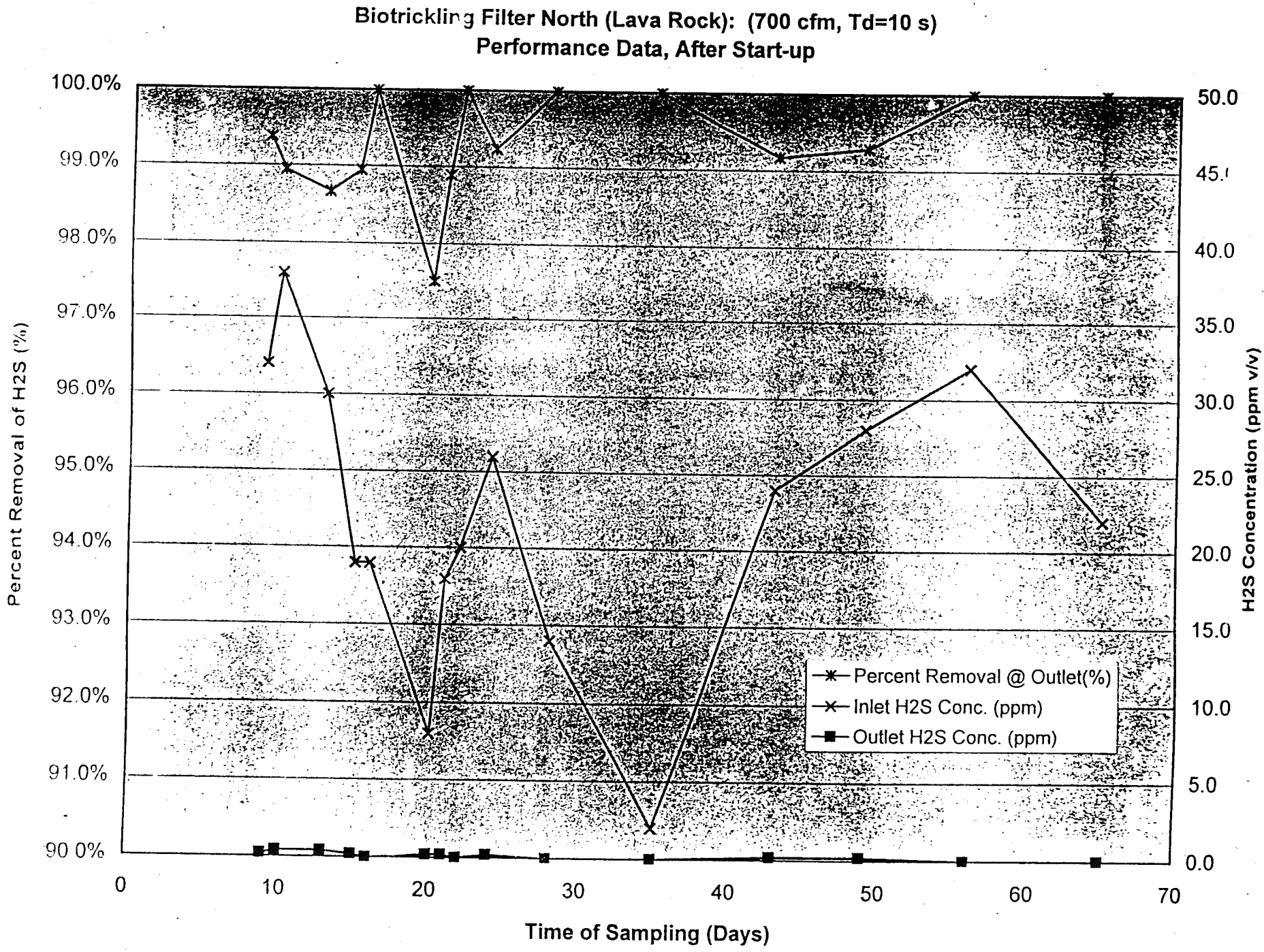
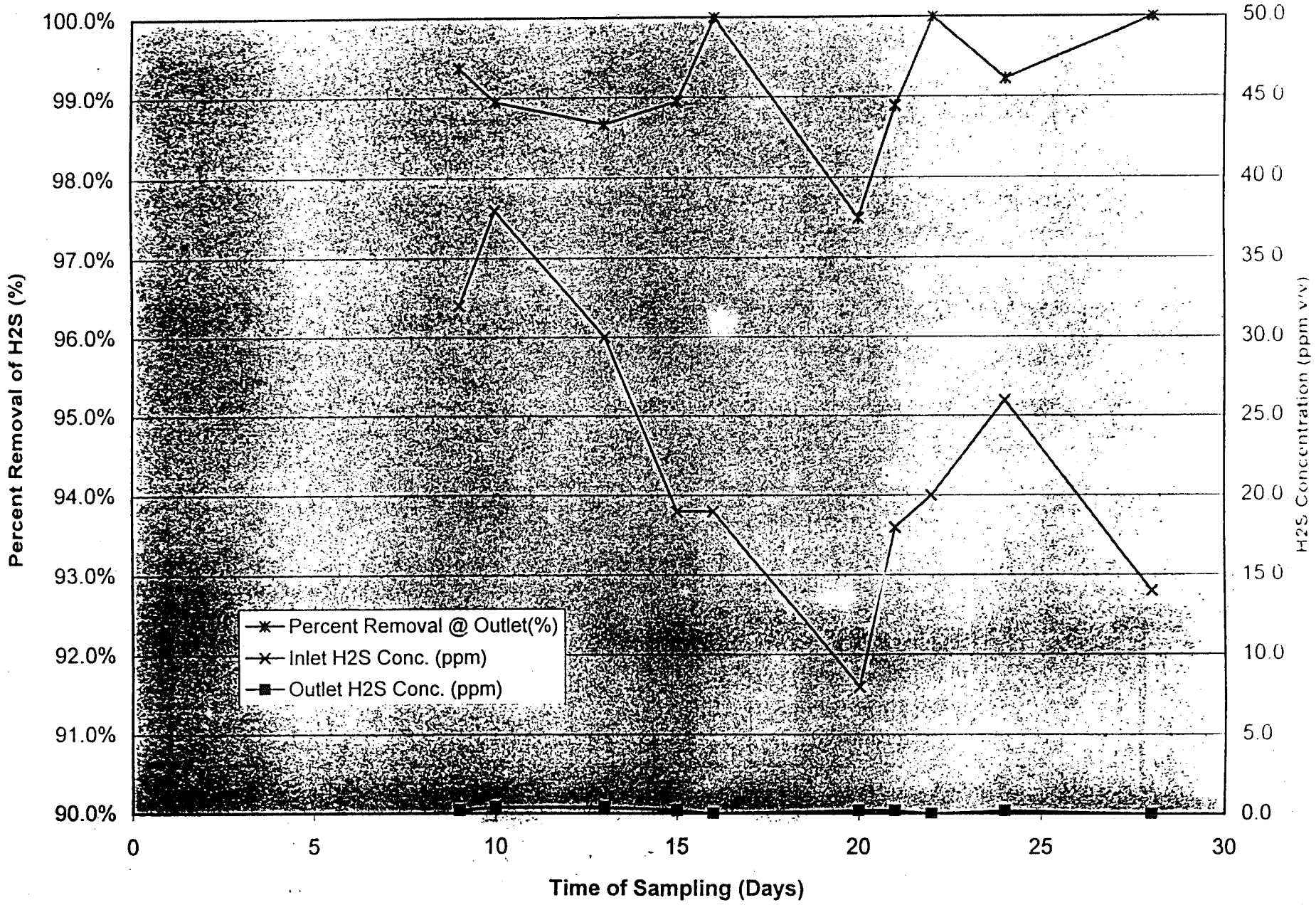
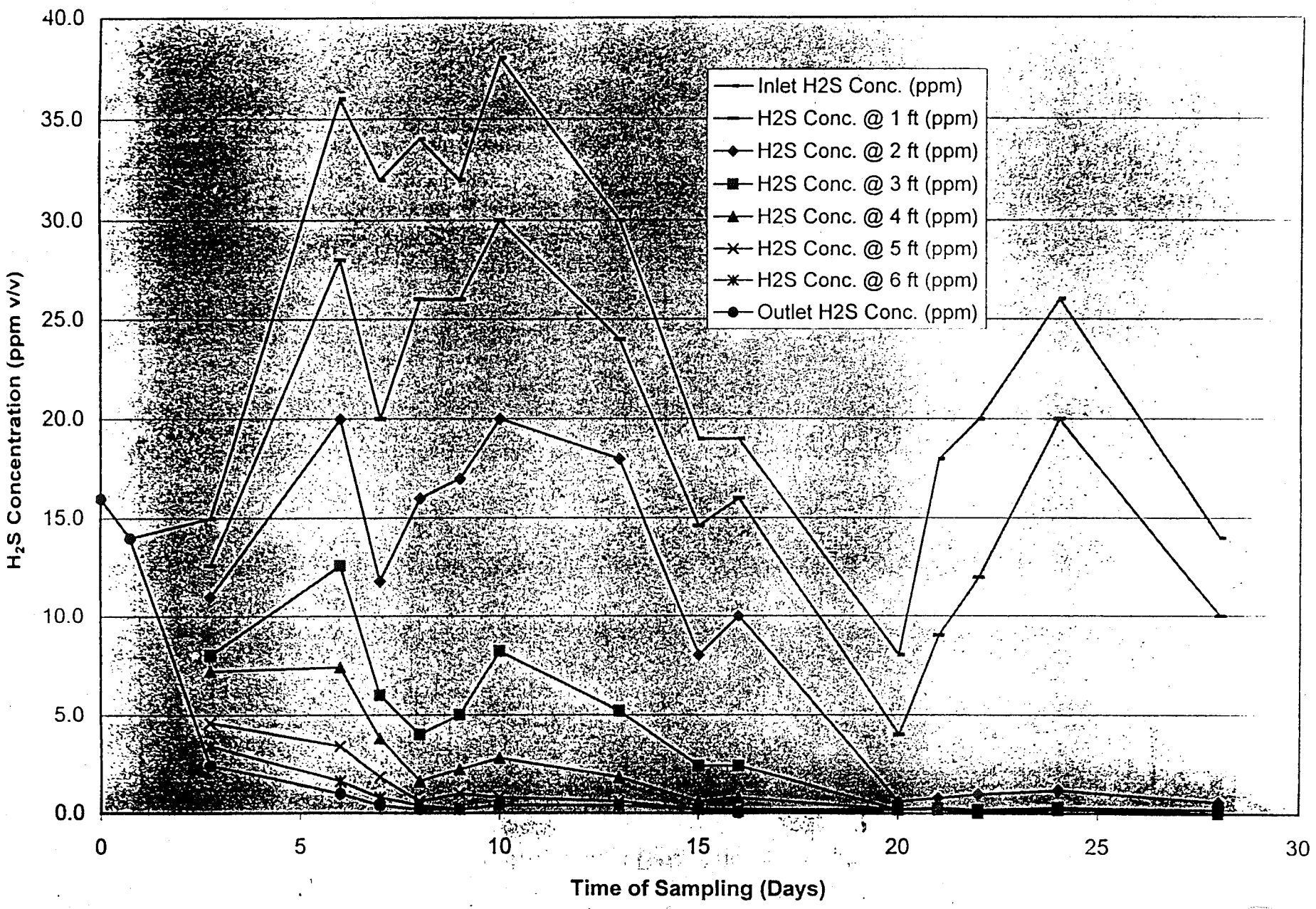
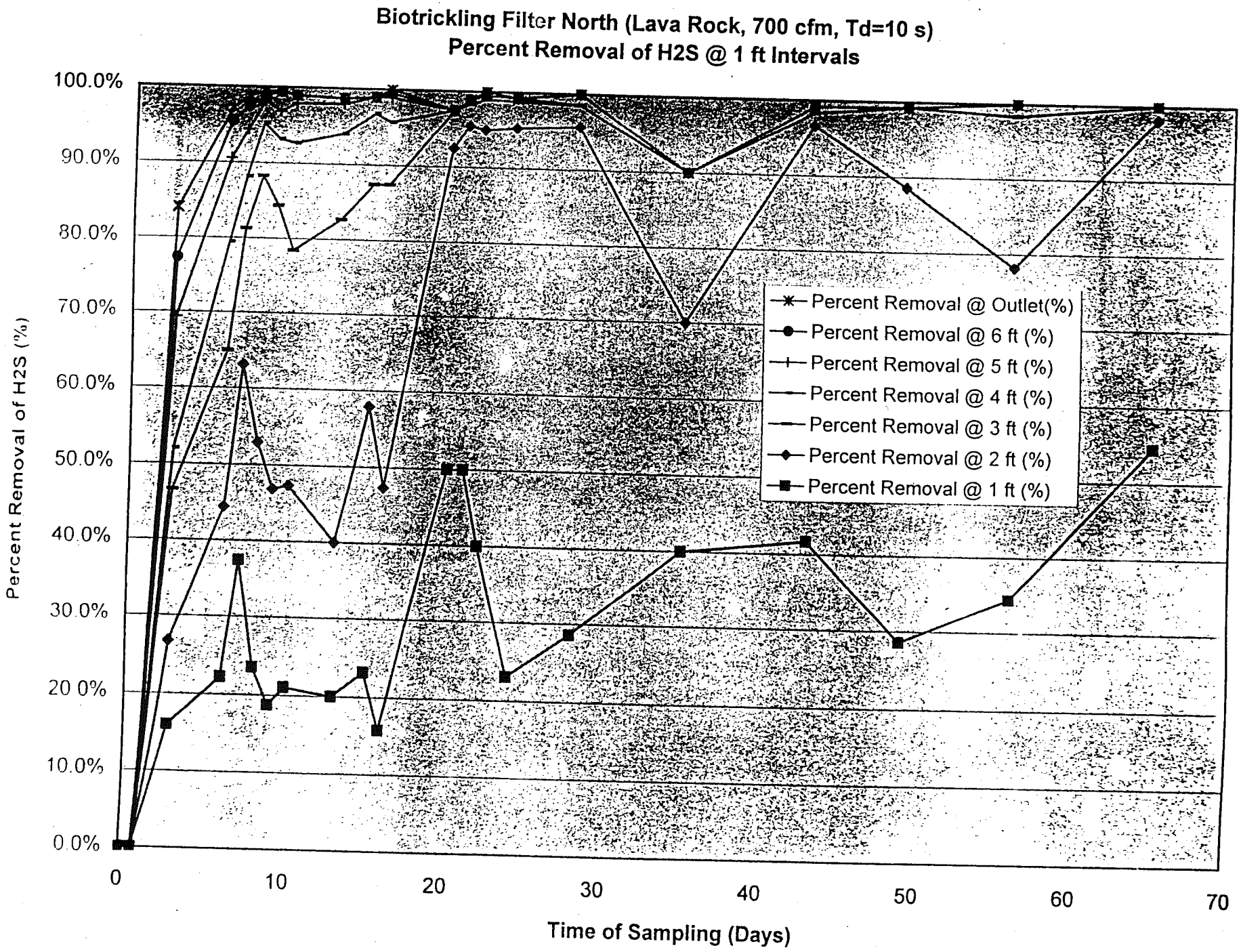
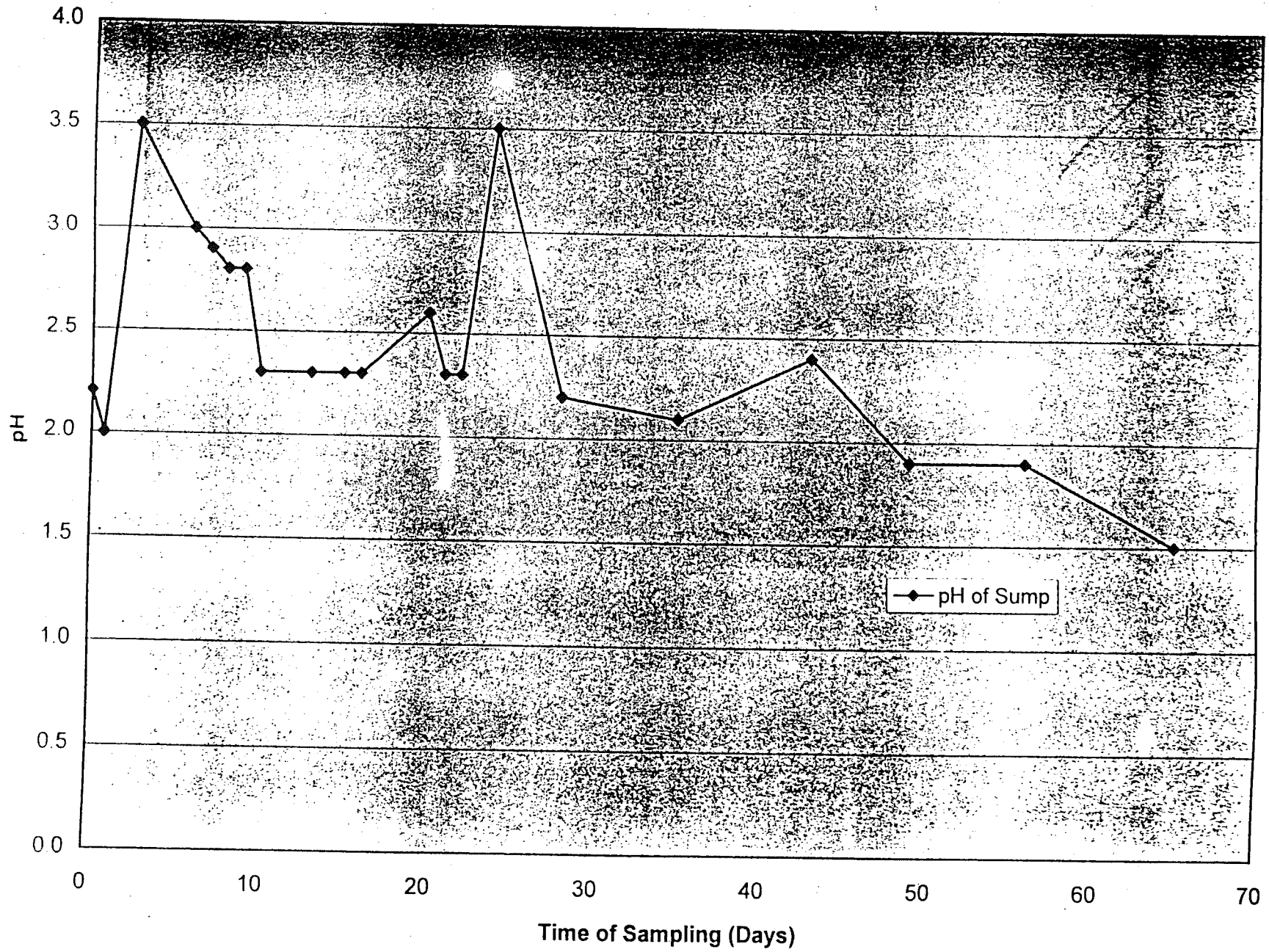
4
5
6
7
8
9
Percent Removal @ Outlet(%)
Inlet H2S Conc. (ppm)
Outlet H2S Conc. (ppm)

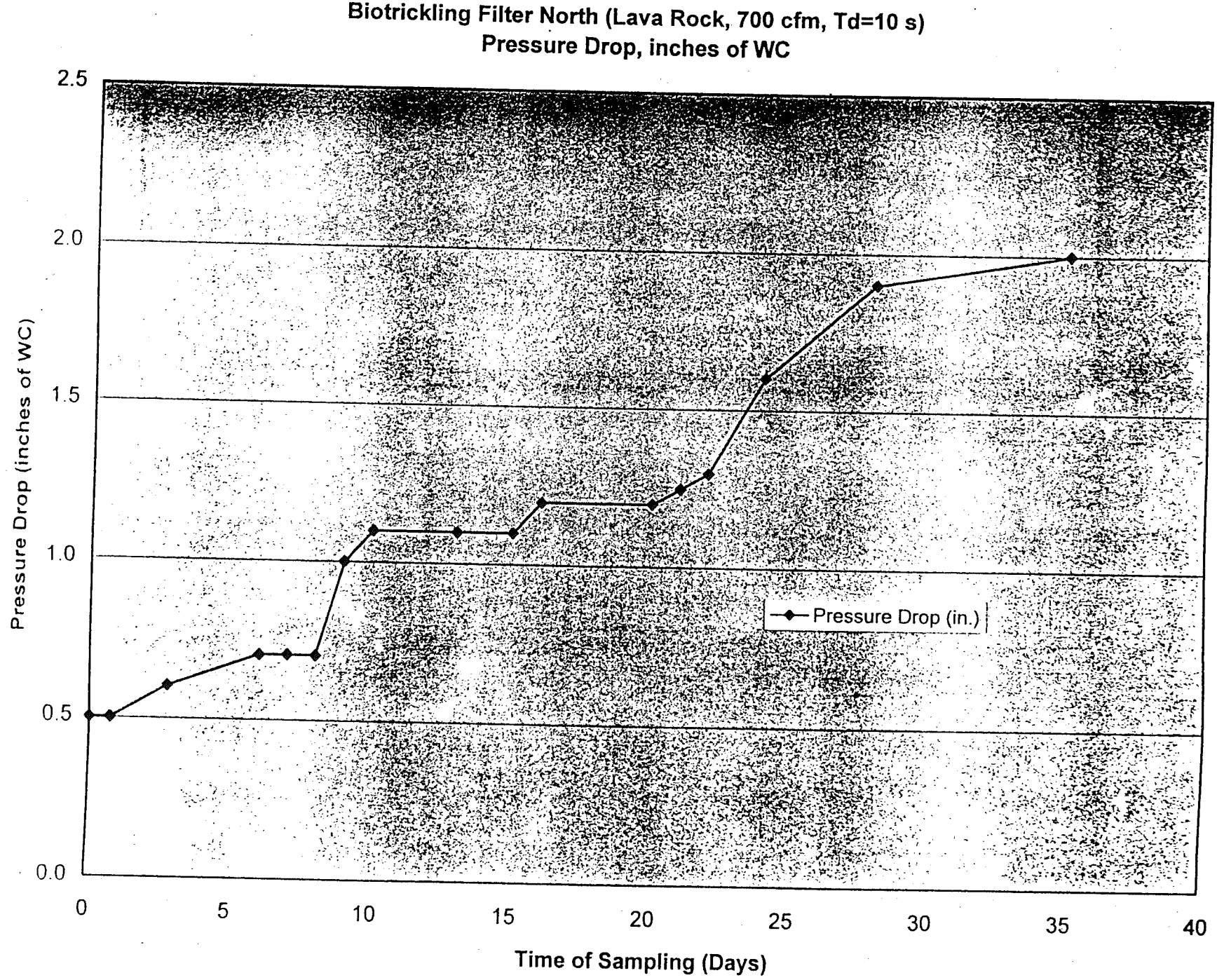

Biotrickling Filter North (Lava Rock): (700 cfm, Td=10 s)
Performance Data, After Start-up
Percent Removal of H2S (%)
H2S Concentration (ppm v/v)
Time of Sampling (Days)
100.0%
99.0%
98.0%
97.0%
96.0%
95.0%
94.0%
93.0%
92.0%
91.0%
90 0%
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
10
20
30
40
50
60
70
Percent Removal @ Outlet(%)
Inlet H2S Conc. (ppm)
Outlet H2S Conc. (ppm)

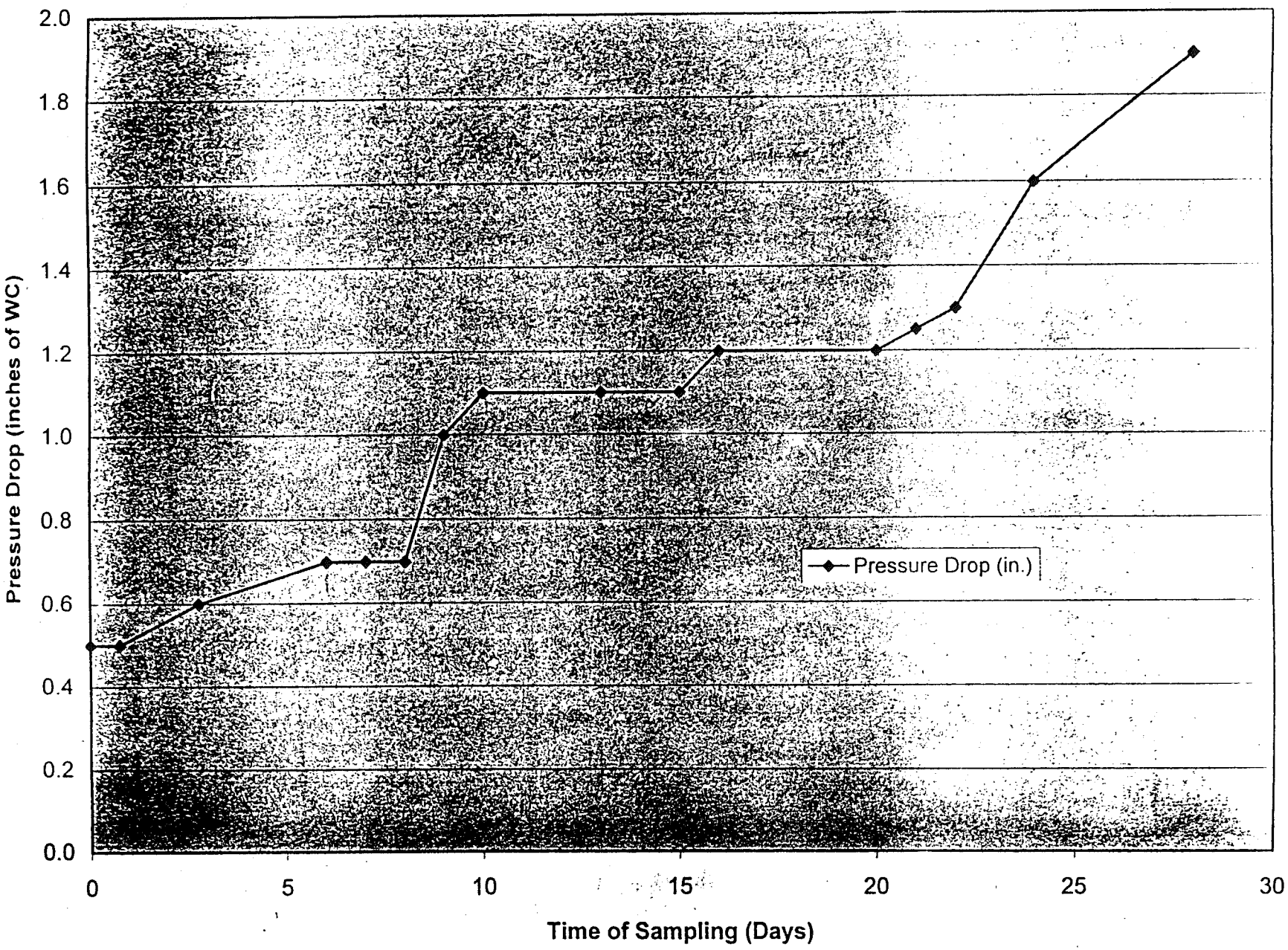

Biotrickling Filter North (Lava Rock): (700 cfm, Td=10 s, w/o Nozzle)
Performance Data, After Start-up
Percent Removal of H2S (%)
100.0%
99.0%
98.0%
97.0%
96.0%
95.0%
94.0%
93.0%
92.0%
91.0%
90.0%
H2S Concentration (ppm v/v)
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
5
10
15
20
25
30
Time of Sampling (Days)
Percent Removal @ Outlet(%)
Inlet H2S Conc. (ppm)
Outlet H2S Conc. (ppm)

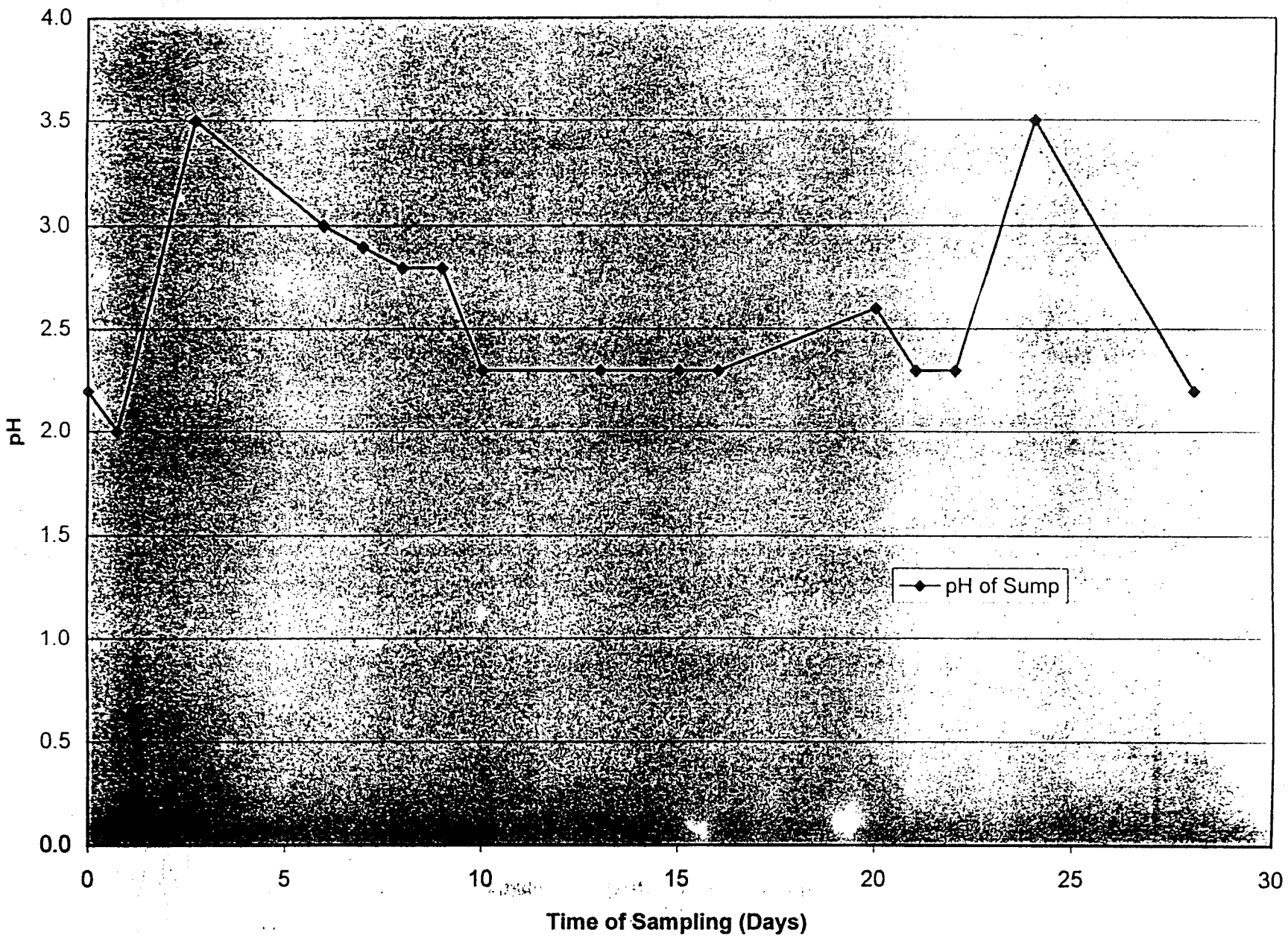

Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)
Removal Data @ 1 ft Intervals
H2S Concentration (ppm v/v)
Time of Sampling (Days)
Inlet H2S Conc. (ppm)
H2S Conc. @ 1 ft (ppm)
H2S Conc. @ 2 ft (ppm)
H2S Conc. @ 3 ft (ppm)
H2S Conc. @ 4 ft (ppm)
H2S Conc. @ 5 ft (ppm)
H2S Conc. @ 6 ft (ppm)
Outlet H2S Conc. (ppm)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
5
10
15
20
25
30

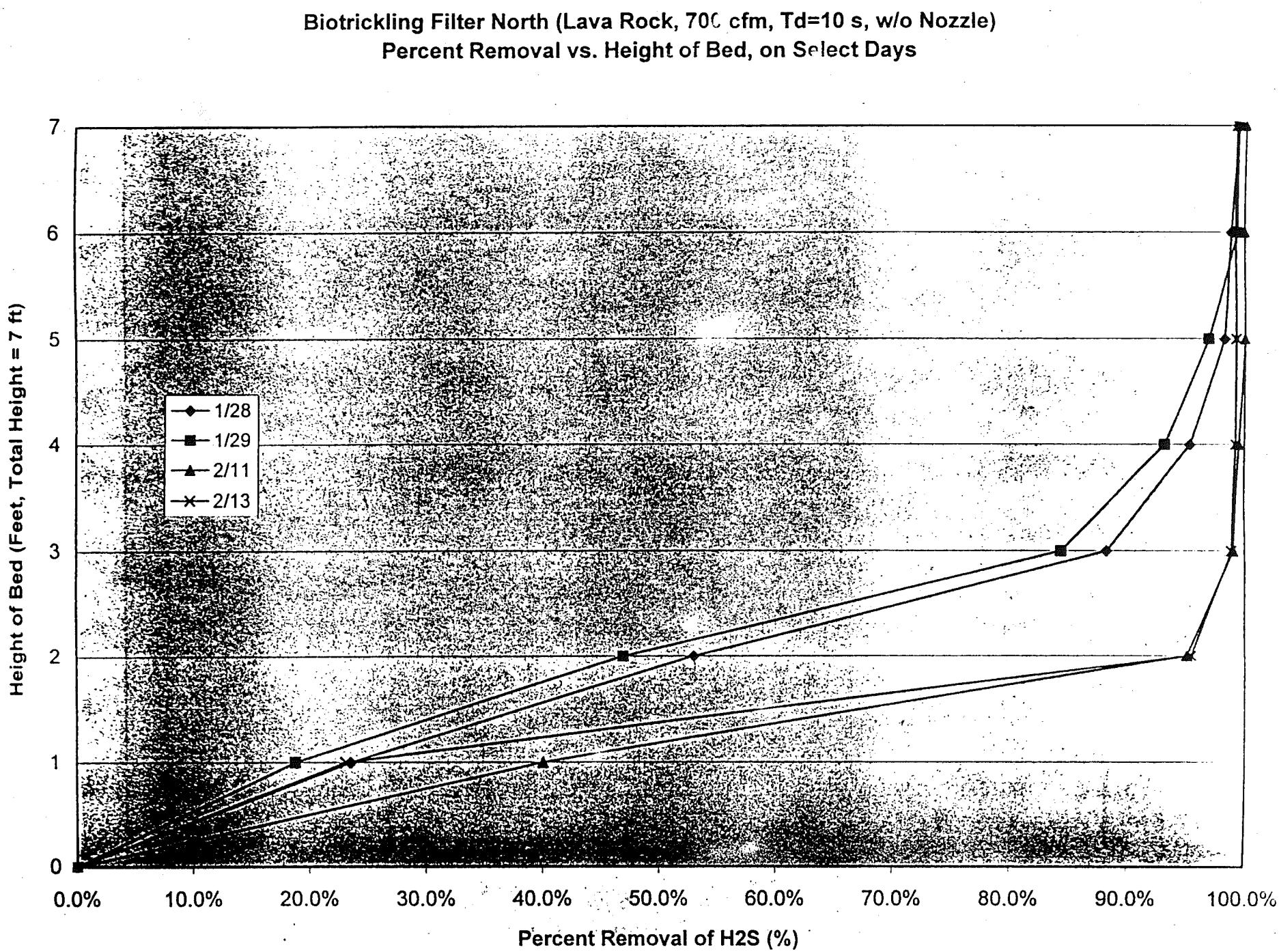

Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s)
Percent Removal of H2S @ 1 ft Intervals
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Percent Removal of H2S (%)
0
10
20
30
40
50
60
70
Time of Sampling (Days)
Percent Removal @ Outlet(%)
Percent Removal @ 6 ft (%)
Percent Removal @ 5 ft (%)
Percent Removal @ 4 ft (%)
Percent Removal @ 3 ft (%)
Percent Removal @ 2 ft (%)
Percent Removal @ 1 ft (%)

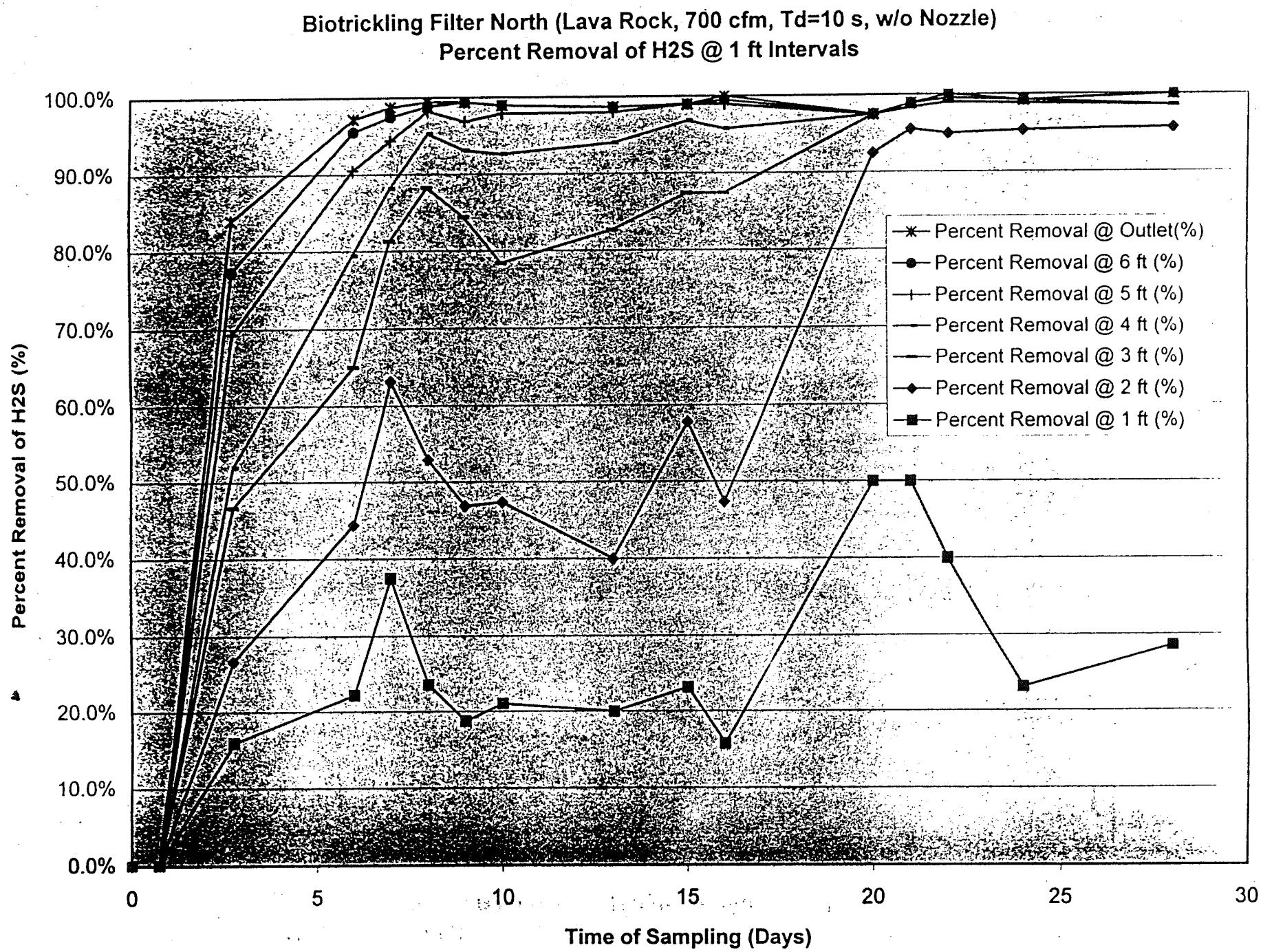

Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s)
pH of Sump
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
pH
0
10
20
30
40
50
60
70
Time of Sampling (Days)
pH of Sump

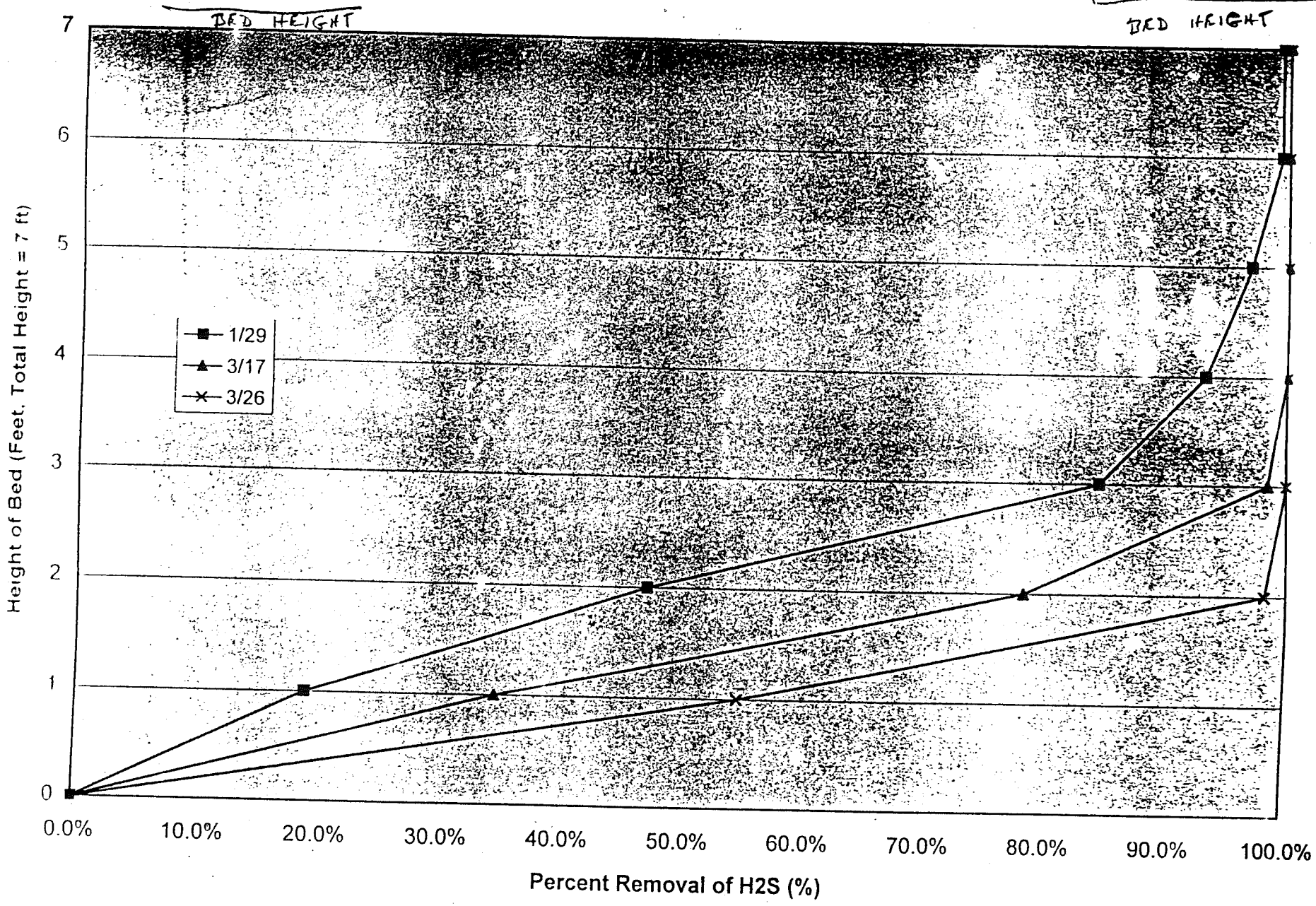

Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s)
Pressure Drop, inches of WC
Pressure Drop (inches of WC)
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
35
40
Time of Sampling (Days)
Pressure Drop (in.)


Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o nozzle)
Pressure Drop, inches of WC
Pressure Drop (inches of WC)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
Time of Sampling (Days)
Pressure Drop (in.)


Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o nozzle)
pH of Sump
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
pH
0
5
10
15
20
25
30
Time of Sampling (Days)
pH of Sump


Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)
Percent Removal vs. Height of Bed, on Select Days
Height of Bed (Feet, Total Height = 7 ft)
Percent Removal of H2S (%)
1/28
1/29
2/11
2/13
0
1
2
3
4
5
6
7
0.0%
10.0%
20.0%
30.0%
40.0%
50.0%
60.0%
70.0%
80.0%
90.0%
100.0%


Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)
Percent Removal of H2S @ 1 ft Intervals
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Percent Removal of H2S (%)
0
5
10
15
20
25
30
Time of Sampling (Days)
Percent Removal @ Outlet(%)
Percent Removal @ 6 ft (%)
Percent Removal @ 5 ft (%)
Percent Removal @ 4 ft (%)
Percent Removal @ 3 ft (%)
Percent Removal @ 2 ft (%)
Percent Removal @ 1 ft (%)


Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)
Percent Removal vs. Height of Bed, on Select Days
Height of Bed (Feet, Total Height = 7 ft)
Percent Removal of H2S (%)
1/29
3/17
3/26
0
1
2
3
4
5
6
7
0.0%
10.0%
20.0%
30.0%
40.0%
50.0%
60.0%
70.0%
80.0%
90.0%
100.0%

Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)

Date	1/20	1/21	1/23	1/26	1/27	1/28	1/29	1/30	2/2	2/4
Time	4:00	10:00	10:00	2:00	1:00	3:00	3:00	3:00	3:00	3:00
Hours (cum.)	0	18	66	144	168	192	216	240	312	360
Days (cum.)	0	0.75	2.75	6	7	8	9	10	13	15
Air Flow Rate (cfm)	700	700	700	700	700	700	700	700	700	700
Recirc. Rate (gpm)	8	8	8	8	8	8	8	8	8	8
pH of Sump	2.2	2.0	3.5	3.0	2.9	2.8	2.8	2.3	2.3	2.3
Make-up Water Totalizer (gal)	2203	2203	2203	2203	2267	2267	2267	2312	2381	2665
Pressure Drop (in.)	0.5	0.5	0.6	0.7	0.7	0.7	1.0	1.1	1.1	1.1
Outlet H_2S Conc. (ppm)	16.0	14.0	2.4	1.0	0.4	0.2	0.2	0.4	0.4	0.2
H_2S Conc. @ 6 ft (ppm)			3.4	1.6	0.8	0.4	0.2	0.4	0.4	0.2
H_2S Conc. @ 5 ft (ppm)			4.6	3.4	1.8	0.6	1.0	0.8	0.6	0.2
H_2S Conc. @ 4 ft (ppm)			7.2	7.4	3.8	1.6	2.2	2.8	1.8	0.6
H_2S Conc. @ 3 ft (ppm)			8.0	12.6	6.0	4.0	5.0	8.2	5.2	2.4
H_2S Conc. @ 2 ft (ppm)			11.0	20.0	11.8	16.0	17.0	20.0	18.0	8.0
H_2S Conc. @ 1 ft (ppm)			12.6	28.0	20.0	26.0	26.0	30.0	24.0	14.6
Inlet H_2S Conc. (ppm)	16.0	14.0	15.0	36.0	32.0	34.0	32.0	38.0	30.0	19.0
Percent Removal @ Outlet(%)	0.0%	0.0%	84.0%	97.2%	98.8%	99.4%	99.4%	98.9%	98.7%	98.9%

NOTE: lava rock bed depth = 7'

Biotrickling Filter North (Lava Rock, 700 cfm, Td=10 s, w/o Nozzle)

Date	2/5	2/9	2/10	2/11	2/13	2/17
Time	3:00	3:00	3:00	3:00	3:00	3:00
Hours (cum.)	384	480	504	528	576	672
Days (cum.)	16	20	21	22	24	28
Air Flow Rate (cfm)	700	700	700	700	700	700
Recirc. Rate (gpm)	8	8	8	8	8	8
pH of Sump	2.3	2.6	2.3	2.3	3.5	2.2
Make-up Water Totalizer (gal)	2665	4160	4538	4793	5366	6623
Pressure Drop (in.)	1.2	1.2	1.3	1.3	1.6	1.9
Outlet H_2S Conc. (ppm)	0.0	0.2	0.2	0.0	0.2	0.0
H_2S Conc. @ 6 ft (ppm)	0.1	0.2	0.2	0.0	0.2	0.0
H_2S Conc. @ 5 ft (ppm)	0.2	0.2	0.2	0.0	0.2	0.0
H_2S Conc. @ 4 ft (ppm)	0.8	0.2	0.2	0.1	0.2	0.2
H_2S Conc. @ 3 ft (ppm)	2.4	0.2	0.3	0.2	0.3	0.2
H_2S Conc. @ 2 ft (ppm)	10.0	0.6	0.8	1.0	1.2	0.6
H_2S Conc. @ 1 ft (ppm)	16.0	4.0	9.0	12.0	20.0	10.0
Inlet H_2S Conc. (ppm)	19.0	8.0	18.0	20.0	26.0	14.0
Percent Removal @ Outlet(%)	100.0%	97.5%	98.9%	100.0%	99.2%	100.0%

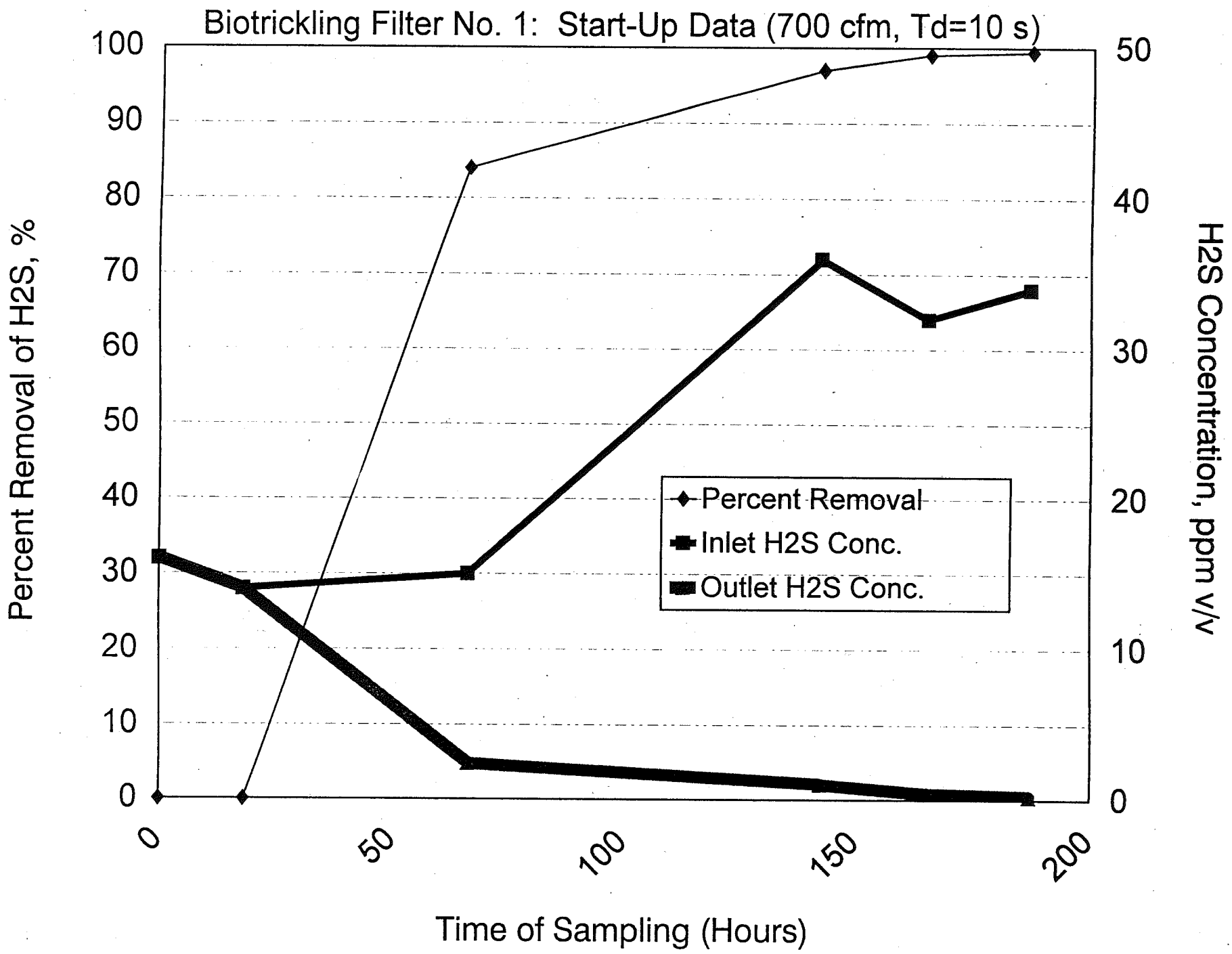
NOTE: lava rock bed depth = 7

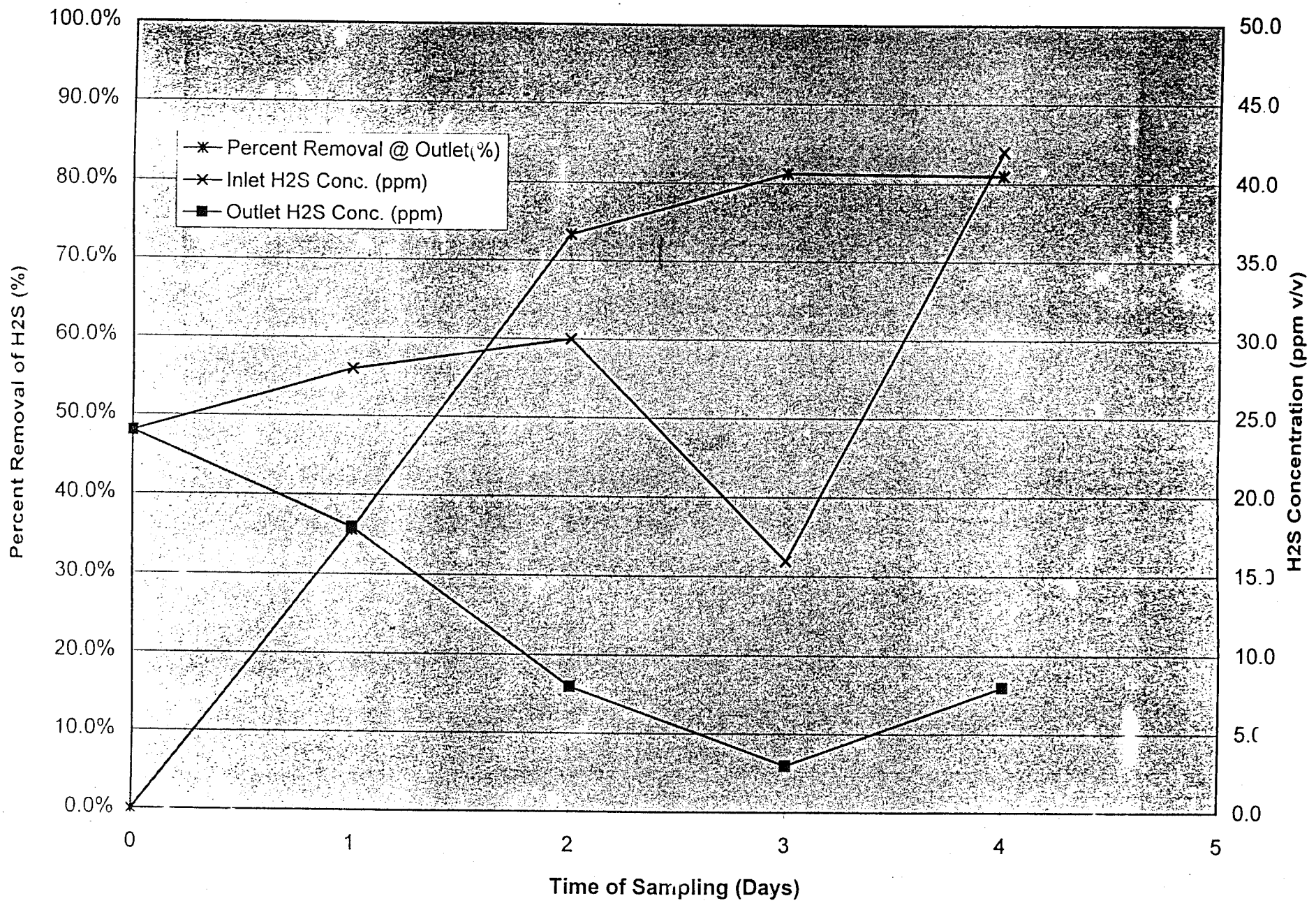
Date	1/20/98	1/21	1/23	1/26	1/27	1/28	1/29	1/30	2/2	2/4
Time	4:00	10:00	10:00	2:00	1:00	3:00	3:00	3:00	3:00	3:00
Hours (cum.)	0	18	66	144	168	192	216	240	312	360
Days (cum.)	0	0.75	2.75	6	7	8	9	10	13	15
Air Flow Rate (cfm)	700	700	700	700	700	700	700	700	700	700
Recirc. Rate (gpm)	8	8	8	8	8	8	8	8	8	8
pH of Sump	2.2	2.0	3.5	3.0	2.9	2.8	2.8	2.3	2.3	2.3
Make-up Water Totalizer (gal)	2203	2203	2203	2203	2267	2267	2267	2312	2381	2665
Pressure Drop (in.)	0.5	0.5	0.6	0.7	0.7	0.7	1.0	1.1	1.1	1.1
Outlet H2S Conc. (ppm)	16.0	14.0	2.4	1.0	0.4	0.2	0.2	0.4	0.4	0.2
H2S Conc. @ 6 ft (ppm)			3.4	1.6	0.8	0.4	0.2	0.4	0.4	0.2
H2S Conc. @ 5 ft (ppm)			4.6	3.4	1.8	0.6	1.0	0.8	0.6	0.2
H2S Conc. @ 4 ft (ppm)			7.2	7.4	3.8	1.6	2.2	2.8	1.8	0.6
H2S Conc. @ 3 ft (ppm)			8.0	12.6	6.0	4.0	5.0	8.2	5.2	2.4
H2S Conc. @ 2 ft (ppm)			11.0	20.0	11.8	16.0	17.0	20.0	18.0	8.0
H2S Conc. @ 1 ft (ppm)			12.6	28.0	20.0	26.0	26.0	30.0	24.0	14.6
Inlet H2S Conc. (ppm)	16.0	14.0	15.0	36.0	32.0	34.0	32.0	38.0	30.0	19.0
Percent Removal (%)	0.0%	0.0%	84.0%	97.2%	98.8%	99.4%	99.4%	98.9%	98.7%	98.9%

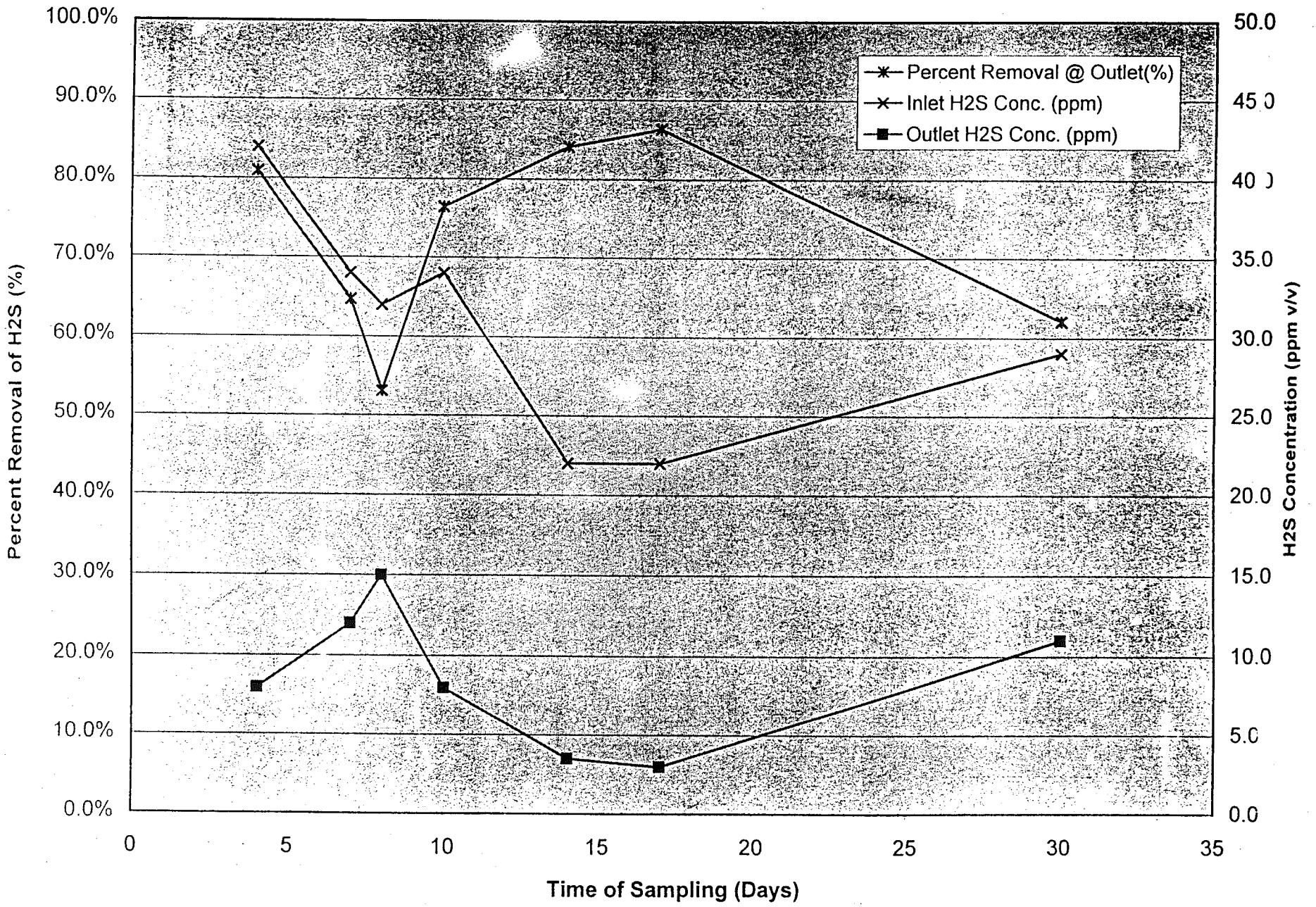
NOTE: lava rock bed depth = 7 feet

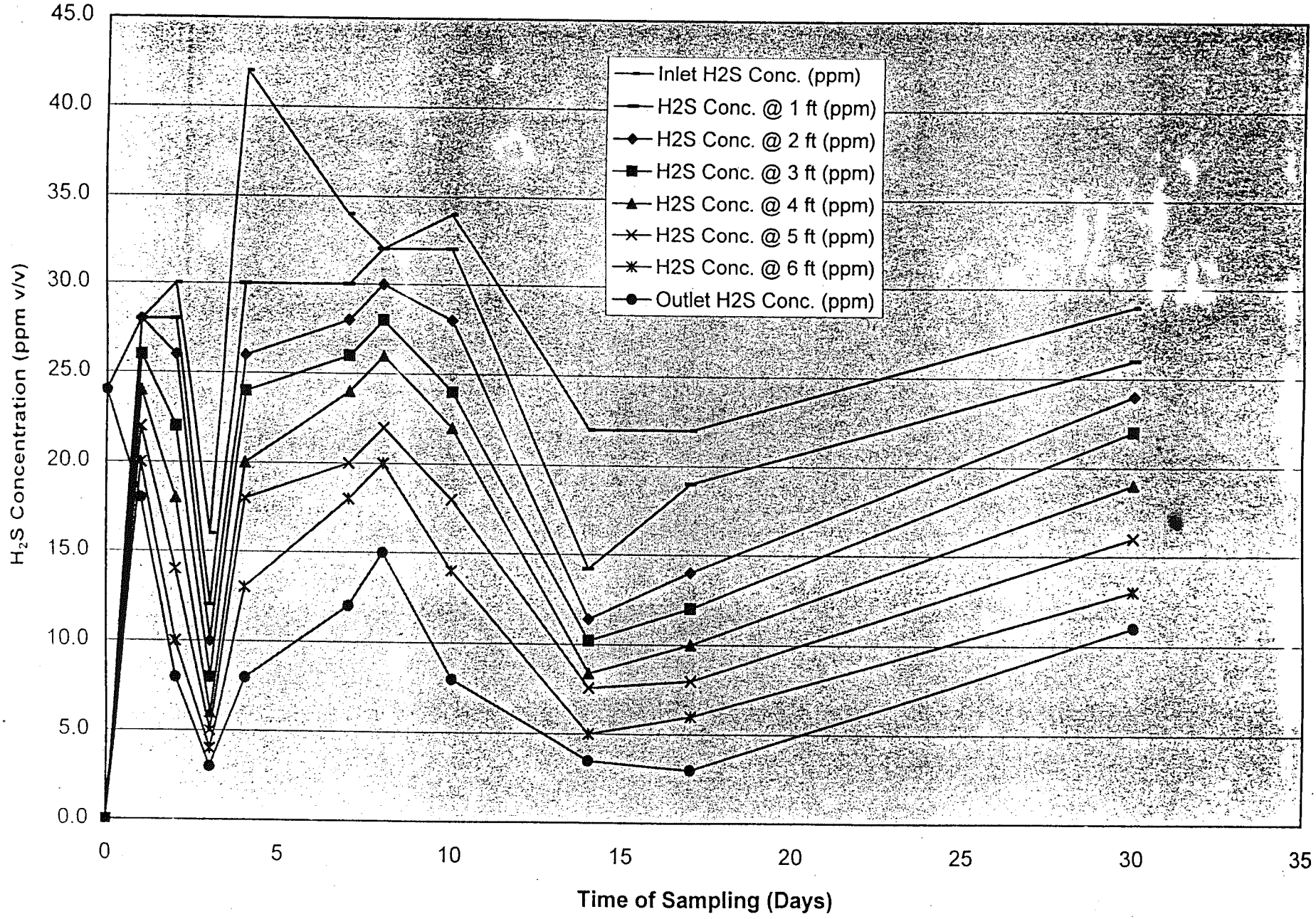
Date	2/5	2/9	2/10	2/11
Time	3:00	3:00	3:00	3:00
Hours (cum.)	384	480	504	528
Days (cum.)	16	20	21	22
Air Flow Rate (cfm)	700	700	700	700
Recirc. Rate (gpm)	8	8	8	8
pH of Sump	2.3	2.6	2.3	2.3
Make-up Water Totalizer (gal)	2665	4160	4538	4793
Pressure Drop (in.)	1.2	1.2	1.3	1.3
Outlet H2S Conc. (ppm)	0.0	0.2	0.2	0.0
H2S Conc. @ 6 ft (ppm)	0.1	0.2	0.2	0.0
H2S Conc. @ 5 ft (ppm)	0.2	0.2	0.2	0.0
H2S Conc. @ 4 ft (ppm)	0.8	0.2	0.2	0.1
H2S Conc. @ 3 ft (ppm)	2.4	0.2	0.3	0.2
H2S Conc. @ 2 ft (ppm)	10.0	0.6	0.8	1.0
H2S Conc. @ 1 ft (ppm)	16.0	4.0	9.0	12.0
Inlet H2S Conc. (ppm)	19.0	8.0	18.0	20.0
Percent Removal (%)	100.0%	97.5%	98.9%	100.0%

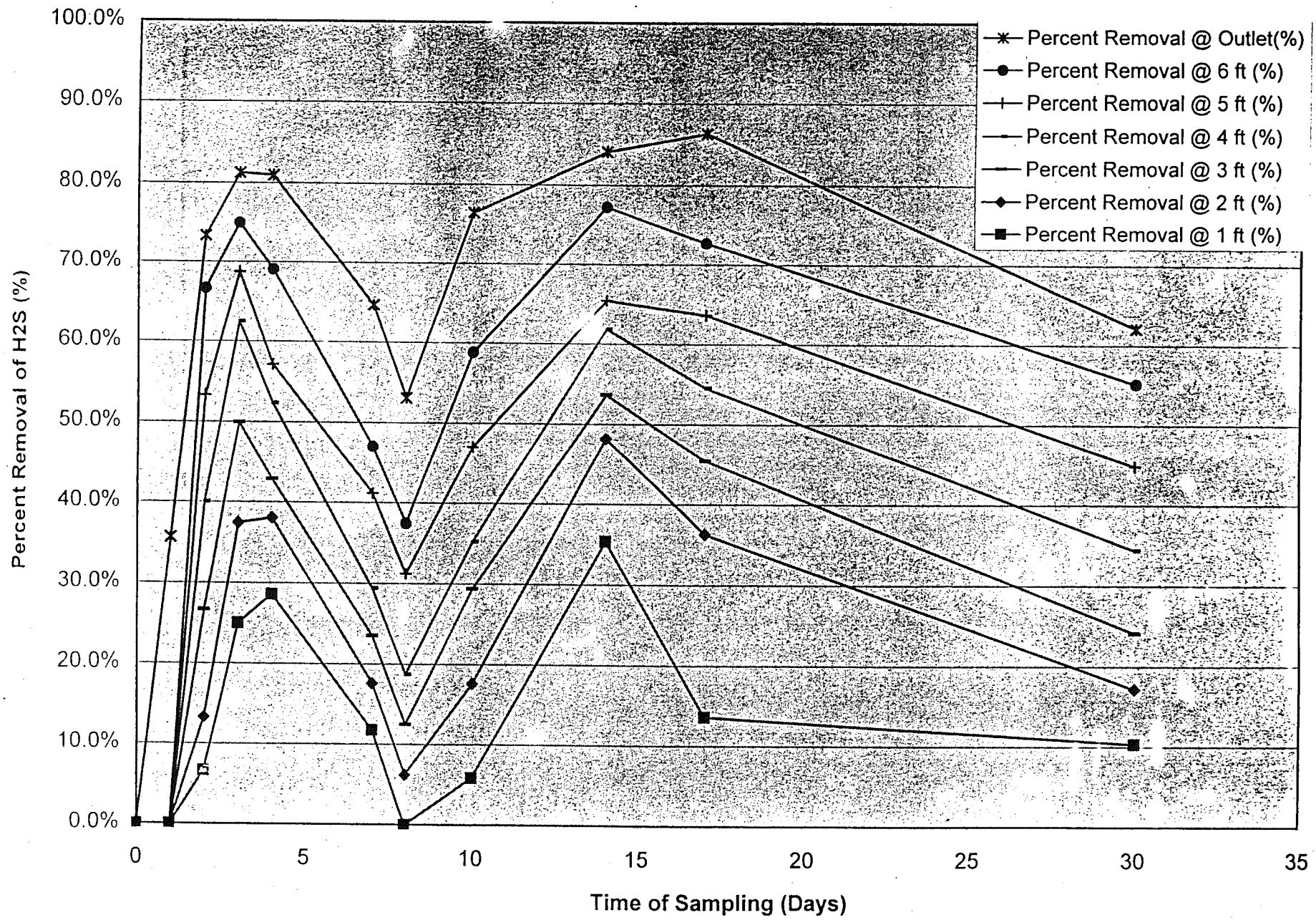
NOTE: lava rock bed depth = 7


Biotrickling Filter No. 1: Start-Up Data (700 cfm, Td=10 s)
Percent Removal of H2S, %
H2S Concentration, ppm v/v
Time of Sampling (Hours)
Percent Removal
Inlet H2S Conc.
Outlet H2S Conc.
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200

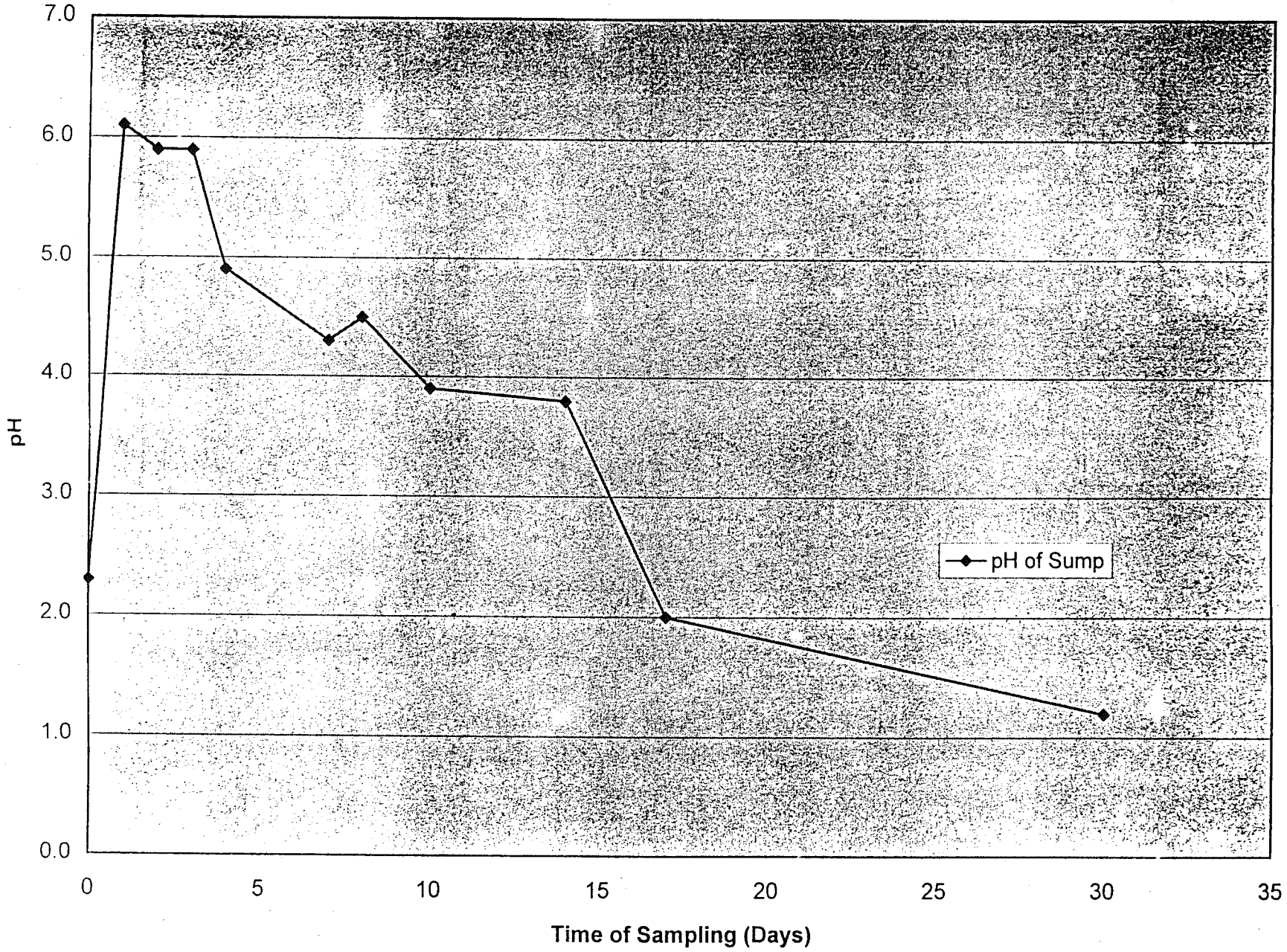

Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s,)
Start-up Data
Percent Removal @ Outlet(%)
Inlet H2S Conc. (ppm)
Outlet H2S Conc. (ppm)
Percent Removal of H2S (%)
H2S Concentration (ppm v/v)
Time of Sampling (Days)
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
1
2
3
4
5

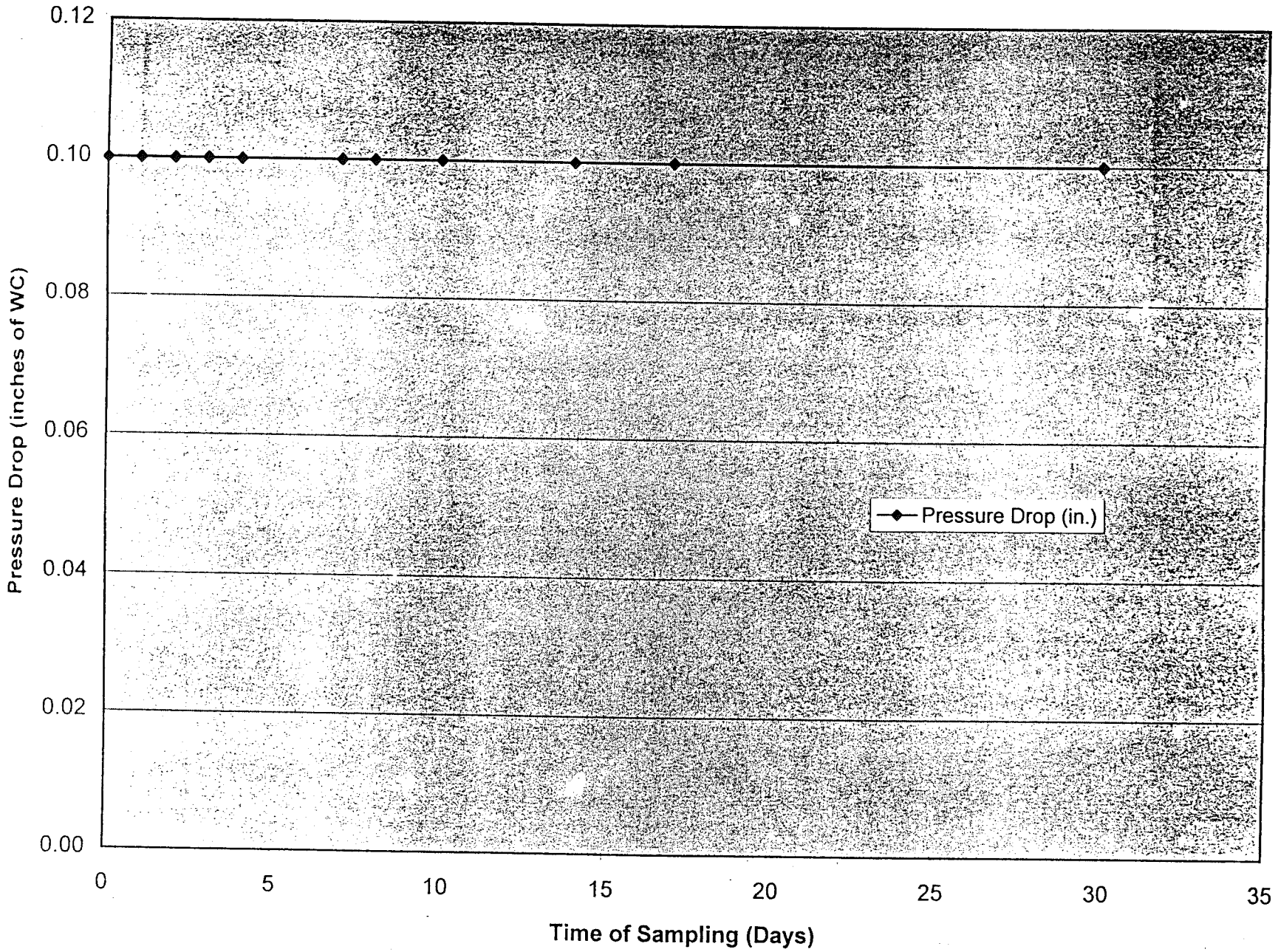

Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s)
Performance Data, After Start-up
Percent Removal @ Outlet(%)
Inlet H2S Conc. (ppm)
Outlet H2S Conc. (ppm)
Percent Removal of H2S (%)
H2S Concentration (ppm v/v)
Time of Sampling (Days)
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
5
10
15
20
25
30
35


Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s)
Removal Data @ 1 ft Intervals
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
H2S Concentration (ppm v/v)
0
5
10
15
20
25
30
35
Time of Sampling (Days)
Inlet H2S Conc. (ppm)
H2S Conc. @ 1 ft (ppm)
H2S Conc. @ 2 ft (ppm)
H2S Conc. @ 3 ft (ppm)
H2S Conc. @ 4 ft (ppm)
H2S Conc. @ 5 ft (ppm)
H2S Conc. @ 6 ft (ppm)
Outlet H2S Conc. (ppm)

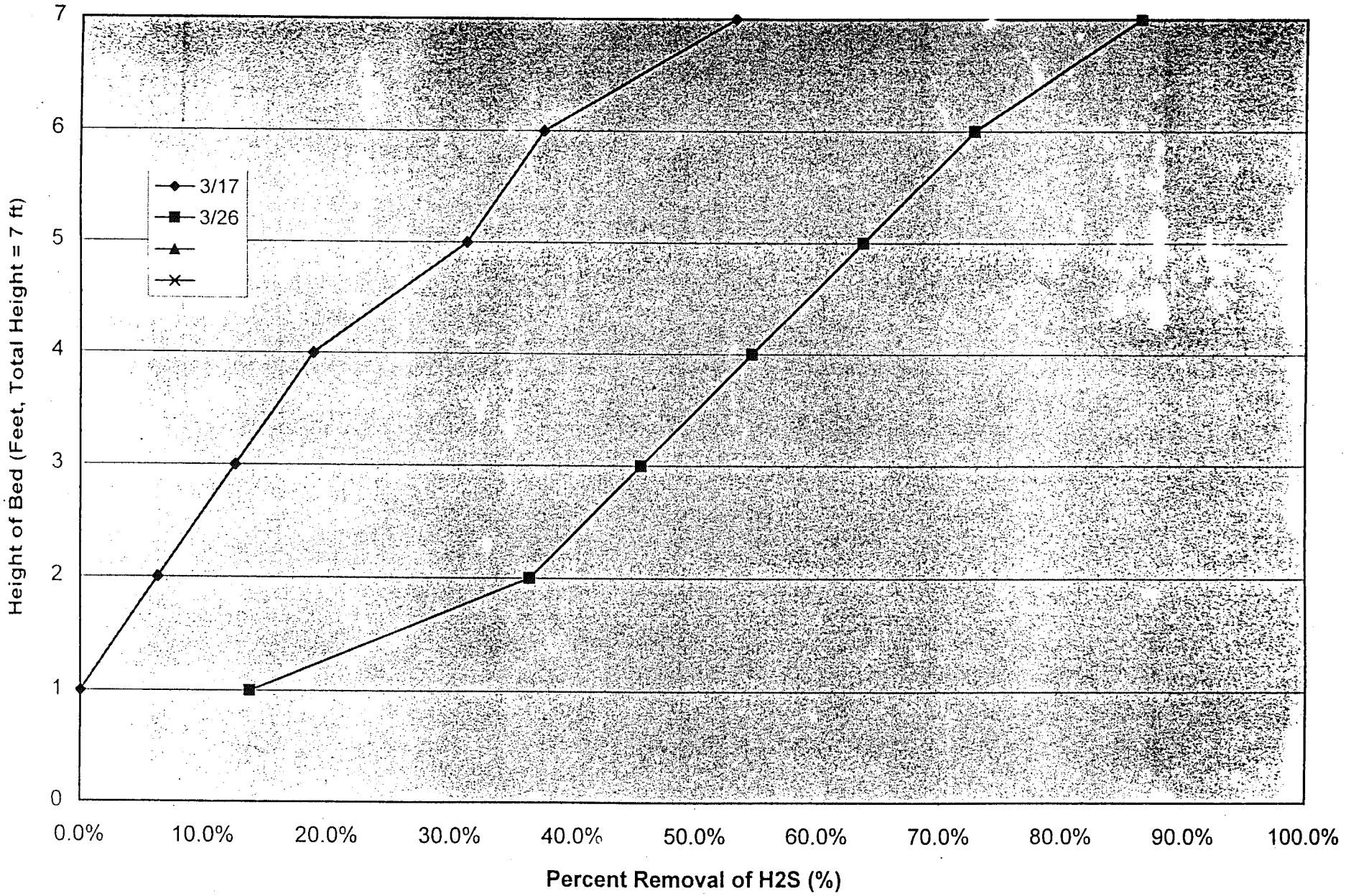

Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s)
Percent Removal of H2S @ 1 ft Intervals
Percent Removal @ Outlet(%)
Percent Removal @ 6 ft (%)
Percent Removal @ 5 ft (%)
Percent Removal @ 4 ft (%)
Percent Removal @ 3 ft (%)
Percent Removal @ 2 ft (%)
Percent Removal @ 1 ft (%)
Percent Removal of H2S (%)
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0
5
10
15
20
25
30
35
Time of Sampling (Days)

Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s)
pH of Sump




Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s)
Pressure Drop, inches of WC
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Pressure Drop (inches of WC)
Pressure Drop (in.)
0
5
10
15
20
25
30
35
Time of Sampling (Days)

Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s)
Percent Removal vs. Height of Bed, on Select Days



Biotrickling Filter South (Random Plastic, 700 cfm, Td=10 s)

Date	3/9	3/10	3/11	3/12	3/13	3/16	3/17	3/19	3/23	3/26	4/8
Time	3:00 PM	3:00 PM	3:00 PM	3:00 PM	3:00 PM	3:00	3:00	3:00	3:00	3:00	3:00
Hours (cum.)	0	24	48	72	96	168	192	240	336	408	720
Days (cum.)	0	1	2	3	4	7	8	10	14	17	30
Air Flow Rate (cfm)	700	700	700	700	700	700	700	700	700	700	700
Recirc. Rate (gpm)	8	8	8	8	8	8	8	8	8	8	8
pH of Sump	2.3	6.1	5.9	5.9	4.9	4.3	4.5	3.9	3.8	2.0	1.2
Make-up Water Totalizer (gal)	1460	1570	1570	1570	1570	1570	1570	1735	2110	2281	3141
Pressure Drop (in.)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Outlet H_2S Conc. (ppm)	24.0	18.0	8.0	3.0	8.0	12.0	15.0	8.0	3.5	3.0	11.0
H_2S Conc. @ 6 ft (ppm)		20.0	10.0	4.0	13.0	18.0	20.0	14.0	5.0	6.0	13.0
H_2S Conc. @ 5 ft (ppm)		22.0	14.0	5.0	18.0	20.0	22.0	18.0	7.6	8.0	16.0
H_2S Conc. @ 4 ft (ppm)		24.0	18.0	6.0	20.0	24.0	26.0	22.0	8.4	10.0	19.0
H_2S Conc. @ 3 ft (ppm)		26.0	22.0	8.0	24.0	26.0	28.0	24.0	10.2	12.0	22.0
H_2S Conc. @ 2 ft (ppm)		28.0	26.0	10.0	26.0	28.0	30.0	28.0	11.4	14.0	24.0
H_2S Conc. @ 1 ft (ppm)		28.0	28.0	12.0	30.0	30.0	32.0	32.0	14.2	19.0	26.0
Inlet H_2S Conc. (ppm)	24.0	28.0	30.0	16.0	42.0	34.0	32.0	34.0	22.0	22.0	29.0
Percent Removal @ Outlet(%)	0.0%	35.7%	73.3%	81.3%	81.0%	64.7%	53.1%	76.5%	84.1%	86.4%	62.1%

NOTE: lava rock bed depth = 7'

Project Tasks

1. Sulfide analysis: The most appropriate method of sulfide analysis will be selected during the first month of the project. If the instrumental method has satisfactory sensitivity it will be used. Responsibility for task 1 will be joint between UC Riverside and UC Davis.

2. Biotrickling filter modification: Laboratory-scale biofilter and biotrickling filter system modifications will be carried out at Davis and Riverside, respectively.

3. Phase I experiments: The experiments will be conducted at the respective campuses. Changes in segment will be made at the same time at both institutions to the extent possible.

4. Biofilter construction, biotrickling filter modification: The biofilter will be constructed at Davis. The pilot/full-scale biotrickling filter will be modified at UC Riverside.

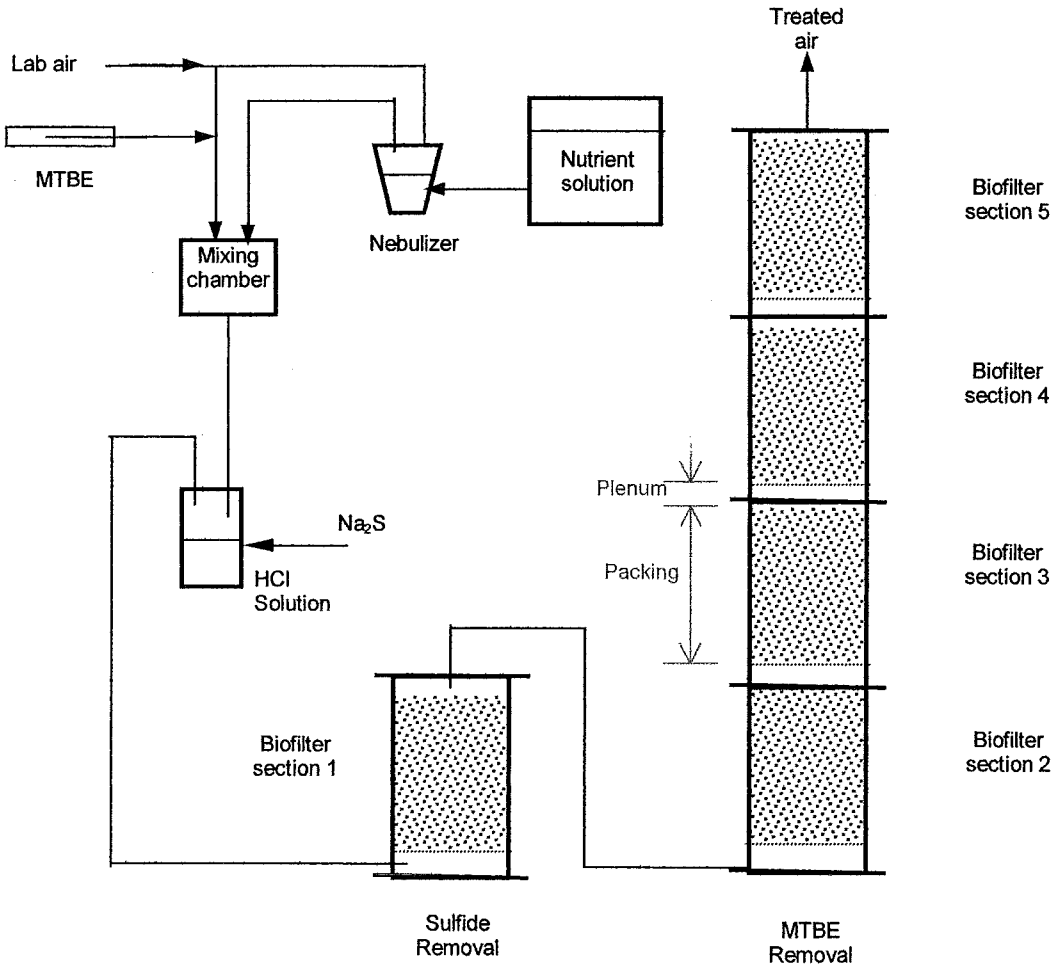
5. Selection of POTW: The selection of a POTW at which to carry out the Phase II field tests will be made in cooperation with the WERF Project Review Committee. The ideal location would be a treatment plant receiving significant amounts of VOCs and located as close to one of the campuses as possible. The selection will be made within the first six months of the project.

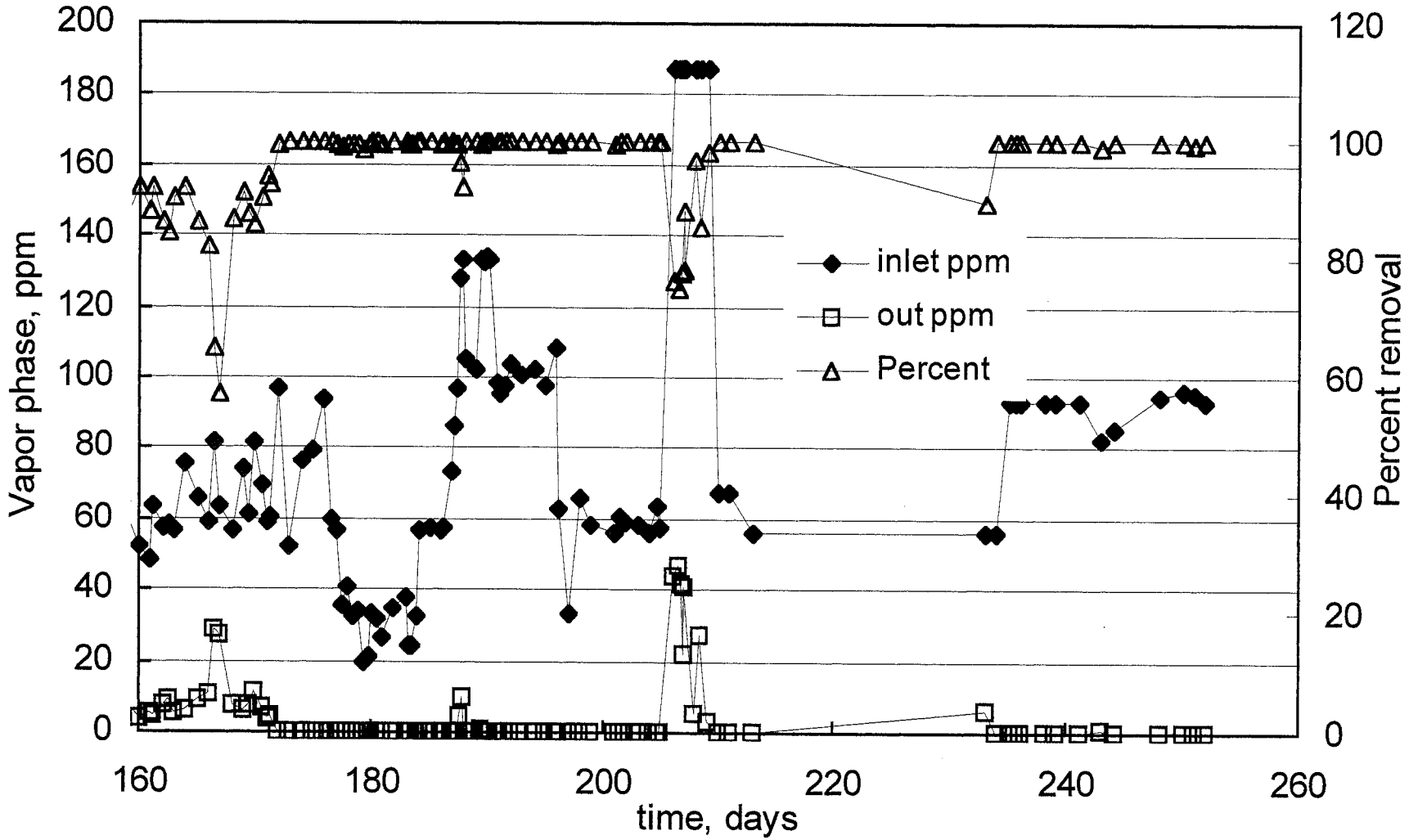
6. Microbial seed development: Development of approximately 2 kg dry weight of MTBE degrading organisms will be desirable for use as part of the microbial seed. Addition of 1 kg of microorganisms to each unit will ensure a rapid start-up. Seed development will be conducted at Davis to allow both systems to start with the same culture.

7. Mobilization and installation of the reactors: The biofilter and the biotrickling filter will be moved to the POTW by the UCD and UCR teams, respectively. The reactors will be connected to the POTW.

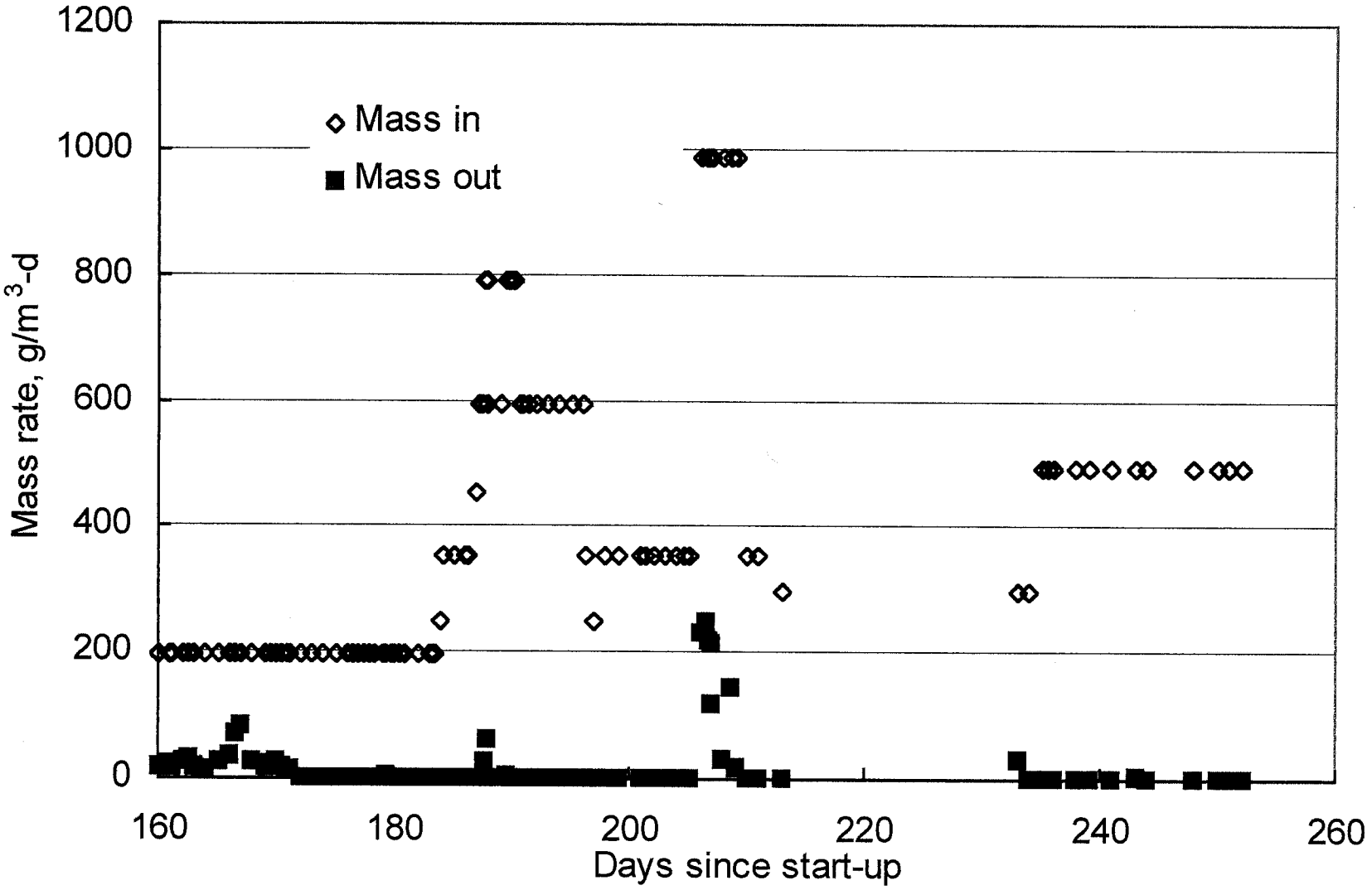
8. Method development and training of the UCR-UCD teams for olfactometry measurements.

9. Phase II experiments: The Phase II experiments will be conducted using researchers from both UC Riverside and UC Davis. Weekly visits to the site are planned. Automatic sampling and data logging will be carried out using the PLC. The host plant will be expected to contribute to some system maintenance.

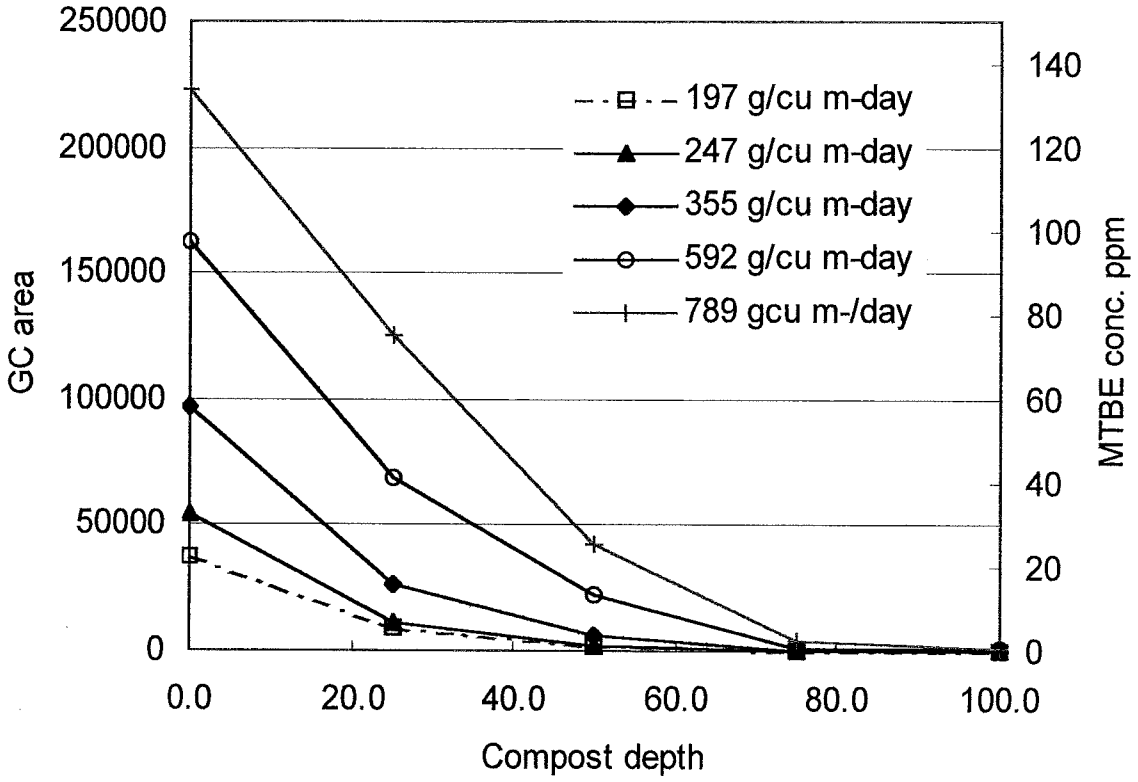

Treated air
Lab air
MTBE
Nutrient solution
Nebulizer
Mixing chamber
Biofilter section 5
Biofilter section 4
Plenum
Packing
Biofilter section 3
Na_2S
HCl Solution
Biofilter section 1
Biofilter section 2
Sulfide Removal
MTBE Removal



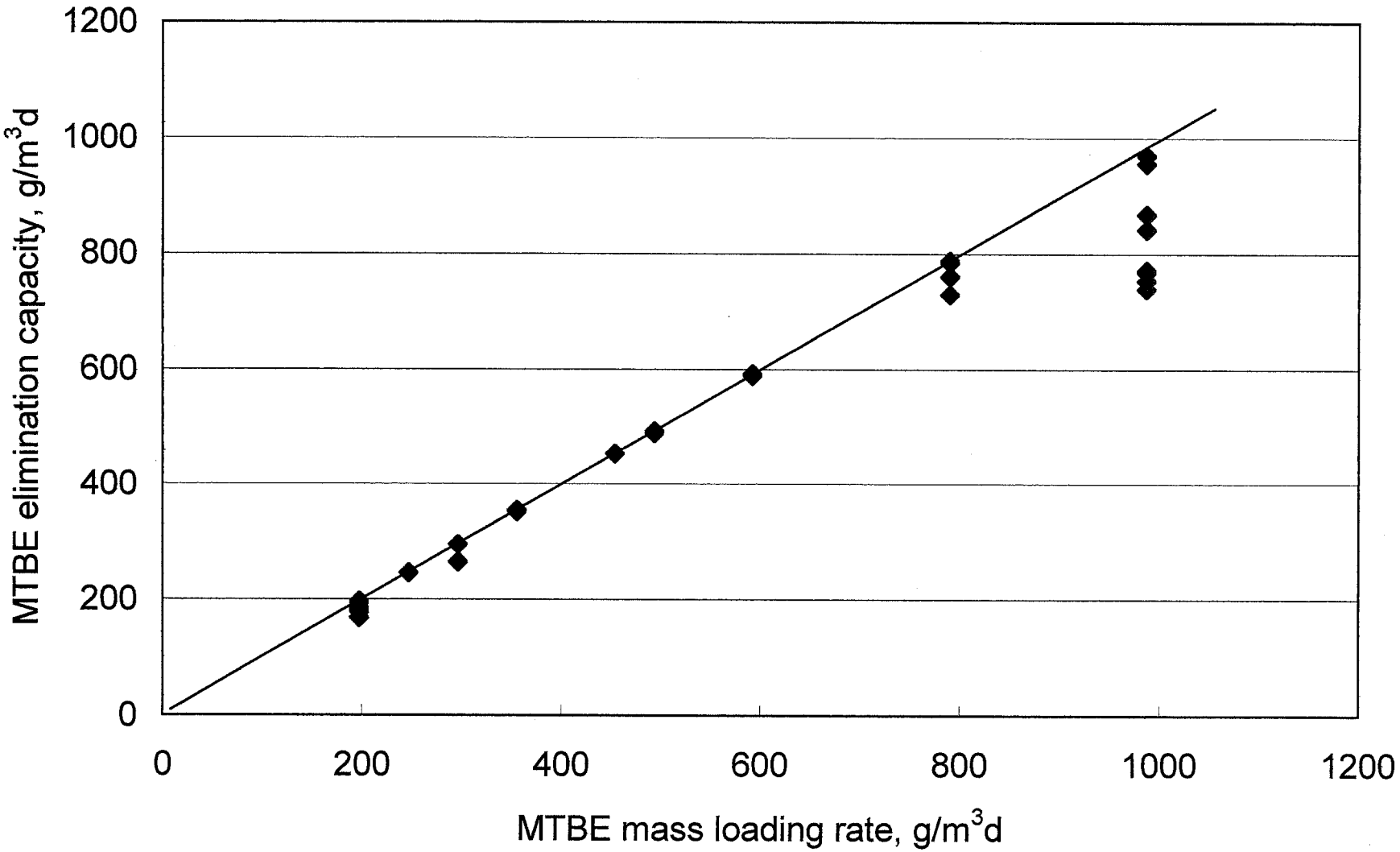
Inlet and outlet concentrations from day 160 to day 250 of laboratory compost biofilter operation. Percent removal is shown on the right ordinate. The EBCT was one minute from day 180 onward



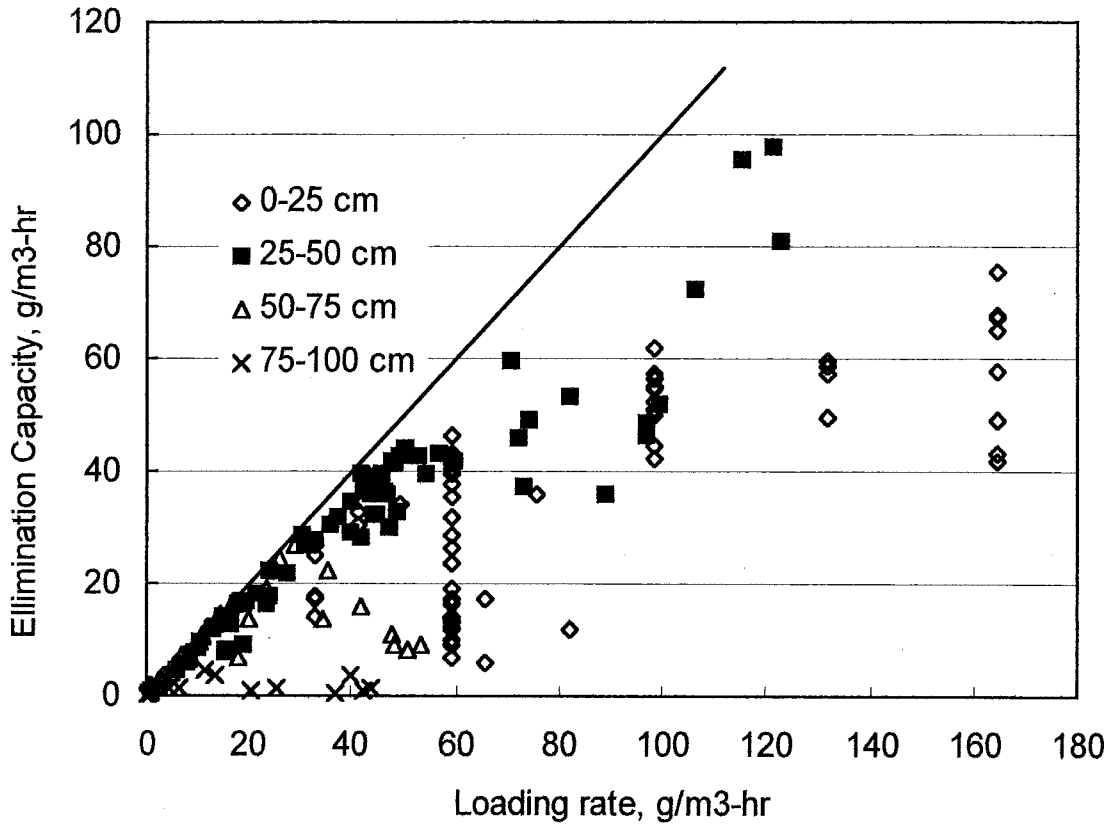
Inlet and outlet mass MTBE rates from day 160 to day 250 of laboratory compost biofilter operation. The EBCT was one minute day 180 onward



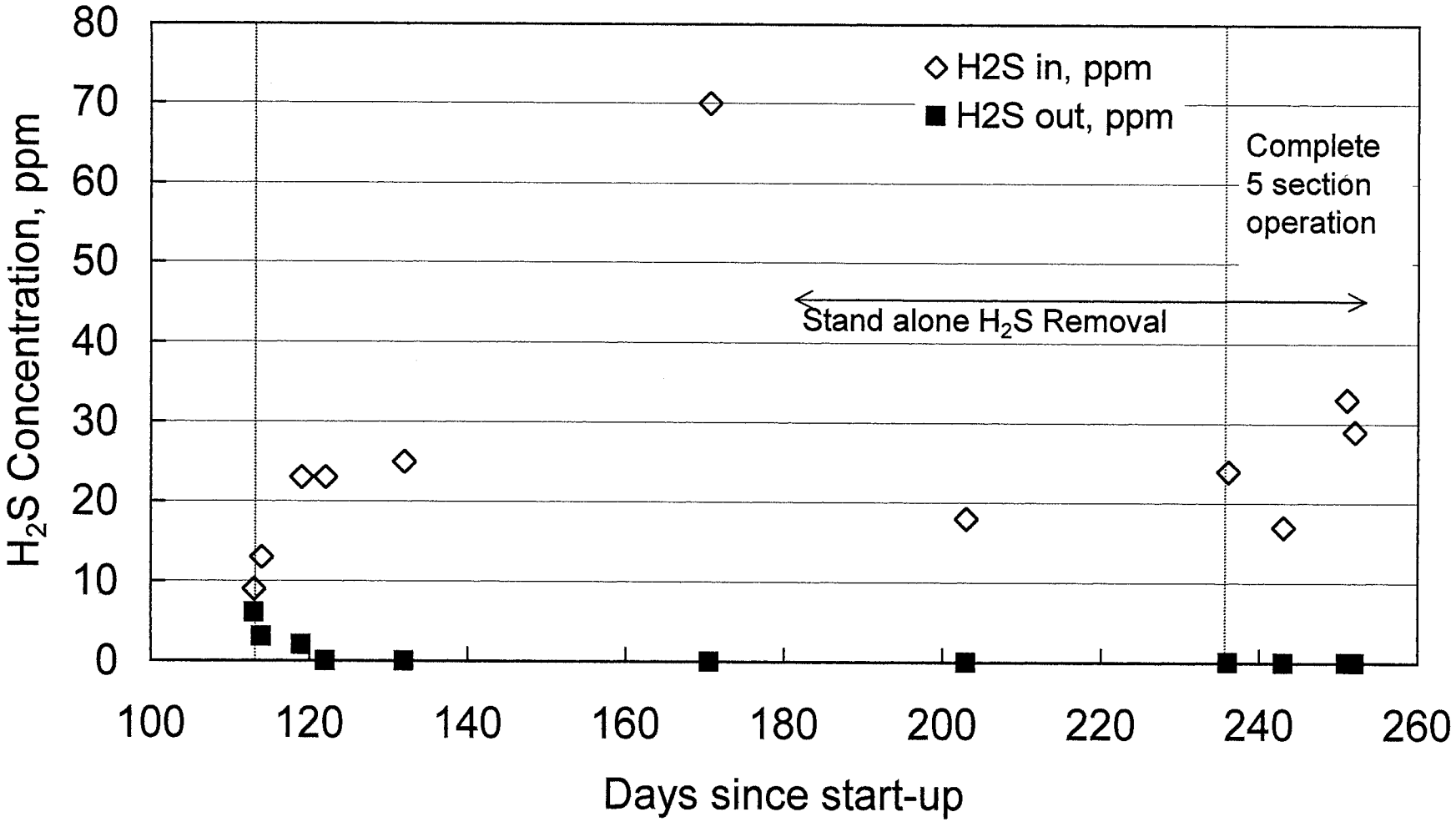
MTBE removal with depth of compost at selected loading rates



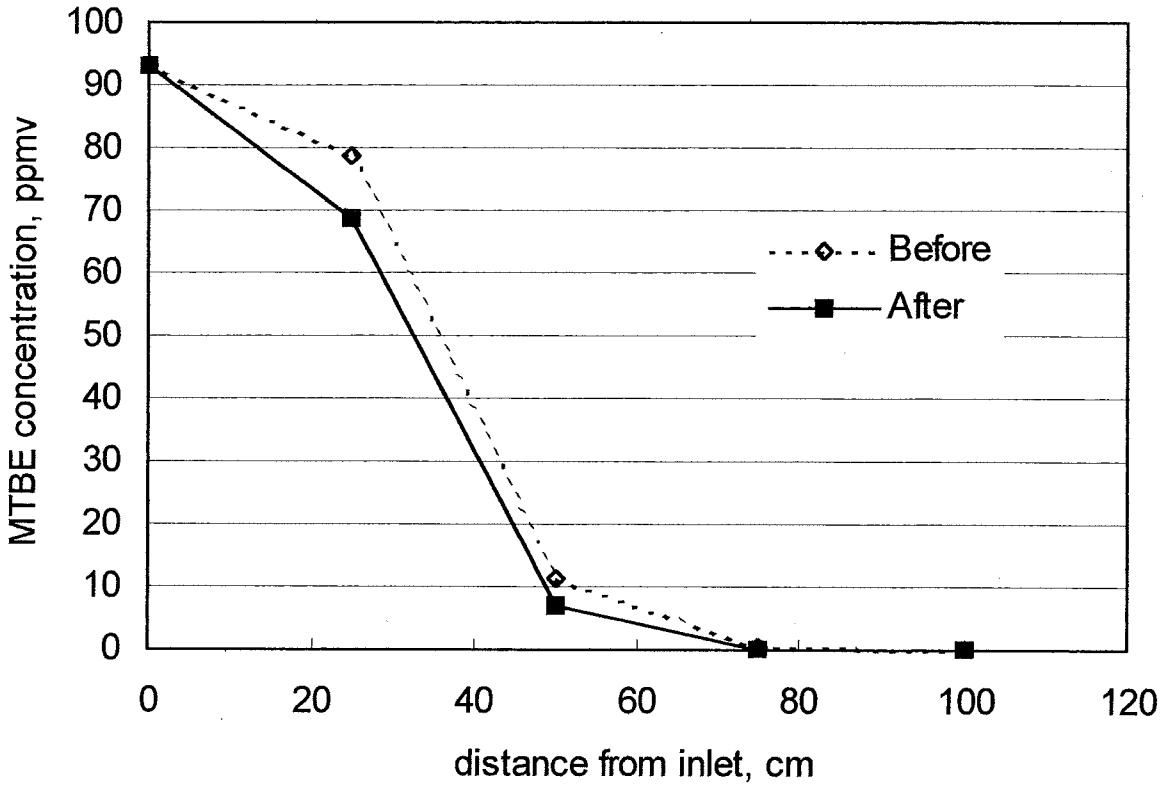
Elimination Capacity as a Function of Mass Loading.
EBCT = 1 minute



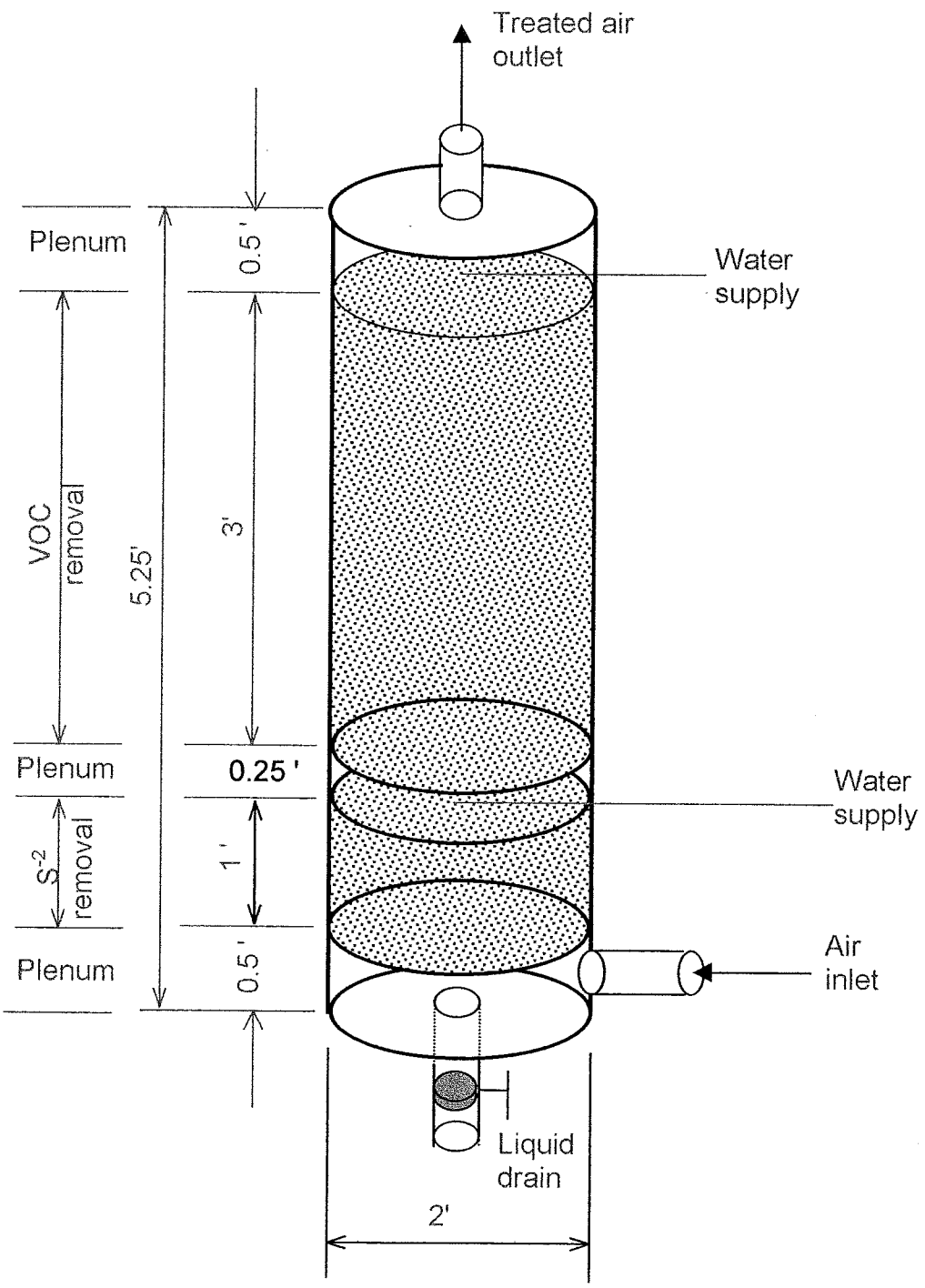
Elimination capacity by 25 cm section as a function of section loading rate

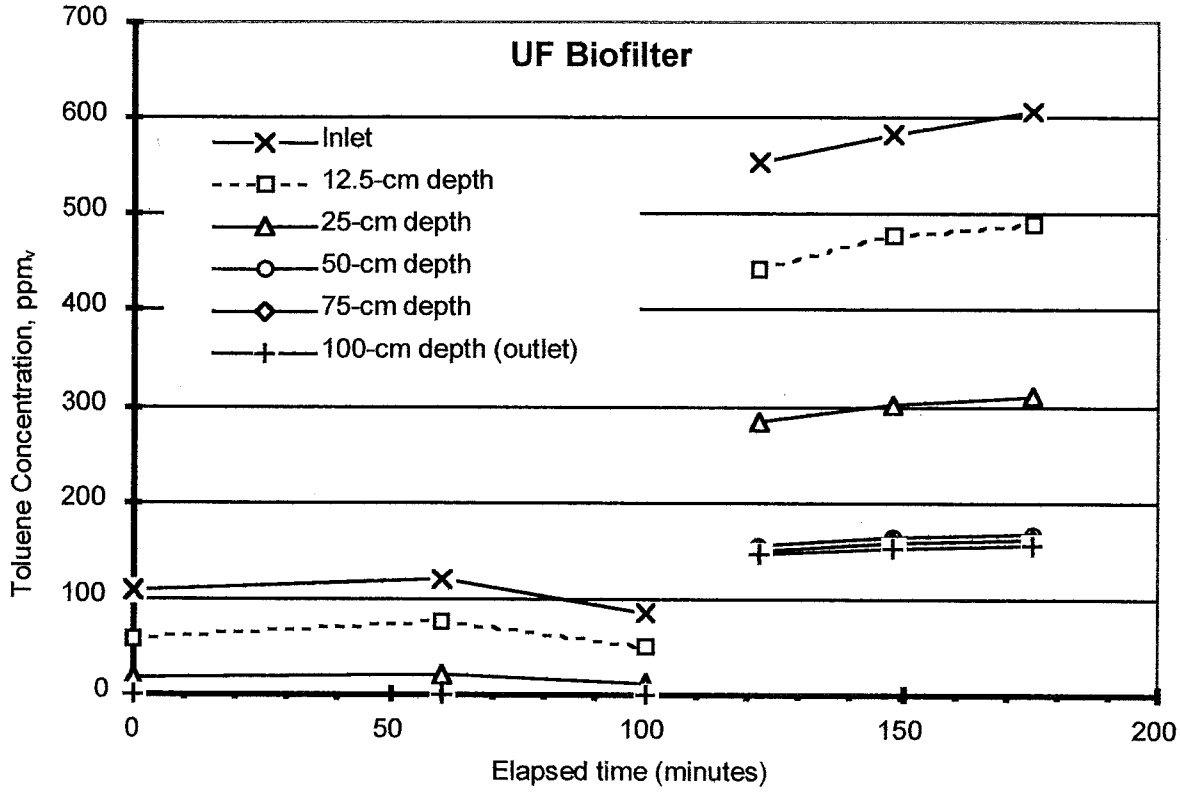


H_2S removal in 25 cm inlet section. Section was attached to MTBE removal unit at day 236

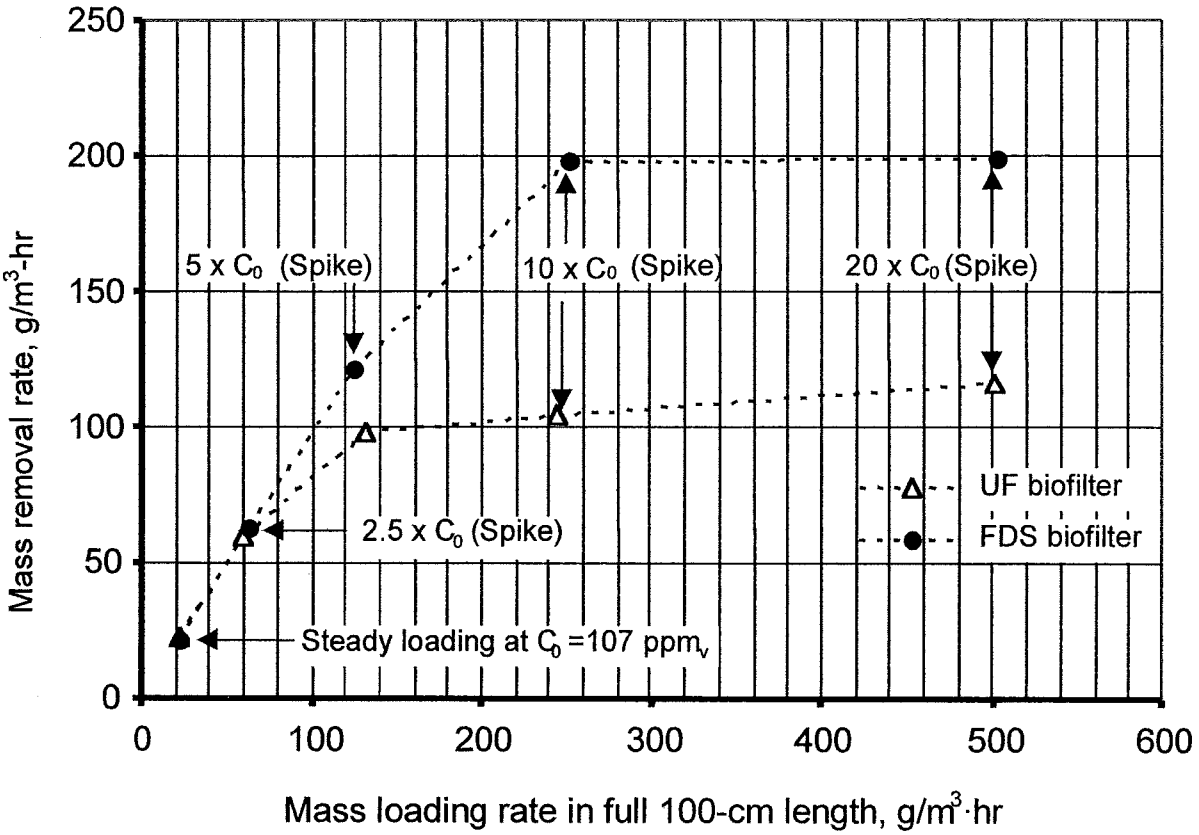


Removal of MTBE before and after introduction of the sulfide oxidation system

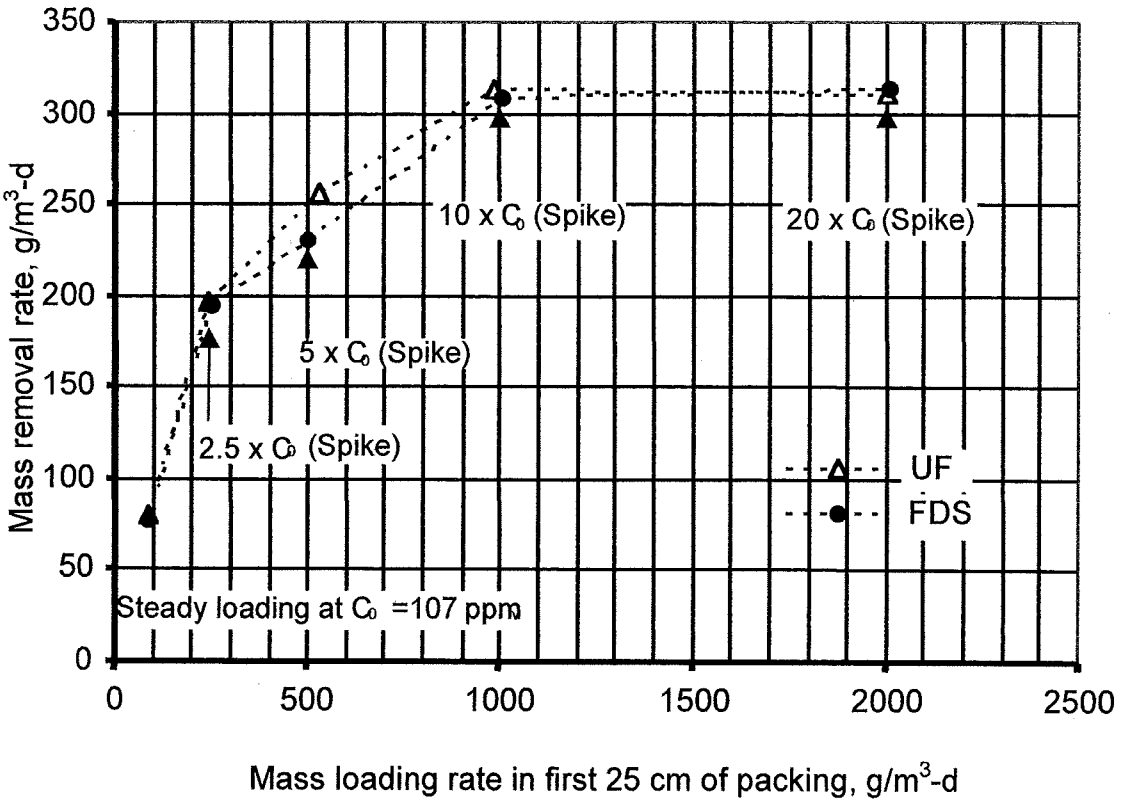

Treated air outlet
Plenum
0.5 '
Water supply
VOC removal
5.25'
3'
Plenum
0.25 '
Water supply
S-2 removal
1 '
Air inlet
Plenum
0.5 '
Liquid drain
2'



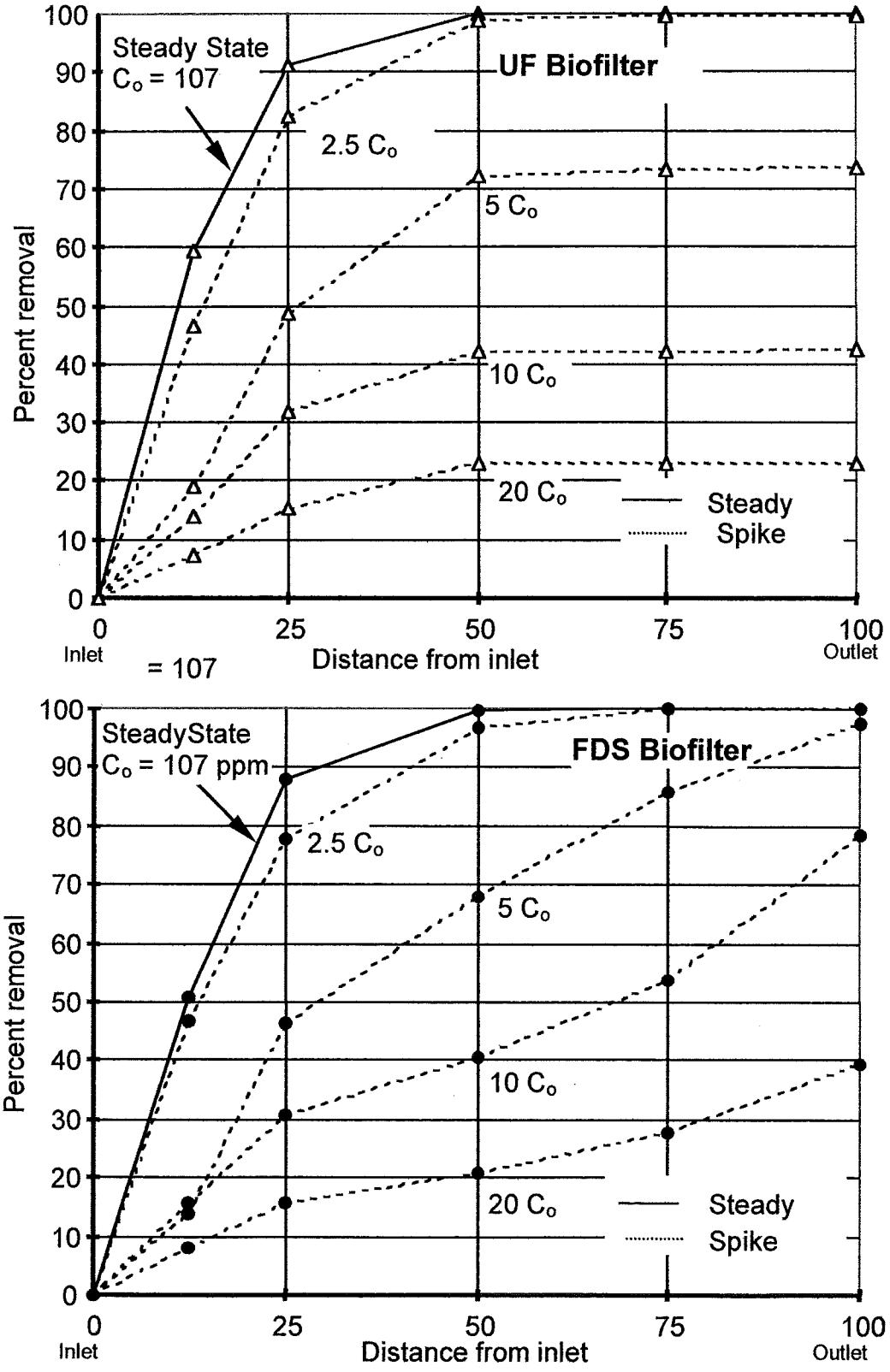
Response of unidirectional flow biofilter to $5xC_o$ spike



Relationship between mass loading rate and mass removal rate for 1-m unit.



Relationship between mass loading rate and mass removal rate in the first 25-cm of bed depth.



Response of unidirectional flow and directional switching flow biofilters to spikes in inlet concentration

Combined VOC and Odor Treatment

Marc A. DESHUSSES
Huub H.J. COX
Department of Chemical and Environmental Engineering
University of California Riverside

Outline

- Introduction
- Summary of Year 1 results (UCR)
  - MTBE and H_2S removal
  - Toluene and H_2S removal
- Year 2 research

Project Objectives and Organization

- Evaluate the feasibility and efficacy of treating VOCs and odor (H_2S) in biofilters and biotrickling filters
  - Performance
  - Simultaneous treatment vs. sequential, reactor design
  - Effect of pH
  - O&M
- Year 1 = Laboratory studies; Year 2 = Field studies
- UC Riverside (M. Deshusses) focuses on biotrickling filters
  UC Davis (E. Schroeder) focuses on biofilters

Definitions

- Removal = $\frac{\text{Inlet - Outlet concentration}}{\text{Inlet concentration}}$ (%)
- Loading = $\frac{\text{Inlet concentration} \times \text{Air flow}}{\text{Bed volume}}$ ($g\ m^{-3}\ h^{-1}$)
- Elimination capacity = $\frac{(\text{Inlet - Outlet concentration}) \times \text{Air flow}}{\text{Bed volume}}$ ($g\ m^{-3}\ h^{-1}$)
- EBRT = $\frac{\text{Bed volume}}{\text{Air flow}}$ (s)
- Volumetric loading = $\frac{\text{Air flow}}{\text{Bed volume}}$ ($m^3\ m^{-3}\ h^{-1}$)

Summary of Year 1: UC Riverside

- Work with **MTBE** (20 rotating biotrickling filters) ... and **H_2S**
  - Startup phase (pH, packing, culture)
  - Performance with MTBE only (flow, concentration, robustness)
  - Effect of adding H_2S
- Work with **toluene** (2 conventional biotrickling filters) ... and **H_2S**
  - Startup phase at two different pH (7 and 4.5)
  - Performance under various conditions (flow, concentration, transient)
  - Microbiological studies
- Preparation of field work

MTBE and H_2S Biodegradation in Biotrickling Filters: Summary of the Results

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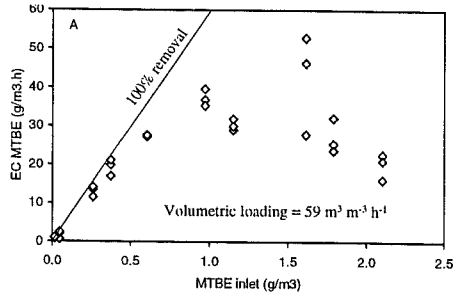
MTBE Removal (alone)



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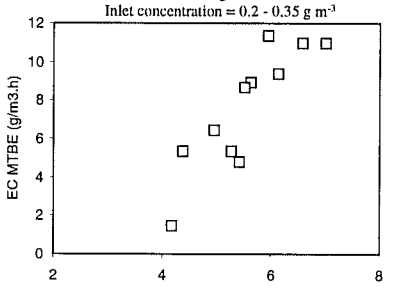

H_2S Removal in MTBE Degrading Biotrickling Filters

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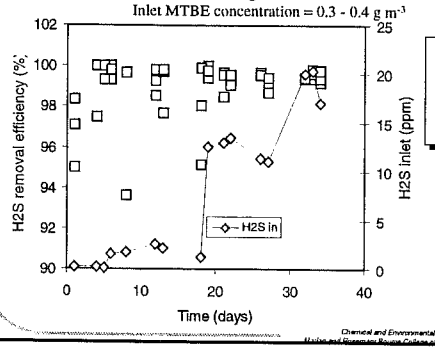

- H_2S is removed
- No effect on MTBE removal

Toluene and H_2S Biodegradation in Biotrickling Filters: Summary of the Results

- The startup was rapid at pH 7.0. At pH 4.5, startup was slow (2-4 weeks)
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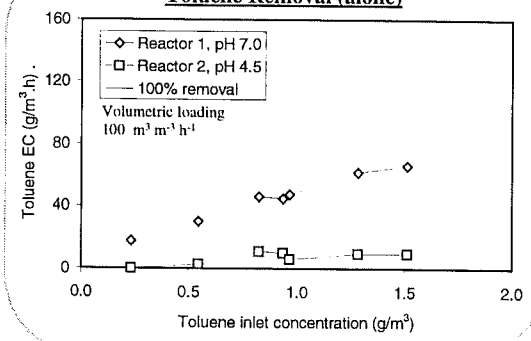
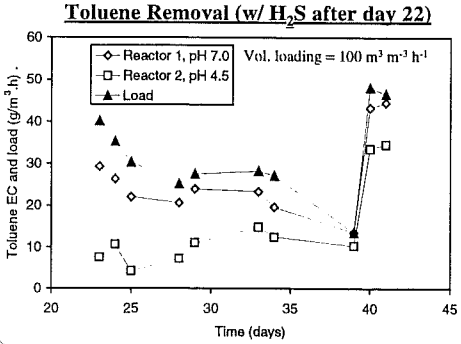
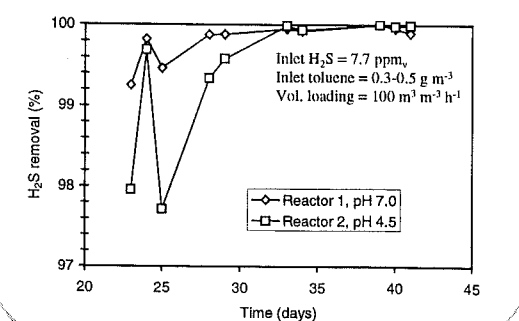


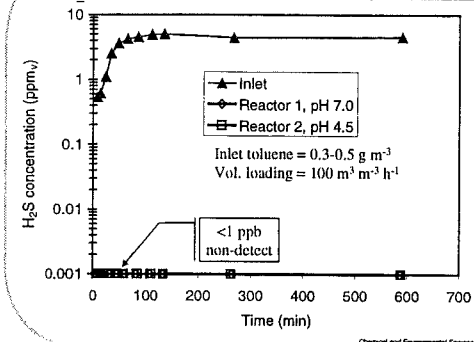
Toluene Removal (w/ H_2S after day 22)



H_2S Removal in the Presence of Toluene



H_2S Removal: Restart after 7 Days without H_2S



Focus for Year 2: UC Riverside

- Removal performance under "real" conditions (complex mixture, changing conditions, larger scale, ...)
- Rate limiting step identification, effect of pH
- Use of secondary effluent water as nutrient/water feed
- Characterization of liquid effluent
- Specific experiments (removal of MTBE, microbiology, mass transfer, ...)
- O&M and monitoring requirement, scale-up, treatment costs

Combined VOC and Odor Treatment

Marc A. DESHUSSES
Huub H.J. COX
Department of Chemical and Environmental Engineering
University of California Riverside

Outline

- Introduction
- Summary of Year 1 results (UCR)
  - MTBE and H_2S removal
  - Toluene and H_2S removal
- Year 2 research

Project Objectives and Organization

- Evaluate the feasibility and efficacy of treating VOCs and odor (H_2S) in biofilters and biotrickling filters
  - Performance
  - Simultaneous treatment vs. sequential, reactor design
  - Effect of pH
  - O&M
- Year 1 = Laboratory studies; Year 2 = Field studies
- UC Riverside (M. Deshusses) focuses on biotrickling filters
  UC Davis (E. Schroeder) focuses on biofilters

Definitions

- Removal = $\frac{\text{Inlet - Outlet concentration}}{\text{Inlet concentration}}$ (%)
- Loading = $\frac{\text{Inlet concentration} \times \text{Air flow}}{\text{Bed volume}}$ (g m^{-3} h^{-1})
- Elimination capacity = $\frac{(\text{Inlet - Outlet concentration}) \times \text{Air flow}}{\text{Bed volume}}$ (g m^{-3} h^{-1})
- EBRT = $\frac{\text{Bed volume}}{\text{Air flow}}$ (s)
- Volumetric loading = $\frac{\text{Air flow}}{\text{Bed volume}}$ (m^3 m^{-3} h^{-1})

Summary of Year 1: UC Riverside

- Work with **MTBE** (20 rotating biotrickling filters) ... and **H_2S**
  - Startup phase (pH, packing, culture)
  - Performance with MTBE only (flow, concentration, robustness)
  - Effect of adding H_2S
- Work with **toluene** (2 conventional biotrickling filters) ... and **H_2S**
  - Startup phase at two different pH (7 and 4.5)
  - Performance under various conditions (flow, concentration, transient)
  - Microbiological studies
- Preparation of field work

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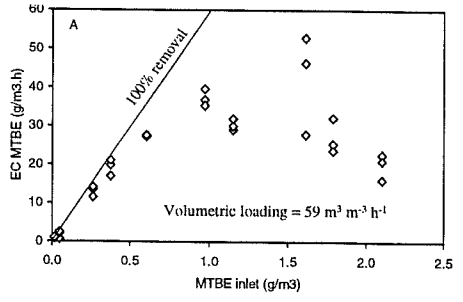

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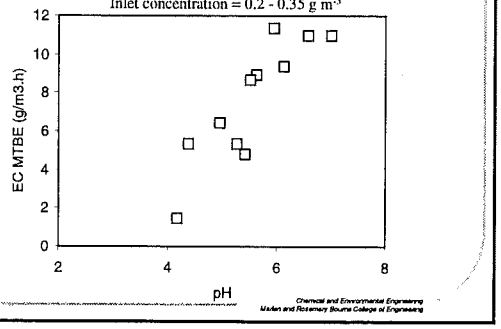

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Marlan and Rosemary Bourns College of Engineering

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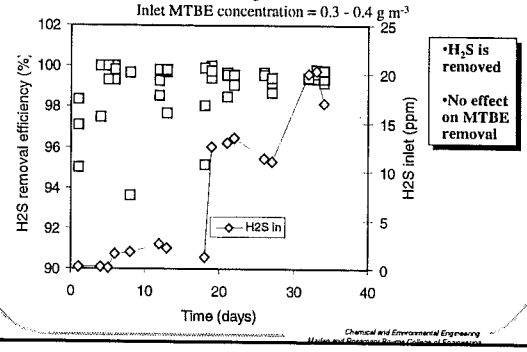

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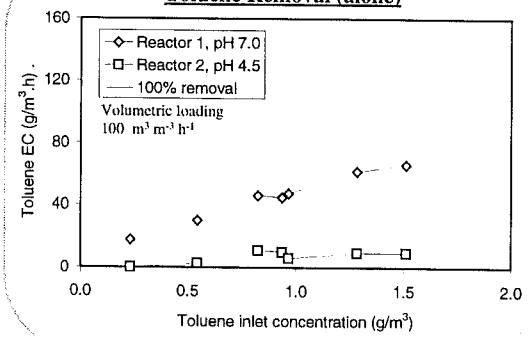

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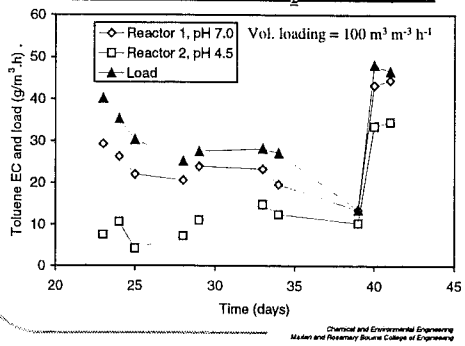
Toluene Removal (w/ H_2S after day 22)



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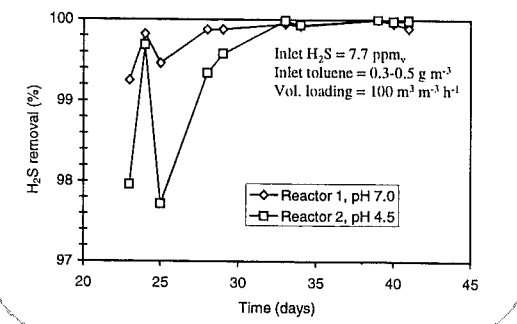

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UNIVERSITY OF CALIFORNIA RIVERSIDE

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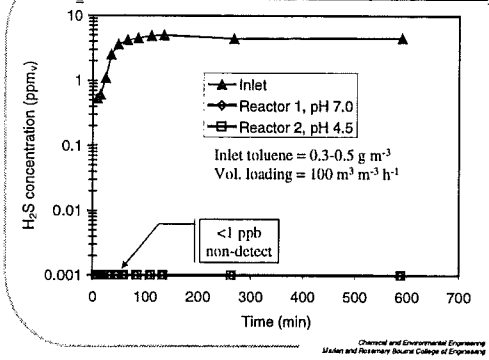

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- Characterization of liquid effluent
- Specific experiments (removal of MTBE, microbiology, mass transfer, ...)
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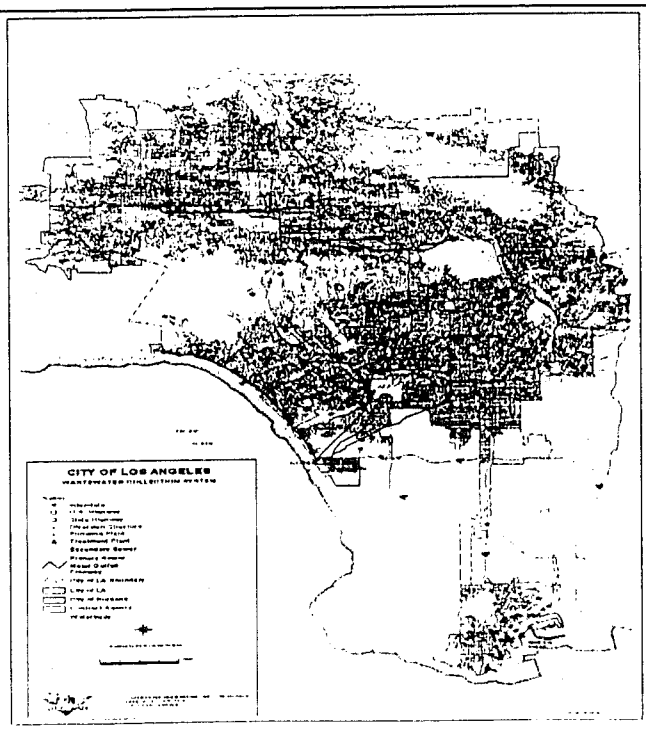
City of Los Angeles

Odor Control Is a Significant Issue for the City of Los Angeles' New East Central Interceptor Sewer

James H. Clark, Gayle Van Durme, Patrick Molloy, and Andrew Lazenby
Black & Veatch
and
Baron Miya
City of Los Angeles

April 20, 2001

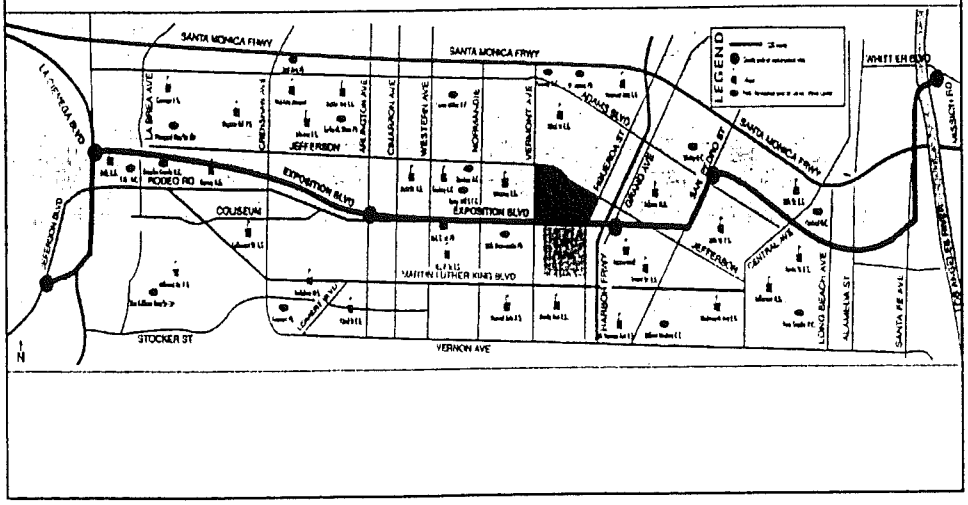
City of LA Collection System



Project Background

- Project Purpose - Provide odor control for new 11-foot diameter, 11.5 mile long East Central Interceptor Sewer (ECIS)
- Cease and Desist Order
  Compliance Deadline of January 1, 2004

ECIS Project



EIR Requirements

Drop Structures

- Seal maintenance holes 1 mile upstream and downstream
- Use liquid-phase treatment upstream and/or install vapor-phase control

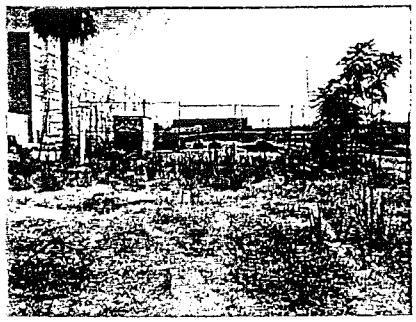
Inverted Siphon

- Seal maintenance holes 1 mile upstream and downstream
- Install air jumper

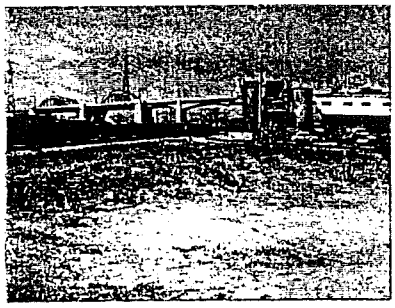
ECIS Odor Control Sites

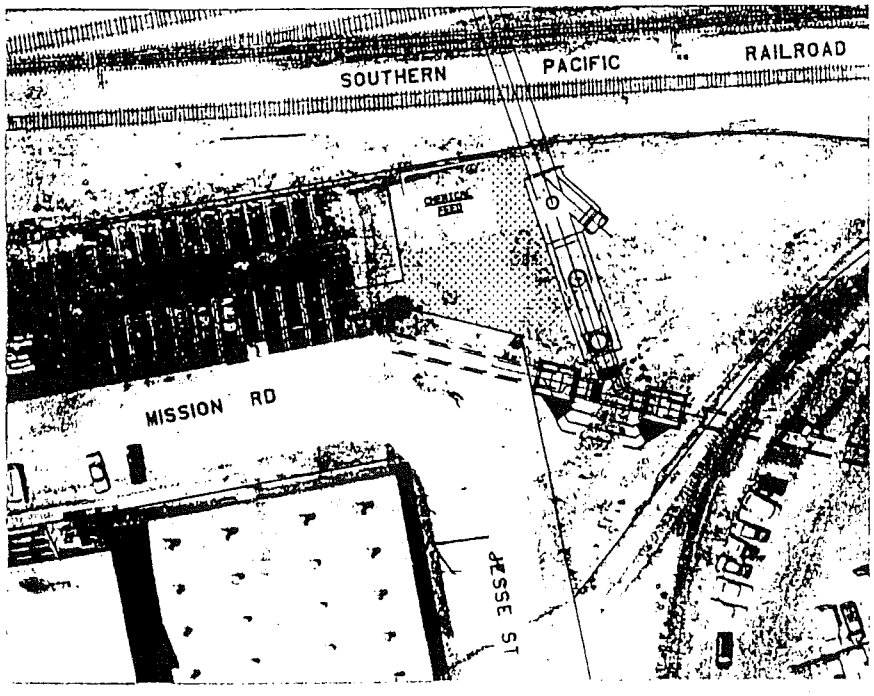
Areas of Turbulent Flow

Odor Control Site	Description	Possible Issues
Mission and Jesse	Industrial/Commercial	Graffiti Vandalism
San Pedro and 23rd	Residential	Graffiti Noise Physical Site Constraints (size) Proximity to Residences Vandalism
Jefferson Siphon	Commercial/Residential	Noise Proximity to Residences

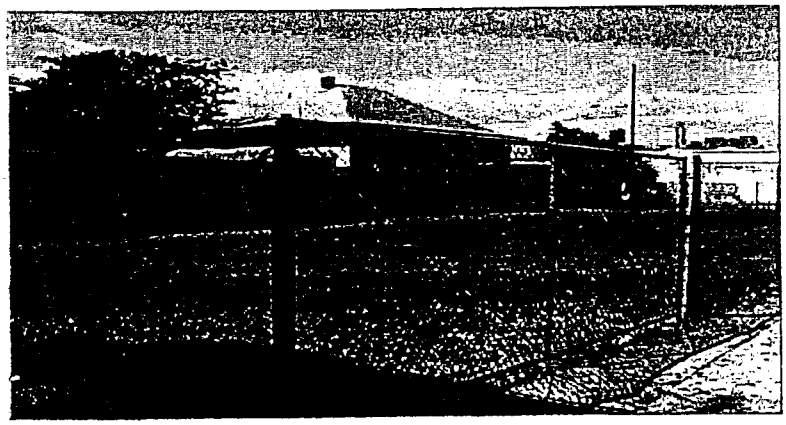


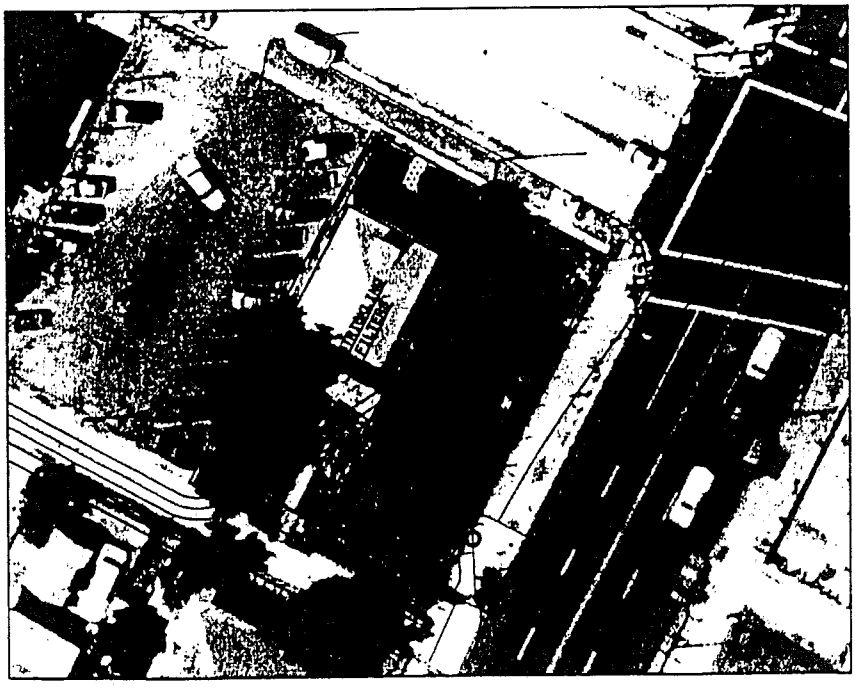
Mission & Jesse Drop Structure

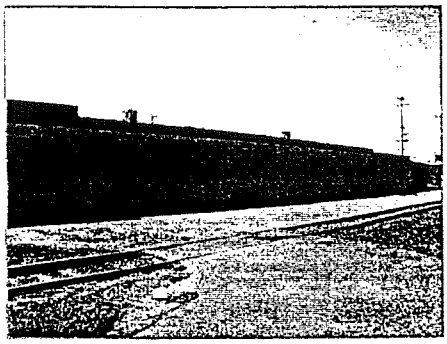


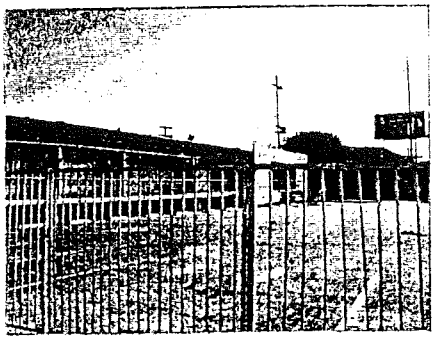


San Pedro and 23rd Diversion Structure/ Drop Structure





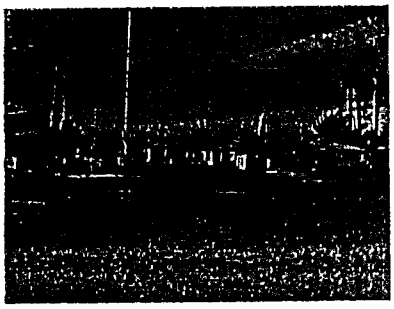






Jefferson Siphon

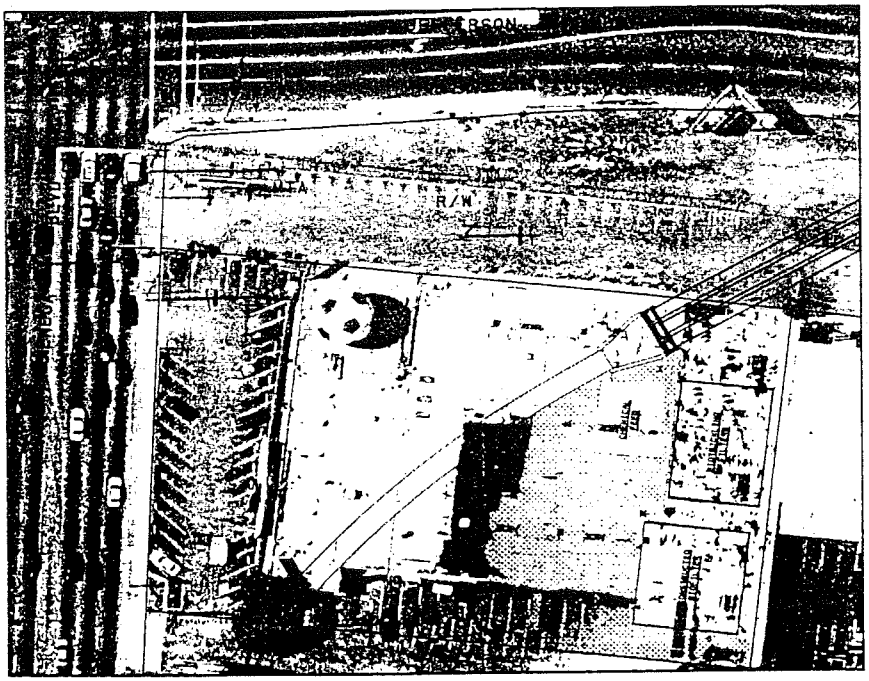




Jefferson Siphon

Surrounding Residences





Timeline

- Workshop No. 1 - June 1999
  - Liquid and vapor phase control technologies presented
- Workshop No. 2 - September 1999
  - Calgon Phoenix™ and Biofilters presented
  - Specific odor control sites evaluated
  - Architectural models presented
- Workshop No. 3 - June 2000
  - Demonstration testing, permitting, and site visits discussed
- Architectural Meeting - November 2000

Timeline

- VOC and Odor Testing January 2001
- Workshop No. 4 - February 1, 2001
- Collection System Pressure Testing - February to March 2001
- Workshop No. 5 - February 27, 2001
  - Final Decision on Odor Control Technologies

Issues

- First Odor Control Units in City Of LA Collection System
- Unattended Operation Required
- Must be Reliable and Effective
- Minimal O&M Attention
- Common Processes Desired

Initial Screening of Odor Control Alternatives

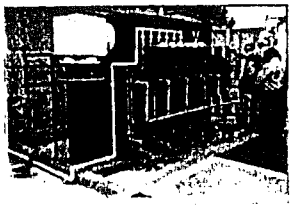
- Wet Scrubbers
  - Vertical Packed Scrubbers
  - R.J. Environmental
- Activated Carbon
  - Caustic Impregnated
  - Virgin Carbon
  - Centaur
  - Phoenix System
- Biofiltration
  - Constructed
  - Vendor Supplied
- Biotrickling Filters
  - Constructed
  - Vendor Supplied
- Chemical Addition
- Turbulence Reduction

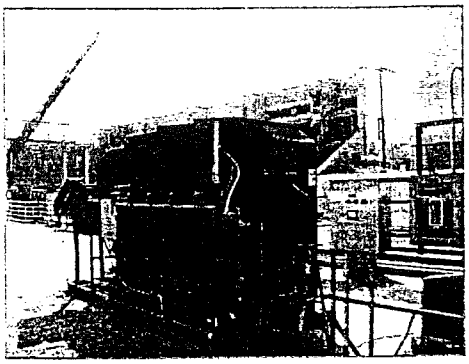
Site Visits

- Biofilters
  - Cleveland, Ohio
  - Houston, Texas



- Calgon Phoenix™ System
  - Alameda, California
  - Newport, Oregon



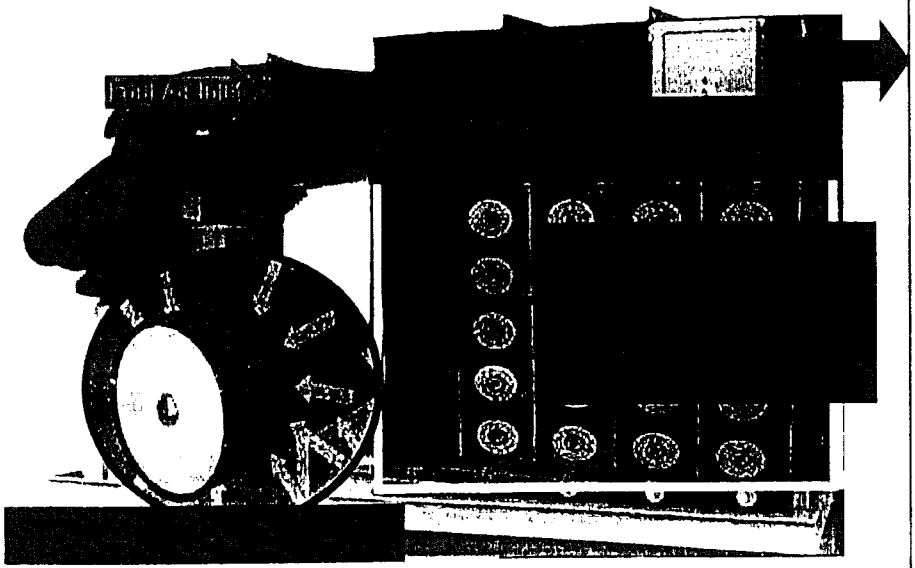


Demonstration Testing

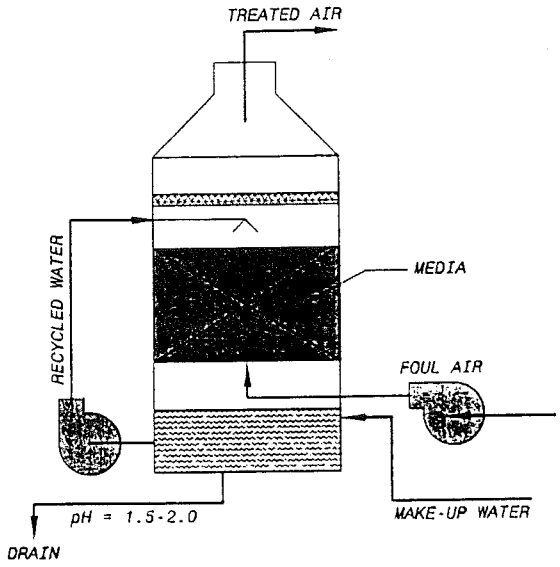


Carbon Adsorption

Calgon - Phoenix System



Biotrickling Filter



Preliminary Decisions

- Two Stage System
  - First stage removes majority of H_2S
  - Second stage acts as a polishing step
- Biotrickling Filter First Stage Treatment
  - Successful demonstration testing
  - Ability to economically treat high H_2S loads
  - Outlet stack easily connected to 2nd Stage

Ventilation Requirements

- Provide an empty sewer air velocity of 100 fpm
- Based on NFPA 820 guidance - 12 air changes/hour in drop structure

Ventilation Requirements

- Mission & Jesse Drop Structure - 9,500 cfm
- San Pedro and 23rd - 12,300 cfm
- Jefferson Siphon - 9,500 cfm

Original Preliminary Design Criteria

- Nominal 10,000 cfm foul air loading rate
- H_2S concentrations
  - Chemical Treatment Expected
    - First Stage - 20 ppm
    - Second Stage - 2 ppm

Short Listed Odor Control Alternatives

First Stage Treatment

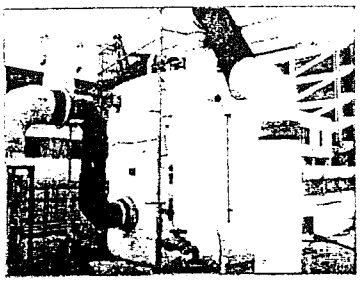
1. Biotrickling Filters

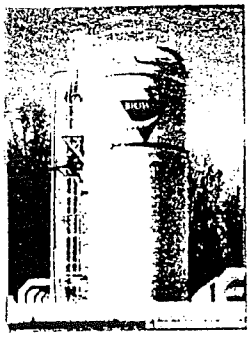
Second Stage Treatment

2. Biofilters
3. Calgon Phoenix™ System
4. Virgin Carbon

Biotrickling Filters

- Constructed
- Vendor Supplied
  - Harrington Bio-Scrubber
  - Bioway

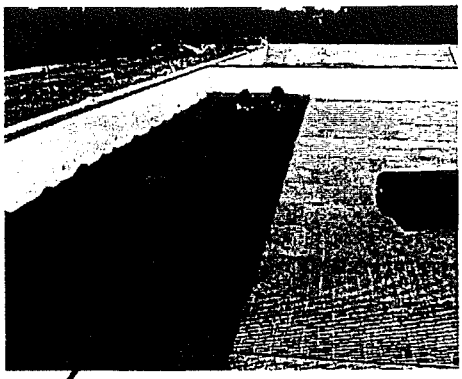




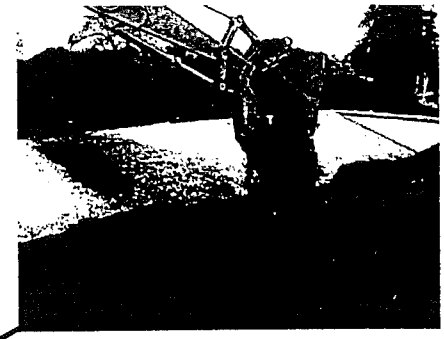
Constructed Biofilter

- Plenum Air Distribution System
  - Concrete walls with one sloped side for access
  - Mechanical equipment can be driven on plenum
  - 3 year life assumed
- Perforated Pipe
  - Earthen sloped walls
  - Perforated pipe replaced with media
  - 3 year life assumed
  - More media inspection and repair

Plenum Type Biofilter



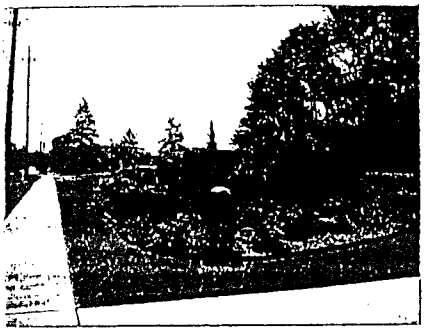
Plenum Air Distribution System



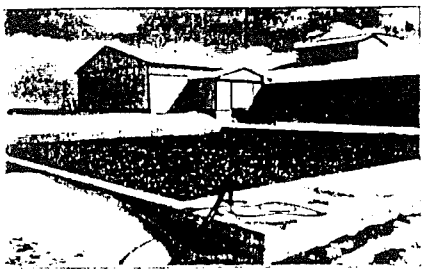
Media placement

Biofilters

- Constructed

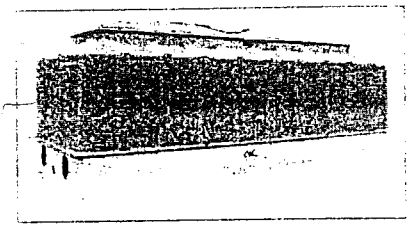


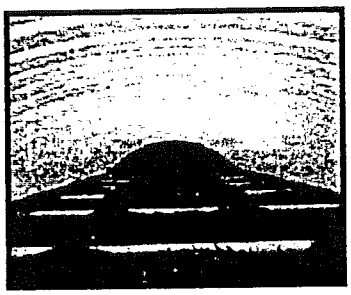
- Vendor Supplied
  - Biorem



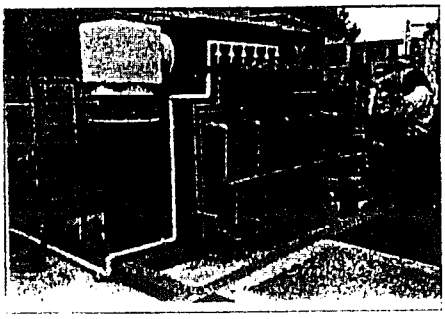
Biofilters

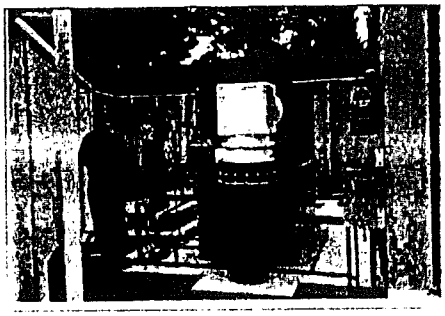
- Vendor Supplied
  - US Filter/Envirogen



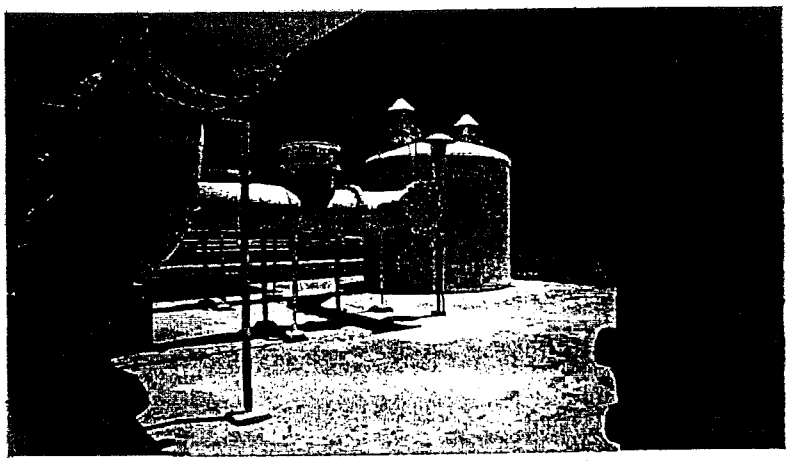


Calgon Phoenix™ System





Virgin Activated Carbon



New Issues

- City utilizes iron salts and caustic shock dosing
- Costs have increased over 130% during the past two years
- At current cost, chemical addition costs $810,000 annually for the NOS system

VOC Testing Results

- FID testing indicated that H_2S levels at Trinity peaked in early afternoon to 115 ppmv and decreased back to 80 ppmv by nightfall. (65 - 80 ppmv in early morning)
- Samples collected simultaneously at three sites along the collection system.
  - Gibbons and Cardinal
  - Trinity and 23rd
  - La Cienega
- Data showed some toxic VOC reduction from Phoenix™ System and minimal removal from Biotrickling Filter.

Predicted Health Risk

	Trinity	La Cienega
Maximum Exposed Individual (MEI)		
Carcinogenic Risk (in one million)	5.2	10.3
Chronic Hazard Index (CHI)	0.1	0.04
Acute Hazard Index (AHI)	0.3	0.05

*Concentrations measured at La Cienega assumed to occur at Trinity

Revised Preliminary Design Criteria

- Nominal 10,000 cfm foul air loading rate
- H_2S concentrations
  - Minimize chemical treatment cost
    - First Stage - 150 ppm (20 ppm original)
    - Second Stage - 20 ppm (2 ppm original)
      - Revised criteria eliminates carbon alternatives.
- T-BACT

Alternative Analysis

- Technology Evaluation
- Site Specific Layouts
- Lifecycle Cost Analysis

Biotrickling Filter Alternatives Cost Evaluation

	First Stage Treatment (Single Stage)		
	Constructed Biotrickling Filter	Harrington Bio-Scrubber	Bioway Purspring (1-Stage)
Capital Cost	$1,189,000	$1,197,000	$1,393,000
O&M Cost	$40,800	$39,800	$39,800
Present Worth[1]	$1,643,000	$1,640,000	$1,836,000

1. Assumes 20 year lifecycle with 6.38% interest rate.
Assumes housings, $0.12/kWh, and H_2S = 150 ppm

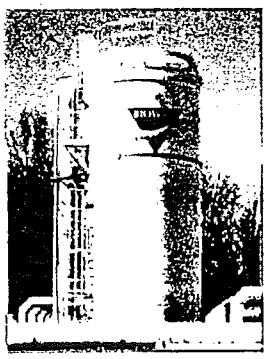
Biotrickling Filter Alternatives Cost Evaluation

	First Stage Treatment			
	Constructed Biotrickling Filter	Harrington Bio-Scrubber	Bioway Purspring (1-Stage)	Bioway Purspring (2-Stage)
Capital Cost	$1,189,000	$1,197,000	$1,393,000	$1,820,000
O&M Cost	$40,800	$39,800	$39,800	$44,300
Present Worth[1]	$1,643,000	$1,640,000	$1,836,000	$2,313,000

1. Assumes 20 year lifecycle with 6.38% interest rate.
Assumes housings, $0.12kWh, and H_2S = 150 ppm.

First Stage Treatment Recommendation

- Bioway 2-Stage Purspring Biotrickling Filter
  - Two stages provides redundancy and increased H_2S removal (99% compared to 75%)
  - Synthetic media with 10-year life
  - Nutrient problem solved
  - Proven design



Second Stage
Virgin Activated Carbon Cost Evaluation

H_2S Conc.	2 ppm		10 ppm		20 ppm	
$/lb.	$1.34/lb	$0.77/lb	$1.34/lb	$0.77/lb	$1.34/lb	$0.77/lb
Capital Cost	$602,000	$581,000	$602,000	$581,000	$602,000	$581,000
O&M Cost	$32,000	$26,000	$85,000	$57,000	$151,000	$95,000
Present Worth[2]	$958,000	$870,000	$1,548,000	$1,215,000	$2,282,000	$1,659,000

1. Assumes housing for carbon units and $0.12 kWh.
2. Assumes 20 year lifecycle with 6.38% interest rate.

Biofilter Alternatives Cost Evaluation

	Second Stage Treatment		
	Constructed Biofilter	Biorem Biofilter	USFilter Biofilter
Capital Cost	$561,000	$777,000	$475,000
O&M Cost	$30,300	$37,900	$45,100
Present Worth[1]	$898,000	$1,199,000	$977,000

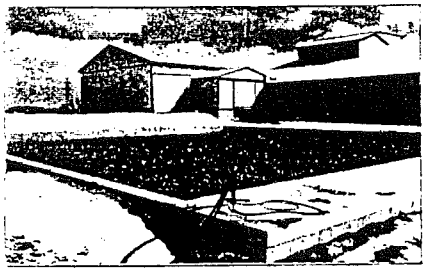
1. Assumes 20 year lifecycle with 6.38% interest rate.
Assumes housings, $0.12kWh and H_2S = 20 ppm

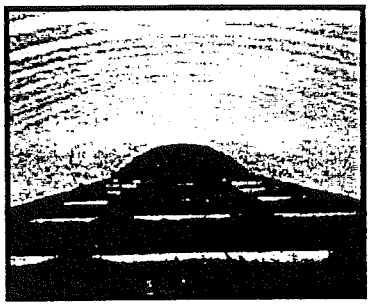
Selection Considerations

- VAC is favorable when considering no housing, H_2S = 2 ppm, and $0.77/lb replacement cost, and replacement interval based on odor removal only
- VAC easily permittable for VOCs.
- Biofilters are reported to provide VOC removal.
- Limited toxic VOC removal with Phoenix™ System.

Second Stage Treatment Recommendation

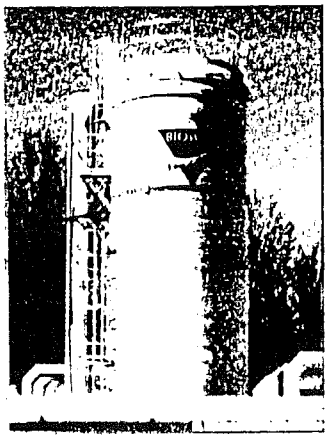
- Vendor Supplied Biofilter
  - Longer Media Life
  - Media Replaced by Vendor
  - Proven Design

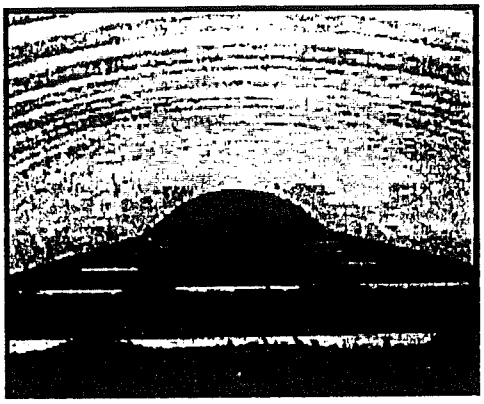




Recommendation

Three 2-Stage Bioway Purspring Biotrickling Filters followed by Vendor Supplied Biofilter





Advantages

- Environmentally Friendly
- Redundancy and Reliability
- Comfort Level with Design
- No Chemicals
- Low Operating Costs
- T-BACT
- BACT for Odors

City of Los Angeles

ECIS Odor Control

PRC Briefing

Presented by

Black & Veatch

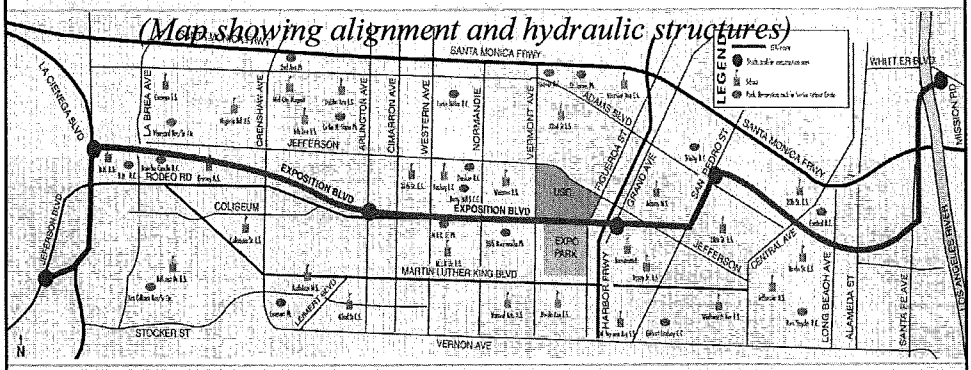
April 11, 2001

Briefing Purpose

- *Present Modified ECIS & NEIS Odor Control Projects*
- *Recommended Odor Control System*
- *Projected CIP Expenditure Plans*

ECIS Project

(Map showing alignment and hydraulic structures)



EIR Requirements

Drop Structures

- Seal maintenance holes 1 mile upstream and downstream
- Use liquid-phase treatment upstream and/or install vapor-phase control

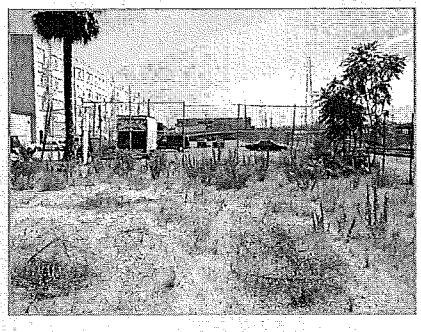
Inverted Siphon

- Seal maintenance holes 1 mile upstream and downstream
- Install air jumper

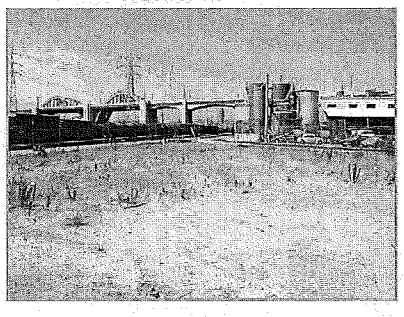
ECIS Odor Control Sites

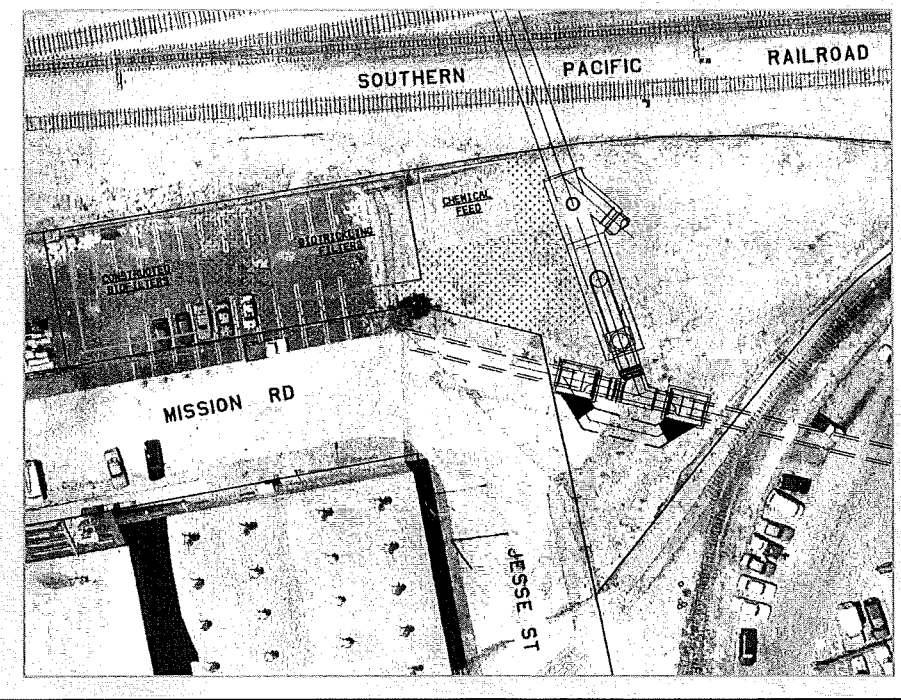
Areas of Turbulent Flow

Odor Control Site	Description	Possible Issues
Mission and Jesse	Industrial/Commercial	Graffiti Vandalism
San Pedro and 23rd	Residential	Graffiti Noise Physical Site Constraints (size) Proximity to Residences Vandalism
Jefferson Siphon	Commercial/Residential	Noise Proximity to Residences

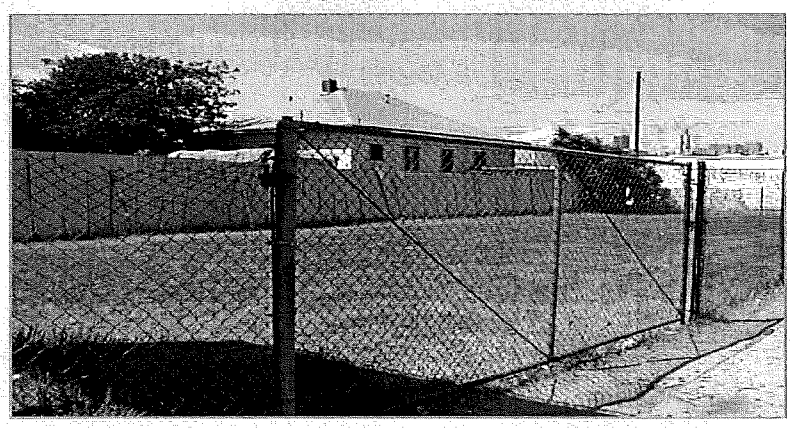


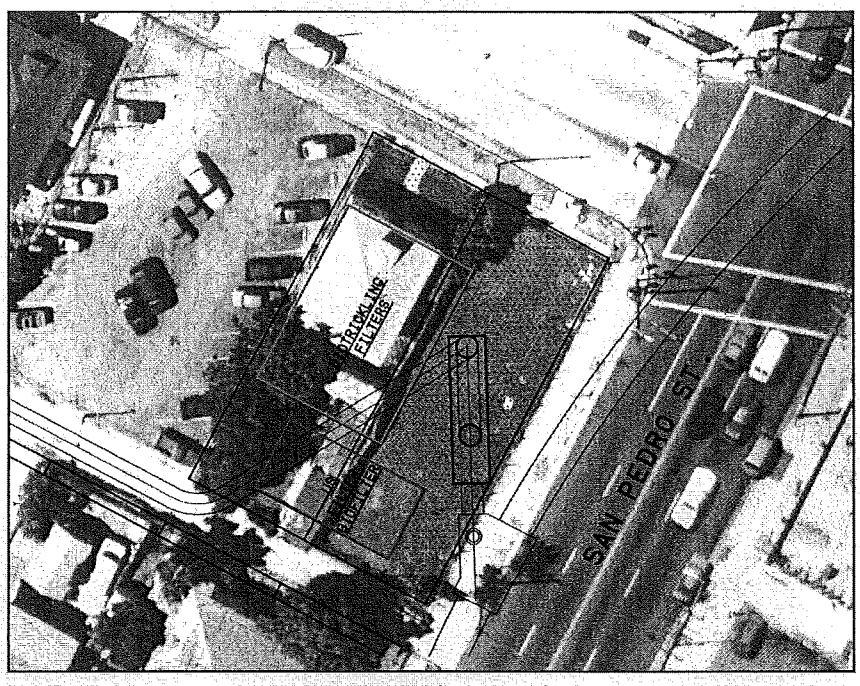
Mission & Jesse Drop Structure

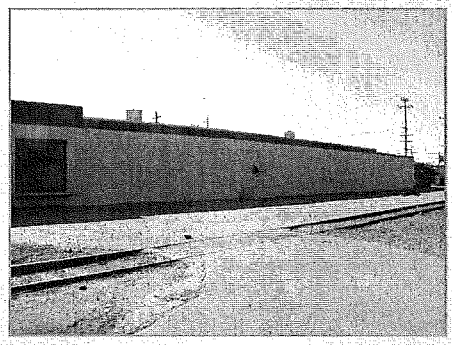


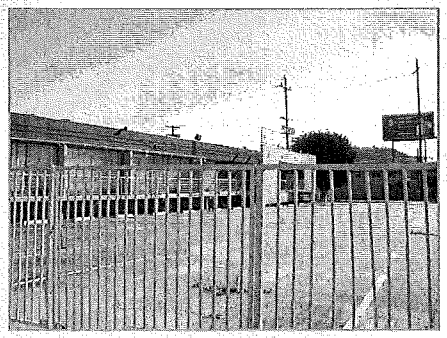


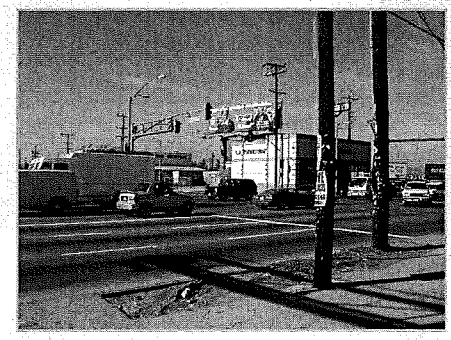
San Pedro and 23rd Diversion Structure/ Drop Structure



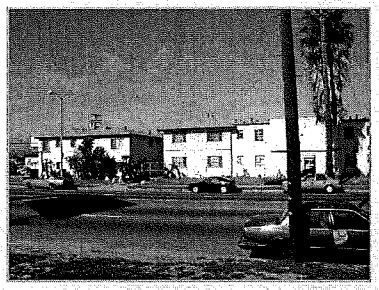


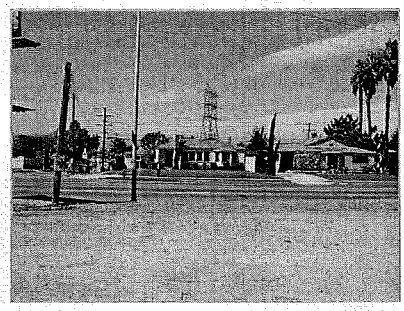






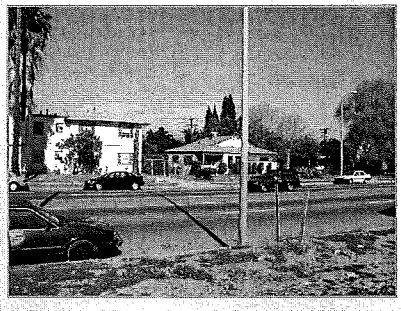
Jefferson Siphon

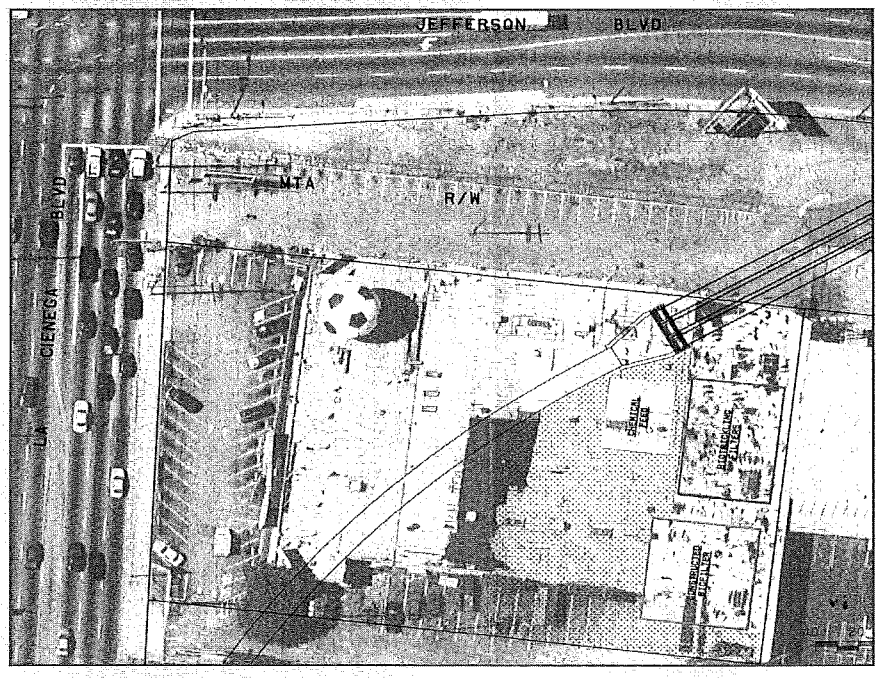




Jefferson Siphon

Surrounding Residences





Timeline

- Workshop No. 1 - June 1999
  - Liquid and vapor phase control technologies presented
- Workshop No. 2 - September 1999
  - Calgon Phoenix™ and Biofilters presented
  - Specific odor control sites evaluated
  - Architectural models presented
- Workshop No. 3 - June 2000
  - Demonstration testing, permitting, and site visits discussed
- Architectural Meeting - November 2000

Timeline

- VOC and Odor Testing January 2001
- Workshop No. 4 - February 1, 2001
- Collection System Pressure Testing - February to March 2001
- Workshop No. 5 - February 27, 2001
  - Final Decision on Odor Control Technologies

Issues

- First Odor Control Units in City of LA Collection System
- Unattended Operation Required
- Must be Reliable and Effective
- Minimal O&M Attention
- Common Processes Desired

Initial Screening of Odor Control Alternatives

- Wet Scrubbers
  - Vertical Packed Scrubbers
  - R.J. Environmental
- Activated Carbon
  - Caustic Impregnated
  - Virgin Carbon
  - Centaur
  - Phoenix System
- Biofiltration
  - Constructed
  - Vendor Supplied
- Biotrickling Filters
  - Constructed
  - Vendor Supplied
- Chemical Addition
- Turbulence Reduction

New Issues

- City utilizes iron salts and caustic shock dosing
- Costs have increased over 130% during the past two years
- Currently, chemical addition costs $810,000 annually for NOS

Revised Preliminary Design Criteria

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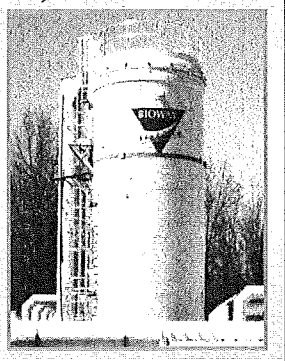
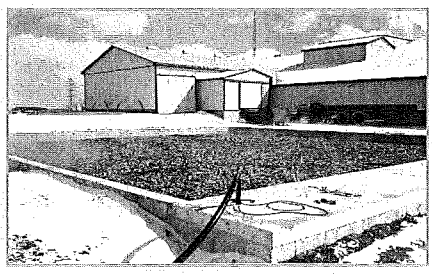
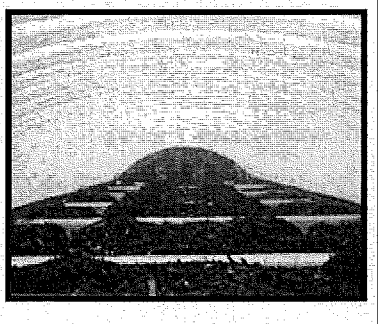


Second Stage Treatment Recommendation

- Vendor Supplied Biofilter
  - Longer Media Life
  - Media Replaced by Vendor
  - Proven Design





Procurement Recommendation

- Sole Source Bioway Biotrickling Filter
- Prequalify Approved Biofilter Vendors

Advantages

- Environmentally Friendly
- Redundancy and Reliability
- Comfort Level with Design
- No Chemicals
- Low Operating Costs
- T-BACT
- BACT for Odors

FIGHTING FOUL ODORS: BIOFILTER BASICS

Presented by

Blake Tresan, Nolte Associates, Inc.

Phil Govea, City of Manteca

April 28, 1999

CWEA Annual Conference

Ontario, California

NOLTE

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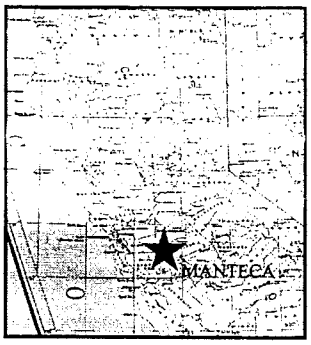
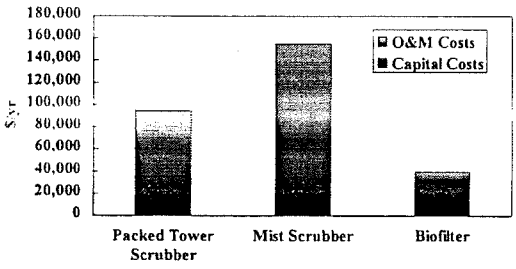
MANTECA



COSTS

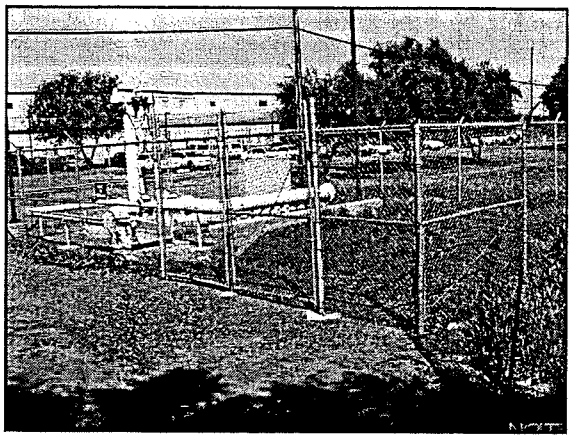


OUTLINE

- WHAT IS A BIOFILTER?
- HOW DOES IT WORK?
- AIR, MEDIA, MOISTURE, & pH
- SIZING A BIOFILTER
- MAINTENANCE/MONITORING
- PROBLEMS AND SOLUTIONS

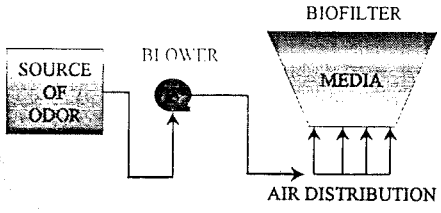
WHAT IS A BIOFILTER?

- *A BIOFILTER IS AN ENGINEERED SYSTEM DESIGNED TO REMOVE SPECIFIC CONSTITUENTS FROM AN AIR STREAM.*

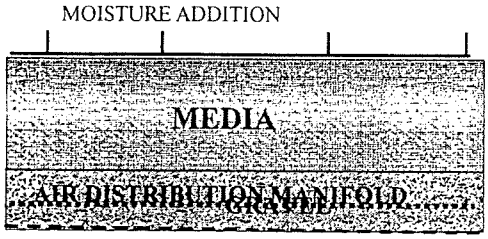




SCHEMATIC DIAGRAM

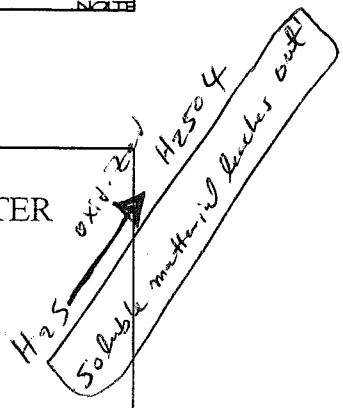


CROSS SECTION

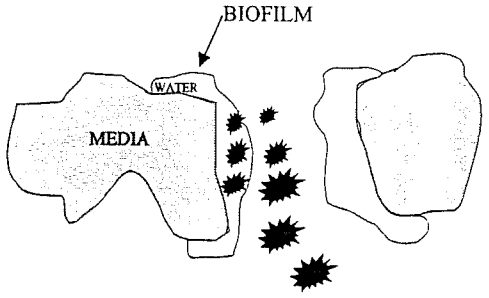


HOW DOES A BIOFILTER WORK?

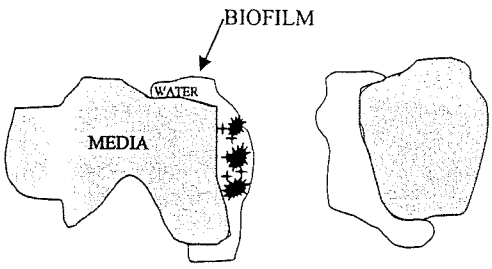
- ABSORPTION
- BIODEGRATION
- ADSORPTION



ABSORPTION



BIODEGRADATION

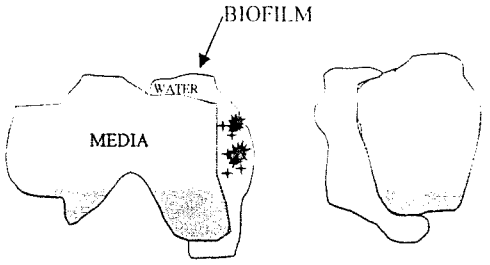


Peat → vegetable
woody material

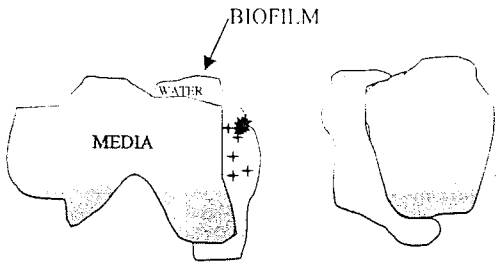
Rice Hulls

covers → white grains

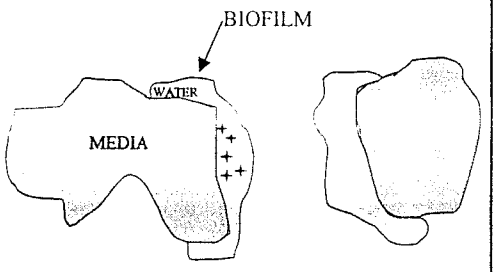
BIODEGRADATION



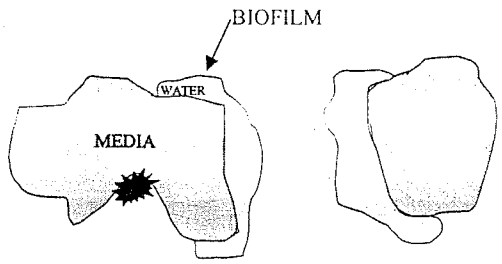
BIODEGRADATION



BIODEGRADATION



ADSORPTION



BIOFILTER MEDIA CHARACTERISTICS

- SUPPORT
- SURFACE AREA
- WATER RETENTION
- PERMEABILITY
- NUTRIENTS
- pH BUFFERING

BIOFILTER MEDIA

- **ORGANIC**
- SOIL
- COMPOST
- PEAT
- BARK — woody
- WOOD CHIPS
- RICE HULLS
- MIXTURE

- **INORGANIC**
- ROCK
- ACTIVATED CARBON
- PLASTIC MEDIA

MEDIA

+ = Best
O = Medium
- = Worst

Media	Static Pressure	Nutrients	pH Buffering	Life	Cost
Soil	-	+	+	O	+
Compost	O	+	+	-	O
Rock	+	-	-	+	-

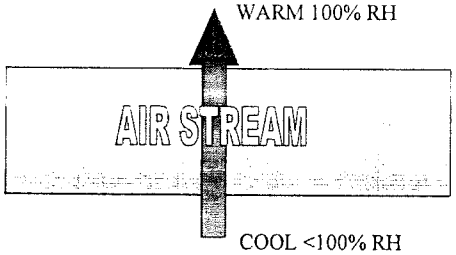
less pressure problem

MOISTURE CONTROL

- IS IT NECESSARY?

YES

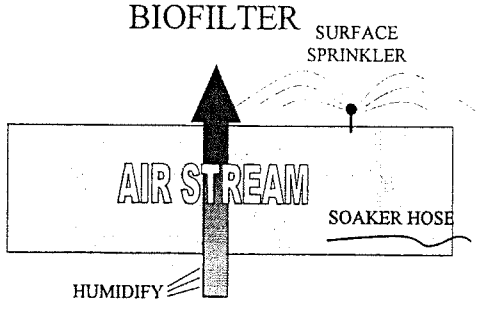
WATER LOSS IN A BIOFILTER

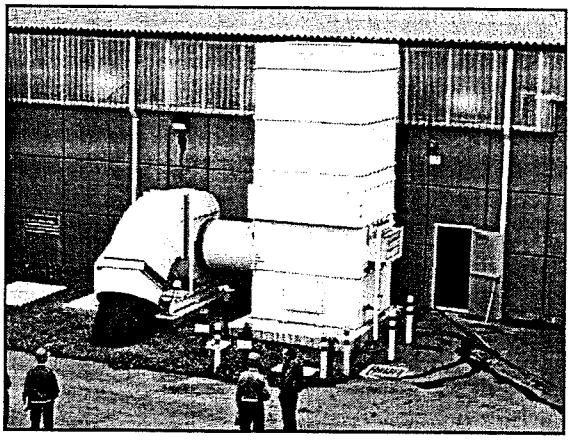


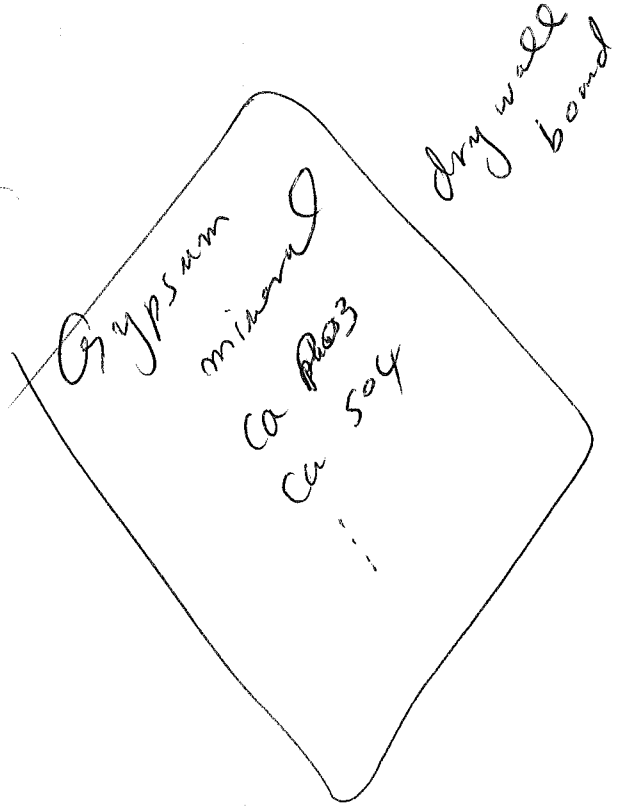
MOISTURE ADDITION

- SURFACE SPRINKLER
- IN-LINE SPRAY CHAMBER
- SUBSURFACE DRIP

WATER LOSS IN A BIOFILTER






Gypsum
mineral
Ca PO_3
Ca SO_4
dry wall
board

pH CONTROL

- WHAT IS THE OPTIMUM pH?
- ACIDIFICATION
- ALKALINITY (ACID BUFFERING CAPACITY)

ACIDIFICATION

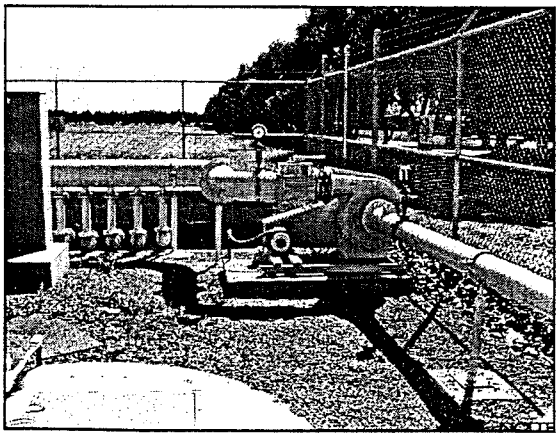
$$H_2S + 2O_2 \Longrightarrow H_2SO_4$$

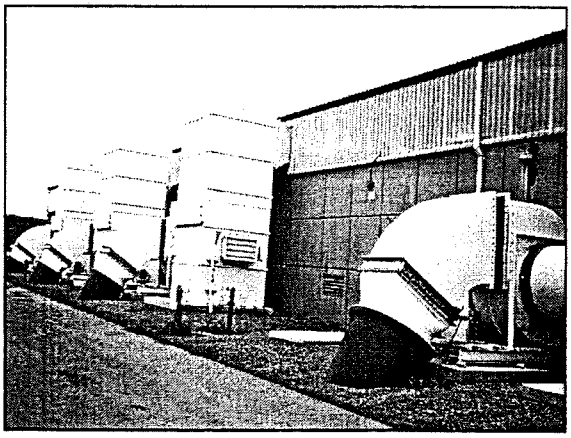
ALKALINITY

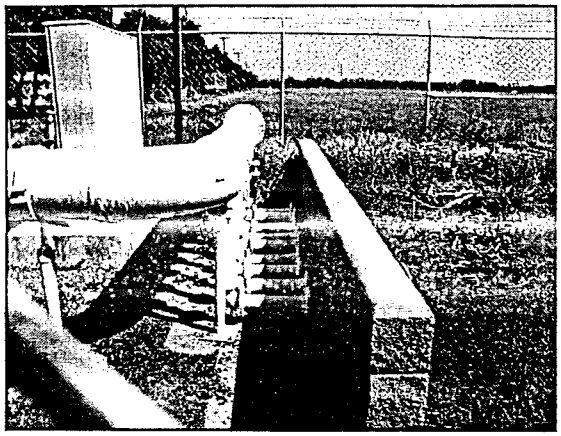
- MEDIA MAY HAVE SUFFICIENT ALK
- GYPSUM
- CRUSHED OYSTER SHELLS
- CRUSHED LIMESTONE
- DOLOMITE

AIR DISTRIBUTION SYSTEM

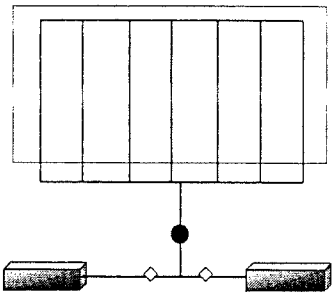
- BLOWER
- PLENUM
- PIPE SYSTEM
- ORIFICES
- HUMIDIFICATION



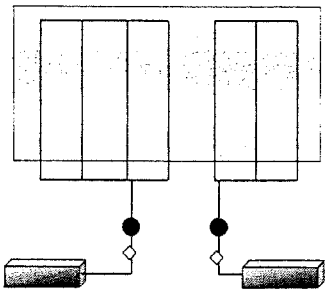




AIR DISTRIBUTION



AIR DISTRIBUTION



SIZING A BIOFILTER

- DETERMINE AIR FLOW
- IDENTIFY CONSTITUENTS OF CONCERN
- ESTIMATE CONCENTRATION

RETENTION TIME

EMPTY BED RETENTION TIME

EBRT = **V / Q**

V = Q x EBRT

EBRT FOR ODOR CONTROL BIOFILTERS
30 TO 60 SECONDS

LOADING RATES

- SURFACE LOADING RATES

SLR = FLOW / AREA

AREA = FLOW / SLR

SLR FOR ODOR CONTROL BIOFILTERS
3 TO 6 CFM/FT^2

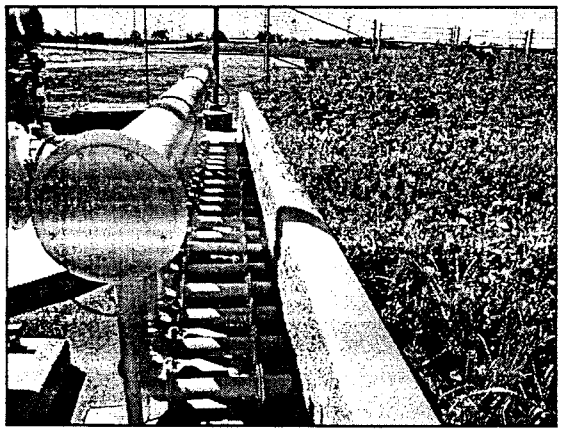
CONTROLS

- PRESSURE GAUGES
- VALVES/DAMPERS
- IRRIGATION TIMER

Sm press. above atmospheric

BIOFILTER MONITORING

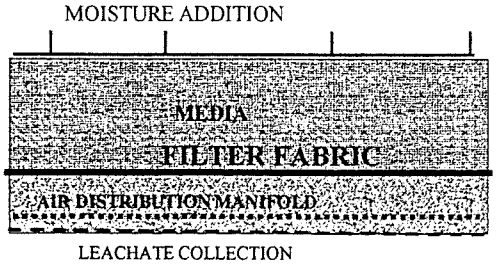
- MOISTURE CONTENT
  - TEST HOLES
  - LEACHATE PRODUCTION
- AIR DISTRIBUTION
  - BACK PRESSURE
  - SMOKE TESTING
- VEGETATION MGT



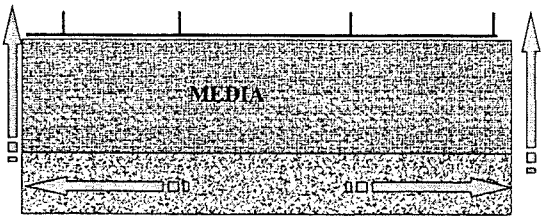
PROBLEMS AND SOLUTIONS

- NO ACCESS
- FOULING FILTER FABRIC
- SHORT CIRCUITING ALONG WALLS

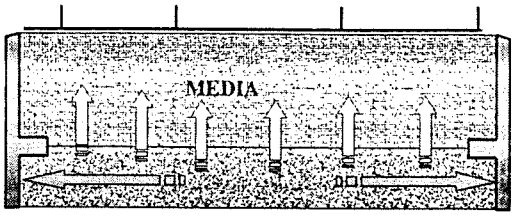
FILTER FABRIC PROBLEMS



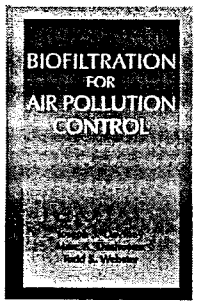
SHORT CIRCUITING ALONG WALLS



BAFFLES



RESOURCE



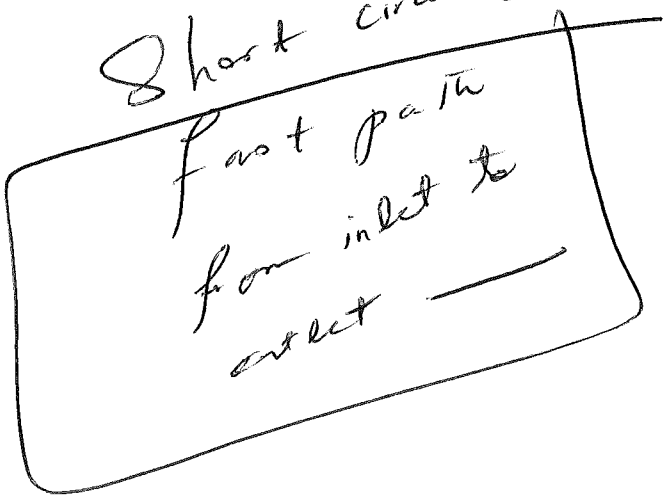
TAKE HOME MESSAGE

- WELL DESIGNED BIOFILTERS CAN PROVIDE WWTP'S WITH A COST-EFFECTIVE, EFFICIENT, NATURAL, EASY TO OPERATE ODOR CONTROL SYSTEM.

FIGHTING FOUL ODORS: BIOFILTER BASICS

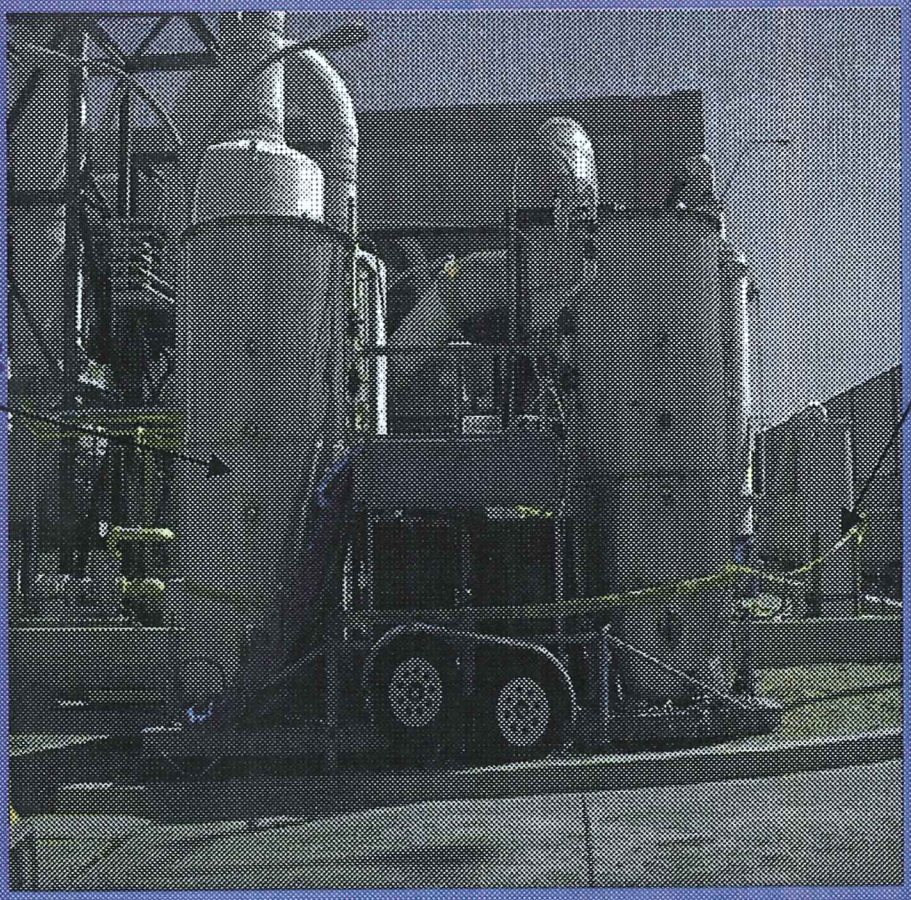
Presented by
Blake Tresan, Nolte Associates, Inc.
Phil Govea, City of Manteca

April 28, 1999
CWEA Annual Conference
Ontario, California


Short circuiting
fast path
from inlet to
outlet

WERF Gas Emission Reduction / HTP

UC Riverside Biotrickling and UC Davis Biofilter



ECIS / NEIS Odor Control Task Force

October 26

Applied Research (WESD), Hyperion Treat. Plant and EMD, Bureau of Sanitation, City of LA

UC Riverside, Riverside, CA
UC Davis, Davis, CA

WERF Gas Emission Reduction Project

Objectives

To Use Biological Systems Instead of Chemical Scrubbers

- Reduce costs
- Remove VOCs

Results

- Setup at HTP
- H_2S removal
- Baseline VOC removal

Future Issues

- Higher H_2S concentrations
- VOC removal
- Parameter variations
- Cost comparisons
- Application
- Etc...

ACKNOWLEDGEMENT

The following have been instrumental in the success of the project.

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Steve Fan
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Patty Jacobs
Staff from maintenance & operations

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Reza Iranpour
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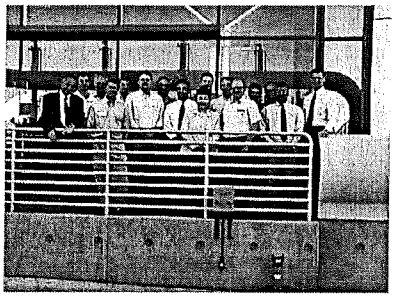
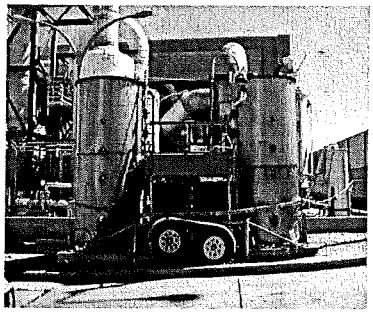
Dipak Patel
Miguel Zermeno
Martin Ruiz
Seung Oh
Parviz Samar, (volunteer postdoctor)

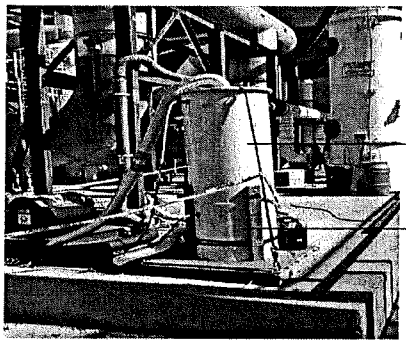
Bureau Management
Judith Wilson
Jim Langley
Vince Varsh
Gill Garnas



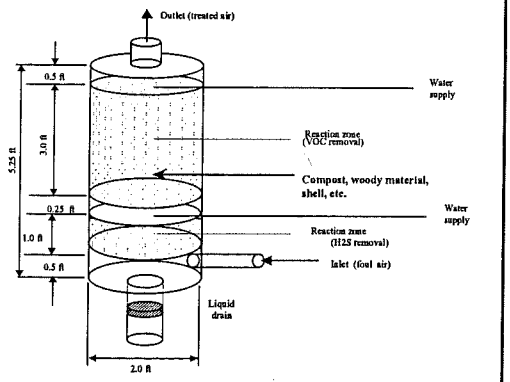
WERF Gas Emission Reduction Project Members, HTP, 3/2000



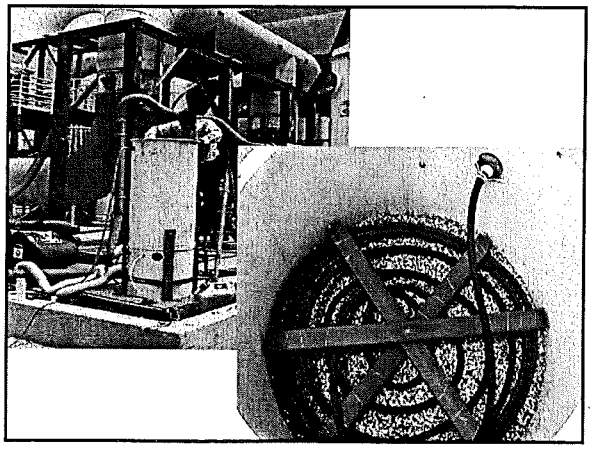
Biofilter / Biotrickling filter, HTP Headworks

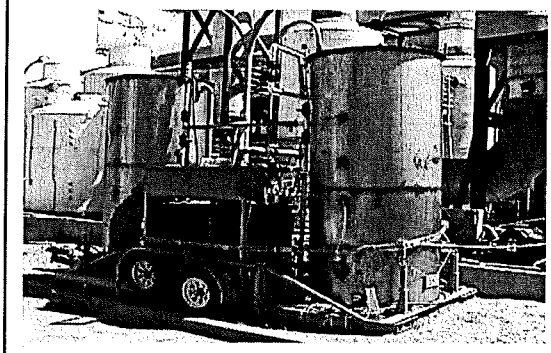


UC Davis Biofilter, HTP

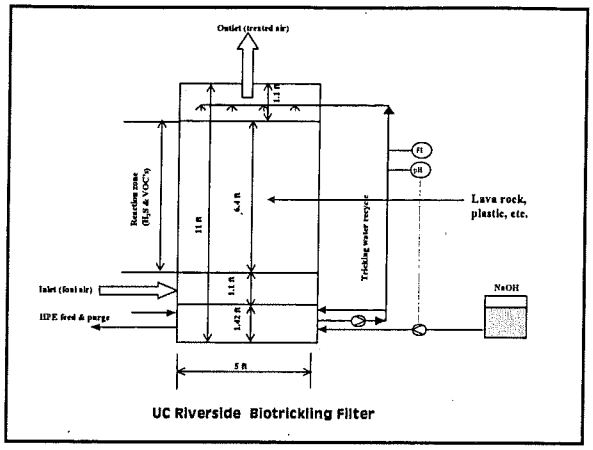


UC Davis Biofilter





UC Riverside Biotrickling Filter, HTP



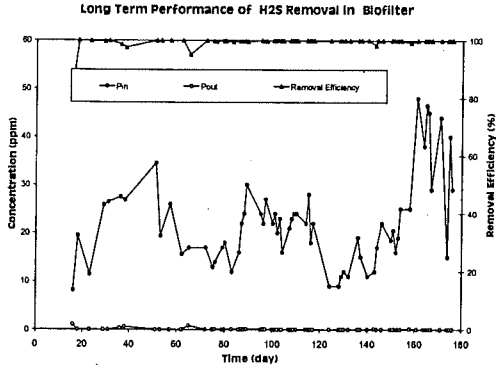
UC Riverside Biotrickling Filter

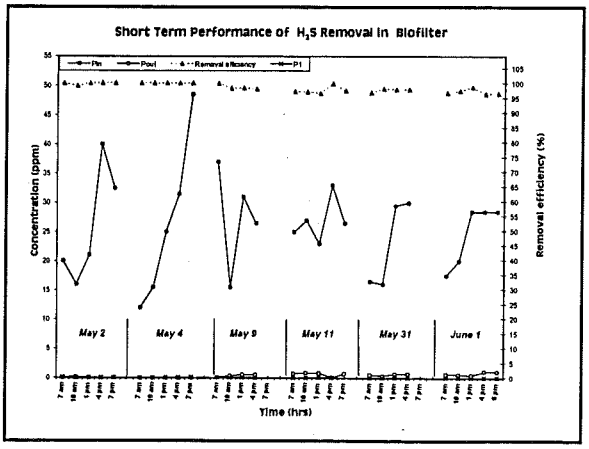
BIOFILTER PERFORMANCE

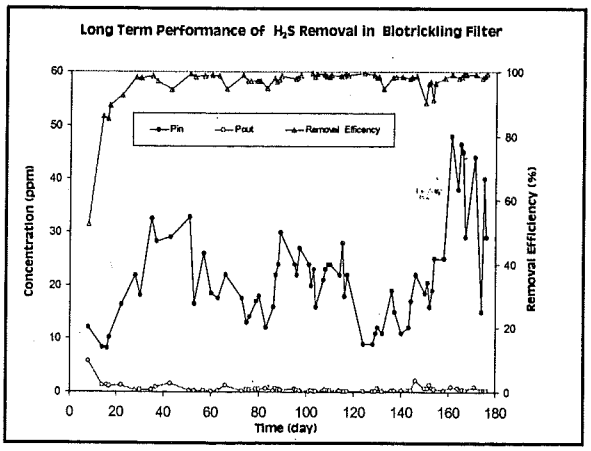
Hydrogen Sulfide (H_2S) (ppmv)				
	Date	inlet (mean ± std. dev.)	outlet (mean ± std. dev.)	Removal eff.
	(4/00-9/00) (daily)	22 ± 7	0.06 ± 0.09	100 ± 1
	(1/5/00-2/6/00) (4 times/day)	26 ± 8	0.37 ± 0.33	98 ± 1
Volatile Organic Compounds (VOCs) (ppbv)				
	(1/5/00-2/6/00) (4 times/day)			
Benzene		8 ± 3	2 ± 2	74 ± 23
Toluene		68 ± 18	12 ± 10	79 ± 20
Xylenes		69 ± 35	31 ± 21	56 ± 28
p-Dichlorobenzene		14 ± 4	11 ± 4	18 ± 17
Meyhylene Chloride		42 ± 27	38 ± 24	5 ± 21
Chloroform		74 ± 19	74 ± 19	0 ± 4
Tetrachloroethylene		79 ± 24	80 ± 24	2 ± 2

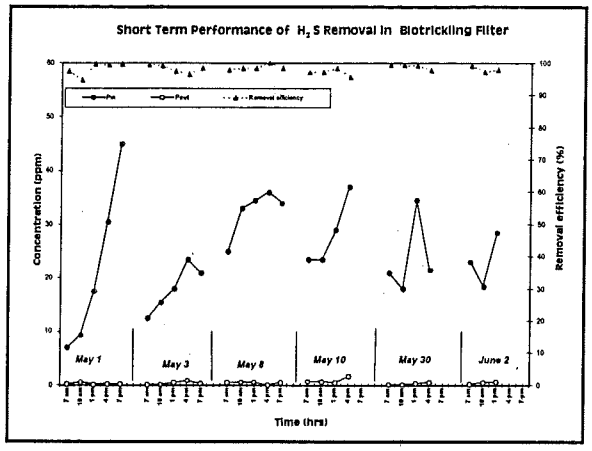
BIOTRICKLING FILTER PERFORMANCE

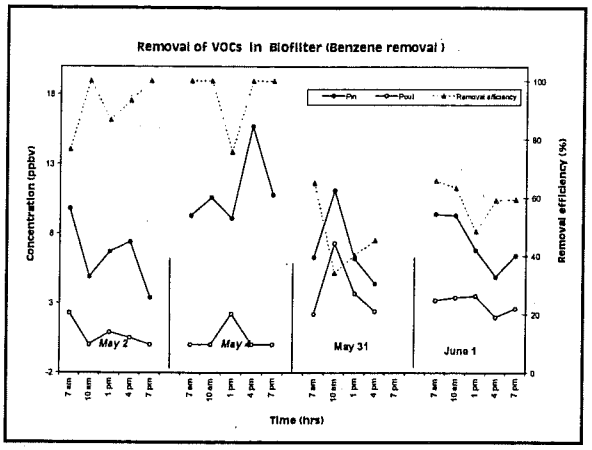
Hydrogen Sulfide (H_2S) (ppmv)				
	Date	inlet (mean ± std. dev.)	outlet (mean ± std. dev.)	Removal eff.
	(4/00-9/00) (daily)	26 ± 7	0.56 ± 0.43	97 ± 3
	(1/5/00-2/6/00) (4 times/day)	25 ± 7	0.40 ± 0.30	98 ± 1
Volatile Organic Compounds (VOCs) (ppbv)				
	(1/5/00-2/6/00) (4 times/day)			
Benzene		10 ± 6	7 ± 4	19 ± 29
Toluene		65 ± 36	55 ± 42	20 ± 35
Xylenes		53 ± 33	53 ± 35	4 ± 27
p-Dichlorobenzene		10 ± 4	11 ± 4	18 ± 39
Meyhylene Chloride		33 ± 22	33 ± 23	2 ± 21
Chloroform		63 ± 17	61 ± 21	3 ± 20
Tetrachloroethylene		68 ± 35	67 ± 38	5 ± 21

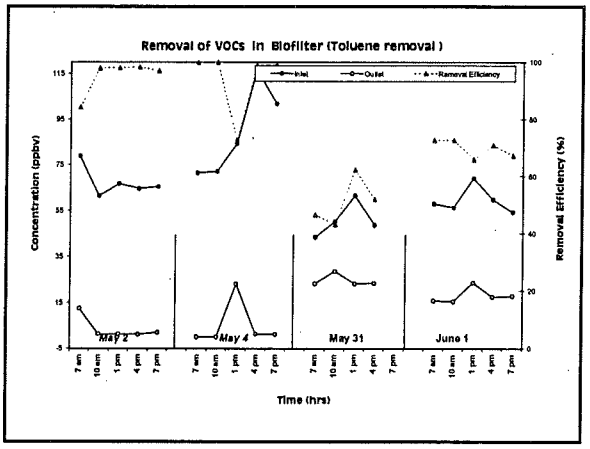


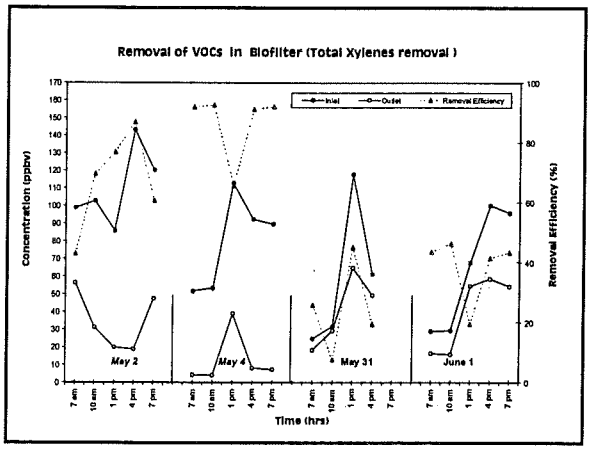


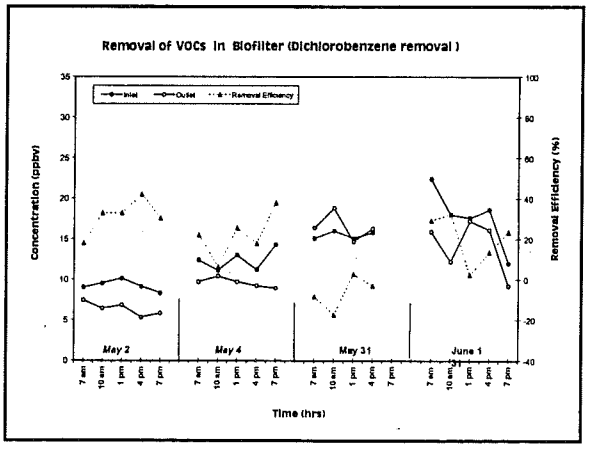


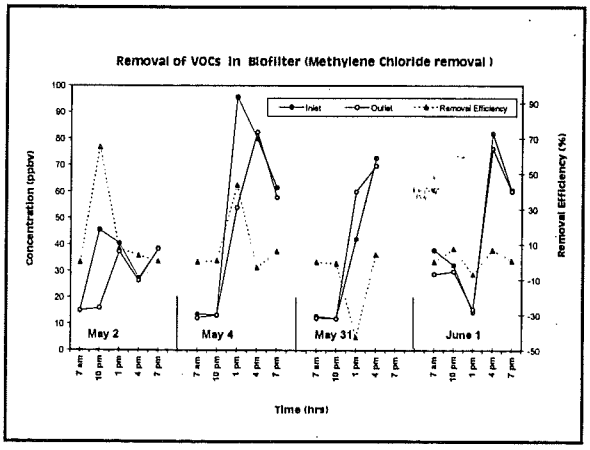

Short Term Performance of H_2S Removal in Biotrickling Filter
Concentration (ppm)
Removal efficiency (%)
Time (hrs)
May 1
May 3
May 8
May 10
May 30
June 2

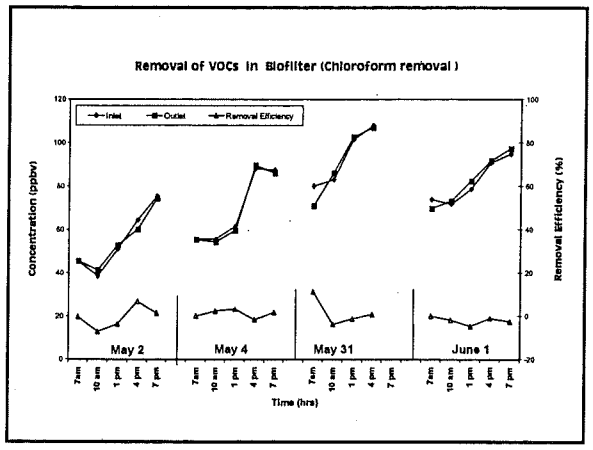

Removal of VOCs in Biofilter (Benzene removal)
Concentration (ppbv)
Removal efficiency (%)
Time (hrs)
May 2
May 4
May 31
June 1

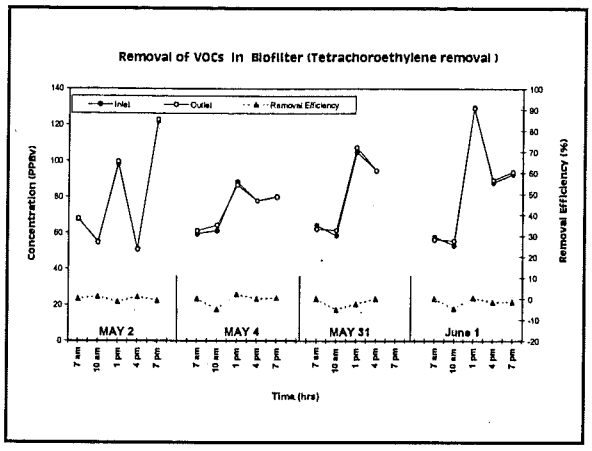

Removal of VOCs in Biofilter (Toluene removal)
Concentration (ppbv)
Removal Efficiency (%)
Time (hrs)
May 2
May 4
May 31
June 1

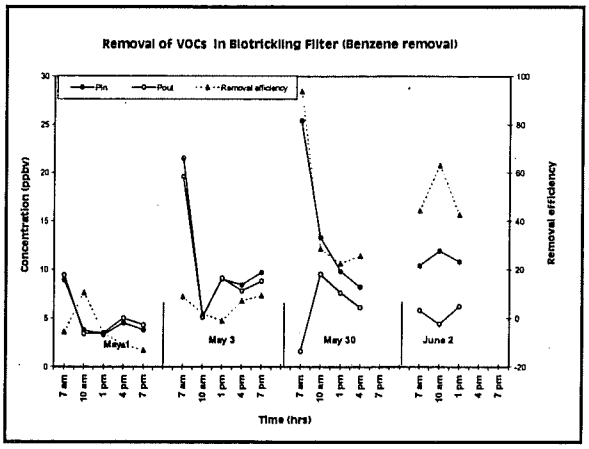

Removal of VOCs in Biofilter (Total Xylenes removal)
Concentration (ppbv)
Removal Efficiency (%)
Time (hrs)
May 2
May 4
May 31
June 1

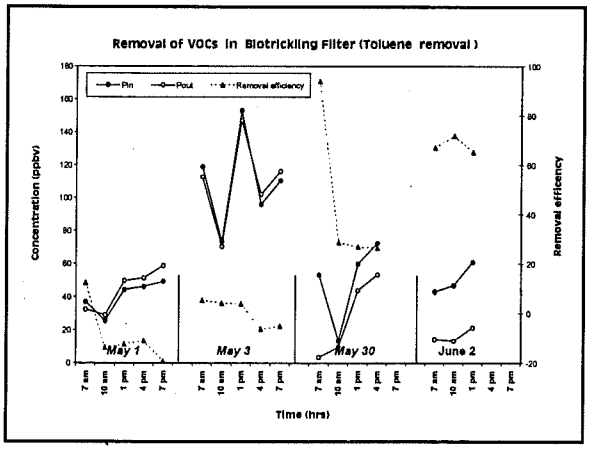

Removal of VOCs in Biofilter (Dichlorobenzene removal)
Concentration (ppbv)
Removal Efficiency (%)
Time (hrs)
May 2
May 4
May 31
June 1

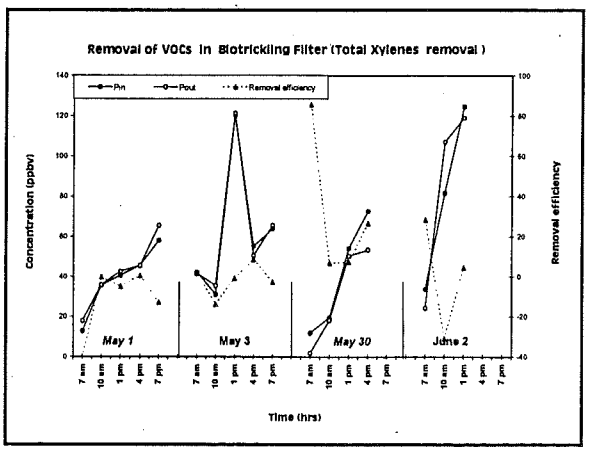

Removal of VOCs in Biofilter (Methylene Chloride removal)
Concentration (ppbv)
Removal Efficiency (%)
Time (hrs)
May 2
May 4
May 31
June 1

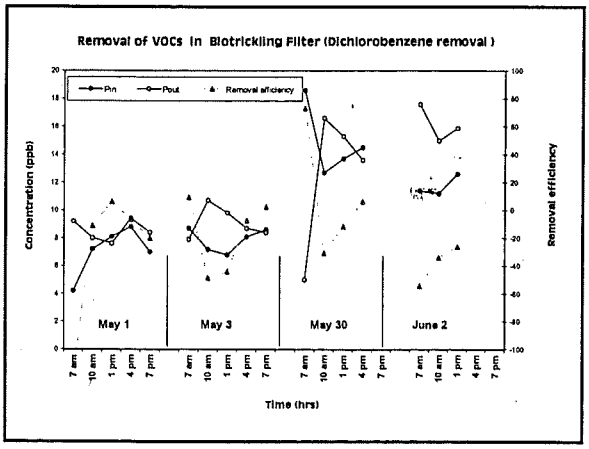

Removal of VOCs in Biofilter (Chloroform removal)
Inlet
Outlet
Removal Efficiency
Concentration (ppbv)
Removal Efficiency (%)
May 2
May 4
May 31
June 1
Time (hrs)

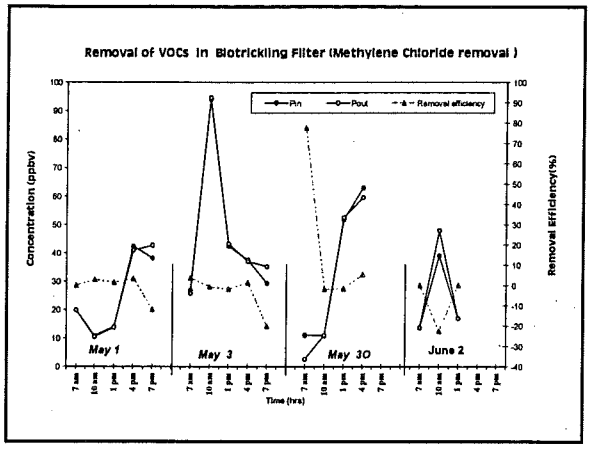

Removal of VOCs in Biofilter (Tetrachoroethylene removal)
Inlet
Outlet
Removal Efficiency
Concentration (PPBv)
Removal Efficiency (%)
MAY 2
MAY 4
MAY 31
June 1
Time (hrs)

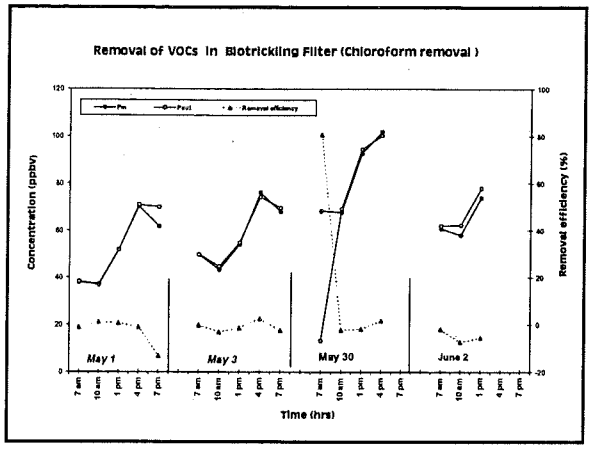

Removal of VOCs in Biotrickling Filter (Benzene removal)
Pin
Pout
Removal efficiency
Concentration (ppbv)
Removal efficiency
May1
May 3
May 30
June 2
Time (hrs)

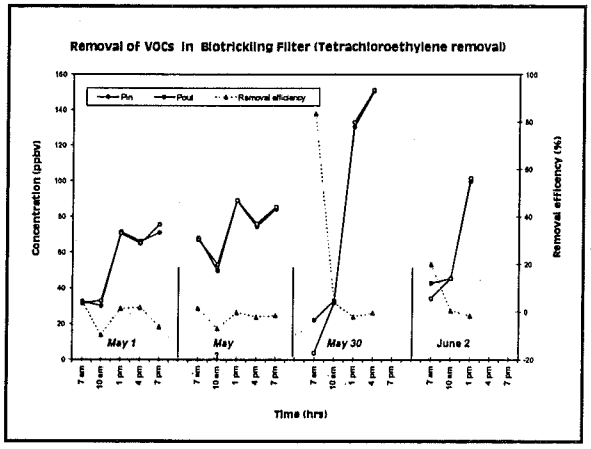

Removal of VOCs in Biotrickling Filter (Toluene removal)
Pin
Pout
Removal efficiency
Concentration (ppbv)
Removal efficiency
May 1
May 3
May 30
June 2
Time (hrs)


Removal of VOCs in Biotrickling Filter (Total Xylenes removal)
Pin
Pout
Removal efficiency
Concentration (ppbv)
Removal efficiency
May 1
May 3
May 30
June 2
Time (hrs)


Removal of VOCs in Biotrickling Filter (Dichlorobenzene removal)
Pin
Pout
Removal efficiency
Concentration (ppb)
Removal efficiency
May 1
May 3
May 30
June 2
Time (hrs)







Applications (rough estimate)

Future Issues

Continue H_2S study to optimize REACTOR SIZE

- H_2S Variation
- Flow Variation

Intensify present VOCs Studies

- Non-chlorinated VOCs
- Chlorinated VOCs

Applications to HTP

- Regulations
- Costs

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PROJECT TITLE:

DESCRIPTION:

W.O.

Wood ... { Cellulose ← C, H, O — Carbohydrates ... on ave. ... 1 C & 1 H_2O
Lignin (protects & bind) — C, H, O, N

Rot Fungi — originally in rotten wood — Vossoughi et al. crude characterization

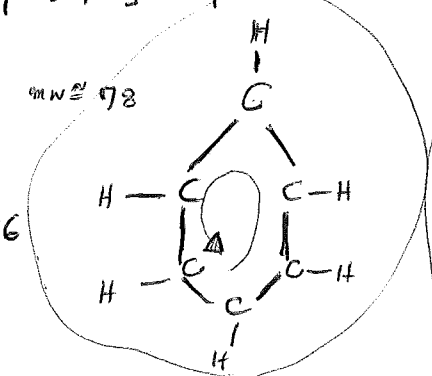
Recalcitrant ~ (hard to do) ... e.g. recalcitrant VOC's

O_2^{--} peroxide ion $\xleftarrow[H]{\text{Loose}}$ H_2O_2 (Hydrogen peroxide) — Enzymes breaking O_2^{--} (Peroxide enzymes)

Zenobiotic (Wet oxidation) — lots of radicals oxidizing each other — Idiosyncratic ~ Unique to (special or particular to ...)

→ all press + high temp

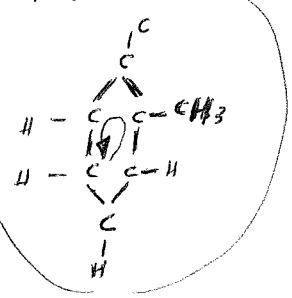
C_6H_6



mw ≅ 78

all free electrons from each C is uniformly shared around the rig (Hexagon + circle inside) fuel to some extend

$C_6H_5CH_3$



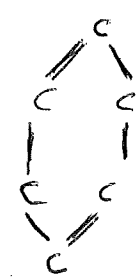
Methyl Benzene (Toluene) used in making TNT (explosive)

Xylenes (several)

C_6H_6 derivatives (used as a solvant) cleaning lab glass wear

Less toxic than C_6H_6 & $C_6H_5CH_3$

ortho meta para of $C_6H_4(CH_3)_2$



dry cleaning ⇐ oily solvant (instead of H_2O) (no polar material)

Any hydrocarbon is non-polar (electron affinity of C & H same) ⟷ { any C H bound covalent → share a pair of electron

VOCs low-boilg point (high vapor pressure at Room T)

→ & since no polar ⟺ even higher molecular weight than $\boxed{\begin{matrix} H_2O \\ 18 \end{matrix}}$

$\boxed{\text{Polarity of } H_2O \Longleftrightarrow \text{high } \overset{(0)}{\text{melt}}\text{g (Freezg) \& boilg } \overset{(100)}{\text{point}}}$

{ 50 ~ 60% / 25 / 25 } Combination mixture of 3

Rubber cement & Slacker (Varnish) → Put on wood (as a solvant)

Liquid at Room T

139°C ~ 144°C

evaporates slowly

attach NO_3 → used a dye

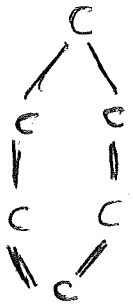
jet fuel ~ Kerosene

(Single ring aromatic)

Vapor press = atmospheric press boiling point

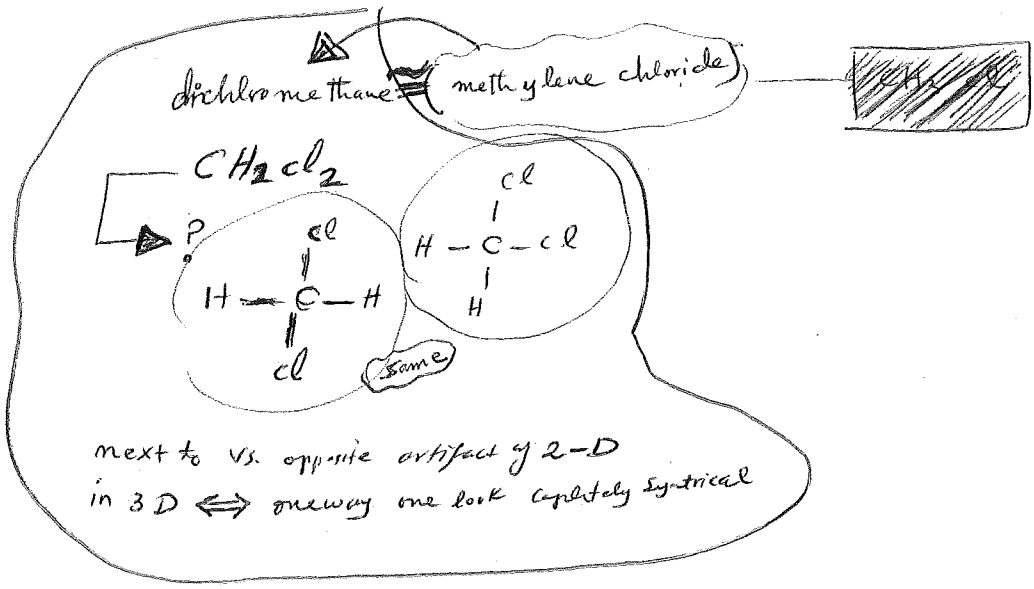
Dichlorobenzene

$C_6H_4Cl_2$



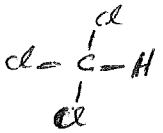
para — next
meta — 120° away other
ortho — opposite

Cl_2 add more weight
volatile but solid



chloroform ... anesthetic ... a few ml ... high mortality in inexperienced hand ... fat solvant ...

trichloromethane (THM)



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PROJECT TITLE:

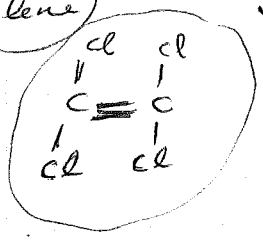
DESCRIPTION:

W.O.

C_2H_4

Tetrachloro ethylene

C_2Cl_4



solvent (dry cleaning) ≅ Toxic

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PROJECT TITLE:

DESCRIPTION:

Biotrickling W.O. Biofilter

$(6.4)\left(\frac{5}{2}\right)^2 \pi = 125.6\ ft^3 \sim 4\ m^3$ $9.42 + 3.14 = 12.56\ ft^3 \sim .4\ m^3$

$\frac{125.6\ ft^3}{30\ sec} \cong 4\ ft^3/sec$ $\frac{12.56}{30} \cong .4$

once/day ~ shower

VOC ⇒ Risk basis Cumulative Accumulation Prioritazation Scor

Wind direction Plant Boundary

VOC removal also $\left\{ CH_4 + NaOCl \Rightarrow CH_4 + Cl \right.$ create

$H_2S + NaOCl \Rightarrow H_2SO_4$ Cl^- active

HPE ⇒ NH_4 ? Use H_2O

200 (1) 6 ft³/sec

$\boxed{600\ ft^3\ (3)\quad (15\ sec)} \Rightarrow \frac{600\ ft^3}{15\ sec} = 40\ ft^3/sec$

$\frac{V}{Q} = 15\ sec$

$2000/40 \Rightarrow 50$ $1500/40 \Rightarrow 30$

$\frac{20^2}{15^2} = \frac{(20)(20)}{(15)(15)} \Rightarrow$

20 ft ⇒ $100 \times 3 = 300 \times 7 = 2000\ ft^3$

$\frac{2000\ V}{15\ sec} \Rightarrow 130\ ft^3/sec$

$2000\ ft^3/sec / 130 \sim 13$ system

Area need

$25 \times 25 \Rightarrow 625\ ft^2$

15 ×

$\boxed{10000\ ft^2}$

1 acre $\boxed{43560}$

$\frac{1}{4}$ acre stack up

mg/L

poll. concentr. in air

$\left\{ grs/m^3 \right\} * \left\{ Q_{air} \left(\frac{V}{T}\right) \right\} = \boxed{grs/hr}$ mass rate

$\left\{ gr/hr / Volume \right\}$

$gr/m^3/hr \sim$

Authotrophs need mineral substances
oxidizing H_2S
so acidic

hetrotrops ⇒ organic substances ⇒

Biofilter large area low concentration degrade fast

{ H_2S in Biotrickling filter
in series remove VOC's by biofilter

Long term ... problem with biofilter
less " " biotrickling filter

Load and media ... efficiency & cost of replacement

15% by vol. MTBES ⟷ Xylene, Toluene, C_6H_6, C_6H_6 / CH_3 CH_2 alkanes

Gass

Tanky gass Pump injecty pure gasolene constant rate {100 ml/hr} is cabined main air stream

Polyuretane ... ⇒

specific surface area of the packing ... area of packing m^2 / Volume m^3 occupied

200 m^2/m^3 normal value for biotrickling filter

Adapted from Groenestijn and Hesselink (1993).

	Biofilter	Biotrickling filter
Characteristics	Immobilized biomass Immobile water phase Single reactor	Immobilized biomass Mobile water phase Single reactor
Application area	Pollutant concentration < 1 g/m^3 Henry coefficient < 10	Pollutant concentration < 0.5 g/m^3 Henry coefficient < 1
Advantages	High gas/liquid surface area Easy operation and start-up Low operation costs	Good control of reaction conditions High overall pollutant removal rate Relatively compact equipment
Disadvantages	Poor control of reaction conditions Large area (foot-print reactor) required Slow adaptation to changing conditions in the raw gas	Lower gas/liquid surface area for mass transfer Complicated start-up Higher operational costs

of gas

Please note:

- Henry coefficient given is dimensionless: C_{gas}/C_{liquid}.
- Biotrickling filter research started about 15 years, and large progresses have been made over the past few years. Especially the application area data in above table are outdated.
- In general, biofilters are the best for gas streams containing mixtures of pollutants, but at low concentrations. Typically odors with a low odor threshold. Biotrickling filters are the first choice when treating gases with high concentrations of one or few pollutants. The waste gas at Hyperion fits both scenario's: complex mixture of various pollutants at low concentrations, but with H_2S as the major component of concern and present at a high concentration.

higher surface area
higher residence time

shorter residence time

BTF 657 m^3/hr = 390 cfm V = 4 m^3

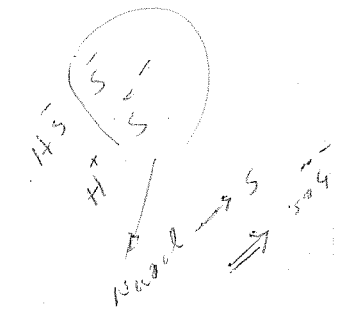
~~BF~~ = 17.5 m^3/hr = 10 cfm V = .36 m^3

First section 18.5 sec?

Hubb?

1. Media

2.



weak acid
H comes off of H_2S

H_2S $\bar{S}$ $\bar{S}$
H^+

NaOCl → S ⇒ SO_4^{--}

3 chemi

NaOH for H_2S → S^0 element
NaOCl + S^0 → H_2SO_4 + SO_4^{--}

PH = 10.5
less chemical

AC adsorption

60 Units

VOC removal if dry GAC

1×10^6 ~~$/year~~
80000/month
Carbone once a year or twice

Acid wash
HCl
bath ?

SO_4^{--} → back to H_2S in Anarobic digers.

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PROJECT TITLE: August 17 ?

DESCRIPTION:

W.O.

bee holes structured packing tell vendor D ≙ 1.5 m dept ≙

(7 layers on the top of each other)

Crane to remove the top ...

recallcitrant hard to break

highest porosity 90%

random ... pall rings ; balls

Lava rock prosity is less — irregular surface

microbes

Hetortrophic bact. PH 6 to 9

other growing

mixed growing

degrading VOC ← Carbon source & energy source

Organic compounds

(autotrophic use CO2 (minerals) in air as C source)

aerobic autotrophs...

self growing

line on mineral substances (H2O & CO2) → mineral (not organic)

H2S a mineral compound

We are hetrotrophic Eucaryotes good nucleic

can not live without organics

50000 ft³/min ⇒ 800 ft³/sec ⇒

hydrogen sulfide

H2S + O2 —Microbes→ H2SO4 + NaOH → 2H⁺ + SO4⁻⁻

S⁻⁻ → SO4⁻⁻

ion sulfide

NaOCl + H2S ⇒ S⁻⁻

Activate C to take out Cl or other gasses

no bacteria action

Plants → autotrophic Eucaryotes

50000 ft³/min

1000 ft³/sec ⇒ present Vol. ⇒ 4 system (biotrickling) ⇒ Dia. 10 ft (4) 10×6 10×7

1 ft³/sec ⇒ 30 × 15 ft³ = 7500 ft³

÷ 750 ft³/6 ⇒ 12 ~ 13 ⇔ 4 6

H2S Toxic mineral compounds

→ is weak acid ... as a natural molecule gets to air

SO4⁻⁻ sufate ion highly very soluble in H2O it does not get out

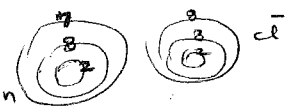
H2SO4 soluble ... dissocides in H⁺ SO4⁻⁻

* Sample of media
* extrapolate ⟺ what size? what would space?
extrapolate cost?
* R & D

(15 mintes)

100 000 ft^3/min
/50 → 2000 ft^3/sec

cl atom



Chloride ion

cl^- is very soluble ... rare to have free cl^- ... stronge charge gives it strong affinity for polar H_2O molecules ...

Chlorinated compounds are rare ...

2 cl atom ⇒ cl_2

so living microbes do not have enzymes to attach these ...

many chlorinated compounds are recalcitrant

Removal of C_6H_6 Tulene Xylene would be oxidation ... (enzym system of microbes)
→ result of bacterial enzyms

{ Cryto, Giardia } {Eucaryotes} single cell parasites

Bacteria ≅ procarotes

Biofilter ... is like a black Box ... solid moist media
→ has it ever been characterized (Microscopic ecology going)

protoza single cells (move around)
→ predator → eat bacteria

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PROJECT TITLE:

DESCRIPTION:

no polar polar

W.O.

Alkohol ⇒ Hydro Cabo — O — H e.g. $C_2H_5 - O - H$ OH

Hydrocabon no polarity by itself

→ OH makes it polar ⇒ higher solubility in H_2O ⇒ degradability goes up

O has high effinity for electron

Esters ... Hydralysis reaction bet. alkohol & acid (fatty or organic)

→ (small molecules)

slight polarity

C_2H_5 COO CH_3

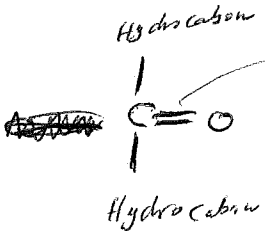
Ethyle acitate

Ketones ...

Hydrocabon

C=O double bond

Hydrocabon



very little polarity so less soluble so less degrable

unsaturated

Aeromatics ... multi ring aeromatic ... partial degradation effect, then merge together

→ one or more C_6H_6 type ring ...

Cellulose by heat in Cigrate form C_6H_6 type of structure.

1000 or 1500 °C pyralysis

1100

→ orange color ⇒ very high temp.

single bonded

Alkanes ... saturated | hydrocabones

straight or branched chain of Cabons (no double bonds)

as many hydrogen as you

CH_4 ...

C_2H_6 ...

C_8H_{18} ...

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PROJECT TITLE:

DESCRIPTION:

W.O.

biofilter or biotrickling filter reverse the situation, that is chang H_2S → oxidation

SO_4^{--} (soluble) ion from strong acid

800 lit ~ 200 gallon UCR biotrickling filter

Plenum ≡ open open area

Pelinum ≡ open area to collect or distribute

Pelinum ô top to distribute flow at top

collect at bottom

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PROJECT TITLE:

DESCRIPTION:

W.O.

100 000 ppb 200 000 ppb 1 min ⟺ non detect for Toluene
no desorption (experience) (50/12)

Start with a system → within a week & 1 min RT can remove 100 %
August Brit results are typical ...

Augmenting cultures ... Added MTBE degraders ...
10 – 12 years ago → Rot fungus produces proxydase that breaks a lot of compounds ...
→ lack of nitrogen ... Texas Austin fungal biofilter ... N~~O~~ nitrox oxide N2O
Rot white fungi ← late 80 early 90's
slow rate ... → successful in lab scale

VOC's in treatment plants in general 15 Yrs { First municipal / now industry

Orange county study ...

gas in sewer saturated, then go to blower (vapor contained) so as cools
vapor shows up ...

Loosing H2O ... inlet air warm can in ... Cause heating
draining off excess H2O in addition to ...
Characterize condensate?
natural ventilation (Wind across holes & barometric press.)

Sept 4 – Oct 20 Ed off.

{ 50 to 60% by weight operate up to 70% without diff. at UCD
{ Channalization ... biofilm (not mobile) ← make

High H2O content → high press. drop 55 sec EBR time 1.5 Q = 10 ft³/sec
RT = 12 sec ← 40

{ H2S → one at short RT 20 ppm
{ H2S → " " high RT 50 ppm

Q (after reactor)?

Tep ...

Separation problems

Retain biomass in voids ?

sludge blanket ⟹ withdraw from bottom ?

other variables ?

Solid Res. time > HRT

Michales Mentow

What type of influent ?

Why so little data ?

SRT < 100 days ?

5. Biofilters

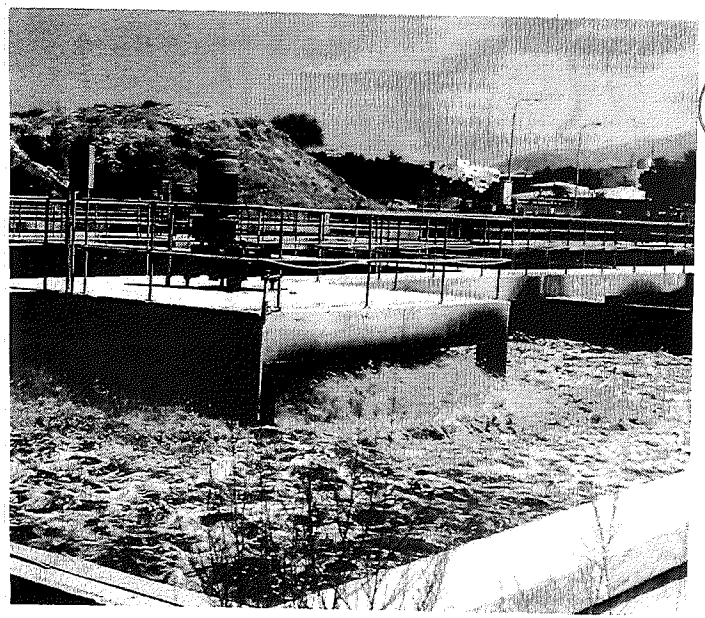
By Poul Harremoës and Mogens Henze

Biofilters are characterized by bacteria being attached to a solid surface in the form of a biofilm. Biofilms are a dense layer of bacteria characterized by their ability to adhere to a solid medium and form a fixed film of polymers in which the bacteria are protected against sloughing off. Biofilters have a short hydraulic retention time and hence free bacteria in the water will be washed out.

The disadvantage of biofilters is the low efficiency of the biomass. The reason is that the substances must be carried through the biofilm to be removed by the bacteria. This transport takes place by molecular diffusion which is a slow process. In practice it proves that the general rule is that the removal is limited by diffusion. This phenomenon must be understood in order to understand the functioning of biofilters.

5.1. Biofilm kinetics

Fig 5.1 shows an idealized biofilm which is assumed to be homogenous. In the water, outside the biofilm, the concentration of a substance is assumed to be S. The transport into the biofilm takes place by molecular diffusion using the diffusion coefficient D.



k. Metamorfosis wastewater treatment plant (Athens, Greece). ·ith surface aeration. Treatment plants in Greece receive large vhich influence design as well as operation of the plants.

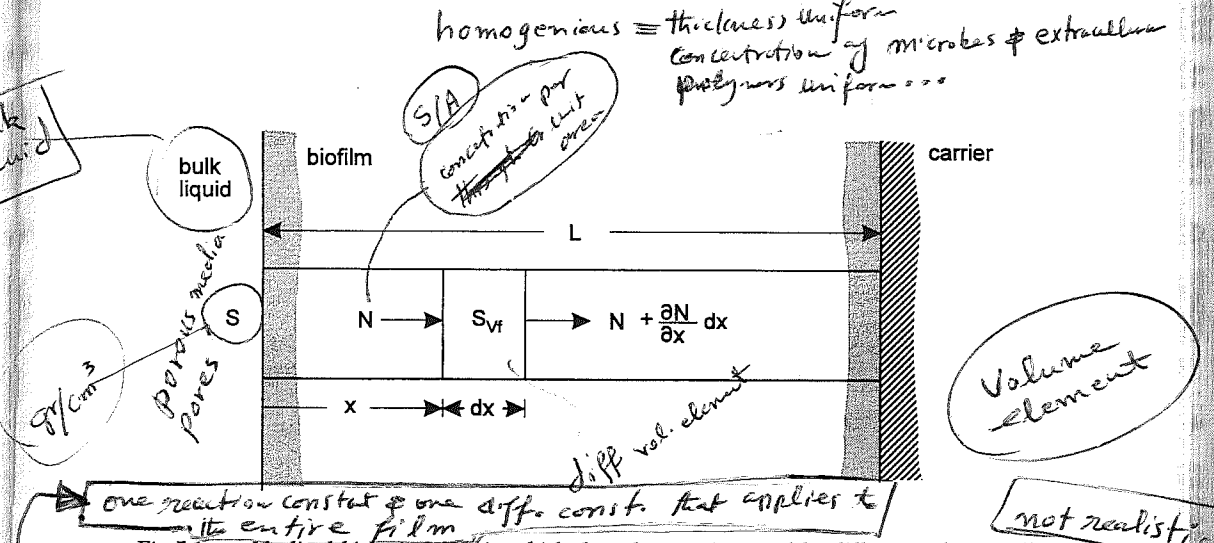


Fig 5.1 *Idealized biological film in which the substance is moved by diffusion. The overall process may be limited by diffusion.*

Michaelis Menten Kinetics

reaction rates

$$\frac{dL}{dt} \triangleq \frac{V_{max}\, L}{K_m + L}$$

ds

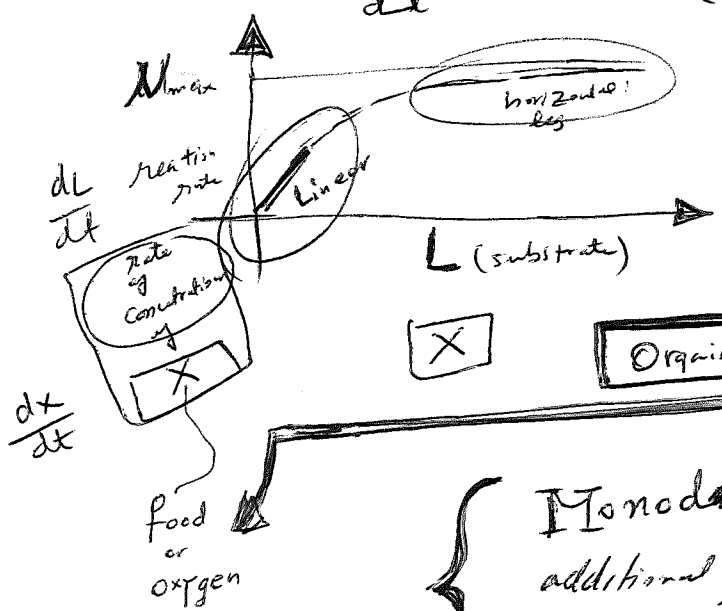
S

L → large → $\frac{dL}{dt} \triangleq V_{max}$ {food not limiting factor}

plenty of food & oxygen → biomass is limiting factor

L → small → $\frac{dL}{dt} \triangleq \frac{V_{max}}{K_m} L$

{food limiting factor to growth}



behavior observed in many situations...

does not take into account toxic & inhibitory

Organism behavior

Horizontal Length
Concentration of food very over long range

If toxicity → biomass decrease
oxygen decrease

limiting factor is biomass

a lot of food + " " oxygen

So biomass so toxicity is there

Monod Kinetics (greater degree of realism...)

additional factor in the formula to show inhibitory...

1. Diffusion
2. Diff. eq.
3. Hyperbolic trig function

For an infinitesimal section of the biofilm, the following balance can be set up under stationary conditions.

$$\text{in} = \text{out} + \text{removed}$$

$$N = N + \frac{\partial N}{\partial x} \cdot dx + r_{Vf} \cdot dx \qquad (5.1)$$

where N is the transport through the cross section

r_{Vf} is the volumetric reaction rate of the biofilm.

$$\frac{\partial N}{\partial x} = -r_{Vf}$$

As the transport through the cross section exclusively takes place by diffusion, we have:

$$N = -D \cdot \frac{\partial S_{Vf}}{\partial x}$$

$$\frac{\partial N}{\partial x} = -D \cdot \frac{\partial^2 S_{Vf}}{\partial x^2}$$

$$\frac{\partial^2 S_{Vf}}{\partial x^2} = \frac{r_{Vf}}{D}$$

Quantitatively, this equation can be interpreted in such a way that the second derivative of a concentration distribution expresses a curvature on the distribution. If there is no reaction, the concentration distribution is rectilinear, for example by diffusion in the water phase, see Section 5.3. If there is production, the distribution curves upwards. If there is removal the distribution curves downwards as it appears from the following pages.

This equation is made dimensionless by measuring relative to the characteristic parameters:

$$s_{Vf} = \frac{S_{Vf}}{S} \qquad \xi = \frac{x}{L}$$

$$\frac{\delta^2 s_{Vf}}{\delta \xi^2} = \frac{r_{Vf} L^2}{DS} \qquad (5.2)$$

As a solution to this second order differential equation, two cases are considered: A zero and a first order reaction:

First order reaction:

$$r_{Vf} = k_{1Vf} \cdot S_{Vf}$$

where S_{Vf} is the concentration in the biofilm

k_{1Vf} is a first order rate constant with the dimension d^{-1}

$$\frac{\partial^2 s_{Vf}}{\partial \xi^2} = \frac{k_{1Vf} L^2}{D} s_{Vf} = \alpha^2 s_{Vf} \quad , \quad \alpha = \sqrt{\frac{k_{1Vf} L^2}{D}}$$

$$\frac{\partial^2 s_{Vf}}{\partial \xi^2} + 0 \frac{\partial s_{Vf}}{\partial \xi} - \alpha^2 s_{Vf} = 0 \qquad (5.3)$$

The characteristic equation of this second order homogenous differential equation with constant coefficients is:

$$R^2 - \alpha^2 = 0$$
$$R = \pm \alpha$$

The complete solution for real values of α is

$$s_{Vf} = A\, e^{\alpha \xi} + B\, e^{-\alpha \xi}$$

The constants A and B are determined by these limiting conditions:

$$\xi = 0 \qquad s_{Vf} = 1$$

$$\xi = 1 \qquad \frac{\partial s_{Vf}}{\partial \xi} = 0$$

from which the complete solution is obtained:

$$s_{Vf} = \cosh \alpha\, \xi - \tanh \alpha \sinh \alpha\, \xi \qquad (5.4)$$

By using the addition formulas, we get:

$$s_{Vf} = \frac{\cosh(\alpha\,(1-\xi))}{\cosh \alpha} \quad , \quad \alpha = \sqrt{\frac{k_{1Vf} L^2}{D}} \qquad (5.5)$$

The concentration distribution for different values of the dimensionless expression of the geometry and diffusion of the biofilm is shown in Fig 5.2.

The transport through the surface of the biofilm is

$$N = -D\left(\frac{\partial S_{Vf}}{\partial x}\right)_{x=0} = -\frac{D}{L}\left(\frac{\partial s_{Vf}}{\partial \xi}\right)_{\xi=0} S$$

By differentiation of 5.5 and substitution, we get:

$$N = \frac{D}{L} \alpha \tanh \alpha\, S = k_{1Vf} L \frac{\tanh \alpha}{\alpha} S$$

from which it can be seen that a first order reaction in the biofilm can be interpreted as a corresponding first order reaction in the water outside the biofilm. The reaction as a

Instead of biofilm (separate low & high concentration)

If a permeable membrane & no reaction in membrane ...

$\frac{\partial^2 S}{\partial x^2} = 0 \Rightarrow S = \alpha + \beta x$

x → + in ↓ concentration

{as x ↑ then S ↓ linearly} (since no reaction)

no way for anything to happen ...

Transport by diffusion gradient ?

How about convection ?

* ?

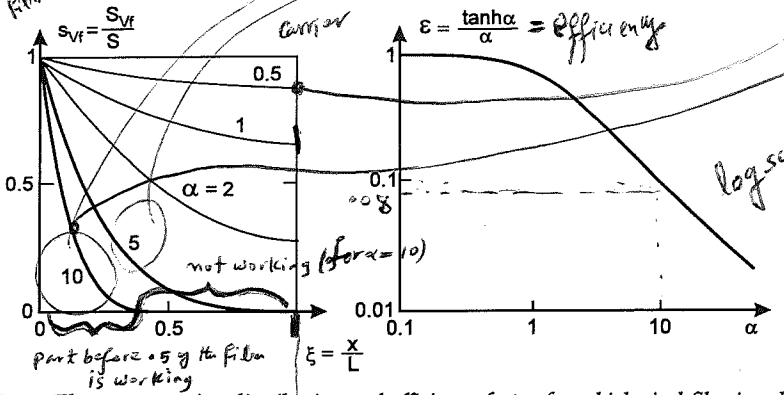


Fig 5.2 *The concentration distribution and efficiency factor for a biological film in which a first order reaction occurs. The efficiency is reduced due to the limited transport capacity of the diffusion.*

transport through the surface of the film is proportional to the concentration just outside the film.

For the reaction per surface area we get:

$$r_A = N = k_{1Vf} L S \cdot \varepsilon \quad , \quad \varepsilon = \frac{\tanh\alpha}{\alpha} \tag{5.6}$$

and for the reaction rate per surface area we get:

$$k_{1A} = k_{1Vf} L \varepsilon \tag{5.7}$$

where k_{1A} is a reduced rate constant, ε is an efficiency factor.

In Fig 5.2 the efficiency factor is shown as a function of the dimensionless expression α for film geometry and diffusion. It appears from the figure that for $\alpha < 1$, $\varepsilon \sim 1.0$, corresponding to a 100 per cent efficiency. The film is fully penetrated. The film is considered to be thick. For $\alpha > 1$ applies

$$\varepsilon \sim \frac{1}{\alpha} = \frac{\sqrt{\frac{D}{k_{1Vf}}}}{L} \tag{5.8}$$

where $\sqrt{\frac{D}{k_{1Vf}}}$ has the dimension "length" and can be understood as the efficient diffusion path.

$$k_{1A} = k_{1Vf} \cdot L \cdot \frac{\sqrt{\frac{D}{k_{1Vf}}}}{L} = \sqrt{D \cdot k_{1Vf}} \tag{5.9}$$

for thick biofilms.

Zero order reaction

For the zero order reaction we have a much simpler expression

$$r_{Vf} = k_{0Vf} \tag{5.10}$$

$$\frac{\partial^2 s_{Vf}}{\partial \xi_2} = \frac{k_{0Vf} L^2}{DS} \tag{5.11}$$

The complete integral is:

$$s_{Vf} = \frac{k_{0Vf} L^2}{2\,DS} \xi^2 + K_1 \xi + K_2$$

For the limiting condition at the surface we get:

$$\xi = 0 \ , \ s_{Vf} = 1 \ \rightarrow \ K_2 = 1$$

If the observed substance can fully penetrate the film, we get the following limiting conditions:

$$\xi = 1 \ , \ \frac{\partial s}{\partial \xi} = 0 \ \rightarrow \ K_1 = \frac{-k_{0Vf} L^2}{DS}$$

$$s_{Vf} = \frac{k_{0Vf} L^2}{2\,DS} \xi^2 - \frac{k_{0Vf} L^2}{DS} \xi + 1$$

$$s_{Vf} = \frac{\xi^2}{\beta^2} - 2\frac{\xi}{\beta^2} + 1 \tag{5.12}$$

$$\beta = \sqrt{\frac{2\,DS}{k_{0Vf} L^2}} \tag{5.13}$$

The concentration distribution in the biofilm is shown in Fig 5.3. For the total transport through the surface of the film we get

$$r_A = N = k_{0Vf} L$$

corresponding to the biofilm being fully efficient, which means that the removal is taking place according to the zero order reaction throughout the full length of the film. This requires, however, that there is something to remove in the very heart of the film, which means that the concentration has to be greater than zero for $\xi = 1$. The result is the following condition:

$$\beta > 1$$

If this condition is not complied with, the limiting conditions must be changed.

at $\xi = \xi' \ , \ s_{Vf} = 0$

5.10 ?

no reaction when no food

$$V_{vf} \begin{cases} = 0 & \text{if } s_{vf} = 0 \\ = K_{ovf} & \text{if } s_{vf} > 0 \end{cases}$$

$\beta = .25 \Rightarrow \overset{\text{distance}}{\tfrac{1}{2}\gamma}$ no reaction
no food

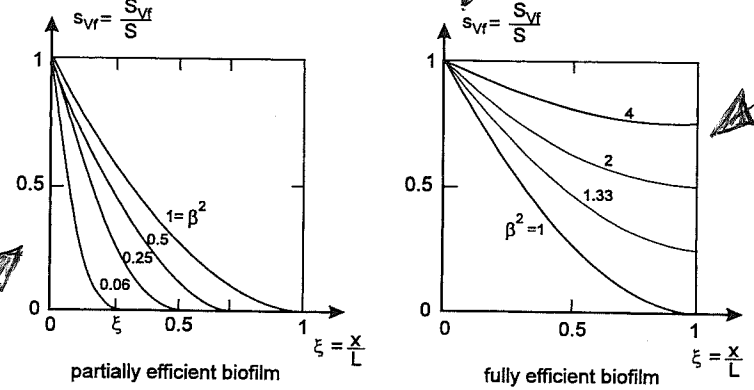


Fig 5.3 *The concentration distributions in a biofilm in which a first order reaction occurs. Right: a biofilm in which the substance diffuses to the bottom. Left: a biofilm in which the substance cannot penetrate to the bottom of the film.*

$$\xi = \xi' \quad , \quad \frac{\partial s_{Vf}}{\partial \xi} = 0$$

From which we get the following solution:

$$s_{Vf} = \frac{k_{0Vf} L^2}{2\,DS} \xi^2 - \frac{k_{0Vf} L^2}{DS} \xi \xi + 1 \qquad (5.14)$$

$$\xi' = \sqrt{\frac{2\,DS}{k_{0Vf} L^2}} = \beta$$

$$s_{Vf} = \frac{\xi^2}{\beta^2} - 2\frac{\xi \xi'}{\beta^2} + 1 \qquad (5.15)$$

where ξ' is the efficient part of the film. The concentration distribution in the film for this case is also shown in Fig 5.3.

From Expression 5.14 it appears that the dimensionless parameter β is an expression of the relative length that a substrate can penetrate the biofilm. Hence β is called the degree of penetration.

Hence, for the overall transport through the surface of the film we get:

$$r_A = N = L\,\xi'\,k_{0Vf} = \sqrt{2\,k_{0Vf}\,D}\,S^{1/2} \qquad (5.16)$$

It is remarkable that while the zero order reaction in the fully efficient biofilm still resulted in a reaction of zero order - independent of S - the zero order reaction in the partially efficient film results in a half order reaction in the water outside the film. For the surface area specific reaction rates of the material, of which the film forms a part, we get:

A fully efficient biofilm:

$$r_A = k_{0A} = k_{0Vf} L$$

A partially efficient biofilm:

$$r_A = k_{1/2A} S^{1/2} = \sqrt{2\,k_{0Vf}\,D}\,S^{1/2} \qquad (5.1$$

$$k_{1/2A} = \sqrt{2\,k_{0Vf}\,D} \qquad (5.1$$

A more detailed study of zero order kinetics in the biofilm can be found in /1/, /2/, /3/ and /4/.

Example 5.1

At the top of a trickling filter there is a high concentration of a removable, dissolved or ganic matter and an oxygen concentration near saturation: 8 g/m^3. Both substances diffuse into the biofilms where the organic matter is mineralized while consuming oxygen at the rate of $k_{0f,O2}$ = 200,000 g/(m^3 · d). The diffusion coefficient of the oxygen is set at

$D_{O2} = 1.7 \cdot 10^{-4}$ m^2/d, see Tables 5.1 and 5.2.

How far does the oxygen penetrate the biofilm:

$$\beta L = \sqrt{\frac{2DS}{k_{0Vf}}} = \sqrt{\frac{2 \cdot 1{,}7 \cdot 10^{-4} \cdot 8}{200{,}000}} = 117\ \mu m$$

It appears that if the biofilm is thinner than 117µm, the film will be fully penetrated. Conversely, if the film is thicker than 117µm, the film is partially penetrated and ir respective of the thickness it is a half order process, the reaction rate for oxygen being

$$k_{1/2A,O2} = \sqrt{2\,k_{0Vf} \cdot D} = \sqrt{2 \cdot 200{,}000 \cdot 1.7 \cdot 10^{-4}} = 8.2\ g^{1/2}\,m^{-1/2}d^{-1}$$

$$r_{A,O2} = 8.2 \cdot 8^{1/2} = 23\ g\ O_2/(m^2 \cdot d)$$

In practice, the biofilm in a trickling filter is considerably thicker than 117 µm (of the order of 1 mm). Hence partial penetration and half order processes are dominant.

The overall reaction pattern for a biofilm can be summarized as follows:

first order: $k_{1A} = k_{1Vf} L \cdot \varepsilon$ $\begin{cases} \varepsilon = \dfrac{\tanh\alpha}{\alpha} \\ \alpha = \sqrt{\dfrac{k_{1Vf} L^2}{D}} \end{cases}$ (5.1

zero order: $\begin{cases} \beta > 1 & k_{0A} = k_{0Vf} L \\ \beta < 1 & k_{1/2A} = \sqrt{2\,D\,k_{0Vf}} \end{cases}$ $\beta = \sqrt{\dfrac{2\,DS}{k_{0Vf} L^2}}$

An overview of the relationship between the three orders of reaction can be obtaine by substituting the following relation between the first and zero orders of reactior

$$k_{0Vf} = k_{1Vf} K_S \qquad (5.2$$

where K_S is the concentration at which the two reaction rates would be identical if there were only first and zero orders, or the saturation constant, if Monod kinetics were applied. Hence:

first order: $$\kappa = \frac{r_A}{k_{0A}} = \frac{k_{1Vf} L \varepsilon}{k_{0Vf} L} S = \varepsilon \cdot \frac{S}{K_S} \qquad (5.21)$$

zero order:
$$\begin{cases} \beta > 1 & \kappa = \dfrac{r_A}{k_{0A}} = 1 \\ \beta < 1 & \kappa = \dfrac{r_A}{k_{0A}} = \dfrac{k_{½A} S^{½}}{k_0 A} = \dfrac{\sqrt{2\, D k_{0Vf} S^{½}}}{k_{0Vf} L} = \beta = \dfrac{\sqrt{2}}{\alpha} \left(\dfrac{S}{K_S} \right)^{½} \end{cases}$$

This is shown in Fig 5.4 in an arithmetic representation. It appears that there is no half order process for $\alpha < 2$. For $\alpha > 2$, the half order process forms a soft transition between the first and zero order reactions. This soft transition has often been confused with Monod kinetics which it resembles. The half order reaction is, however, an expression of a diffusional limitation in the biomass and depends on the diffusion path, whereas Monod kinetics in theory apply to the individual bacterium.

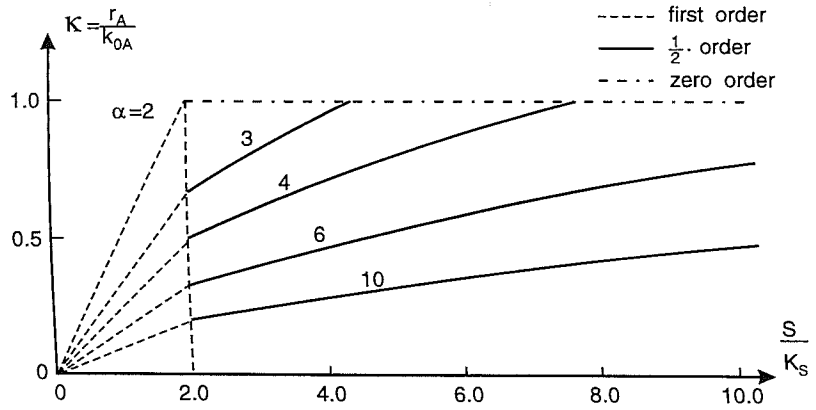


Fig 5.4 *A dimensionless representation of the reaction rate as a function of the concentration outside a biofilm. There are three orders of reaction, a zero order, a first order and a half order for $\alpha > 2$.*

Example 5.2

In the last part of a filter, the concentration of the easily degradable organic matter is reduced to 10 g /m^3. For the removal of the organic matter in the biofilm K_S = 10 g/m^3 and k_{0Vf} = 300 kg/(m^3· d). The biofilm is 200 µm thick. The diffusion coefficient is 0.4 · 10^{-4} m^2/d.

Find the order of reaction and the rate of reaction.

$S/K_S = 10/10 = 1.0$

The change in the order of reaction takes place at $S/K_S = 2$; hence it is a first order process. The change from a half order to a first order takes place at S = 20 g/m^3.

The internal first order rate constant is

$k_{1Vf} = k_{0Vf}/K_S = 300 \cdot 10^3/10 = 30{,}000\ d^{-1}$

It is estimated that the biofilm is only slightly penetrated because

$$\alpha = L\sqrt{\frac{k_{1Vf}}{D}} = 200 \cdot 10^{-6} \sqrt{\frac{30{,}000}{0.4 \cdot 10^{-4}}} = 5.5$$

$$\varepsilon = \frac{1}{\alpha} = 0.18$$

The removal per surface area without diffusional limitation ($\varepsilon \sim 1$) would be

$k_{1A} = k_{1Vf} \cdot L = 30{,}000\ d^{-1} \cdot 200 \cdot 10^{-6}\ m = 6$ m/d

$r_A = k_{1A}\, S_{org} = k_{1Vf}\, L S_{org} = 60$ g/(m^2 · d)(without limitation)

Due to the diffusional limitation, the removal has been reduced to

$k_{1A} = 6 \cdot 0.18 = 1.1$ m/d

$r_A = 60 \cdot 0.18 = 11.0$ g/(m^2 · d) (with diffusional limitation)

These theories for diffusional limitation of reactions in biomass, specifically biofilms and bioflocs, can be generalized to a random process of order n. Hence it proves that the generally governing parameter can be written:

$$\Phi = \sqrt{\frac{(n+1) k_{nVf} L^2 S^{n-1}}{2D}} \qquad (5.22)$$

For zero order we get:

$$\Phi = \sqrt{\frac{k_{0Vf} L^2}{2DS}} = \frac{1}{\beta} \qquad (5.23)$$

For first order we get:

$$\Phi = \sqrt{\frac{k_{1Vf} L^2}{D}} = \alpha \qquad (5.24)$$

The quantity Φ is called the **Thiele module**.

5.2. Biofilm kinetic parameters

The removal of a substrate in a biofilm takes place through bacterial reactions inside the biofilm where the individual bacterium behaves in the same manner as bacteria

Biofilm kinetic parameters

$$r_{V,XB} = \mu_{max} \frac{S}{S + K_S} \cdot X_B$$

where V is understood as the volume inside the biofilm. This is analogized by the substrate removal. For the substrate removal, the following zero order and first order approximations apply:

$$k_{0Vf} = r_{V,S} = \frac{\mu_{max}}{Y_{max}} \cdot X_B \qquad (5.25)$$

$$k_{1Vf} \cdot S = r_{V,S} = \frac{\mu_{max}}{Y_{max}} \cdot \frac{S}{K_S} X_B$$

In these expressions, kinetic constants as those known from suspended cultures can be used.

Compared with suspended cultures the difference is the concentration of bacteria which is much higher in a biofilm than in a suspension. In activated sludge plants, the concentration varies from 2 to 6 kg VSS/m^3. In biofilms the concentration varies from 10 to 60 kg VSS/m^3. The only new parameter which comes into use is therefore the diffusion coefficient D. The measurement of this coefficient in the biofilm is uncertain and should not be relied upon. In practice, the diffusion coefficient can be put equal to or a little lower than the molecular diffusion coefficient which can be looked up in standard reference books, for example /5/. Table 5.1 shows relevant diffusion coefficients in pure water. Often a reduction factor of 0.8 is used, see Table 5.2; it should be stressed, however, that the variation is wide, depending for example on the surface structure of the biofilm /6/.

Substance	D	Substance	D	Substance	D
O_2	2.1	CH_3COO^-	1.0	NH_4^+	1.7
CO_2	1.6	$C_6H_{12}O_6$	0.6	NO_2^-	0.9
HCO_3^-	1.0			NO_3^-	1.6
CO_3^{2-}	0.4				

Table 5.1
Diffusion coefficients in pure water at 25°C. Unit 10^{-4} m^2/d.

Substance	D 10^{-4} m^2/d	$v_{O2,S}$* g COD/g O_2	k_{0Vf} kg COD/(m^3 · d)
Oxygen	1.7 - 2.1	-	25 - 200
Acetic acid	0.3 - 0.7	2.1	230 - 300
Methanol	0.8 - 4	1.2	40 - 110
Glucose	0.1 - 0.7	2.4	350 - 550
unspec. COD	0.3 - 0.6	1.4 - 2	50 - 500
unspec. BOD	0.3 - 0.6	0.8 - 1.2	25 - 250

* in connection with biological growth.

Table 5.2
Diffusion coefficients for oxygen and organic substrates, stoichiometric conditions, and estimated removal rate internally in biofilms. The estimates are uncertain and should not be relied upon.

The bacterial density is a difficult quantity to predict since it is not a constant, but varies in a rather unknown manner with the growth history of the biofilm: Growth on small concentrations yields a large bacterial density and conversely for easily degradable, dissolved substrates.

Example 5.3

In an ideally mixed trickling filter the specific surface is 100 m^2/m^3. COD is removed in a 1 mm thick biofilm by kinetic constants corresponding to activated sludge plants (Table 3.7):

μ_{max} = 6 d^{-1}

$K_{S,COD}$ = 20 g COD(B)/m^3

Y_H = 0.67 g COD(B)/g COD(S)

The concentration of bacteria in the biofilm is 40 kg VSS /m^3, corresponding to 40 · 1.4 = 56 kg COD(B)/m^3

What is the volumetric concentration of bacteria in the biofilter:

$X = 100\ m^2/m^3 \cdot 1 \cdot 10^{-3}\ m \cdot 40\ kg\ VSS/m^3 = 4\ kg\ VSS/m^3$
$= 5.6\ kg\ COD(B)/m^3$

It appears that the effective biomass in a trickling filter is not bigger than in an activated sludge plant. The bigger specific biomass is obtained in filters with a very large specific surface, for example in fluidized filters.

How big is the removal per surface area when the COD-concentration in the filter is 50 g/m^3?

This is a zero order process in the biofilm because the concentration in the water is higher than 2 · K_S.

$$k_{0Vf} = \frac{6}{0.67} \cdot 56 = 500\ kg\ COD/(m^3\ biofilm \cdot d)$$

The diffusion coefficient for the organic matter is set at 0.4 · 10^{-4} m^2/d.

$$k_{½A} = \sqrt{2\ k_{0Vf} \cdot D} = \sqrt{2 \cdot 500 \cdot 10^3 \cdot 0{,}4 \cdot 10^{-4}} = 6.3\ g^{½} m^{-½} d^{-1}$$

$$r_A = 6.3 \sqrt{50} = 45\ g\ COD/(m^2 \cdot d)$$

This yields 45 · 100 m^2/m^3= 4,500 g COD/(m^3 · d) volumetric removal in the filter, corresponding to a **high-rate** trickling filter. (It is assumed that there is sufficient oxygen; see Example 5.5).

5.3. Hydraulic film diffusion

Apart from the diffusional limitation in the biofilm itself, a limitation occurs in practice by transport of substrate from the bulk water to the surface of the biofilm. This transport can be described in a simplified manner by a proportionality between the difference in transport and concentration

$$N = h(S - S_g) \tag{5.26}$$

where h is the transfer coefficient (m/d). The phenomenon is an analogue for the transport of impulse, heat and substance. Much literature is available on tubes, plane surfaces, etc.; but it may be difficult to transfer the information to a biofilm whose surface structure is often badly defined in respect of hydrodynamics. Very few figures from experience are available for biofilms.

In the case where there is a diffusional limitation in the hydraulic film and in the biofilm, the result for a zero order reaction in the biofilm is:

$$N = h(S - S_g) = -D\left(\frac{dS_{Vf}}{dx}\right)_{x=0} \tag{5.27}$$

because the flux across the interface must be the same, both in relation to the hydraulic film as well as the biofilm. The concentration profile from the concentration S in the bulk water to $S_f = 0$ in the biofilm is shown in Fig 5.5.

By integration of the differential equation for biofilm diffusion:

$$s_{Vf} = \frac{k_{0Vf} L^2}{2\,DS}\xi^2 + K_1\xi + K_2$$

where $s_{Vf} = \frac{S_{Vf}}{S_g}$, $\xi = \frac{x}{L}$

The limiting conditions are:

$$\xi = 0 \begin{cases} s_{Vf} = s_g \\ \frac{ds_{Vf}}{d\xi} = \frac{hL}{D}(s_g - 1) \end{cases} \qquad \xi = \xi' \begin{cases} s_{Vf} = 0 \\ \frac{ds_{Vf}}{d\xi} = 0 \end{cases}$$

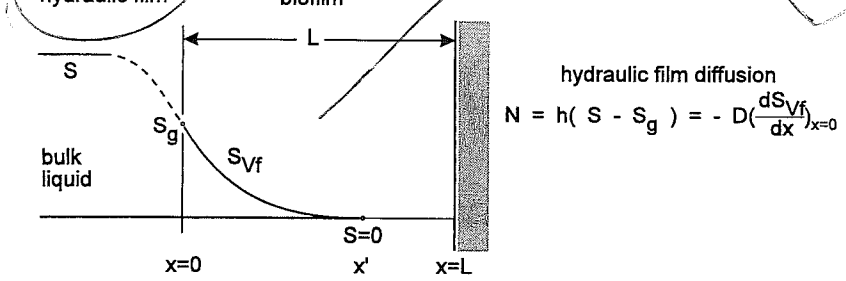


Fig 5.5 *Concentration distribution in the hydraulic film and in the biofilm for a partially penetrated biofilm.*

h is the transfer coefficient for the hydraulic film diffusion. The solution of the equations is:

$$\left.\begin{aligned} \frac{r_A}{k_{1/2A}S^{1/2}} &= \sqrt{1 + \frac{1}{4\lambda^2}} - \frac{1}{2\lambda} \\ \text{or} \quad \frac{r_A}{h \cdot S} &= \frac{1}{2\lambda^2}\left(\sqrt{1 + 4\lambda^2} - 1\right) \end{aligned}\right\} \lambda = \frac{hS}{k_{1/2A}S^{1/2}} \tag{5.28}$$

where λ is a dimensionless quantity which expresses the ratio between hydraulic film diffusion and biofilm diffusion corresponding to:

$$\lambda \to 0 \;\rightarrow\; r_A \to hS$$
$$\lambda \to \infty \;\rightarrow\; r_A \to k_{1/2A}S^{1/2}$$

The result is shown in Fig 5.6. Hence there is a soft transition between the pure hydraulic film diffusion, which corresponds to a first order reaction, and the half order reaction for the biofilm.

For the first order reaction in the biofilm, a corresponding condition for the flux through the area can be set up:

$$N = h(S - S_g) = r_A = k_{1A}S_g$$

$$\left.\begin{aligned} \frac{r_A}{k_{1A}S} &= \frac{\lambda}{\lambda + 1} \\ \frac{r_A}{hS} &= \frac{1}{\lambda + 1} \end{aligned}\right\} \lambda = \frac{h}{k_{1A}} \tag{5.29}$$

but the order of reaction will in any case be a reaction of first order, only reduced by the diffusional limitation. In this case it may thus be difficult to distinguish between the two kinds of diffusional limitation.

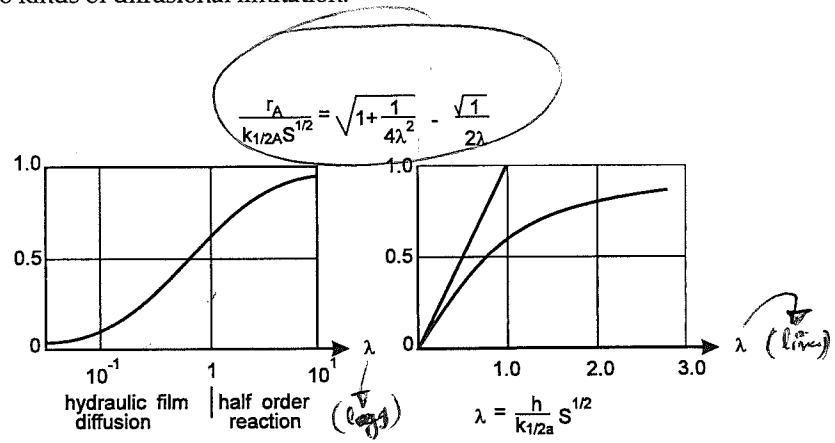


Fig 5.6 *The transition between dominant hydraulic film diffusion and dominant half order heterogeneous biofilm reaction.*

Example 5.4

By interpretation of tests it is necessary to take into consideration the possibility that both hydraulic film diffusion and diffusional limitation in the biofilm have an effect. Fig 5.7 shows a number of measuring points for the removal rate per surface area of nitrate which is removed by denitrifying bacteria in a thick biofilm. Apparently the following relationship is obtained:

$r_A = 0{,}09 \cdot S^{0.64}$

hence a deviation from the expected ½ order.

By substitution

$h = 0.15$ m/h

$k_{½A} = 0.13\ g^{½}m^{-½}h^{-1}$

the full line shown in Fig 5.7 is obtained. For S equal to approx. 50 g NO_3^-–N/m³, the reaction is half order. Hence the exponent found (n = 0.64) can be attributed to the fact that the data are located in the transfer zone between a half order (n = 0.5) and a first order (n = 1.00); but the data do not have a sufficient span to distinctly show the first order reaction. Therefore it is sometimes tempting to make a linear regression on something which is, in fact, a curved graph.

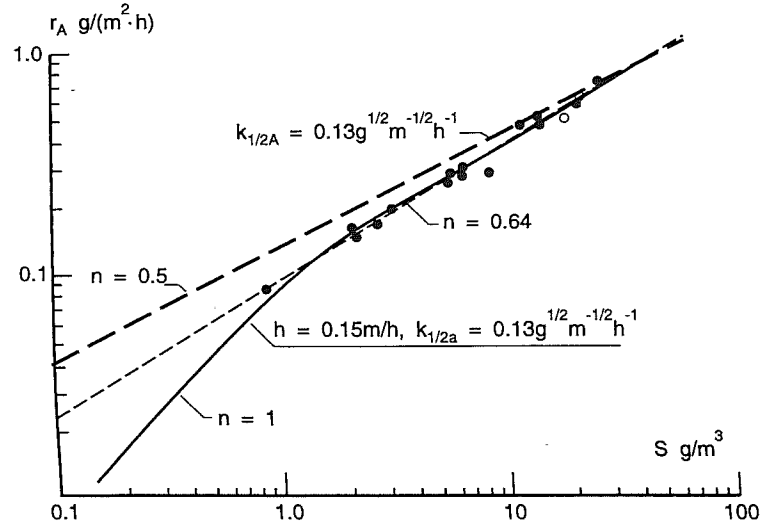


Fig 5.7 *Surface area specific reaction rates of nitrate in a rotating disc as a function of the nitrate concentration in the water phase.*

5.4. Two-component diffusion

Biological removals are almost always redox-processes which require two substrates: an oxidant and a reductant; in this case oxygen and organic matter. One of the most significant results of the biofilm kinetics is the determination as to which substrate is limiting for the removal. This is regulated by the removal rate and the diffusional rate for each of the two substrates.

Oxidant:

$$\frac{d^2 S_{Vf,ox}}{dx^2} = \frac{k_{0,ox}}{D_{ox}}$$

$$S_{Vf,ox} = \frac{1}{2}\frac{k_{0,ox}}{D_{ox}} x^2 + K_{1,ox}\, x + K_{2,ox}$$

$$x = 0 \quad S_{Vf,ox} = S_{ox} = K_{2,ox}$$

$$x = x_1 \quad \frac{dS_{Vf,ox}}{dx} = 0 \ , \quad K_{1,ox} = -\frac{k_{0,ox}}{D_{ox}} x_1$$

$$S_{Vf,ox} = \frac{1}{2}\frac{k_{0,ox}}{D_{ox}} x^2 - \frac{k_{0,ox}}{D_{ox}} x_1 \cdot x + S_{ox} \qquad (5.30)$$

where the index "ox" stands for oxidant. x_1 is the point in the biofilm beyond which no removal takes place because one of the substrates has been used up. This is illustrated in Fig 5.8.

By analogy we correspondingly get for:

Reductant:

$$S_{Vf,red} = \frac{1}{2}\frac{k_{0,red}}{D_{red}} X^2 - \frac{k_{0,red}}{D_{red}} X_1 \cdot X + S_{red} \qquad (5.31)$$

If it is assumed that there is sufficient reductant (Fig 5.8, left), the oxidant will be used up for $x = x_1$.

$$x = x_1 \quad S_{Vf,ox} = 0 \quad x_1 = \beta_{ox} \cdot L = \sqrt{\frac{2\, D_{ox}\, S_{ox}}{k_{0,ox}}}$$

$$r_{A,ox} = \sqrt{2\, D_{ox}\, k_{0,ox}} \cdot (S_{ox})^{½}$$

as previously derived for a limiting substrate.

For the reductant we then get the removal per surface area of the biofilm

$$r_{A,red} = k_{0,red} \cdot x_1 = k_{0,red} \sqrt{\frac{2\, D_{ox}\, S_{ox}}{k_{0,ox}}}$$

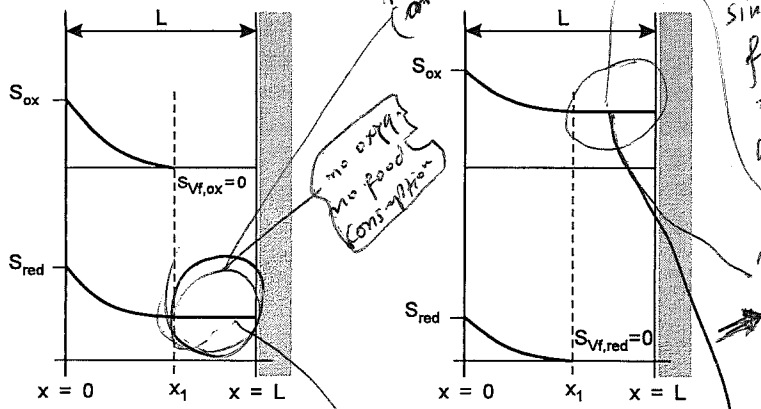


Fig 5.8 *Illustration of partial penetration and rate limitation for two components.*

The removal of the reductant is controlled by the penetration of the oxidant. The reductant is present throughout the film, but cannot be removed for $x > x_1$ because no oxidant is present (Fig 5.8, left).

The substrate which is limiting for the removal is determined by the substrate which penetrates the shortest distance into the biofilm:

$\beta_{ox} < \beta_{red}$ the oxidant is limiting
$\beta_{red} < \beta_{ox}$ the reductant is limiting

$$\frac{\beta_{ox}}{\beta_{red}} = \frac{\sqrt{\frac{2\,D_{ox}\,S_{ox}}{k_{0,ox}}}}{\sqrt{\frac{2\,D_{red}\,S_{red}}{k_{0,red}}}} \gtreqless 1$$

On the basis of the above, the following criterium is developed:

$$\frac{S_{ox}}{S_{red}} \gtreqless \frac{D_{red}}{D_{ox}} \cdot \frac{k_{0,ox}}{k_{0,red}} = \frac{D_{red}}{D_{ox}} \cdot \frac{1}{\nu_{ox,red}} \qquad (5.32)$$

where $\nu_{ox,red}$ is the stoichiometric coefficient.

If the sign of inequality > applies, the reductant is potentially limiting for the removal. Conversely for <, the oxidant will be potentially limiting because it has the shortest penetration depth.

Example 5.5

A biofilter treats wastewater where the organic matter can be assumed to be soluble, that is, diffusible in the biofilm. The influent concentration is 150 g COD/ m^3.

For the kinetic constants it can be estimated (Table 5.2):

$D_{O2} = 1.7 \cdot 10^{-4} m^2/d$

$D_{COD} = 0.4 \cdot 10^{-4} m^2/d$

$\nu_{O2,COD} = 1.7$ g COD/g O_2

Controlling for the removal rate applies:

$$\frac{S_{O2}}{S_{COD}} \gtreqless \frac{D_{COD}}{D_{O2}} \frac{1}{\nu_{O2,COD}} = \frac{0.4 \cdot 10^{-4}}{1 \cdot 7 \cdot 10^{-4} \cdot 1.7} = 0.14 \text{ g } O_2/\text{g COD}$$

If the oxygen concentration is less than 0.14 S_{COD}, it is limiting for the removal. At the influent, the oxygen concentration is less than 0.14 g O_2/g COD · 150 g COD/m^3 = 21 g O_2/m^3 because it is greater than the saturation with the air: 10 g O_2/m^3 at 15°C.

If the oxygen concentration in the filter just ahead of the outlet is assumed to be 2 g O_2/m^3, the COD-concentration should be less than $S_{O2}/0.14 = 2/0.14 = 14$ g COD/m^3 in order to be limiting.

The conclusion is that in a filter treating dissolved organic matter with oxygen as the only oxidant, the oxygen will be limiting for the removal in the major part of the filter.

5.5. Filter kinetics

For a given medium in a filter, the analysis of the filter processes can be made in two stages as shown in Fig 5.9:

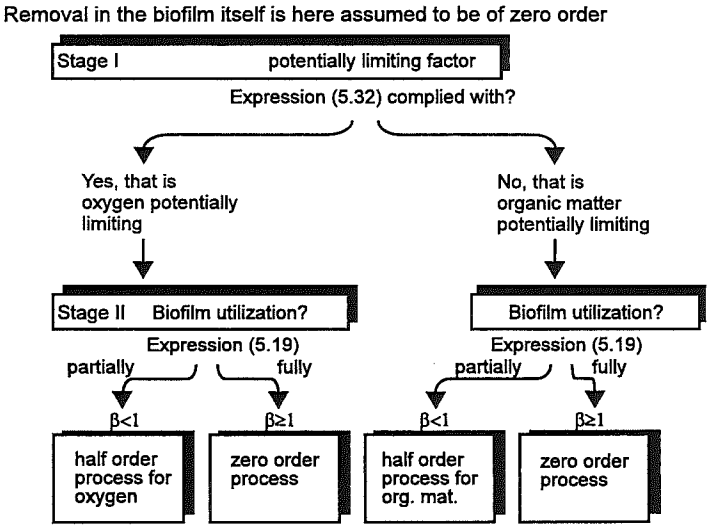


Fig 5.9 *Biofilm kinetic user guide. The calculation procedure is shown which is used to determine the kinetics in relation to the wastewater (bulk phase).*

I. It is determined whether oxygen or organic matter is the potentially limiting factor and hence controls the removal rate and the kinetics.

II. It is determined whether the whole biofilm is active (that is, whether the potentially limiting matter is found throughout the biofilm, or whether only the outer part of the biofilm removes substances). This is important for the order of reaction.

The calculation path is shown in Fig 5.9.

Fig 5.10 shows an ideally mixed tank in which a heterogeneous process takes place without hydraulic film diffusion. For each of the three orders of reaction we get zero order:

$$r_A = k_{0A} \qquad (5.33)$$

$$S_3 = S_1 - \frac{k_{0A} A_{2*}}{Q}$$

half order:

$$r_A = k_{½A} \cdot S_3^{½} \qquad (5.34)$$

$$S_3^{½} = \sqrt{\left(\frac{k_{½A} A_{2*}}{2Q}\right)^2 + S_1} - \frac{k_{½A} A_{2*}}{Q}$$

first order:

$$r_A = k_{1A} S_3 \qquad (5.35)$$

$$S_3 = \frac{QS_1}{Q + k_{1A} A_{2*}}$$

Notice that the volume of the reactor, and hence the retention time, are not included in the expressions at all. These expressions can be used for simulation of processes in filters where the whole reactor can be considered to be ideally mixed. The data given in Example 5.4 have been obtained through measurement of nitrate removal on a rotating disc with an ideal mix.



Fig 5.10 *Ideally mixed reactor in which a heterogeneous process occurs.*

The flow through a submerged filter (that is, a filter which is fully submerged in the water) can, with reasonable approximation, be considered to be plug flow. Fig 5.11 shows a submerged filter. For a infinitesimal section, the following balance can be set up under stationary conditions:

$$\text{in} - \text{removed} = \text{out} \qquad (5.36)$$

$$QS - r_{V,S} A dy = Q\left(S + \frac{\partial S}{\partial y} dy\right)$$

where Q is the flow through the filter

S is the concentration

A is the cross sectional area of the filter

$r_{V,S}$ is the volumetric removal rate of the filter

$$\frac{\partial S}{\partial y} = -r_{V,S} \frac{A}{Q} \qquad (5.37)$$

or dimensionless:

$$s = \frac{S}{S_1}, \quad \eta = \frac{y}{H}, \quad HA = V, \quad \theta = \frac{V}{Q} \qquad (5.38)$$

$$\frac{\partial s}{\partial \eta} = -\frac{r_{V,S}}{S_1} \theta$$

where θ is the hydraulic retention time (corresponding to an empty filter).

Here $r_{V,S} = \omega \cdot r_{A,S}$ can be substituted where ω is the surface area of the filter medium per unit volume of the filter. For $r_{A,S}$ the three cases observed during the biofilm diffusion can be substituted:

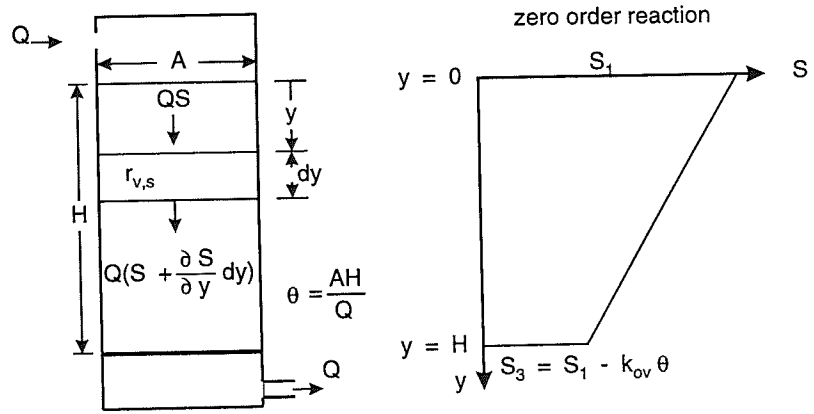


Fig 5.11 *Mass balance for a submerged filter in which a heterogeneous process takes place, and the concentration distribution in the filter if a zero order reaction occurs.*

Zero order reaction:

$$\frac{\partial s}{\partial \eta} = -\frac{k_{0V}}{S_1}\theta \tag{5.39}$$

$$s = 1 - \frac{k_{0V}}{S_1}\theta \cdot \eta \tag{5.40}$$

$$E = \frac{S_1 - S}{S_1} = 1 - s = \frac{k_{0V}}{S_1}\theta \cdot \eta \tag{5.41}$$

where E is the treatment efficiency. This is shown in Fig 5.11. The expression applies, of course, only to

$$0 < \frac{k_{0V}}{S_1} \cdot \theta < 1$$

Half order reaction:

$$r_V = \omega\, r_A = \omega\, k_{½A}\, S^{½} = k_{½V}\, S^{½} = k_{½V}\, S_1^{½}\, s^{½} \tag{5.42}$$

$$\frac{\partial s}{\partial \eta} = -\frac{k_{½V}}{S_1^{½}}\theta^{½} \cdot s^{½} \tag{5.43}$$

$$s = \left(1 - \frac{1}{2}\frac{k_{½V}}{S_1^{½}}(\theta\,\eta)\right)^2 \tag{5.44}$$

$$E = 1 - \left(1 - \frac{1}{2}\frac{k_{½V}}{S_1^{½}}(\theta\,\eta)\right)^2 \tag{5.45}$$

First order reaction:

$$\frac{\partial s}{\partial \eta} = -k_{1V}\,\theta\, s \tag{5.46}$$

$$s = e^{-k_{1V}\theta \cdot \eta} \tag{5.47}$$

Each of these expressions for the relationship between treatment efficiency and retention time for different values of the respective reaction rates and influent concentrations can be used independently. A special case is, however, a filter with biofilm diffusion because all three cases can occur at different levels in the same filter. At the influent, the concentration may be sufficiently big for the medium to diffuse to the bottom of the biofilm - a zero order reaction. After some treatment, the reduced concentration means that the biofilm becomes partially efficient - a half order reaction. Further down in the filter the concentration outside the biofilm will drop from values corresponding to a reaction of half order to values corresponding to a reaction of first order. The whole biofilm will then behave as having a first order reaction with reduced efficiency; see Section 5.1.

The transition between the zero and half order reaction can be directly determined. The transition criterium is, according to the previous section:

$$\beta = 1 \qquad \begin{cases} S > S_0 & k_{0V} = \omega\, k_{0A} \\ S < S_0 & k_{½V} = \omega\sqrt{2\, k_{0Vf}\, D} \end{cases}$$

$$S_0 = \frac{L^2 k_{0Vf}}{2\,D}$$

The transition from half order to first order can be determined correspondingly

$$S_1 = 2\,K_S \quad \begin{cases} S > S_1 & k_{½V} = \omega\,\sqrt{k_{0Vf}\, D} \\ S < S_1 & k_{1V} = k_{1Vf} \cdot L \cdot \varepsilon \end{cases}$$

Example 5.6

A 4 m high submerged filter filled with plastics packing with a specific surface of 100 m^2/m^3 has a nominal filter velocity of 1 m/h. The wastewater has a concentration of 500 g COD/m^3. The same process constants as in Examples 5.3 and 5.5 are used.

Air is constantly bubbled into the filter resulting in an efficient aeration so that the whole water column on the whole depth is assumed to have an oxygen concentration of 2 g O_2/m^3. According to Example 5.5, the filter will be oxygen limited from the top to the position in the filter where S_{O2}/S_{COD} = 0.14 g O_2/g COD, that is, when S_{COD} has been reduced to 14 g COD/m^3.

In the upper part of the filter, the removal is of a half order in the oxygen concentration which, however, occurs in the filter itself as a zero order because the oxygen concentration is assumed to be constant.

$$k_{0V} = \omega \cdot k_{½A,O2} \cdot S_{O2}^{½}$$

$$k_{½A,O2} = \sqrt{2\, D_{O2} \cdot k_{0f,O2}} \tag{5.48}$$

$$k_{0f,O2} = \frac{\mu_{max}}{Y_H} \cdot X \cdot \frac{1}{\nu_{O2,COD}}$$

$$k_{0f,O2} = \frac{6}{0.67} \cdot 56\,\frac{1}{1.7} = 295\ gO_2/(m^3 \cdot d)$$

$$k_{½A,O2} = \sqrt{2 \cdot 1.7 \cdot 10^{-4} \cdot 295 \cdot 10^3} = 10\ (g\ O_2)^{½} m^{-½} d^{-1}$$

$$k_{0V} = 100 \cdot 10 \cdot \sqrt{2} = 1400\ g\ O_2/(m^3 \cdot d) = 2400\ g\ COD/(m^3 \cdot d)$$

which corresponds to a high-rate filter.

(Hence the result in Example 5.3 was not realistic because oxygen is limiting for the removal.)

The filter is loaded with 1 m/h corresponding to 24 m/d and a concentration of 500 g COD/m^3, or 500 · 24 = 12,000 g COD/(m^2 · d) . The filter removes 2400 g COD/(m^3 · d) over 4 m, that is, 9600 g COD/(m^2 · d). Residue: 2400 g COD/(m^2 · d), corresponding to an effluent concentration of 2400/24 = 100 g COD/m^3. Hence a COD-limited removal (100 g COD/m^3 > 14 g COD/m^3) does not occur.

5.6. Mass balances for biofilters

Normally it is not necessary to recycle sludge over a biofilter plant, as the sludge concentration becomes sufficiently large by means of the biofilm and a sufficiently large specific solid surface (the carrier). As recycle of sludge is not necessary, we can, in certain cases, leave out a secondary settling tank - see Section 6 about nitrification. Normally, however, the sludge present in the water which has passed the biofilter needs a subsequent settling. The sludge comes from sloughed off biofilm and from the content of suspended solids in the influent water.

5.6.1 Biofilters without recycle

A mass balance for material over the biofilter itself looks as follows:

$$Q_1 \cdot C_1 - r_{V,S} \cdot V_2 = Q_3 \cdot C_3 \qquad (5.49)$$

The removal can also be expressed by means of the sludge concentration, X_2, as

$$r_{V,S} \cdot V_2 = r_{X,S} \cdot V_2 \cdot X_2 \qquad (5.50)$$

As X_2 should only include the active biomass which is usually unknown, it is frequently common practice to relate the removal to the volume or the surface of the carrier.

If the removal is expressed per unit area of carrier, Expression (5.50) will look as follows:

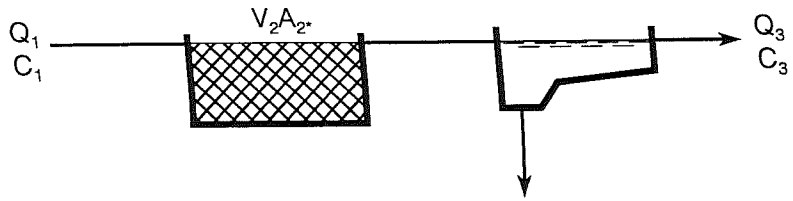


Fig 5.12 *Biofilter without recycle.*

$$Q_1 \cdot C_1 - r_{A,S} \cdot A_{2^*} = Q_3 \cdot C_3 \qquad (5.51)$$

where $r_{A,S}$ is the removal rate per unit area of carrier (unit for example kg COD/(m^2 · d)),

A_{2^*} is the overall area of the carrier (for example m^2).

5.6.2 Biofilters with recycle

Most biofilter plants have recycle which is normally made by recycling directly over the filter (Fig 5.13). The recycle ratio, R, is defined as

$$R = Q_6/Q_1 \qquad (5.52)$$

The purpose of recycling is to ensure a suitable flow of water through the filter. This is important for most types of biofilter plants. Also, the recycle lowers the influent concentration to the biofilter and can therefore affect the process, both through the order of reaction and as to whether oxygen is limiting or not.

The equation for the removal of substrate will be the same as for biofilters without recycle, but the reaction term will be influenced by the recycle.

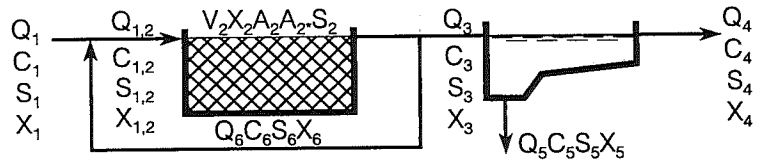


Fig 5.13 *Biofilter with recycle.*

5.7. Concepts and definitions

The concepts and definitions for biofilters are in most cases identical to those used in activated sludge plants.

Treatment efficiency is defined as (see Fig 5.13)

$$E = (C_1 - C_4)/C_1 \qquad (5.53)$$

Similar to the treatment efficiency in activated sludge plants, the treatment efficiency includes the effect of the secondary settling.

Recycle ratio is defined in Expression (5.52).

Volumetric loading rate is defined as

$$B_V = Q_1 \cdot C_1/V_2 \qquad (5.54)$$

The weight of material added per unit volume per unit time, $Q_1 \cdot C_1$, is calculated at a position prior to a possible recycle. The volumetric loading rate cannot be increased by an internal recycle in the plant.

Biofilm surface area has two meanings, the area of the filter tank in a horizontal section and the surface area of the carrier. The latter area is normally calculated from Expression (5.55)

$$A_{2*} = \omega \cdot V_2 \tag{5.55}$$

where ω is the specific surface of the carrier (for example m^2/m^3).

The surface area in a horizontal section, A_2, is used for the calculation of the hydraulic surface loading rate.

Organic surface loading rate is an expression of the load of the surface of the carrier in the filter:

$$B_{A,C} = \frac{Q_1 \cdot C_1}{A_{2*}} \tag{5.56}$$

This is the figure which comes closest to the kinetic conditions in the filter.

Hydraulic surface loading rate (or nominal filter rate) is defined by the symbols in Fig 5.13 as

$$B_{A,V} = Q_{1.2}/A_2 = (Q_1 + Q_6)/A_2 \tag{5.57}$$

This parameter is a simple expression of the flow passing the biofilm and hence is an expression of the hydraulic erosion which is considered to be crucial for the control of the thickness of the biofilm. (In German literature Q_1 is set at the flow during the daytime, for example calculated as the diurnal flow distributed over 18 hours for large plants, see Fig 1.6).

Sludge production, F_{SP}, is the mass of sludge leaving the plant per unit time. According to Fig 5.13 it is

$$F_{SP} = Q_5 \cdot X_5 + Q_4 \cdot X_4 \tag{5.58}$$

For further details concerning sludge production, see Chapter 4, Section 4.2. The comments made in that chapter also apply to biofilter plants. Hence the sludge production can be calculated from Expression (4.13). Note that yield constants for biofilters deviate from yield constants for activated sludge plants.

Surplus sludge production is the part of the sludge production to be further treated in the plant, that is, $Q_5 \cdot X_5$, see Fig 5.13.

5.8. Types of plants

Biofilters must be able to carry out four functions to be able to treat the wate satisfactorily to remove organic matter. The tank should be designed so that:

- the bacteria necessary for the required process can be attached to a carrie (filter medium),
- the water gets into efficient contact with the sludge attached to the carrie (the biofilm/slime),
- the growth of the biofilm can be controlled so that no clogging will occur,
- oxygen is supplied to the water for the degradation of the organic matter.

Bacteria have a remarkable ability to adhere to solid surfaces, whether it concern stone, wood or plastics which are the three types of media used in practice. Th engineering control of the adhesion of such bacteria which carry out the require process is very practical in water and wastewaster treatment - as opposed t industrial production by means of biological reactors which are often based o carefully selected types of bacteria. In water and wastewater treatment such cond tions are established which from experience are known to favour the bacteria whic carry out the required process. This also applies to biofilters: the bacteria whic cannot adhere to a surface will be washed out of the system. The bacteria whic cannot degrade the material concerned cannot compete, see Chapter 3, Section 3.1.: This may occasionally cause difficulties when starting up biofilter plants.

To achieve an efficient removal of the materials in the water, the water must pass th surface of the biofilm in order that a continuous renewal of water at the biofil surface takes place. For this purpose the medium is either solid and the water passe the medium as is the case in the conventional biofilters (trickling filters), or th medium is continually carried through the water as the case is in rotating discs.Th efficiency in the plant type depends to a large extent on how this contact betwee biofilm and water is arranged.

Control of the growth of the biofilm and the conditions concerning the oxyge supply are further discussed in Sections 5.10.2 and 5.10.1.

5.8.1 Trickling filters

The trickling filter is the conventional biofilm reactor and many different types trickling filters have been used during the last century. Fig 5.14 shows the chara teristic type which is a typical three-phase system. The filter medium is stationar typically consisting of 5-20 cm large stones. Any other conceivable materials hav been tried out - only plastics are, however, widely used as an alternative to stone.

The wastewater is distributed over the filter and trickles down over the stones to b collected under the stones and carried out. The ventilation through the bottom the filter is made efficient so as to ensure a steady air current through the filter. I

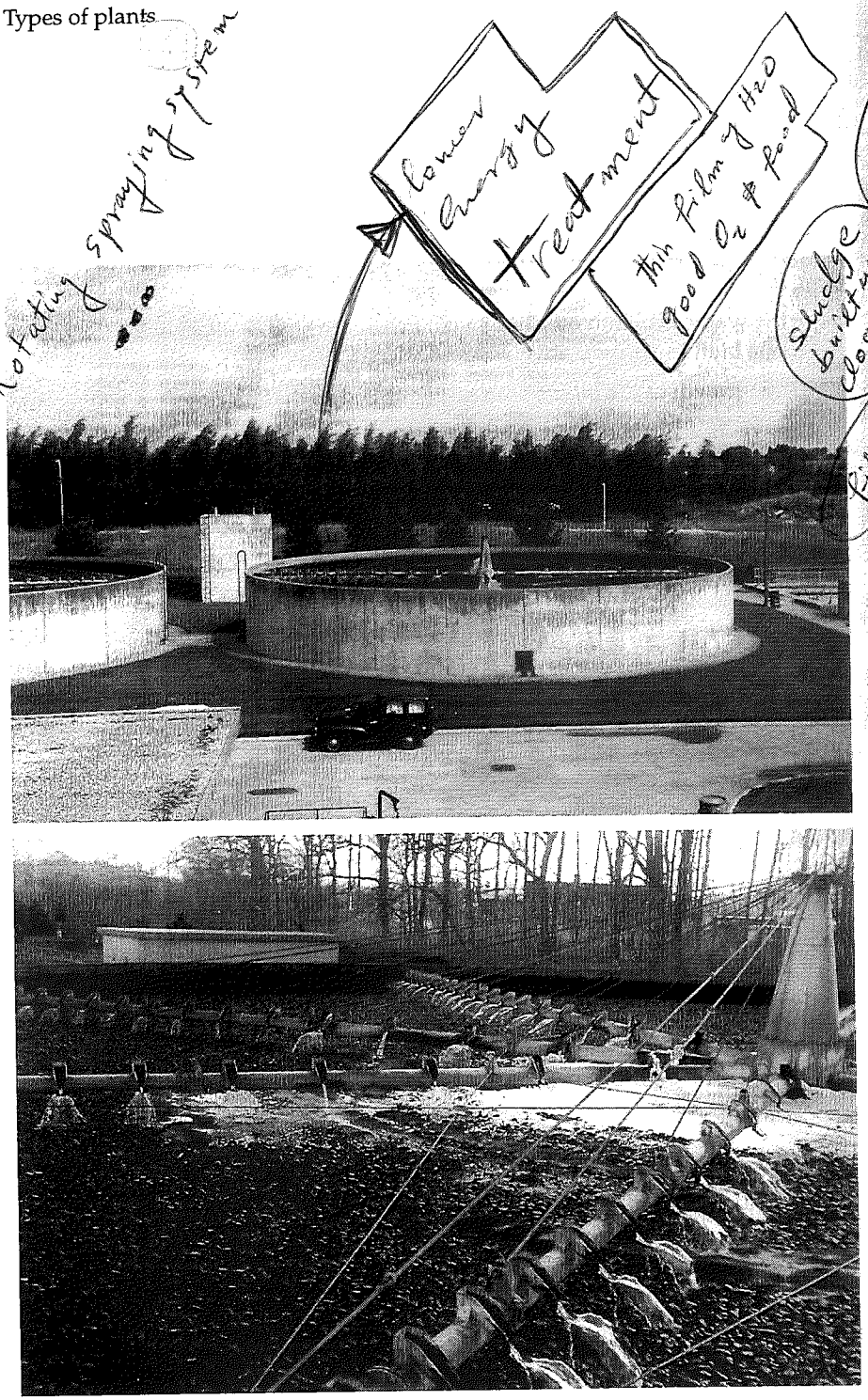


Fig 5.14 *Trickling filters. In the lower picture the filter suffers from partial clogging (or ponding).*

the course of the development it was believed to be necessary to use forced ventilation through such filters, but in practice it has proved that the variation in temperature between filter medium, wastewater and the surrounding air is sufficient to ensure air renewal and reaeration of the water during the trickling from top to bottom. The trickling filter is very efficient with respect to adhesion of bacteria, contact between water and biofilm, and reaeration of the water. The most essential problem with trickling filters is the control of the growth of the biofilm. This is the function making the greatest demand on design and operation. In the oldest, very low-rate plants, the control is biological. The biofilm is allowed to develop uninhibited which leads to local cloggings. The clogging will prevent that oxygen is supplied to the biomass, and it will putrefy locally and be degraded, until there is passage again. Higher animals, such as worms and larvae, also contribute to the degradation of the biomass. Thus the filter can become a hatching plant for insects, especially filter flies, and they can be such a nuisance that this is, in fact, the reason why the low-rate trickling filter is not commonly used. To this should be added that due to the low rate the demand for land space is so big that it can only be satisfied for very small plants.

It is especially bad if the loading is increased (often simultaneously hydraulically and with respect to organic matter) on a low-rate plant as the cloggings spread at a higher rate than the rate at which the cloggings can be degraded. But if the load is increased beyond a certain point, something new happens: From being exclusively biologically controlled, the thickness of the biofilm will now mainly be controlled by hydraulic sloughing off. This is the type of biological trickling filter which is still found in great numbers. In recent years, the trickling filter has experienced a renaissance because plastics have made it possible to create a large volumetric surface in filters of little weight, and these can therefore be built high without incurring considerable costs. Such filters are typically used for the treatment of wastewater with high concentrations as a pretreatment prior to any other treatment.

5.8.2 Submerged filters

Submerged filters are filters where the filter medium is located under the surface of the water. Among many different characteristic designs of filters, the most important characteristic is a stationary or movable filter medium.

Stationary filter medium

Fig 5.15 shows a filter design in principle. What is especially important for the design is: The control of the thickness of the biofilm and the supply of oxygen to the water.

In respect of the thickness of the biofilm and problems with clogging, there are only two solutions to the problem: 1) Spacious filter media with sufficient space and hydraulic conditions, which prevent excessive thicknesses of the film, can be used. With such filter media it is not possible to obtain a large specific surface area, and

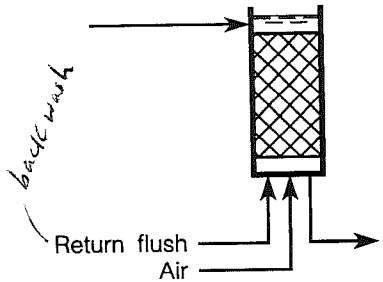


Fig 5.15 *Submerged biofilter with stationary filter medium such as small-size filter media (5-10 cm in diameter) or larger surfaces in ingenious patterns to ensure a smooth distribution of water in the filter.*

these plants take up correspondingly more space. 2) The alternative is to backwash the filter. This is done by applying a high flow of water. In filters with a filter medium consisting of small objects, usually sand, the particles are lifted free of each other and whirled around in the high flow whereby the biofilm is scoured by the particles - just as it is known from the traditional filters at waterworks. In filters containing an immobilized filter medium, the washing effect is reached through the flow of water eroding the biofilm off the material.

In filters for the removal of organic matter to which oxygen must be supplied, the oxygen can be blown in at the bottom of the filter. When the bubbles rise, the water in the filter is oxidized.

Water can be supplied to the submerged, fixed filter, both at the top and at the bottom, and we will often see that this is used to characterize the filter. However, it is in fact of no importance for the functioning of this type of filter, whether it is an "upflow" or a "downflow" filter.

Movable filter medium

Whereas trickling filters and submerged filters with a fixed filter medium are well known, filters with a movable filter medium were developed during the 70s. The three possibilities, which are in principle different, are illustrated in Figs 5.16, 5.17 and 5.18.

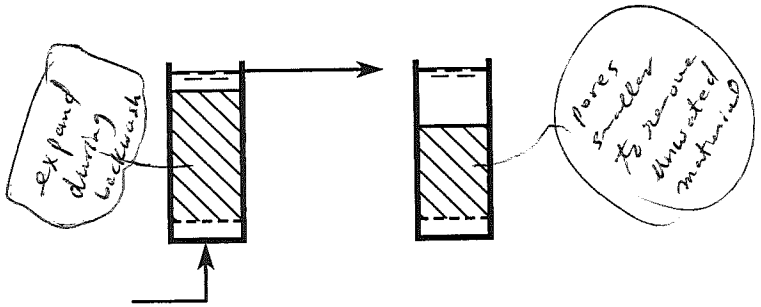


Fig 5.16 *Expanded filter in operation and at a standstill. The expansion of the filter layer in operation is typically 30-40 per cent.*

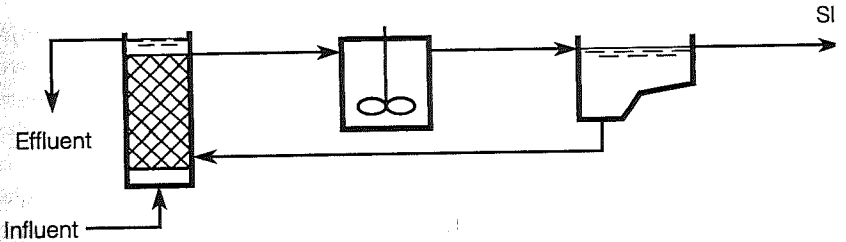


Fig 5.17 *Fluidized filter in operation. The filter layer is typically expanded 100 per cent. are several ways to check biofilm, one of the possibilities being the one shown here the biofilm on the biofilm particles is sloughed off during vigorous stirring after the biofilm and the carrier are separated by settling.*

A filter with an upflow through a loose filter medium, typically sand, will h stationary filter medium as long as the filter medium is not lifted off the pr gradient from bottom to top. If the pressure in the bottom of the filter equals the v corresponding to the weight of the filter above, a lifting of the filter medium will The contact between the individual sand particles is broken and the pa become movable. A filter can be operated at the point just where the particl released from each other. This is called an **expanded filter** - see Fig 5.1 particles constantly grate against each other and keep the biofilm thin. So fa knowledge is not sufficient to establish how safe this biofilm control is in pra

If the upflow in the filter is increased beyond the point where a lifting occu filter medium will expand and for a given rate through the filter a balance be the upflow rate and the settling velocity of the particles will occur which de on the density of the particles. To a given rate corresponds therefore a given d of expansion. The individual particles of the filter medium will be separatec each other and whirled around in the turbulent upflow. This is called a **flui filter** - see Fig 5.17. The fluidization creates a very fine hydraulic contact be the water and the biofilm, but it does not facilitate an automatic biofilm contrc must be established separately and takes place by taking out a separate flow fluid mix of water and filter medium coated with biomass. Fluidized filters a most volumetric efficient biological reactors available - with a biomass in th of up to 40 kg VSS/m^3. The reactor is, however, not simple to operate in pr and we have not yet sufficient experience with long-term operation, but this t plant no doubt has a potential and will find its special niche of application.

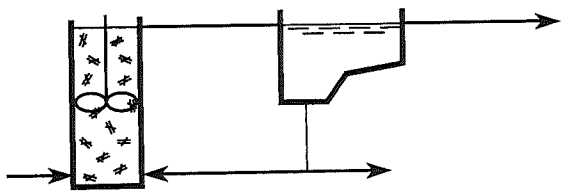


Fig 5.18 *Movable filter with stirring. The filter medium is typically different plastics m both solid and porous.*

In the fluidized filter, the filter medium is kept in suspension in the upflow turbulence. This turbulence can, of course, be established without upflow, and hence we have the **suspended biofilm reactor**, see Fig 5.18. Consequently the connection to the activated sludge plant has been established. The difference is just that for the aeration tank, an inert carrier is intentionally added to which the bacteria adhere. In this way the separation properties can be improved either on account of the weight which the filter medium adds to each individual particle, or because the bigger biofilm particles are easier to retain in the plant (due to a higher rate of settling). It may, on the other hand, be necessary to supply more energy in the form of turbulence to the aeration tank to keep the material suspended. At the same time it is a complication that the added filter medium must be handled in the sludge part of the plant. The intentional addition of filter medium to the "activated plants" is as yet at the experimental stage.

5.8.3 Rotating discs

As early as at the turn of the century, experiments were made to solve the three-phase problem by rotating a filter medium alternately through water and air. All kinds of filter media were used, for example branches fixed to a rotating shaft. Today this principle is solely based on plastics in the form of semi-submerged, rotating discs or a rotating tank containing a filter medium. This is illustrated in Fig 5.19. These discs or bodies of plastics can be shaped so that they give a very large specific surface and hence a large volumetric efficiency. With a remarkably low energy consumption, the rotation creates an efficient aeration of the water and an efficient contact between water and biofilm. The thickness of the biofilm is controlled by the turbulence which is controlled by the rotational speed. In Germany and Switzerland, rotating discs are widespread in the small treatment plants. In the USA this type of plant has been used in all sizes of plants up through the 70s.

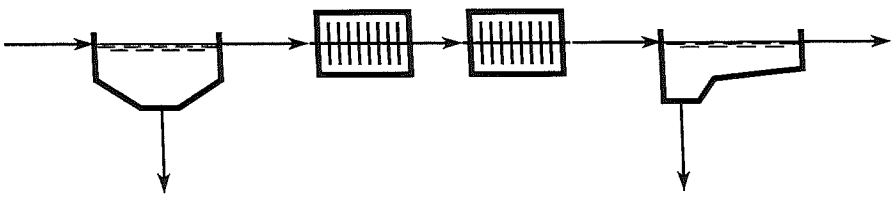


Fig 5.19 *Rotating disc plant. The discs are often divided into sections which are operated in series. Similar to all other filter plants, a good mechanical treatment is needed before the water enters the filter.*

5.9. Design of biofilters

Based on experiences from many years' operation of conventional biofilters, a s
design criteria has been established which is generally used for the practical de
of these plants. These criteria are based on the idea that a given type of plant ca
loaded hydraulically or with organic matter up to a limit which can be determ
for ordinary use in the design phase. This may sometimes be combined
requirements of the retention time in the system. These design criteria are not b
on any special understanding of the phenomena on which the treatment is b
but they are exclusively based on a systematizing of experiences from an en
number of thoroughly measured plants. The criteria are very simple, just like
remarkable that in spite of this simplicity they have actually been most usefu
decades. Likewise there is no doubt that they have given rise to design e
because the circumstances change from one plant to another to a greater extent
it can be expressed in such simple relationships as it will be illustrated for tric
filters and for rotating discs.

5.9.1 Design of trickling filters

According to the classic design criteria for trickling filters the treatment r
exclusively depends on the organic volumetric loading rate and the hydr
surface loading rate.

Based on these parameters and many years' of experience, German design cr
for trickling filters are shown in Table 5.3.

Load category:	Low	Moderate*	Normal	High	Unit
Org. volumetric loading rate:	200	200-450	450-750	>750	g BOD/(m^3 ·
Hydraulic surface loading rate:	approx. 0.2	0.4-0.8	0.6-1.2	>1.2	m/h
Estimated treatment efficiency:	92 ± 10	88 ± 12	83 ± 15	75 ± 20	%
Estimated effluent concentration:	<20	<25	20-40	30-80	g BOD/m

*) This load category is not considered to be applicable because there will be a tendency of clogging. T
loading is too excessive and therefore the internal degradation of biomass cannot keep pace. It is too s
to ensure biofilm control by hydraulic erosion.

Table 5.3
Allowable (German) loading of trickling filters using rocks/stones as carrier loaded with ordinary municipal wastewater /7/.

The German literature (/8/) states the following treatment which is to be exp

$$E = 93 - 0.017\, B_V \quad \text{for} \quad B_V < 1000 \text{ g BOD/(m}^3 \cdot \text{d)}$$

where E is the treatment efficiency in per cent. There is great uncertainty as
observations. For the settled effluent from an ordinary trickling filter loaded
domestic wastewater where B_V = 400 g BOD/(m^3 · d), a 24 hours' flow w

composite sample will show concentrations in the range 5 - 20 g BOD/m^3; for B_V = 1000 g BOD/(m^3 · d) in the range 20 - 50 g BOD/m^3.

It is recommended to carry out the design on the basis of B_V = 400 g BOD/(m^3 · d), 0.5 m/h < $B_{A,V}$ < 1.0 m/h and R < 1.0. For trickling filters with plastics media it is recommended that B_A = 4 g BOD/(m^3 · d), 0.8 < $B_{A,V}$ < 1.8 m/h in the range 100 < ω < 200 m^2/m^3 and R < 1. For these loads no nitrification will take place.

The experience values in Table 5.3 only apply to ordinary municipal wastewater which is considered to have a relatively homogenous composition. All the curves of treatment results (whether expressed as treatment efficiency or as concentration in the effluent), which can be found in great numbers in the literature, are characterized by a very large spread. This expresses that these simple loading rules cannot take into account the numerous special circumstances which occur in practice. In the above, for example, such basic conditions as: Filter medium, surface area, influent concentration and the special property of the organic matter have not been taken into consideration. We have to be very cautious about using the above loading rules uncritically - although these rules have formed the basis of the successful design of numerous full-scale trickling filters.

Example 5.7

A trickling filter with a diameter of 10 m and a height of 2 m is loaded with 235 m^3/d of mixed domestic and industrial wastewaters. The concentration of BOD is 500g/m^3.

Find the volumetric loading rate and the necessary recycle.

According to Expression (5.54), the volumetric loading rate is:

$$B_V = Q_1 \cdot C_1/V_2 = Q \cdot C_1/(\pi \cdot r^2 \cdot h) \qquad (5.59)$$

Substitution gives:

B_V = (235 m^3/d) · (500 g BOD/m^3)/(π · (5m)^2 · 2 m)
B_V = 748 g BOD/(m^3 · d)

Hence the filter is interfacing normal and high loading.

The necessary recycle is controlled by the requirement of the hydraulic surface loading rate which, based on Table 5.3, in this case is estimated at 1.2 m/h.

From Expression (5.57) the necessary recycle, Q_6, can be determined:

$$B_{A,V} = (Q_1 + Q_6)/A_2 \qquad (5.60)$$

Substitution gives:

1.2 m/h · 24 h/d = (235 m^3/d + Q_6)/(π · (5m)^2)

Q_6 = 2,027 m^3/d

that is, a recycle ratio R = Q_6/Q_1 = (2,027 m^3/d)(235 m^3/d)$^{-1}$ = 8.6

This is a high recycle. It appears from Table 5.3 that the requirement of the hydraulic surface loading rate, and hence the recycle, increases by increasing organic volumetric loading rate. For industrial wastewater with high influent concentrations, the requirement of recycle could be quite unrealistic. Therefore filter media in plastics have now become popular as they can be built high without incurring considerable costs. Nor do such filters need correspondingly large hydraulic loadings because of the large void volume of the media which prevents clogging. On the other hand, small effluent concentrations are seldom found. Therefore plastic filters are normally used for pretreatment only.

5.9.2 Design of discs

Some of the rules for rotating discs are very good examples to show how differen the loading rules may be. Table 5.4 lists North American and European examina tions which have resulted in recommended loadings. It clearly appears that there not agreement and that the variation is quite considerable: 5-26 g BOD/(m^2 · d). also appears that the more optimistic figures are those given by companies. Notic that the allowable load is stated per m^2 surface of the discs which is a theoretica much more relevant size to relate the treatment to, than to m^3 of the tank in whic the discs rotate.

Recommended loading g BOD/(m^2 · d)	Year	References
14	1974	Steels /9/
8,5	1978	Murphy and Wilson/10/
26	1976	Autotrol Corp. /11/
13	1977	Envirodisc Corp. /12/
4,9	1974	Ontario Ministry of Environment /13/
8-10	1980	Abwassertechnische Vereinigung /14/

Table 5.4
List of references stating allowable loads for rotating disc plants, applicable for ordinary municipal wastewater at approx. 15°C, to obtain an expected effluent concentration of approx. 15 g BOD/m^3 or less. The influent BOD is based on diurnal measurements.

The biofilm control on rotating discs is regulated by the rotational speed which usually stated as a requirement of a peripheral speed on the discs of not less than 0 m/s. To this should be added a minimum requirement of the distance between th discs which is usually stated at 1.5-2.5 cm.

5.9.3 Rules for other types of filter

None of the submerged filter types have gained such common practical use th actual recommendations are available in respect of loading. The biggest volumetr loading has been achieved with fluidized filters which could be loaded with 10 k BOD/(m^3 · d).

5.9.4 Design of biofilters for dissolved organic matter

Today there are no design criteria for biofilters for the removal of organic matter, based on the biofilm theory. In the first section of this chapter it was suggested how a biofilter for the removal of organic matter from wastewater can be designed. The design takes place in 4 stages. (The calculation procedure for stages I and II are shown in Fig 5.9).

Stage 0: Determine the order of reaction in the biofilm itself. It is typically zero order.

Stage I: Calculate, using Expression (5.32), whether oxygen or organic matter is potentially limiting.

Stage II: Calculate whether the biofilm is fully active ($\beta \geq 1$) or only partially active ($\beta < 1$). Often we will find that the biofilm is only partially active, that is, $\beta < 1$.

Stage III: The removal in the filter can be calculated by means of a mass balance, for example Expression (5.50), for an ideally mixed plant. The removal rate for organic matter, $r_{A,S}$, or oxygen, $r_{A,O2}$, is calculated using one of the 4 expressions below.

For $\beta \geq 1$ the consumption of substrate

$$r_{A,S} = k_{0Vf,S} \cdot L \qquad (5.61a)$$

or if, instead, we look at the oxygen consumption

$$r_{A,O2} = k_{0Vf,O2} \cdot L \qquad (5.61b)$$

$$\text{where } k_{0Vf,O2} = \frac{k_{0Vf,S}}{\nu_{O2,S}} \qquad (5.61c)$$

For $\beta<1$ and organic matter as a limiting factor

$$r_{A,S} = (2 \cdot D_{S,2} \cdot k_{0Vf,S} \cdot S_2)^{1/2} = k_{1/2A,S} \cdot S_2^{1/2} \qquad (5.61d)$$

For $\beta<1$ and oxygen as a limiting factor

$$r_{A,O2} = (2 \cdot D_{O2,2} \cdot k_{0Vf,O2} \cdot S_{O2,2})^{1/2} = k_{1/2A,O2} \cdot S_{O2,2}^{1/2} \qquad (5.61e)$$

A mass balance for organic matter over the plant with for example organic matter as the limiting factor is then (with symbols from Fig 5.13):

$$Q_1 \cdot C_1 - k_{1/2A,S} \cdot S_2^{1/2} \cdot A_2^* = Q_4 \cdot C_4 + Q_5 \cdot C_5 \qquad (5.62)$$

In Table 5.5, half order rate constants for both removal of organic matter and nitrogen are stated.

Process	Equipment	Substrate	$k_{1/2A}^*$ $g^{1/2}m^{-1/2}d^{-1}$
Oxidation of org. matter	Lab. rot. disc	Acetic acid	3.5-6.2
		Oxygen	3.2-4.1
	-	Methanol	1.4-1.8
	-	Oxygen	4.2
	-	Glucose	3.2-3.8
	-	Oxygen	3.3
Nitrification	Rot. discs	Ammonium	1.5
	-	Oxygen	3.8
	Lab. filter	Oxygen	1.4
	Lab. rot. disc	Ammonium	5.6
	-	Ammonium	4.5
	-	Nitrite	5.1
Denitrification	-	Methanol	2.8-5.4
	-	Nitrate	0.6-3.7
	-	Nitrate	3.1

*$k_{1/2A,S}=(2 \cdot D_{S,2} \cdot k_{0Vf})^{1/2}$

Table 5.5
List of half order rate constants for biofilters.
Data from /14/,/16/,/24/,/25/,/26/,/27/.

Example 5.8

A filter is loaded with 100 m^3 of industrial wastewater per day, containing 500 g/m^3 tic acid, HAc. For practical reasons, the filter plant is constructed by units of a surf area of 500 m^2 each. Experience has shown that each unit can, at a full loading ra sustain 4 g/m^3 oxygen in the water. Each unit is ideally mixed. The biofilm is very t and is considered to be partially penetrated, $k_{1/2A,O2} = 3.5\ g^{1/2}m^{-1/2}d^{-1}$. How man units are needed in order that the effluent concentration is less than $2 \cdot K_{S,HAc}$, wh $K_{S,HAc} = 2\ g\ HAc/m^3$?

According to the examples given earlier, the removal will be controlled by oxygen i the first units:

$r_{A,O2} = 3.5\ g^{½}\ m^{-½}\ d^{-1} \cdot (4\ g\ O_2/m^3)^{½} = 7\ g\ O_2/(m^2 \cdot d)$

$r_{A,O2} \cdot A_2^* = 7 \cdot 500 = 3500\ g\ O_2/d.$

From Example 3.2 we get the stoichiometric conditions for the biological removal HAc: 1 mole of HAc ~ 60 g HAc consumes 0.9 mole of O_2 ~ $0.9 \cdot 32 = 29\ g\ O_2$

Hence

$$\nu_{O2,HAc} = \frac{60\ g\ HAc}{29\ g\ O_2} = 2.1\ g\ HAc/g\ O_2$$

and thus

$r_{A,HAc} \cdot A_2^* = 3500 \cdot 2.1 = 7.3\ kg\ HAc/d$

The flow of organic matter $C_1 = S_1 = 500\ g/m^3$

$Q_1C_1 = 100 \cdot 500 = 50\ kg\ HAc/d$

Hence at least 7 units must be arranged in a series. The first six will work identically because the HAc-concentration is greater than the limit for being rate limiting in relation to oxygen. In the first six units $6 \cdot 7.3 = 44$ kg HAc/d are removed, and hence there are 6 kg HAc/d left corresponding to an influent concentration of 60 g HAc/m^3.

In the seventh unit, HAc is expected to be rate limiting.

$$k_{½,HAc} = \left(2 \cdot D_{HAc} \cdot k_{0Vf,HAc}\right)^{½}$$

$$k_{½,O2} = \left(2D_{O2} \cdot k_{0Vf,O2}\right)^{½}$$

$$\frac{k_{0Vf,HAc}}{k_{0Vf,O2}} = \nu_{O2,HAc} = 2.1 \text{ g HAc/g}O_2$$

$$\frac{k_{½,HAc}}{k_{½,O2}} = \left(\frac{2\, D_{HAc}\, k_{0Vf,HAc}}{2\, D_{O2}\, k_{0Vf,O2}}\right)^{½} = \left(\frac{D_{HAc}}{D_{O2}} \cdot \nu_{O2,HAc}\right)^{½}$$

$D_{HAc} = 0.7 \cdot 10^{-4}$ m^2/d

$D_{O2} = 1.7 \cdot 10^{-4}$ m^2/d , see Table 5.2

$$k_{½,HAc} = k_{½A,O2}\left(\frac{D_{HAc}}{D_{O2}} \cdot \nu_{O2,HAc}\right)^{½} = 3.5 \cdot \left(\frac{0.7}{1.7} \cdot 2.1\right)^{½} = 3.3 \text{ (g HAc)}^{½}\, m^{-½} d^{-1}$$

The balance for HAc:

$$Q\, S_1 - r_{A,HAc} \cdot A_2^* = Q\, S_3$$

$$6000 \text{ g HAc/d} - 3.3 \cdot 500 \cdot S_3^{½} = 100 \cdot S_3$$

This gives the solution:

$$S_3^{½} = 3.1 \quad \left(\text{or } S_3^{½} = -19\right)$$

$$S_3 = 9.6 \text{ g HAc/m}^3$$

At this concentration HAc will be limiting for the removal:

$$\frac{D_{red}}{D_{ox} \cdot \nu_{ox,red}} = \frac{0.7}{1.7 \cdot 2.1} = 0.20$$

$$\frac{S_{ox}}{S_{red}} = \frac{4 \text{ g } O_2/\text{m}^3}{9.6 \text{ g HAc/m}^3} > 0.20 \text{ g } O_2\text{/g HAc}$$

Notice: The reductant is thus limiting for the process, see Expression (5.32). HAc is limiting when S_{HAc} is less than $4/0.20 = 20$ g HAc/m^3.

An eighth unit is necessary as the concentration is still higher than $2 \cdot K_S$. In the eighth unit, the removal follows a first order process as the concentration is less than a $2 \cdot K_S = 4$ g HAc/m^3.

Expression (5.20) gives:

$$k_{1Vf,HAc} = k_{0Vf,HAc}/K_{S,HAc} = \frac{(k_{½,HAc})^2}{2\, D_{HAc} \cdot K_{S,HAc}}$$

$$k_{1Vf,HAc} = \frac{3.3^2}{2 \cdot 0.7 \cdot 10^{-4} \cdot 2} = 3.9 \cdot 10^4 \text{ d}^{-1}$$

As the biofilm is considered to be very thick, we have from Expresssion (5.9):

$$k_{1A,HAc} = \sqrt{D_{HAc} \cdot k_{1Vf,HAc}} = \left(0.7 \cdot 10^{-4} \cdot 3.9 \cdot 10^4\right)^{½} = 1.7 \text{ m/d}$$

Balance:

$$Q\, S_1 - k_{1A} \cdot A_2^* \cdot S_3 = Q\, S_3$$

$$960 \text{ g HAc/d} = (1.7 \cdot 500 + 100)\, S_3$$

$$S_3 = 1 \text{ g HAc/m}^3$$

5.10. Technical conditions concerning biofilters

A number of important conditions will be briefly discussed below. The conditions are important for the functioning of biofilter plants and include

- aeration
- growth and sloughing off of the biofilm

5.10.1 Aeration in biofilters

As it appears from the above, the supply of oxygen to biofilters is of greater importance than for other biological plants because the oxygen supply is not just stoichiometrically decisive, but frequently it is also governing for the reaction rate. The following types of aeration can be used:

Separate aeration of the flow of recycle

This type of aeration is not different from the aeration which is required in activated sludge plants. The theories gained from the activated sludge plants can be used directly /15/.

5.10.2 → 2 types of biofilm

dense (good removal substances in WW)

filamentous biofilm

→ ~~[illegible]~~ mostly filamentous

→ many types of filamentous organisms ...

Attached to solid surfaces

{ Chlamydobacteriales

Sphaerotilus

Nutans }

order? class?

→ faily

→ genus

→ species

in WW → bulking is Nocardia

(General situation)

Go to Zero order Kenetics

reaction rate constant

→ more surface to reach organisms

turbulent movement cause more transport than molecular difusion in dense ...

→ turbulence causes more rapid transport than diffusion ... more surface area contribute to rapid transport ...

Import point

(*) Surface of film is identical to the surface of carrier ... but filmentous branches out so far more surface area with filamentous growth

* Turbulence ... promotes transport

Hydraulic film ≡ boundary layer ⇐ close laminar flow

more ordered or slower

Aeration in the filter itself

The theory for this type of aeration is in principle not different either from the aeration in an activated sludge plant, but of course the presence of the filter medium has a certain effect.

Aeration of the biofilm

In discs the filter medium is covered by a thin water film on the surface of the biofilm. Hence the conditions for the transfer of oxygen from air to biofilm are very special. More details on the subject can be found in /16/.

5.10.2 Growth and sloughing off of the biofilm

Biofilters are based on the ability of the bacteria to attach and develop on a solid medium. Technologically it is desirable that a stable state with equilibrium between growth and sloughing off is developed. No matter how fundamental these conditions might be it is, however, a fact that too little is known about these conditions, apart from the very technological empiricism.

Adhesion

In practice, bacteria will adhere to any surface - they have in fact a partiality for adhesion - irrespective of the type of surface (except where countermeasures have been taken, for example marine coating). The start of a biofilm is simply that the medium concerned is in contact with water, in this case with the wastewater. In practice, the development of a functional film takes approx. 14 days under aerobic conditions. The building up is commenced faster on surfaces with earlier growth than on completely clean surfaces. The building up is selective and the bacteria which are not attached will simply be washed out of the plant. For special substances and processes the starting up may be a big problem.

Types of biofilm

The characteristics of the biofilm are of course a function of the characteristics of the bacteria which form the biofilm. No applicable examinations are available whatsoever of the relationship between microbiological determination of species and measured biofilm characteristics. It can only be concluded that two types of biofilm generally occur: The dense film and the filamentous film. The dense film is a coherent, immobilized biomass. In its ideal form, it has a plane, smooth surface. For this type of biofilm there is clear experimental proof of the good, theoretical description of the removal as described earlier in the biofilm kinetics. The filamentous biofilm is dominated by filamentous bacteria which grow in continuation of each other and form filaments attached to the filter medium, typically the Chlamydobacteriales *Sphaerotilus Natans*, (also known from highly polluted streams under the name of: Sewage fungus). In its extreme form, this type of film forms a mat whose filaments are moved by the liquid flow. This causes turbulent movements around the filaments for which reason the transport of substrate into the biofilm is increased compared with

molecular diffusion. These films will therefore remove material according to a zero order reaction at lower concentrations than calculated according to the biofilm kinetics as discussed above.

The bacterial density in the film is decisive for the removal rate. What is interesting is the mass of the bacteria which carry out the process observed. It is difficult to determine this quantity by measurement, but it can be calculated as a fraction of the total mass in the same way as for the bacteria in the sludge in an activated sludge plant. The total mass may vary within wide ranges: 10-100 kg VSS/m^3; but data primarily fall in the range 40-60 kg VSS/m^3.

The sloughing off of the biofilm

The removal of organic matter corresponds to a continuous growth of bacteria and hence a growth of the thickness of the biofilm. If this is not balanced by a corresponding sloughing off, the result must necessarily be clogging. The following conditions are important for the sloughing off and are used technologically, intentionally or unintentionally, as part of the control of the biofilm:

- Hydraulic erosion acts continually on the surface of the biofilm and leads to a steady sloughing off on the outer side. In its extreme version it is the total sloughing off of the biofilm on the sand in the recycle flow of a fluidized filter in a tank where a stirrer creates a very high turbulence level. The requirements of the hydraulic loading of trickling filters and of the rotational speed of rotating discs are empirically dictated from a desire to cause sloughing off, but the flow of water is not so strong that it can by itself cause the sloughing off. Other factors release the film so that it can be sloughed off hydraulically.
- Degradation of starved out bacteria in the bottom of biofilms may cause a weakening of the adhesion. Biofilms will in practice have a tendency to grow to a thickness where they are only partially penetrated with substrate. In the aerobic filter, whose reaction rate is controlled by the oxygen, anaerobic conditions will occur in the bottom of the film. This will degrade the bacteria in the bottom and destroy the adhesion. Sufficiently weakened, the film will be sloughed off completely over a smaller area by hydraulic erosion.
- Super saturation and bubble formation in the bottom of the biofilm may destroy the adhesion - for example methane production under anaerobic conditions and the production of pure nitrogen by denitrification.

In the last two cases the film is sloughed off completely, and a naked area is left on the filter medium where new growth starts. The filter is thus continuously in a state of sloughing off and regrowth. Therefore the biofilm never has a well-defined thickness in practice which applies to the whole film.

A special phenomenon is the grazing of higher animals on the bacterial mass in the filter. Very little is known about this, but it is undoubtedly of importance and is for example reflected in seasonal variations in the biomass in a trickling filter and in sudden changes in the biofilm in for example nitrifying plants /17/. A conventional

... Highly polluted streams we see more filamentous Growth (dominated)

⟹ cause more eff removal of pollutant compounds ...
more effective transporting food, then food ~~[illegible]~~ ceases (stops) to be limiting factor

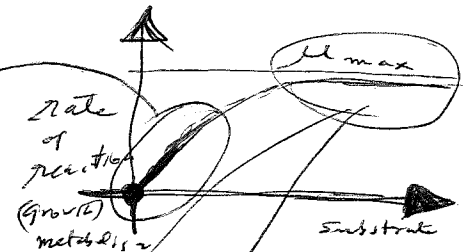
so we observe

Typical density for fixed film ~~60~~ VS (volatile solids)
[10 – 60 Kg/m³]

Suspended Growth [VSS] [2 – 6 Kg/m³]

VSS
10 to 100 Kg VS/m³

Volatile suspended solids



linear
rate ≙ f (food)
first order Kenitics

Something else is limiting factor
Rate of Growth ≠ f (substrate)

Zero Order Kenitics ≡ rate is const.

⟹ 3 major mechanisms of sloughing off (more actual than previous behavior) (if not ⟹ clogging)

- Hydraulic ~~[illegible]~~ errosion
- degradation of starved bacteria near carrier (attachment becomes weakened)
- bubble formation ⟺ (thick film ⟹ so anaerobic condition ⟹ CH_4 production)
  ↳ not homogeneous so some anaerobic condition
  ORP gets to a point ... ⟹ CH_4

denitrification
↳ also Nitrogen bubbles formed

single cell protozoa

Eukarotoes
warm and larvae
↳ insects

- higher animals —— grazing on food

trickling filter will contain most biomass in the early spring which makes the risk of clogging correspondingly higher.

5.11. Removal of particulate organic matter

As discussed in the previous sections, we do not today have an applicable hypothesis for the removal of organic matter which cannot diffuse into a biofilm. Until such a hypothesis has been found, we have to rely on emperical load norms, but new knowledge is on its way.

A distinction should be made between two types of substrates:

diffusible
non-diffusible

Diffusible means that the substrate can be carried into the biofilm by molecular diffusion. There is no well-defined analyzeable limit, but genuine soluble substances such as oxygen, acetic acid, methanol and glucose clearly belong to the diffusible category whereas suspended solids as defined for the filtering through a filter (GF/A filter, pore size 1 - 1.6 µm) definitely belong to the non-diffusible category. In this connection it is misleading that the substance running through the filter mentioned above is traditionally called "dissolved" (Chapter 1).

A major part of organic matter in municipal wastewater consists of fractions which pass a 1 - 1.6 µm filter, but which are not genuinely soluble.

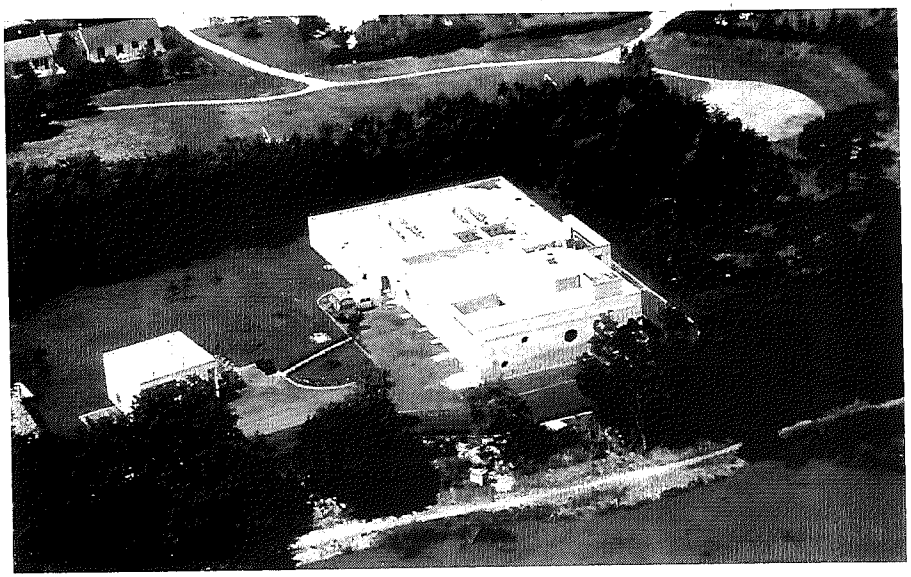


Fig 5.20 *Real-life biofilters must also be able to remove particulate organic matter. The photo shows a biofilter plant (Biocarbone) in Meyzieu (France).*

Molecules with a molecular weight of less than 10^3 can be absorbed through the ce membrane on the bacteria. It is not known where the diffusion limit into the biofilr lies. 40-80 per cent of COD in municipal wastewater are particles bigger than 0.1 µr /18/. Very little material in the size fraction 0.01 - 0.1µm has been found. Howeve there is a significant fraction in the range 0.1-1 µm which is not included i suspended solids, but in the "dissolved" fraction which certainly cannot diffuse int the biofilm.

Fig 5.21 shows concentrations of organic matter in municipal wastewater fro Lyngby (Denmark) which are a result of different methods of analysis.

It is a condition for the removal of a non-diffusible material that it is degrade extracellularly in a diffusible form in order to subsequently diffuse into the biofil where it is mineralized while consuming oxygen. The collective name for tl extracellular degradation is hydrolysis (see Chapter 3, Section 3.2.2.).

There are two different theories of the mechanism for hydrolysis in biofilm reacto

Particle adsorption. According to this thesis the particles will be adsorbed to tl surface of the biofilm. This can be done by diffusion from the bulk water to tl surface, by settling and by entrapment on a rough (or filamentous) biofilm surfa /20/. Only qualitative determinations are available. We have no verification n any operational formulation of kinetic expressions.

External hydrolysis. From the biofilm extracellular enzymes are released to the bu water in which the hydrolysis takes place. The hydrolyzates should subsequen diffuse into the biofilm and be degraded there. This mechanism is experimenta

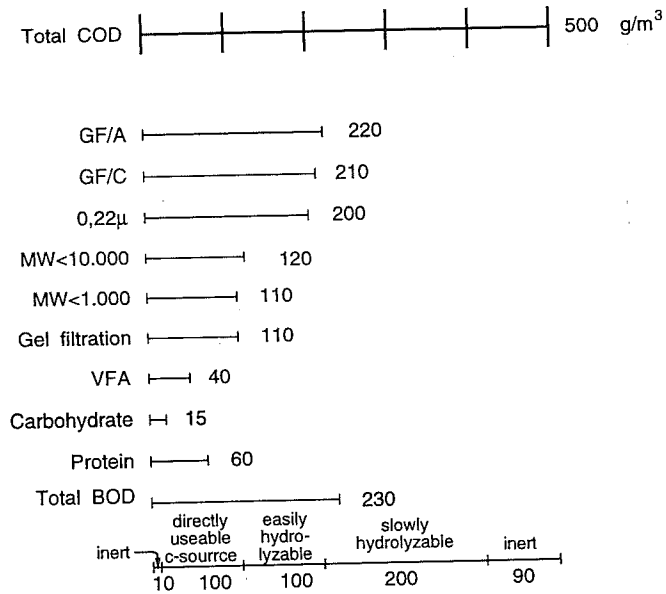


Fig 5.21 *Characterization of the COD content in raw wastewater. All units in COD/m^3.*

Gaseous

UCR UCD

Biotrickling

gas → fluid → media

Keep media wet

always flowing water ...

In Biofilter → simple & cheap media ...
(thin layer of H_2O) always there
Spray time & time & keep biofilter moist

Even transport effects in gas

Dissolved molecule by molecule

Mathematical formulas ⇒ dissolved substances that diffuse into bacteria (consumed by diffusion)

Large molecules or some of can not diffuse into the film & bacteria)

Biofilm remove Suspended matter ...

Liquid

Over long time ⇒ built-up occur so clogging

local
Sometimes clogging happens sometime it does not

* Most trickling filter had high enough flow so slough-off so no clogging happens

demonstrated for starch as a non-diffusible substance, and kinetic expressions are available, see the simplified representation below:

Balance for non-diffusible matter (for example starch) in an ideally mixed tank:

$$Q\,X_{R,1} = r_{V,XR}\,V_2 + Q\,X_{R,3} \tag{5.63}$$

where X_R is the non-diffusible matter. $r_{V,XR}$ is the volumetric hydrolysis rate in the reactor. The process is assumed to be a first order process in both X_S and S_E (the concentration of enzyme in bulk water)

$$r_{V,XR} = k_E\,S_{E,2}\,X_{R,2} \tag{5.64}$$

where k_E is the hydrolysis constant.

The enzymes are produced in the biofilm at a surface area specific production rate $r_{A,E}$ It is assumed that there is no significant enzyme in the influent and that no removal of the enzyme takes place in the reactor. This leads to the following **enzyme balance**:

$$Q_1\,S_{E,2} = r_{A,E}\cdot A_{2*} \tag{5.65}$$

In an ideally mixed reactor $X_{R,2} = X_{R,3}$, $S_{E,2} = S_{E,3}$.

$$Q_1\,X_{R,1} = k_E\cdot r_{A,E}\,X_{R,3}\,A_{2*}\frac{V_2}{Q_1} + Q_1\,X_{R,3} \tag{5.66}$$

$$D_H = \frac{X_{R,1} - X_{R,3}}{X_{R,1}} = \frac{1}{1 + \dfrac{Q_1^2}{k_E\,r_{A,E}\,A_{2*}\,V_2}} \tag{5.67}$$

where D_H is called the degree of hydrolysis, which means the part of the non-diffusible substrate which is hydrolyzed to diffusible substrate.

Notice that the retention time = V_2/Q_1 and that the hydraulic surface loading rate of the biofilm Q_1/A_{2*} cannot be used individually to describe a loading. It is the combination $Q_1^2/(A_{2*}\cdot V_2)$ which we can call the combined load. Fig 5.22 shows the degree of hydrolysis as a function of these quantities.

It is now simple to set up the **balance for diffusible matter**, S_D:

$$Q_1\cdot S_{D,1} + Q_1\,X_{R,1}\cdot D_H = k_{1/2A,D}\,A_{2*}\cdot S_{D,2}^{1/2} + Q_1\,S_{D,3} \tag{5.68}$$

Apart from the loading with diffusible substrate in the influent, the reactor is loaded with the diffusible matter which is produced by hydrolysis. It is assumed that the biofilm is thick and that the diffusible matter is removed by a half order process.

The filter kinetics from Section 5.5 can be directly used if the influent concentration is understood as

$$S_1 = S_{D,1} + X_{R,1}\cdot D_H \tag{5.69}$$

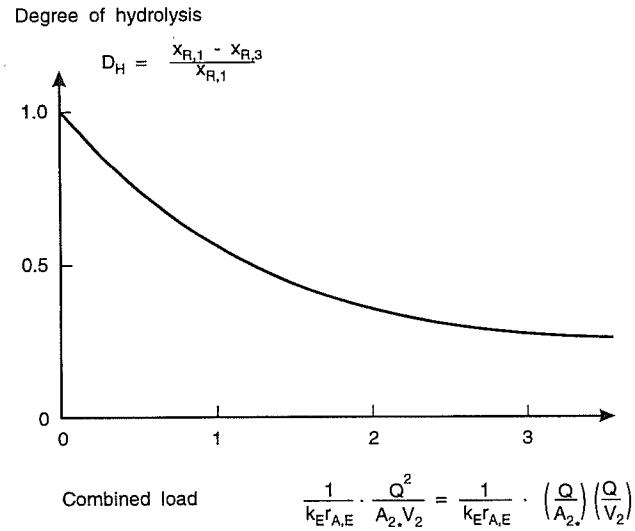


Fig 5.22 *The degree of hydrolysis as a function of the water flow, the biofilm surface water volume. /21/*

$$S_{D,3}^{1/2} = -\frac{k_{1/2A,D}\cdot A_{2*}}{2\,Q_1} + \sqrt{\left(\frac{k_{1/2A,D}A_{2*}}{2\,Q_1}\right)^2 + \left(S_{D,1} + X_{R,1}\cdot D_H\right)}$$

$$E = \frac{C_{T,1} - C_{T,3}}{C_{T,1}} = \frac{(S_{D,1} + X_{R,1}) - (S_{D,3} + X_{R,3})}{(S_{D,1} + X_{R,1})}$$

as $C_T = S_D + X_R$

The result is shown in Fig 5.23 for the degree of hydrolysis 1.0.

In a biofilm reactor the removal only depends on the accessible biofilm area, a on the volume. By hydrolysis, the volume is included as a modifying factor b the enzymes are washed off the reactor. If only the volume is reduced, the de hydrolysis will decrease, SD,3 will decrease and the surface area specific re will decrease.

This effect is reinforced by the fact that the enzyme production depends removal in the biofilm:

$$r_{A,E} \propto \beta\,L$$

By reduced volume the degree of hydrolysis decreases further because r creases by reduced removal.

Example 5.9

A filter plant is used for the treatment of wastewater from a potato flour factory v wastewater is assumed only to contain starch:

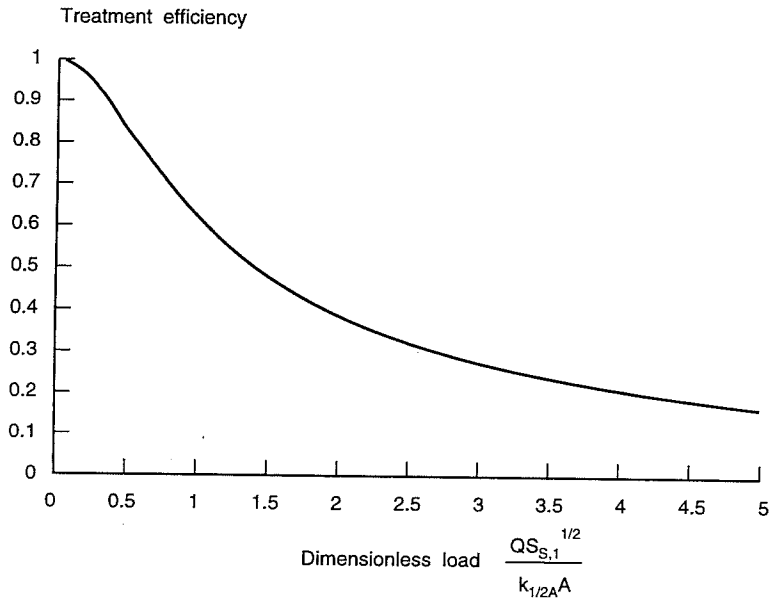


Fig 5.23 *Treatment efficiency as a function with the load for a half order process with a degree of hydrolysis of 1.0. /20/*

Flow of wastewater: $Q = 500\ m^3/d$
Starch concentration: $C_1 = 100\ g\ COD/m^3$
Biofilm area: $A_{2*} = 500\ m^2$
Tank volume: $V_2 = 5\ m^3$
Oxygen concentration: $C_{O2,2} = 1\ g/m^3$

and as a preliminary assumption, the oxygen is assumed to be limiting for the removal:

Internal oxygen removal $k_{0Vf,O2} = 200\ kg\ O_2/(m^3 \cdot d)$
Diffusional coeff. for oxygen $D_{O2} = 1.7 \cdot 10^{-4}\ m^2/d$
Stoichiometry $\nu_{O2,COD} = 2.4\ g\ COD/\ gO_2$

$$\beta L = \left(\frac{2D_{O2} \cdot C_{O2,2}}{k_{0Vf,O2}}\right)^{1/2} = \left(\frac{2 \cdot 1.7 \cdot 10^{-4} \cdot 1}{200{,}000}\right)^{1/2} = 41\ \mu m$$

The starch is hydrolyzed to glucose. The removal rate for glucose is:

$$r_{A,glu} = \beta L \cdot k_{0Vf,O2} \cdot \nu_{O2,COD}$$
$$= 41 \cdot 10^{-6} \cdot 200{,}000 \cdot 2.4$$
$$= 20\ g\ COD/(m^2 \cdot d)$$

If all of the starch is hydrolyzed: $D_H = 1.0$, the glucose balance would look as follows:

$$Q_1 \cdot C_1 \cdot D_H = r_A \cdot A_{2*} + Q_1 S_3$$

$$S_3 = C_1 \cdot D_H - r_A \frac{A_{2*}}{Q_1} = 100 \cdot 1.0 - 20 \cdot \frac{500}{500} = 100 - 20 = 80 g/m^3$$

which is such a large concentration of glucose that oxygen is limiting for the removal.

Empirical constants for the volumetric enzyme production of biofilm and hydrolysis:

Enzyme prod. $r_{V,E} = 300 \cdot 10^6\ IU/(m^3\ biofilm \cdot d)$
Hydrolysis $k_E = 0.05\ m^3/(IU \cdot d)$

where IU is the "International Unit" for enzymes.

$$r_{A,E} = \beta L \cdot r_{V,E} = 41 \cdot 10^{-6} \cdot 300 \cdot 10^6 = 12{,}300\ IU/(m^2 \cdot d)$$
$$k_E \cdot r_{A,E} = 0.05 \cdot 12{,}300 = 615\ m/d^2$$

(These quantities are still very uncertain.)

Substitution in the formula for the degree of hydrolysis (5.67) gives:

$$D_H = \frac{1}{1 + \frac{1}{k_E r_{A,E}} \cdot \frac{Q_1^2}{A_{2*} \cdot V_2}} = \frac{1}{1 + \frac{1}{615} \cdot 100} = 0.86$$

where the "combined load" is $Q_1^2/A_{2*} \cdot V_2 = 500^2/500 \cdot 5 = 100\ m/d^2$.

Starch concentration in the effluent is

$$X_{R,3} = C_1(1 - D_H) = 100 \cdot 0.14 = 14\ g/m^3$$

Glucose concentration in the effluent is

$$S_3 = 100 \cdot 0.86 - 20 \cdot \frac{500}{500} = 86 - 20 = 66\ g/m^3$$

If the filter is made more efficient, for example by using a fluidized filter with a carrier of fine particles and by increasing the specific volume to $1000\ m^2/m^3$, the volume is reduced to $0.5\ m^3$.

$$\frac{Q_1^2}{A_{2*}V_2} = \frac{500^2}{500 \cdot 0.5} = 1000\ m/d$$

$$\frac{1}{1 + \frac{1000}{615}} = 0.38$$

$$X_{R,3} = 100 \cdot 0.62 = 62\ g/m^3$$

$$S_3 = 100 \cdot 0.38 - 20\frac{500}{500} = 38 - 20 = 18\ g/m^3$$

It is the hydrolysis which is the rate limiting step for the process.

5.12. Detailed model

So far the description of the processes in the biofilm has been influenced by such simplifying assumptions that the equations can be solved analytically and that the interaction of parameters is relatively easily ignored. Such a description has its advantage in that it facilitates the understanding and gives a general view; but the more complicated the interaction of processes is, the more difficult it is to find

hand, be described by detailed, deterministic modelling by which the door is opened to a alienating world of complicated differential equations, complicated functional expressions and solutions which are difficult to understand and which can only be obtained by computer calculations. However, there is no doubt about the need for the increased realism in the description and the need for such models for scientific examinations and soon also for the practical design.

The following description mainly follows the description in /22/. Fig 5.24 shows an element in the biofilm and the corresponding definitions.

The biofilm consists of several phases such as water, solids (and possibly air). The concentration, C_{ki}, of a substance is stated as the amount of a given substance in a unit volume of the phase concerned. The volume fraction, ε_k, of a solid k is stated by the volume of the solid in a unit volume of the biofilm containing all the phases k.

For the phases it applies:

$$\sum_k \varepsilon_k = 1 \tag{5.72}$$

For the concentration it correspondingly applies that the concentration distributed on a total unit volume is $C_{fi} = \varepsilon_k \cdot C_{ki}$, where C_{ki} is the definition of the model concentration which has been used so far. It is necessary to make this distinction when there are many phases; for example several phases of solids and different types of bacteria.

The differential equation for an element in the biofilm can be written as:

$$\frac{\partial \varepsilon_k C_{ki}}{\partial t} = \varepsilon_k \frac{\partial C_{ki}}{\partial t} + C_{ki} \cdot \frac{\partial \varepsilon_k}{\partial t} = -\frac{\partial j_{ki}}{\partial x} + r_{V,ki} \tag{5.73}$$

where j_{ki} is the flux of the substance i in phase k

$r_{V,ki}$ is the removal rate for the substance i in phase k per unit volume

ε_k is the volume fraction of phase k

C_{ki} is the concentration of substance i in phase k.

The first term ahead of the equals sign is the local time derivative from the mean concentration which, just after the first equals sign, is split into a time derivative for the concentration and one for the volume fraction of a phase. The last term but one is the local, geometrical derivative of the flux through a unit cross section. The last term expresses the removal in the biofilm.

$$\frac{\partial \varepsilon_k C_{ki}}{\partial t} = -\frac{\partial j_{ki}}{\partial x} + r_{V,ki} = 0 \tag{5.74}$$

$$j_{ki} = D_i \frac{\partial \varepsilon_k C_{ki}}{\partial x}$$

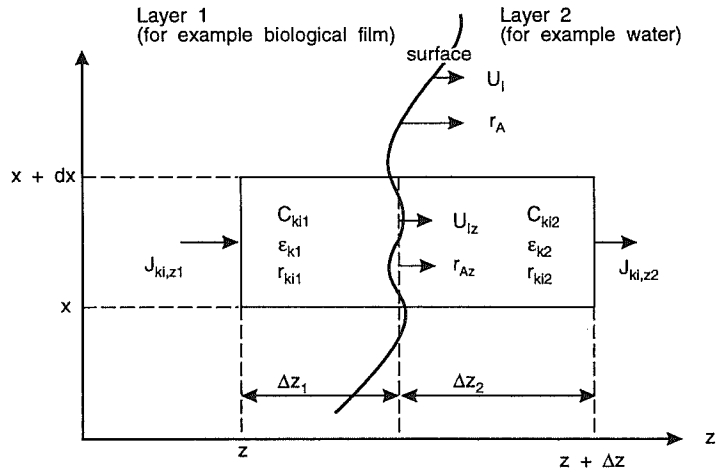


Fig 5.24 *The balance for a calculation element in the interface between water phase and biofi /22/*

which yields the well-known expression

$$D_i \frac{\partial^2 \varepsilon_k C_{ki}}{\partial x^2} = D_i \frac{\partial^2 C_{fi}}{\partial x^2} = r_{V,ki} \tag{5.}$$

corresponding to the derived equations in Section 5.1. The well-known equatic have thus been generalized in respect of phase and component, as well as time a place.

The processes are described by the well-known process table, for example Table 4

In principle, all that is left now is to define the limiting conditions:

$$u_1\left(\varepsilon_{k1} \cdot C_{ki1} - \varepsilon_{k2} \cdot C_{ki2}\right) = j_{ki1} - j_{ki2} + r_{Aki} \tag{5.}$$

where u_1 is the rate at which the interface moves (for example due to growth)

1 is on the one side the interface

2 is on the other side of the interface

The first term describes the transport of substance by a movement of the interfa The second term describes the flux to and from the interface and the last term i surface reaction rate (for example adsorption of particles to the surface (positive) erosion from the surface). Simple cases will illustrate the limiting condition:

Back wall: $u_1 = 0$, $j_{ki1} = 0$, $r_{A,ki} = 0$, which results in

$$j_{ki2} = 0 \;\; ; \;\; D_i \frac{\partial \varepsilon_k C_{ki}}{\partial x} = 0 \tag{5.}$$

The concentration profile has a horizontal tangent as already described.

Stationary surface without reaction:

$$u_1 = 0, \quad r_{A,ki} = 0$$

$$j_{ki1} = j_{ki2}$$

The diffusion of a substance must be the same on both sides of the area because no accumulation can take place in the interface with the given assumptions.

With these equations all processes can be described if we know the kinetic expressions for the processes; for variations in time and place, for random composition of the phase (types of bacteria) and for selected limiting conditions.

On the other hand it is not easy to solve these differential equations under the given practical conditions.

However, today we have computer programs which are tailored for the solution of these equations for conditions corresponding to the biofilm /23/. Such programs will be increasingly used for analysis, operation and design.

In the next chapter an example is given which is based on a solution with this program.

References

/1/ Harremoës, P. (1976): The Significance of Pore Diffusion to Filter Denitrification. Journal, WPCF, 48, No. 2, 377-388.

/2/ Harremoës, P. and Riemer, M. (1977): Pilot-Scale Experiments on Down-Flow Filter Denitrification. **Progress in Water Technology**, 8, No. 4/5, 557-576

/3/ Harremoës, P. and Riemer, M. (1975). **Report on Pilot Studies of Denitrification in Down-flow Filters**, Department of Environmental Engineering, Technical University of Denmark, Lyngby, Denmark

/4/ Harremoës, P. (1978): Biofilm kinetics. Chapter 4 in: Mitchell, R. (ed.): Water Pollution Microbiology, 2, s. 71-109. John Wiley & Sons, New York, N.Y.

/5/ Perry, J. (1963): **Chemical Engineers Handbook**, McGraw-Hill.

/6/ Siegrist, H. and Gujer, W. (1985): Mass transfer Mechanisms in a Heterotrophic Biofilm. **Water Research, 19**, 1369-1378.

/7/ Triebel (ed.) (1975): **Lehr- und Handbuch der Abwassertechnik, Bd II** (Textbook for Wastewater Engineering, Volume II). Verlag von Wilhelm Ernst & Sohn, Berlin.

/8/ Abwassertechnishe Vereinigung (1985): **Lehr- und Handbuch der Abwassertechnik, Bd IV** (Textbook for Wastewater Engineering, Volume IV), 900 pp, ISBN 3-433-00905-8, Ernst & Sohn.

/9/ Steels, I.H. (1974): Design Basis for the Rotating Disc Proces. **Effluent and Water Treatment Journal**, 14, No.9, 431-445.

/10/ Murphy, K.L. and R.W. Wilson (1978): Pilot Plant Studies of Rotating Biological Contactors Treating Municipal Wastewater, Prepared for the Central Mortgage and Housing Corporation. International Environmental Consultans Ltd., Toronto, Ontario.

/11/ Autotrol Corporation (1976): Wastewater Treatment Systems. Manufacturers Design Manual, Autotrol Corp., Section C, USA.

/12/ Envirodisc Corporation (1977): Rotating Disc Wastewater Treatment. Manufacturers Design Manual. USA.

/13/ Ahlberg, R.N. and T.S. Kwong (1974): **Process Evaluation of a Rotating Biological Contactor for Municipal Wastewater Treatment**. Research paper no. W2041. Ontario Ministry of Environment, Wastewater Treatment Section, pollution Control Plannning Branch.

/14/ ATV (1989): Grundsätze für die Bemessung von Tropfkörpern und Tauchkörpern mit Anschlusswerten über 500 Einwohnergleichwerten (Principles for the Design of Trickling Filters and Submerged Filters for more than 500 Population Equivalents). **ATV-Arbeitsblatt**, No. A 135,. GFA, St. Augustin.

/15/ Harremoës, P. et al (1989): Teoretisk vandhygiejne. (Water Chemistry) Polyteknisk Forlag, Lyngby, Denmark.

/16/ Gönenç, E. (1982): Nitrification on Rotating Biological Contactors. Department of Environmental Engineering, Technical University of Denmark, Lyngby, Denmark.

/17/ Iwai, S., Y. Oshino and T. Tsukada (1990): Design and Operation of Small Wastewater Treatment Plants by the Microbial Film Process. **Water Science & Techology, 22**, No. (3/4), 139-144.

/18/ Levine, A.D., Tchobanoglous, G. and Asano, T. (1985): Characterization of the Size Distribution of Contaminants in Wastewater Treatment and Reuse Implications. **Journal WPCF, 57**, No. 7, 805-816.

/19/ Henze, M., Kristensen, G.H. and R. Strube (1992): Determination of Organic matter and nitrogen in wastewater. Department of Environmental Engineering, Technical University of Denmark, Lyngby, Denmark.

/20/ Bouwer, E.J. (1987): Theoretical Investigation of Particle Deposition in Biofilm Systems. **Wat.Res., 21**, 1489-1498.

/21/ Larsen, T.A. (1991): **Degradation of Colloidal Organic Matter in Biofilm Reactors**, Department of Environmental Engineering, Technical University of Denmark, Lyngby, Denmark.

/22/ Characklis, W.G., et al (1989): Modelling of Biofilm Systems. **IAWPRC Task Group on Modelling of Biofilm Systems**, Inst. Proces Analysis, Montana State University, USA.



Editors Choice

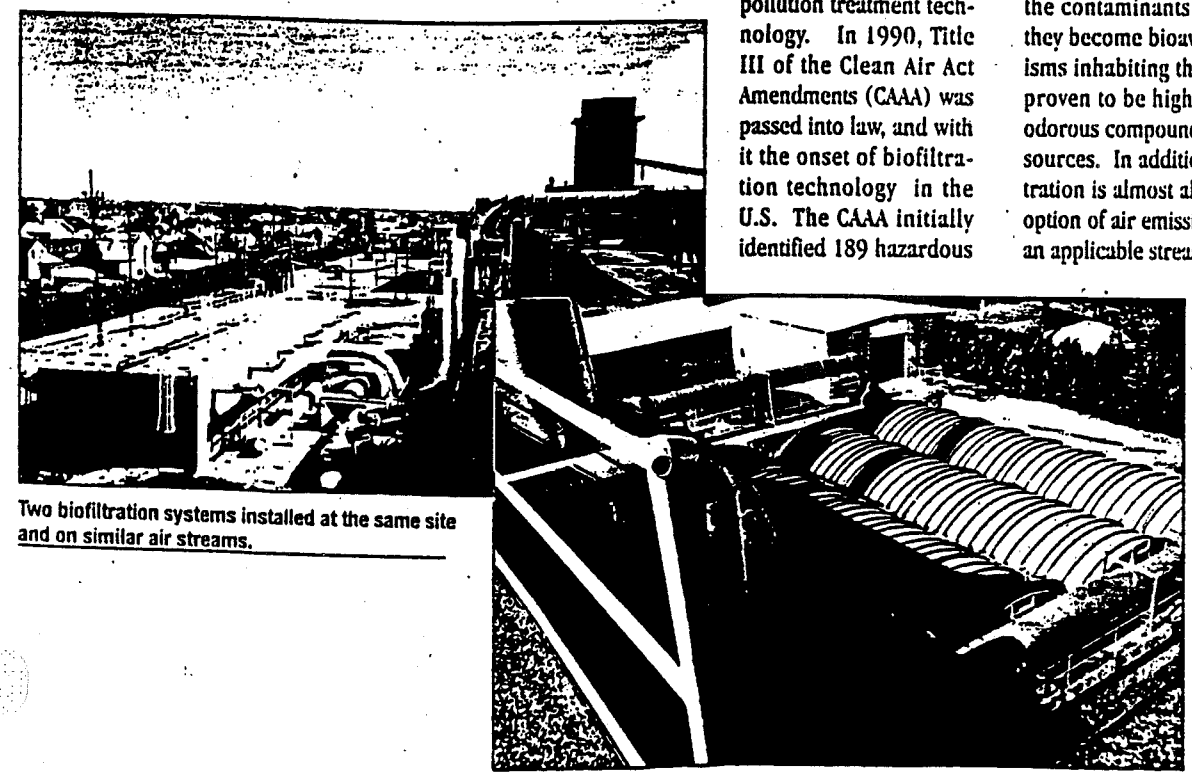
Academic-Industrial Collaborations Enhance Biofiltration Development

By Gregory T. Kleinheinz, Ph.D.

Transferring biofiltration technology from academia to "real-world" applications is a "win-win-win" situation for the vendors, clients, and academic investigators.

The use of biofilters for the control of odorous emissions in Europe has been well understood since the 1970s. Additionally, the first U.S. patent for biofiltration was issued in 1957. However, until the early 1990s, there was little development or research in the area of biofiltration in the U.S. This was mostly due to the fact there were few regulations regarding the discharge of toxic air pollutants or volatile organic compounds (VOCs). In fact, even today many environmental professionals still appear not to realize that biofiltration is a successful and widely used air pollution treatment technology. In 1990, Title III of the Clean Air Act Amendments (CAAA) was passed into law, and with it the onset of biofiltration technology in the U.S. The CAAA initially identified 189 hazardous air pollutants (or HAPS) that would be strictly regulated by the U.S. EPA. Given these more stringent air regulations and enforcement in the United States, industry had to adopt innovative and cost-effective air treatment systems. Biofiltration is one of these technologies.

The process of biofiltration utilizes a biofilm containing microorganisms immobilized on a porous substrate such as peat, soil, sand, wood, compost, or numerous synthetic media. As an air stream passes through the biofilter, the contaminants in the air stream partition from the air phase to the liquid phase of the biofilm. Once the contaminants pass into the liquid phase, they become bioavailable for the microorganisms inhabiting the biofilm. Biofiltration has proven to be highly effective in treating both odorous compounds and VOCs from a variety of sources. In addition to its effectiveness, biofiltration is almost always the most cost-effective option of air emission control (when applied to an applicable stream).

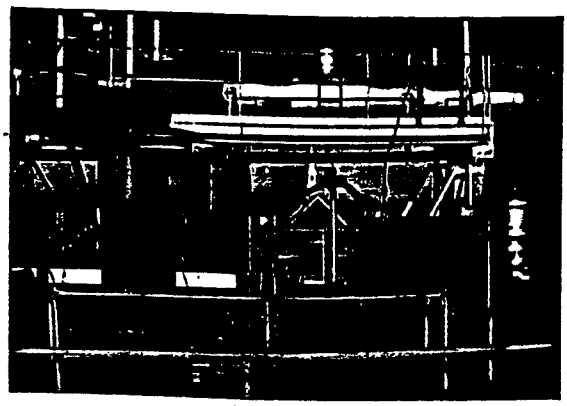


Two biofiltration systems installed at the same site and on similar air streams.

Close Investigation

While biofiltration has proven itself a worthy technology in many applications, there are still quite a few examples of biofiltration failures. However, a closer investigation of these failures reveals that there may have been other factors, aside from the biofilter technology, which greatly influenced the overall success or failure of these

units. The choice of solid support materials, size of the unit, geometry of the unit, humidification system, characteristics of the air stream, chemicals present, residence time, etc. all contribute to the success or failure of a full-size biofiltration system. As can be seen from the above list, there are numerous decisions which influence the success and/or failure of biofiltration systems.



On-line analysis and monitoring of industrial biofilter operation.*

To date, one of the major limitations in biofiltration technology utilization has been the lack of adaptability of the technology to a wide variety of sites and industrial processes. That is, a biofilter for a wood products facility or wastewater treatment plant (WWTP) in one location (Site A) may on the surface appear to be the same as similar facility in another location (Site B). However, the air to be treated in the two locations could in fact be very different due to proprietary differences in processes, or subtle differences in other operational considerations. If the same biofiltration unit is sold to each location, it may work very well at Site A and very poorly at Site B. This could be due to one of many factors such as particulate problems, chemical differences in the air stream, operational differences at the site, etc.

Each potential application needs to be independently investigated for such parameters as the characteristics of the air stream, chemicals present in the air, particulate issues, breakdown products of the chemicals present, residence time required for removal, available space on-site, water and waste water issues, and cost, to name a few. Based upon preliminary investigations of the particular site, decisions on such things as solid support material, type of humidifacation unit, and size, can then be made. Once these individualized site decisions are made, one may look at existing systems to determine the following: if a current system would be feasible for this application, if a current system could be easily modified for the application, or if a new system should be designed for the application.

While the preliminary work on investigating the unique parameters of each site is critical to maximizing biofilter performance, it is seldom performed to the extent needed to make informed decisions on biofilter design and/or installation. In many cases the biofiltration systems are installed with the philosophy that they have worked at another site and will work at this site as well. This has not always been the case, and biofilter clients are often left to try and get systems running to the point they are successful in dealing with their air emissions problem. This is one point where industrial and academic collaborations can develop into a mutually beneficial relationship. For example, our research group has conducted over $2,000,000 in applied research into biofilters and the development of new and improved systems (second- and third-generation systems). During our work into biofiltration system operation and optimization, we have investigated the novel use of adsorption/desorption systems coupled to biofilters, coupling multiply biological treatment systems for complex air streams, the effects of microbial activity on various solid supports, the effectiveness of various solid supports (synthetic and natural), thermophilic biofiltration, microbial activity, pH effects, the effects of bed washing, and surfactant enhanced biofiltration.

Win-Win-Win

We have made a concerted effort to transfer the technology and knowledge gained as part of our projects to "real-world" applications. Our group constantly works to assist biofilter clients and vendors develop and apply their technology so that it will be successful. This is a "win-win-win" situation for the vendors, clients, and academic investigators. The vendor benefits include the sale of a biofiltration system which has the operational support from people who are not rival vendors, and who understand biofiltration operation and optimization. The vendors also get "free" new ideas and concepts to integrate into further biofiltration developments. The client gets a biofilter which is cost-effective and a long-term solution to their air emission needs. The academic collaborators get an avenue for technology transfer from their labs and pilot-scale studies to "real-world" applications.

We have been involved in biofiltration applications in the forest products industry for both odor and VOCs/HAP removal, as well as odor issues at WWTPs. We have developed collaborative projects with both vendors and industrial partners to provide routine monitoring and optimization of their current systems. Routine monitoring of these systems is the best and most cost-effective way to prevent many problems, and to solve problems quickly by having a record of operational data to make decisions on. However, it is not always easy to convince new biofilter owners that a small investment in routine monitoring most likely will save them money and headaches in the long-run by preventing potential problems. The costs for academic people to do this monitoring is quite low when compared to that of traditional consultants.

In addition, we have helped these industrial partners work through operational problems, resulting in minimal downtime and in optimal biofiltration performance. Two companies in Michigan and one in Wisconsin, have developed these collaborative arrangements with our group and it has proven to be a truly mutually beneficial relationship. The industrial partners in these endeavors have had us available to rectify major operational problems associated with poor biofilter design or choice of solid support. In addition, we have provided monitoring and optimization services for the past several years. Innovative vendors and our industrial collaborators have used our laboratory facilities to study a variety of concepts and to simultaneously test multiple variables. Our university research laboratories have been a "tool" which has been effectively used by our collaborators to cost-effectively solve their air emission and treatability problems. Academic and industrial partners have worked on common problems to keep biofiltration systems running efficiently. There is no limit to the type of relationship and collaboration possible between industry and academia.



Pilot-scale biofilter work at an industrial site.

There are almost endless possibilities for industrial-academic collaborations in the area of biofiltration. Industrial-academic relationships are truly mutually beneficial and they benefit all parties involved, in addition to further establishing biofiltration technology as a viable, highly effective treatment option for air emissions.

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PROJECT TITLE: Biofiltration Development.	Sheet No.	of	Date
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one of major limitations in biofiltration technology utilization has been the lack of adaptability of the technology to a wide variety of sites and industrial process.

The area investigated: ① the novel use of adsorption/desorption system coupled to biofilters.

② coupling multiply biological treatment systems for complex air streams

③ the effects of microbial activity on various solid supports

④ the effectiveness of various solid supports (synthetic and natural)

⑤ thermophilic biofiltration

⑥ micro-bial activity, ph effects the effects of bed washing, surfactanct enhaced biofiltration.

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CONSTRUCTION AND ECONOMICS OF A PILOT/FULL-SCALE BIOLOGICAL TRICKLING FILTER REACTOR FOR THE REMOVAL OF VOCs FROM POLLUTED AIR

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IMPLICATIONS

With increasing interest in biological techniques for air pollution control, 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.

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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 to a previous conceptual scale-up of a laboratory reactor. The reactor construction costs are detailed and show that about half of the total reactor costs ($97,000 out of $178,000) were for personnel and engineering time, whereas about 20% was for monitoring and control equipment. A detailed treatment cost analysis demonstrated that for an empty bed contact time of 90 s, the overall treatment costs (including capital charges) where as low as $8.7/1,000 m^3_{air} in the case where a non chlorinated VOC was treated, and $14/1,000 m^3_{air} for chlorinated compounds such as methylene chloride. 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 benefits of biotrickling filtration is expected to increase for full technical-scale bioreactors.

INTRODUCTION

Biological waste air treatment is an emerging technology that is gaining acceptance with environmental regulation becoming increasingly stringent in the U.S.. 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 air stream 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 cost effective operation.[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 where a pollutant-containing waste air stream is contacted with a scrubbing solution. The most promising bioscrubber setup is the biotrickling filter where 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 by growing biomass over time.[8,16,17] Even so, biotrickling filters have sometimes proven superior than 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 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 methylene chloride contaminated air streams. 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 per 1000 m^3 of air treated.[13]

In the present paper, the actual design and construction of a 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 one 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 as a basis for actual reactor design. The conceptual flow-sheet and this 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. (1997) was applied to obtain reactor dimensions, air and water flow rates.[13] A few modifications from the original design had to be performed. The original design included one column of approximately 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 m x 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, Saugerties, NY) to provide the air pressure. At the exit of the second tank, a knock-out pod (Solberg Manufacturing, Itasca, IL) 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, New Lenox, IL) is in parallel. The bottom of the two tanks are being used for the control of pH and temperature (liquid height of approximately 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 (Gardena, CA) 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 iron, magnesium, calcium, zinc, copper, manganese, and sulfur, was added with tap water to produce a feed of 0.7/1.2/0.8 g L^{-1} 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, Austin, TX), was developed to monitor and/or control important parameters. Inlet and outlet concentrations, air and water flowrate, pressure drop, temperature, and recycle water conductivity were continuously monitored. Nutrient and caustic addition, water addition and removal, 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 Table 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 rather 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 allowed to monitor directly the changes in the amount of biomass present in the system. As mentioned, the air flow was in series, downward through the two tanks. However, the connections between the stainless steel piping sections was made with flexible polyvinyl chloride (PVC) tubing so that both the sequence of the tanks, and the air flow 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 air flow[19] or by alternating the sequence of the tanks in series.[20] Monitoring of the gaseous pollutant concentration was performed on-line using two SRI (Torrance, CA) detectors in series: a dry electrolytic conductivity detector (DELCD) for monitoring chlorinated compounds and a flame ionization detector (FID) to monitor hydrocarbons. 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 build up of condensation in the sampling lines.

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 methylene chloride treatment. Lower pollutant removal performance was expected since styrene is known to be much more difficult to biodegrade than methylene chloride.[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} h^{-1} 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 (day 45-63) to develop an active and effective biofilm. After such adjustments, elimination capacity increased to steady-state values of 24 g m^{-3} h^{-1} (35 g m^{-3} h^{-1} 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 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 percentages of each expenditure is shown in Figure 5.

In general, during actual reactor design, efforts were directed towards minimizing all construction costs. As a result, in several instances, stainless steel was replaced by polyvinyl chloride, polypropylene, or polyethylene 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 represents only 4% of the total reactor costs when 20% of the basic investment were 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 mark-up. 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 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 (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 a 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/h. Although it was not always possible to distinguish between 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 efforts were dedicated to material selection. For the construction of subsequent reactors of lesser complexity, the length of the 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 next 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 utilized 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 1,000 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 non-chlorinated 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 high rate of methylene chloride 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) through the biotrickling filter can be varied. This will obviously affect the normalized treatment cost, but will also change the pollutant removal. Hence this phenomena should be fully taken into account when comparing various biological reactors for waste air treatment. In both cases, the design value (EBRT ~90 s) which was a relatively high value, was used for the calculation. A lower EBRT will decrease specific costs substantially.

The results of Table 6 demonstrate that the real costs were much lower than estimated previously. The reasons are 1) high expenses were projected that did not occur (in particular water and personnel, cheap fertilizers were used instead of technical purity chemicals), and 2) 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 most differences where 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 VOC degraded. Because near neutral pH needs to be maintained in the reactor, not much flexibility exists as far as reducing these costs. While 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 a variable speed blower might prove advantageous. As pressure drop increases over time due to biomass build-up, the blower speed can be adjusted so that the air flowrate 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 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 over-dimensioning biotrickling filters to allow for starvation or nutrient limitation, i.e., 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 prefered.[16,17] It also suggests that retrofitting existing scrubbers to accommodate for biotrickling filter operation might 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 to \$14/1,000 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 airflow rate, the concentration and nature of the pollutant, and the emission pattern (steady concentration, vs. frequent variations or week-end shut down). In a first approximation, it is possible to use the numbers of Table 6 (Case 1 and 2) and adjust them for the other expenses associated with competing technologies. Adsorption onto granular activated carbon (GAC) or thermal incineration do not require water, mineral salts, NaOH, water pump and 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 Case 1 and Case 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 about 30% cheaper than those of the biotrickling filter. A cost \$9 per kg for the GAC (including regeneration) was used in the calculation, and adsorption of 0.3 kg VOC per kg of GAC was assumed..[24-26] The resulting total treatment costs for GAC adsorption are \$9.3 and \$66 per 1000 m^3 of air treated, for Case 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 about 30% higher than for the biotrickling filter,[24,25,27] and additional heating or fuel costs are estimated to be \$1 to \$5 per 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 to \$13.6 /1000 m^3 air irrespective of Case 1 or Case 2. This is relatively similar to the biotrickling filtration costs of 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. (1997) showed that biofiltration of airstreams ranging from 10,000 to 60,000 $m^3 h^{-1}$ was 55 to 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 to 4 million dollars with yearly operating costs ranging from $150,000 to $300,000. Such a reactor could treat 10,000 to 150,000 $m^3 h^{-1}$ 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 per 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 the 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 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 per 1000 cubic meter 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 to 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 efforts should be directed towards optimization of pollutant elimination in biotrickling filters so that the smallest possible reactors can be constructed.

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REFERENCES

1. Fucich, W.J.; Yang, Y.; Togna, A.P. "Biofiltration for control of carbon disulfide and hydrogen sulfide vapors," In *Proceedings of the 90th Annual Meeting and Exhibition of the Air and Waste Management Association*, Paper 97-RP114B.04, 11 pp. Pittsburgh, PA; 1997.
2. Mildenberger, H.J.; van Lith, C. "Long term experience with large enclosed biofilter at sewage water treatment facility," In *Proceedings of the 89th Annual Meeting and Exhibition of the Air and Waste Management Association*, Paper 96-RA87B.03, 9 pp. Pittsburgh, PA; 1996.
3. VDI-Berichte 3477. "Biological waste gas/waste air purification: Biofilters," In *VDI-Handbuch Reinhalten der Luft*, Band 6. Düsseldorf, Germany. 1991.
4. Devinny, J.S.; Hodge, D.S. "Formation of acidic and toxic intermediates in overloaded ethanol biofilters," *J. Air & Waste Manage. Assoc.* **1995**, *45*, 125-131.
5. Van Lith, C.; Leson, G.; Michelsen, R. "Evaluating design options for biofilters," *J. Air & Waste Manage. Assoc.* **1997**, *47*, 37-48.
6. Webster, T.S.; Devinny, J.S.; Torres, E.M.; Basrai, S.S. "Biofiltration of odors, toxics and volatile organic compounds from publicly owned treatment works," *Environ. Prog.* **1996**, *15*, 141-147.
7. Deshusses, M.A.; Johnson, C.T.; Hohenstein, G.A.; Leson, G. " Biofiltration of high loads of ethyl acetate in the presence of toluene," *J. Air & Waste Manage. Assoc.*, **1999**, *49*, 174-180.
8. Cox, H.H.J.; Deshusses, M.A. "Biological waste air treatment in biotrickling filters," *Current Opinion in Biotechnology*, **1998**, *9/3*, 256-262.
9. Morton, R.L.; Caballero, R.C. "Removing hydrogen sulfide from wastewater treatment facilities'air process streams with a biotrickling filter," In *Proceedings of the 90th Annual Meeting and Exhibition of the Air and Waste Management Association*, Paper 97-RA71C.06, 22 pp. Pittsburgh, PA; 1997.
10. Mpanias, C.J.; Baltzis, B.C. "Chlorinated solvent vapor removal in biotrickling filters," In *Proceedings of Emerging Technologies in Hazardous Waste Management IX*, September 15-17, 1997, Pittsburgh, PA. 1997.
11. VDI-Berichte 3478. "Biological waste air purification, Bioscrubbers," In *VDI-Handbuch Reinhaltung der Luft*, Band 6. Düsseldorf, Germany, 1985.
12. Webster, T.S.; Deshusses, M.A. "Operation of a full-scale biotrickling filter for the removal of styrene from contaminated air," In *Proceedings of Emerging Technologies in Hazardous Waste Management IX*, September 15-17, 1997, Pittsburgh, PA. 1997.
13. Zuber, L.; Dunn, I. J.; Deshusses, M. A. "Comparative scale-up and cost estimation of a biological trickling filter and an airlift reactor for the removal of methylene chloride from polluted air," *J. Air & Waste Manage. Assoc.* **1997**, *47*, 969-975.
14. Loy, J.; Heinrich, K.; Egerer, B. "Influence of filter material on the elimination rate in a biotrickling filter," In. *Proceedings of the 90th Annual Meeting and Exhibition Air Waste Management Association*. Paper 97-RA71C.01, 20 pp. Pittsburgh, PA; 1997.

15. Hugler, W.; Benavente, J.L.; Acosta, C.M. "BIOCYDR technology demonstration project for carbon disulfide bioremediation in waste gas," In *Proceedings of Emerging Technologies in Hazardous Waste Management IX*, September 15-17, 1997, Pittsburgh, PA. 1997.
16. Cox, H.H.J.; Deshusses, M.A. "Evaluation of different technologies to control biomass growth in biotrickling filters for waste air treatment," In *Proceedings of Emerging Technologies in Hazardous Waste Management IX*, September 15-17, 1997, Pittsburgh, PA. 1997.
17. Smith, F.L.; Sorial G.A.; Suidan M.T.; Breen A.W.; Biswas P.; Brenner R.C. "Development of two biomass control strategies for extended, stable operation of highly efficient biofilters with high toluene loadings," *Environ. Sci. Technol.*, **1996**, *30*, 1744-1751.
18. Zuber, L. "Trickling filter and three-phase airlift bioreactor for the removal of dichloromethane from air," Ph.D. thesis, Swiss Federal Institute of Technology Zurich, Switzerland, 1995.
19. Kinney, K.A.; Chang, D.P.Y.; Schroeder, E.D.; Scow, K.M. "Performance of a directionally-switching biofilter treating toluene contaminated air," In *Proceedings of the 89th Annual Meeting and Exhibition Air Waste Management Association.* Paper 96-RP87C-05. Pittsburgh, PA; 1996.
20. Farmer, R.W.; Chen, J.S.; Kopchynski, D.M.; Maier, W.J. "Reactor switching, Proposed biomass control strategy for the biofiltration process," In *Proceedings of the 3rd International In Situ and On-Site Bioreclamation Symposium vol 9*, Battelle Press, Columbus, OH, 1995; pp 243-248.
21. Cox, H.H.J., Moerman, R.E., van Baalen, S., van Heiningen, N.M., Doddema, J., Harder, W., "Performance of a styrene-degrading biofilter containing the yeast Exophiala jeanselmei," Biotechnol. Bioeng. **1997**, 53, 259-266.
22. Webster, T.S., Cox, H.H.J., Deshusses, M.A. "Resolving operational and performance problems encountered in the use of a pilot/full-scale biotrickling filter reactor," *Environ. Progr.* **1999**, *xx*, xx-xx (in press).
23. Wolff, F.; Klein, T. "Biologische Abluftreinigung mit einem intermittierend befeuchteten Tropfkoerper," *Chem. Ing. Tech.* **1992**, 64, 854.
24. Heumann, W.L. *Industrial Air Pollution Control Systems*, McGraw-Hill: New York, New York, 1997, 620 pp.
25. Menig, H.; Krill, H.; Jaeschke, T. "Kosten und Effizienz biologischer Verfahren im Vergleich zu anderen Abluftreinigungssystemen," In *Biological Waste Gas Cleaning, Proceedings of an International Symposium*, Prins, W.L., and van Ham, J., Eds.; VDI Verlag GmbH, Duesseldorf, Germany, 1997; pp 27-58.
26. Anguil, G.H. "Adsorption: Carbon," In *Odor and VOC Control Handbook*; Rafson H.J., Ed.; McGraw-Hill, New York, New York, 1998; pp 8.66-8-91.
27. Anguil, G.H. "Thermal oxidation," In *Odor and VOC Control Handbook*; Rafson H.J., Ed.; McGraw-Hill, New York, New York, 1998; pp 8.31-8-65.
28. Devinny, J.S.; Deshusses, M.A.; Webster, T.S. *Biofiltration for Air Pollution Control*; CRC-Lewis Publishers: Boca Raton, FL, 1999, 300 pp.

FIGURE CAPTIONS

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.

Figure 2. CAD drawing of the constructed biotrickling filter. Full arrows indicate air flow, open arrows indicate water flow;. 1) contaminated air inlet; 2) blower; 3) knock-out 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; 12) water return to tank bottoms (for mixing).

Figure 3. Picture of the constructed biotrickling filter.

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).

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

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

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 methylene chloride 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	Co-current, two bed layers on top of each other	Co-current[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 ($m^3\ h^{-1}$)	0.5-3	100	350
EBRT[b] (s)	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 per tank (bottom of the tank)

[a]Flow direction can be switched, [b]EBRT: empty bed retention time

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

Reactor parts	**Material**
Reactor tanks	304L stainless steel (12 gauge)
Skid	Steel
Air piping	304L stainless steel, 8.1 cm ID, in part flexible PVC with quick connect/disconnect
Water piping	Schedule 40 and 80 PVC 2.5 to 7.6 cm ID
Nutrient and caustic tanks	Polyethylene

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

Parameter to be measured	Type of instrument
Air flowrate	Orifice plate (using differential pressure calculations)
Air phase concentration	FID/DELCD[a], inlet between the tanks and outlet concentrations
Air pressure	Pressure gauges, 3 different locations
Air temperature	Thermocouples, 3 different locations
Tank weights	Load cells, 3 per tank
Water conductivity	Conductivity probe, one after the water pumps
Water flowrate	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/direct electrolytic conductivity detector (for chlorinated compounds)

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 air flow	5,500		1,800
2 water pumps (trickling flow)	2,500		2,900
Tank in the upper loop	1,200		none
Tank for NaOH	2,800[c]		300[d]
Tank for the mineral nutrients	100[d]		300[d]
2 heat exchangers	15,600		1,300[e]
Secondary cost:		**Sub-totals by categories**	**Totals**
Monitoring and controls (12% of the basic investment)	13,900	Total monitoring and controls	30,000
		Computer 1,300	
		Metering pumps, meters, and electrodes, and transducers 12,100	
		Data acquisition 6,000	
		Load cells 3,600[f]	
		FID/DELCD detectors 7,000	
Piping (20% of the basic investment)	23,100		7,600
Insulation (7% of the basic investment)	8,100		none
Building (20% of the basic investment)	23,100	Total building	9,500
		Skid and various structural 5,100	
	none	Installation of wheels 4,400[f]	
Engineering costs		**Sub-totals 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 per 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]polyethylene; [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.

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

	Previously used[13]	Actual values
Tap water ($ m^{-3})	2.73	1.32[a]
Waste water (industrial) ($ m^{-3})	2.02	n/a
Mineral salts ($ kg^{-1})	9.5[b]	1.7[c]
Sodium hydroxide ($ kg^{-1})	0.95	1.32
Electricity ($ kWh^{-1})	0.10	0.05
Steam at 3 bar ($ kg^{-1})	0.026	none
Personnel ($ h^{-1})	60	40

[a]Combined water and sewage cost; [b]technical grade chemicals; [c]premix fertilizers.

Table 6. Estimated and actual operating costs normalized for 1,000 m^3 of air treated.

Category	Previously estimated[13] ($/1,000 m^3 of air treated)		Actual Case 1: (low cost) ($/1,000 m^3 of air treated)		Actual Case 2: (upper end cost) ($/1,000 m^3 of air treated)	
	Subtotals	Totals	Subtotals	Totals	Subtotals	Totals
Tap water		3.55		0.05[a]		0.62
Waste water (industrial)		2.62		-		-
Mineral salts		4.17		0.58		1.74
Sodium hydroxide		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/1,000 m^3		62.1		8.71		14.05

[a]Sewer discharge included in tap water; [b]steam; [c]384 h per year; [d]220 h per 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).

Figure 1

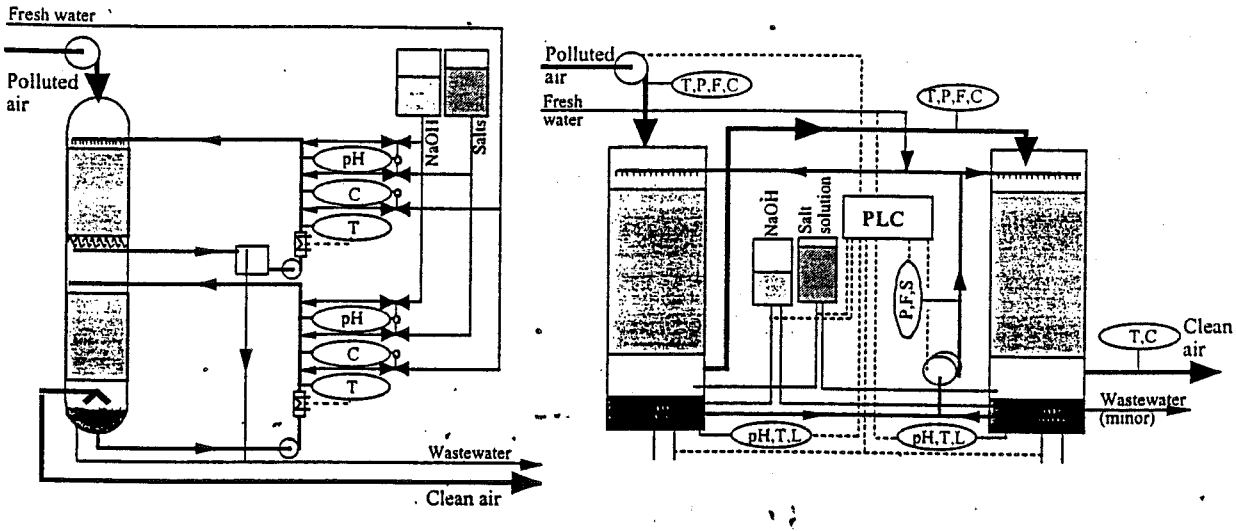

Fresh water
Polluted air
NaOH
Salts
pH
C
T
pH
C
T
Wastewater
Clean air
Polluted air
Fresh water
T,P,F,C
T,P,F,C
NaOH
Salt solution
PLC
P,F,S
T,C
Clean air
Wastewater (minor)
pH,T,L
pH,T,L

Figure 2

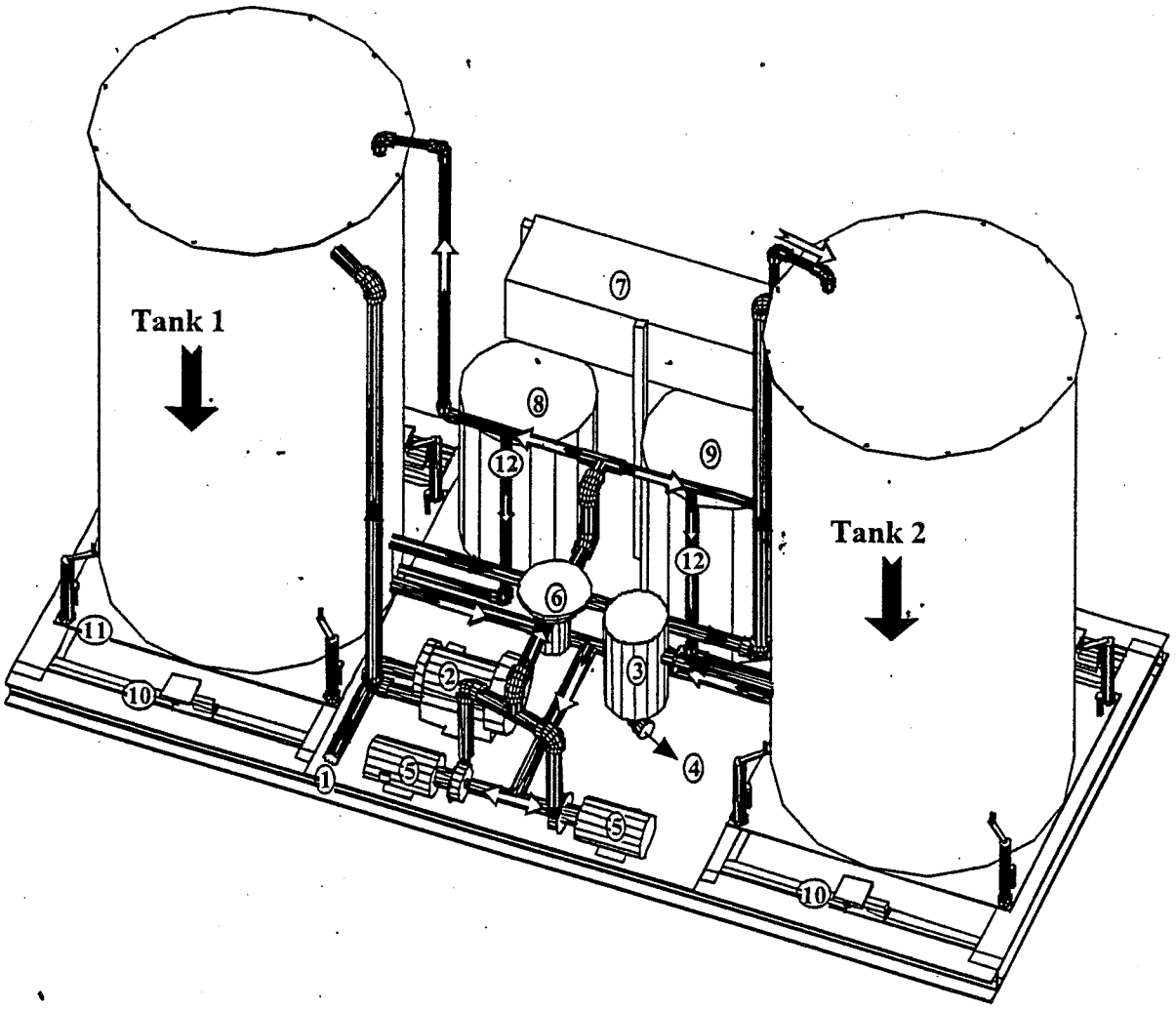


Figure 3

picture (hard copy)

Figure 4

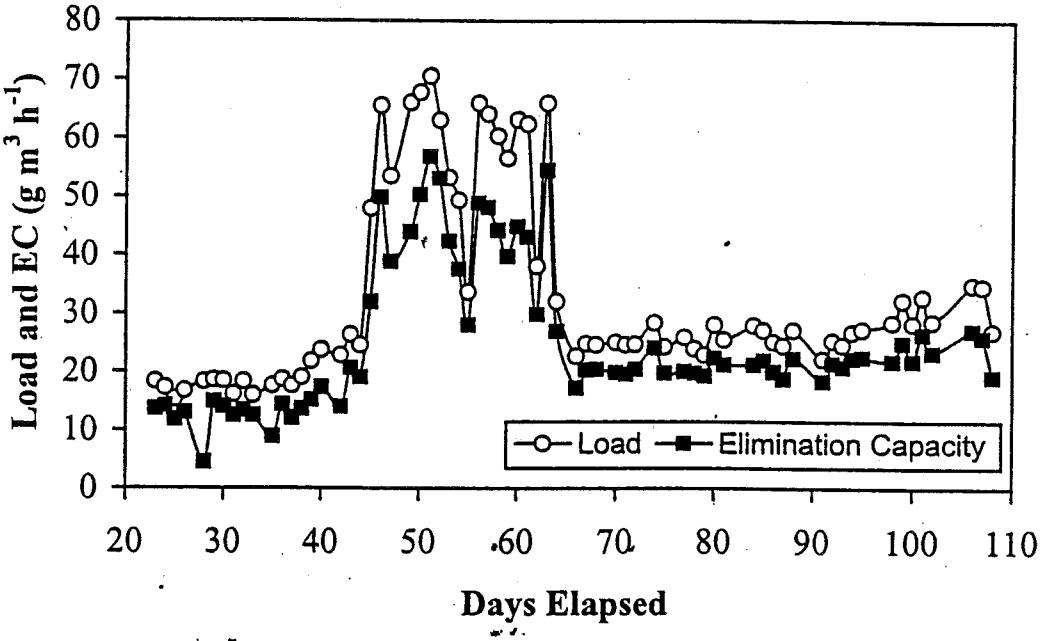

Load and EC (g m^{-3} h^{-1})
80
70
60
50
40
30
20
10
0
20
30
40
50
60
70
80
90
100
110
Days Elapsed
Load
Elimination Capacity

Figure 5

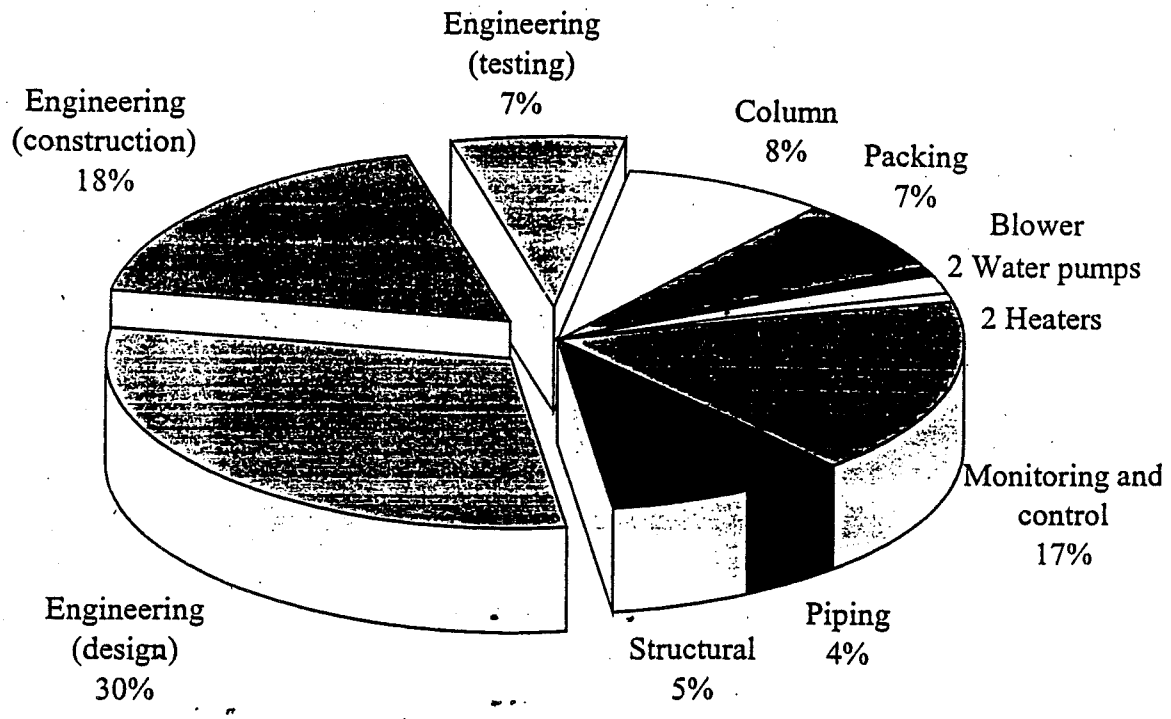
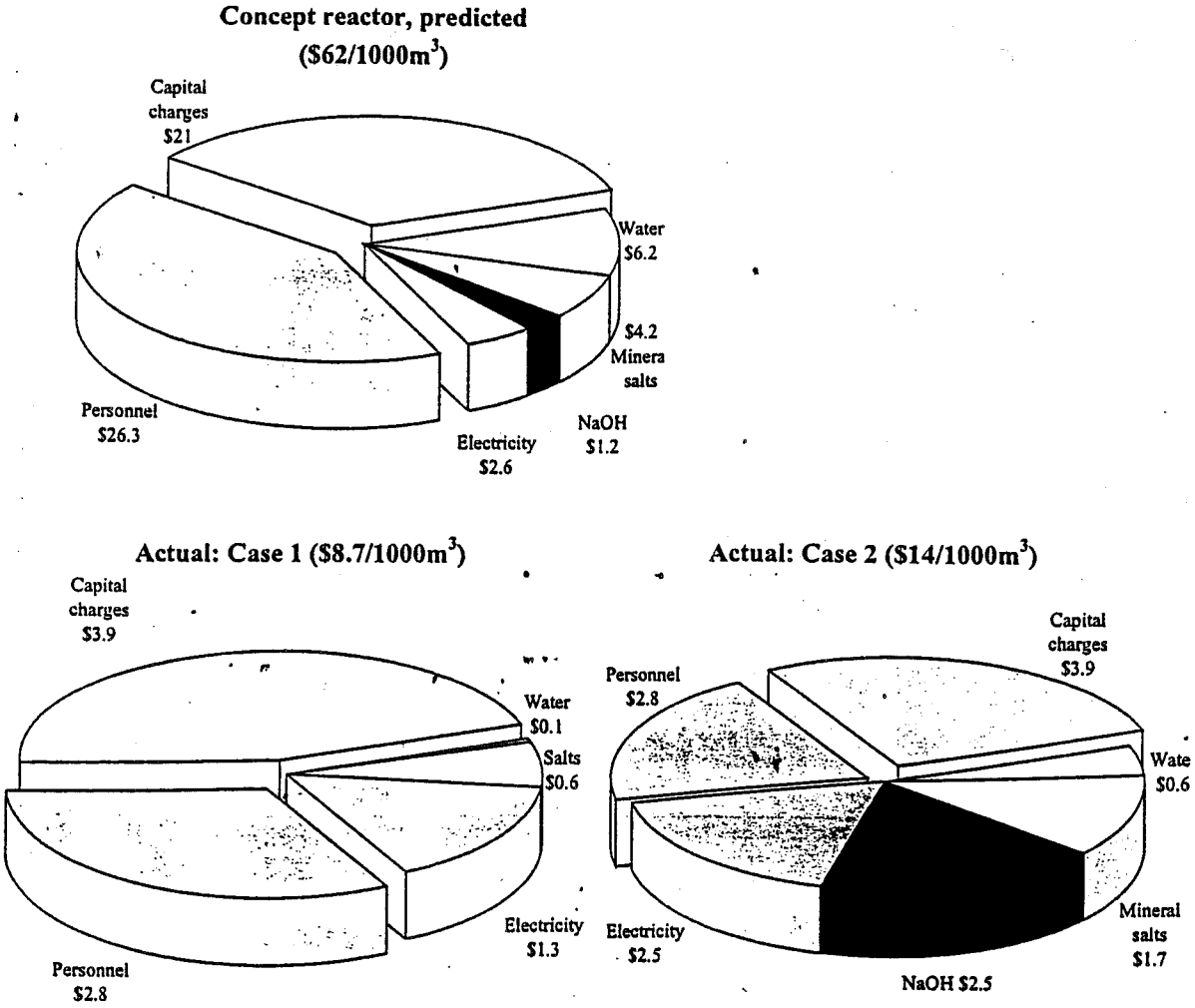
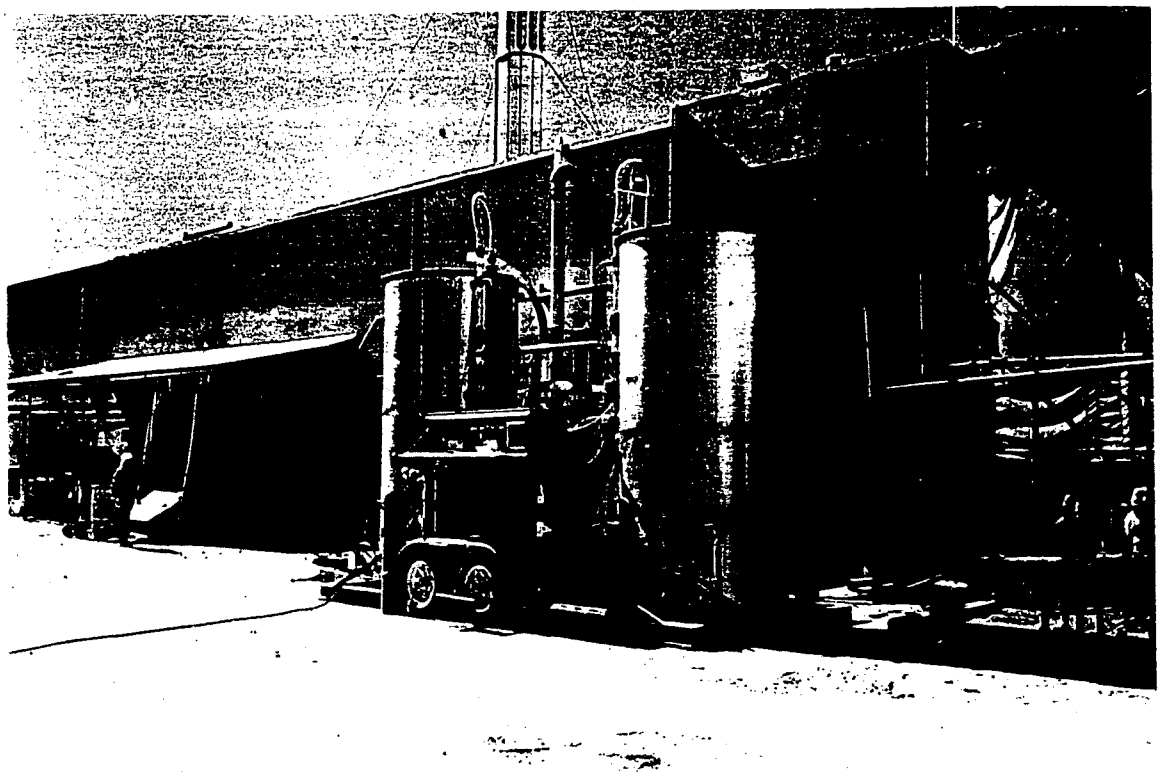

Engineering
(testing)
7%
Engineering
(construction)
18%
Column
8%
Packing
7%
Blower
2 Water pumps
2 Heaters
Monitoring and
control
17%
Engineering
(design)
30%
Structural
5%
Piping
4%

Figure 6


Concept reactor, predicted
($62/1000m3)
Capital charges $21
Water $6.2
$4.2 Minera salts
NaOH $1.2
Electricity $2.6
Personnel $26.3
Actual: Case 1 ($8.7/1000m3)
Capital charges $3.9
Water $0.1
Salts $0.6
Electricity $1.3
Personnel $2.8
Actual: Case 2 ($14/1000m3)
Capital charges $3.9
Personnel $2.8
Wate $0.6
Mineral salts $1.7
Electricity $2.5
NaOH $2.5

An Assessment of the Performance of a Pilot-Scale Biotrickling Filter Reactor at the Lasco Bathware Manufacturing Facility (Anaheim, CA)



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July 25, 1997

Executive Summary

A biotrickling filter reactor demonstration project was performed at Lasco Bathware, Inc. (Anaheim) in conjunction with the University of California-Riverside. The pilot-scale system is the largest of its kind in the USA and was used to treat the styrene off-gas emissions from Lasco's manufacturing process. Initial data demonstrated 80-90% removal by the system at elimination capacities of 20-25 $g/m^3/h$. Higher elimination capacities, up to 50 $g/m^3/h$ were demonstrated but at removal efficiencies below 70%.

Numerous experiments were performed to enhance the performance of the biotrickling filter reactor system. First, simple parameters such as temperature and nutrients were altered to demonstrate their effects on removal performance. However, little dependence could be seen. During the first 60 days of operation, the biomass accumulation was not prevalent. It was believed that this could be limiting the performance of the system. Hence, to increase the biomass, the styrene load was doubled by means of artificial styrene addition. Biomass increased five folds, while elimination capacity increased only slightly.

Experiments were then conducted to establish if an engineering problem might be a factor. Tracer test studies, water recirculation rate tests, and load modification experiments were conducted. The results of the test showed that approximately 10% of the filter bed was not being used, due possibly to channeling. However, the performance of the reactor would not improve dramatically if this 10% were recovered. The flow rate experiment demonstrated that the higher recirculation rates improved the performance of the system. However, the water recirculation rate was not the primary reason why the performance of the system was low. The load modification experiments showed that better removal (95%) could be achieved if air residence times were increased from 45 to 90 seconds. Though some insight was gained into the system performance, little improvement resulted.

Finally, tests to determine the robustness of the biology of the system were performed. Evidence of a slow growing microbial consortium with low styrene uptake rates was determined. Hence, it is believed that this particular system was encumbered by a slow growing styrene degrading organism that could not degrade the styrene easily. The system was inoculated with an activated sludge and the dominant species of microbes flourished. It may be more advisable to inoculate the system with another specific styrene degrading microbial species.

Based on the findings, if Lasco wanted to treat 50% of their air effectively (at 60% removal efficiency), they would require four 5-meter tall tanks in parallel, each with an internal diameter of 7 meters. If they wish to achieve much higher removal efficiencies, more tanks would need to be added to eliminate the remaining contaminant.

Because the reactor is a prototype system and Lasco was the first test site, system malfunctions frequently interrupted reactor operation. Presumably, if these system malfunctions could have been eliminated, the continuous operation of the reactor would only have enhanced the reactor performance by providing a constant load to the system and preventing short times where anaerobic conditions were allowed to exist. Future experiments are still warranted to enhance the performance of the reactor.

Introduction

Lasco Bathware and the University of California at Riverside (UCR) have combined efforts to assess the feasibility of implementing a biotrickling filter reactor to treat styrene off-gas emissions. Currently, Lasco Bathware Corporation manufactures approximately 600 fiberglass bathtubs per day. In the process of applying a fiberglass resin/styrene mixture to each bathtub, small quantities of styrene are emitted to the atmosphere. The plant has two large blowers that move the contaminated air through two discharge stacks at an approximate combined rate of 102,000 m^3/h. The sole volatile organic compound (VOC) in the effluent air is the aromatic contaminant styrene. Concentrations vary, but average emissions are 150 ppmv, or 0.63 g/m^3. Because of variances given to Lasco by the South Coast Air Quality Management District (SCAQMD), Lasco has no VOC control technology currently in place. However, concern over the need to implement such a technology in the future serves as the impetus for Lasco to study the feasibility of a biotrickling filter reactor at their site.

UCR's objectives in this project involved studying the performance of the biotrickling filter reactor under industrial conditions. The biotrickling filter reactor was designed and constructed by UCR personnel and Environmental Biosystems (Denver, CO). The largest of its kind in the United States, this reactor serves as a prototype for future system development. The Lasco Bathware site was the first site tested with this prototype reactor. Hence, besides testing the performance of treating styrene with the reactor at an industrial setting, acknowledgement and control of system operational problems were also crucial objectives of the experiment.

This final report describes those experiments and results obtained in optimizing the performance of the reactor. An experiment timeline is given to detail the step-by-step progression of the reactor performance with changing conditions. Detailed discussions are presented for all crucial experimental findings. Explanations of operational problems unique to the industrial setting and the prototype are presented. Finally, estimates are made and conclusions are drawn as to the efficacy of implementing such a technology at the Lasco plant.

Theory

A biotrickling filter reactor is essentially a scrubber, or gas absorber, in which aerobic microbiological reactions take place. Contaminant vapor is passed through an inorganic media bed where immobilized microorganisms are attached (Figure 1). As the air passes through the bed, contaminants are absorbed into the biofilm on the media (Figure 2). The organisms convert this contaminant into carbon dioxide, water, heat, and more biomass. A constant recirculating water phase is provided over the media bed and the biofilm to ensure essential nutrients are delivered which are necessary for the degradation of the contaminant. The recirculating water phase also maintains a moist environment for the microbes and allows for enhanced operator control of the environmental conditions within the filter bed (temperature, pH, conductivity, etc.). The filter operates concurrently, that is both the water and contaminated air enters the column at the top and exit at the bottom. It is possible that the system could be operated counter currently, with bottom loaded air distribution and top loaded

water distribution. However, the possibility of water hold-up and contaminant entrainment at the air effluent makes such a scenario less practical.

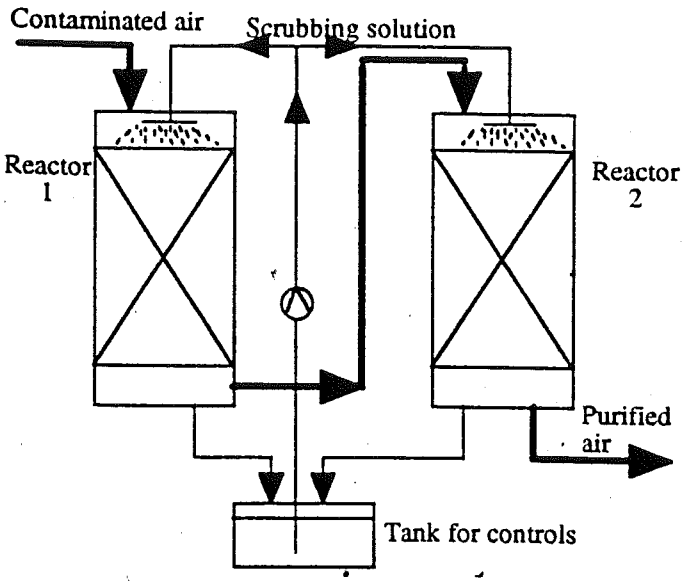


Figure 1. Schematic of a biotrickling filter reactor.

Microorganisms require a carbon source in order to survive. Those microorganisms that use organic material as a supply of carbon are classified as heterotrophs. This fact is the basis for biological treatment of VOCs. The microorganisms in a biotrickling filter use the VOC in the air as their carbon and energy source. The simplified chemical reaction that occurs is:

$$VOC + O_2 \xrightarrow{microorganism} CO_2 + H_2O + Biomass$$

As can be seen by the above reaction, the VOC is degraded. This is the major advantage of using biological treatment of VOCs. Instead of the pollutant being transferred to another phase, it is destroyed.

Oxygen is also needed for the growth of microorganisms. Oxygen serves as the terminal electron acceptor during cellular respiration. This is known as aerobic decomposition. Thermodynamically speaking, aerobic conditions supply microorganisms with the maximum energy and may lead to complete oxidation of the contaminant. Generally, this is a desirable condition for VOC degradation. When oxygen is absent, microorganisms will use nitrate (NO_3^-) as the terminal electron acceptor. This route, called anoxic decomposition, or denitrification is slightly less energy efficient and will not be used if any oxygen is available. If both oxygen and nitrate are absent, the microorganisms will resort to anaerobic decomposition. Sulfate (SO_4^{2-}), CO_2, or any other terminal electron acceptors present will be used. Anaerobic decomposition is less energy efficient and can produce byproducts such as H_2S and ammonia. In some cases, mercaptans and low molecular weight carboxylic acids may be formed which are detrimental to the microorganisms if not removed from their environment. To ensure VOC degradation along with microorganism growth,

oxygen should be present in a biotrickling filter at all times. This is generally the case in biotrickling filters because the VOC being treated is mixed in oxygen-laden air.

Besides a carbon source and a good electron acceptor such as oxygen, microorganisms require a suitable environment in which to grow. Such parameters as moisture content, temperature, and pH should be well maintained. The water that trickles through the filter bed supplies the moisture to the microorganisms immobilized on the bed material. Microbes will generally grow best at a mesophilic temperature between 25 and 40°C. These conditions can be maintained using heat exchangers or heating elements. pH should be maintained near neutral. A low pH may inhibit growth significantly as will the less observed high pH situation. If a VOC is being oxidized which produces acidic intermediates, a low pH may occur in the recirculating liquid phase. This may be controlled by adding appropriate amounts of caustic to neutralize and buffer the pH declines.

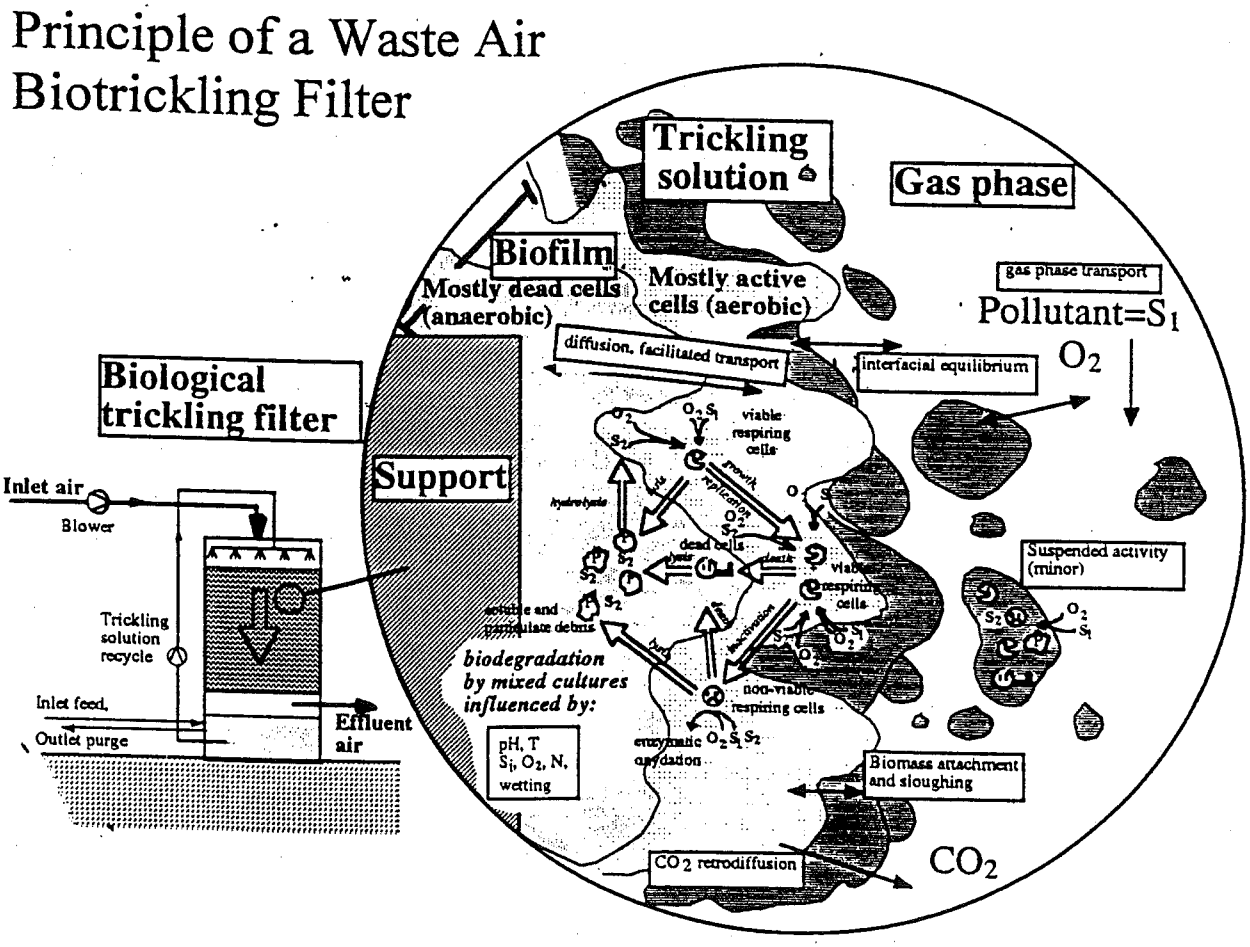


Figure 2. Principles of air treatment in a biotrickling filter reactor.

Definitions

The amount of time it takes the air to pass through a biotrickling filter reactor is defined as the empty bed residence time:

$$EBRT = V/Q \tag{1}$$

Where,

Q = air flow rate, m^3/h
V = packing volume, or filter bed volume, m^3

The amount of VOC being treated by a biotrickling filter is known as the load. The load is a measure of the flow rate of contaminated air, the concentration of the contaminant and the volume of the reactor that is treating the air.

$$Load = \frac{C_i \cdot Q}{V} \tag{2}$$

Where,

C_i = inlet VOC concentration, g/m^3
Q = air flow rate, m^3/h
V = packing volume, or filter bed volume, m^3

The environment that is best suited for microbial growth will result in the optimum removal efficiency and elimination capacity. Elimination capacity is the amount of VOC that the biotrickling filter degrades per unit time and filter bed volume:

$$E.C. = \frac{(C_f - C_i) \cdot Q}{V} \tag{3}$$

Where,

E.C. = elimination capacity, g/m^3 h
C_f = outlet VOC concentration, g/m^3
C_i = inlet VOC concentration, g/m^3
Q = air flow rate, m^3/h
V = packing volume, or filter bed volume, m^3

Equations 2 and 3 can be combined to form another equation, the removal efficiency, which describes biotrickling filter performance.

$$R.E. = \left(\frac{E.C.}{Load}\right) \cdot 100 \tag{4}$$

Equation 4 is less descriptive of biotrickling filter performance than equation 3. The removal efficiency reveals minimal information about the size of the filter bed or the amount of contaminated gas being treated. Two biotrickling filters cannot be compared by removal efficiency alone because the volume of the filter bed of one may be enormous in comparison to the other. Therefore, elimination capacity is a better equation for evaluating the performance of a biotrickling filter reactor. It effectively describes the amount of VOC being treated per the volume of filter bed. However, elimination capacity can be misleading, in that a fraction of the filter bed may be responsible for degrading most of the VOC while the rest of the filter bed volume is unutilized. This will result in a smaller elimination capacity because the volume used in the calculation is the total filter bed volume and not the volume that is responsible for the most degradation. To compensate for this, sampling of VOC concentrations can be done along the filter bed instead of at the inlet and outlet only. This will give a more realistic description of biotrickling filter performance, which is requirement for reactor scale-up calculations.

Figure 3 is a typical plot of elimination capacity versus load for a biotrickling filter. The curved line is the performance line. In the design of a biotrickling filter, one should consider if high removal efficiency or a high amount of VOC degradation is desired. If high removal efficiency is desired, the filter should be operated at a lower load where the slope of the line is unity. If a high amount of VOC is to be degraded, then the filter should operate closer to where the slope is zero.

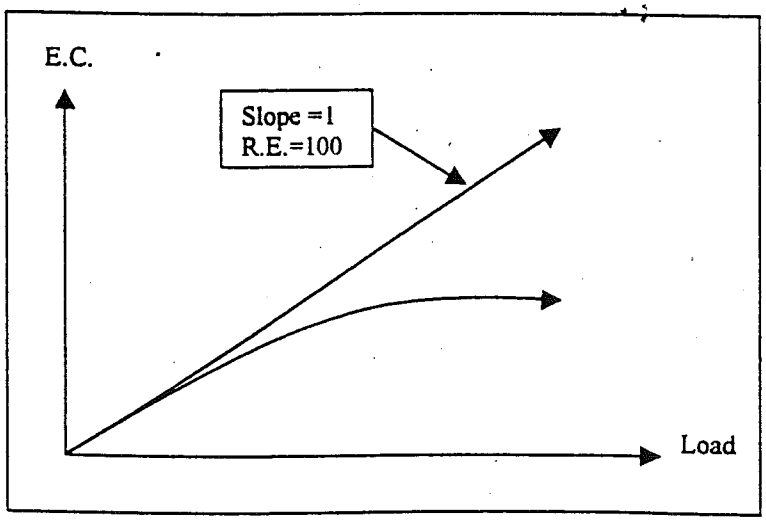


Figure 3. Typical Elimination Capacity. vs. Load for a biotrickling filter reactor.

Experimental Set-Up

The two main systems of the biotrickling filter reactor are the air and water distribution systems. The biotrickling filter reactor consists of two stainless steel tanks in which air is passed through in series (Figure 4). The system uses a regenerative blower to pull a side stream from one of the stacks at a flow rate of 357 m^3/h (less than 1 % of Lasco's total

emissions). Each reactor has an internal diameter of 1.6-m (5.25 ft) and height of 2.4 m (7.9 ft). The packing material consists of 9 cm diameter Jaeger tri-pack spheres with a 95% void space. The bed volume is 4 m^3, giving an empty bed residence time per tank of 45 seconds. Concurrent with the air, two centrifugal pumps deliver water in parallel to the top of each tank bed at flowrates ranging from 40-400 L/min. There, it is evenly dispersed via a network of five nozzles over the filter bed. Additionally, approximately 100 L/min of water is pumped into the bottom of the column to produce a mixing effect.

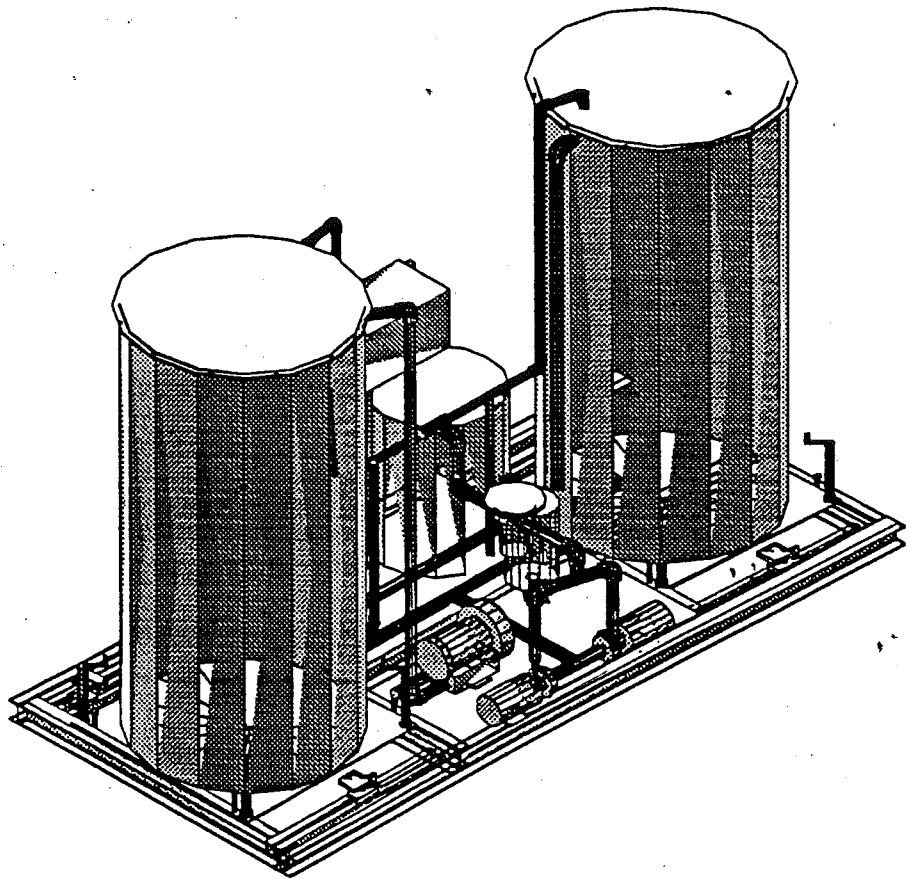


Figure 4. Schematic of UCR's full-scale biotrickling reactor.

Water is removed from the system either through evaporation or drainage. Because of the intimate contact that is made between vapor and liquid in scrubbers, the air exiting the system is saturated with water. Assuming dry air enters the system and saturated air at 25°C leaves the system at a flow rate of 357 m^3/h, then at least 7 kg/h of water will be evaporated from the system. Water is drained from the system at regular intervals to clean the system of suspended by-products produced by the microorganisms. Water is added to the system via a computer controlled logic system. Level meters on each tank control the height of water at the bottom. If the floats in the level meters rise or descend beyond certain points, a switch is tripped and water is accordingly added or drained. It is vital that the water level in each tank is maintained or the pumps will draw air. This causes cavitation in the pumps and will severely damage the water pumping system. The computer controlled logic system will shut

the biotrickling filter down if a low pressure in the water line ensues as a result of pumping air.

Immersed in the reservoir of water in each tank is a 12 kW heating element that can heat the water, and thus the reactor bed, to desired values. A nutrient tank and caustic tank supply nutrients and NaOH via computer control to the two columns. Probes measure the pH of the water reservoir and caustic is supplied as needed to maintain a neutral liquid solution.

A flame ionization detector (FID) is used to measure the concentration of styrene at the inlet, between tanks, and the outlet of the system. Several sampling ports are also present on each tank to measure styrene concentration along the filter bed.

Timeline

Over the course of the five month experiment, January 10 to July 18, 1997, three the elimination capacity has been measured for the reactor. Figure 5 illustrates the day by day average elimination capacity with labels indicating important changes made to the system. The plant operates 24 hours per day, five days of the week.

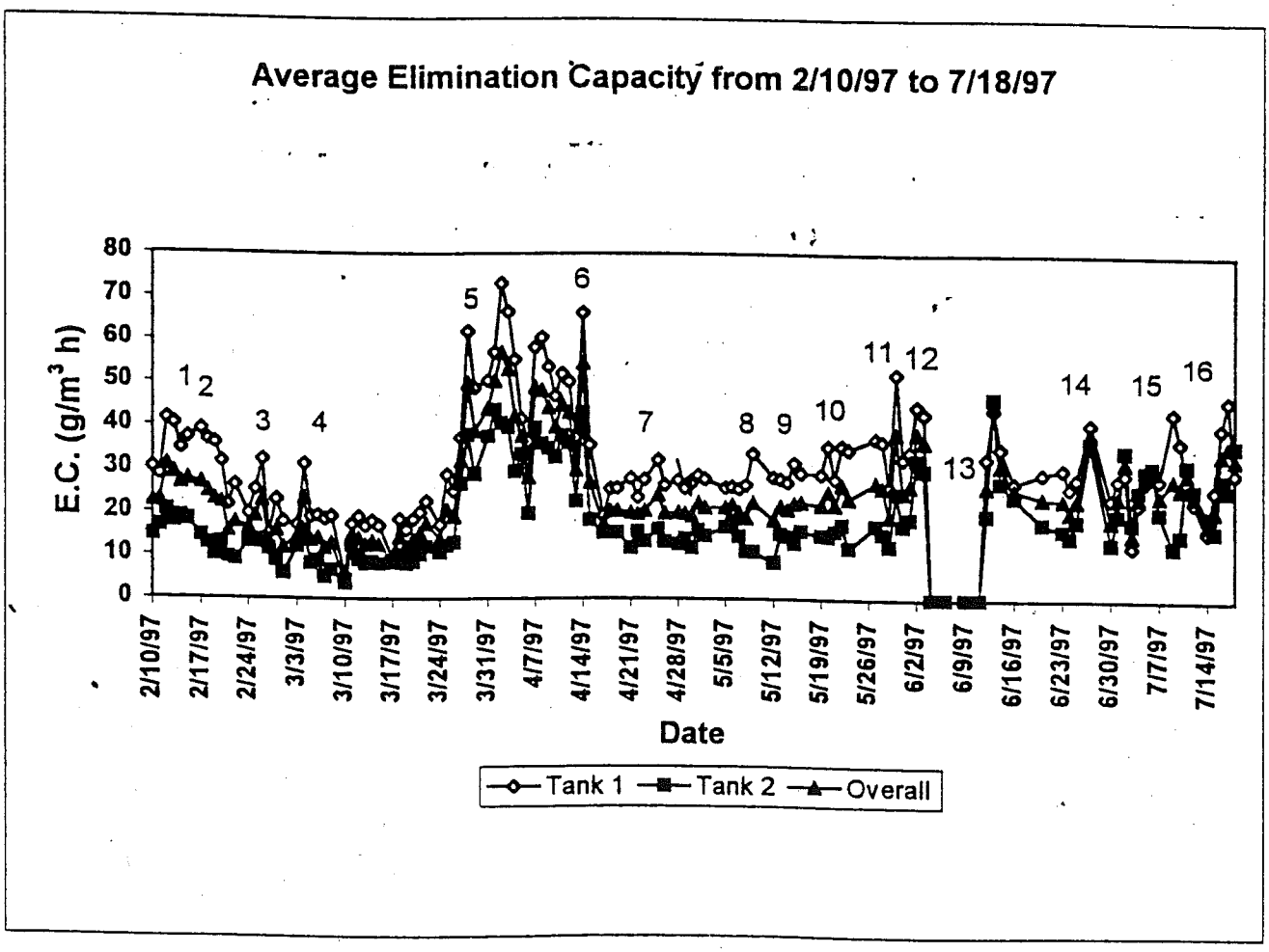


Figure 5. UCR full-scale biotrickling filter timeline.

1. **Reactor Started in Batch Mode**

Contaminated air introduced at 357 m^3/h. Activated sludge from a local wastewater treatment plant was added to the reactor for inoculation of the system. Except for evaporation, water was not removed from the system. This prevented dilution of the seed organisms. Nitrogen/Phosphorus/Potassium in a 12/20/13 ratio fertilizer were added to the reactor at 0.73/1.2/0.75 g/l to ensure microbial growth.

2. **Continuous Mode Operation**

From this point to the end of the experimental run, the reactor operated in a continuous mode. Water was drained and added at a rate of 10 liters per hour via computer control. A steady addition of nutrients (0.38/0.64/0.4 lbs/day of N/P/K) was maintained based on the concentrations described in timeline item 1. The pH of the system fluctuated from 6 to 7 as nutrient supply increased acidity. The computer system controlled the caustic addition to neutralize generated acids and increase the alkalinity of the liquid.

3. **Water Flow Rate Decreased**

Because it was surmised that the higher flow rate might have been stripping the biofilm from the packing material, the water flow rate that trickles down through the filter bed was decreased from 284 to 208 L/min.

4. **Nutrient Load Increased**

A low elimination capacity continued to be seen. It was postulated that a low elimination capacity might have been caused by nutrient limitations. Hence, the nutrient load was doubled from 0.38/0.64/0.40 lbs/day to 0.77/1.28/0.80 lbs/day of N/P/K to prevent a possible nutrient limitation.

5. **Styrene Load Increased**

Despite the increase in the nutrient load rate, the elimination capacity remained low. There may have been a reaction limitation due to the small amount of biomass. To increase the biomass and biofilm thickness on the packing, the styrene load was increased from 28 to 66 g/m^3 h by artificial styrene addition. A thicker biofilm on the packing material would presumably increase the number of reaction sites for the styrene to be oxidized. A thicker biofilm could also allow for more styrene to diffuse into the biofilm, thus improving the elimination capacity.

6. **Styrene Load Reduced**

The artificial supply of styrene was removed and the styrene supply came solely from the plant. With increased biofilm thickness, more biocatalysts were available for styrene degradation. The elimination capacity of the reactor improved from an average of 15 g/m^3

h before the styrene load increase to 20 g/m^3 h after styrene load decrease. Over the course of the time of the increased styrene load, the reactor biomass increased by a factor of 5 (Figure 6).

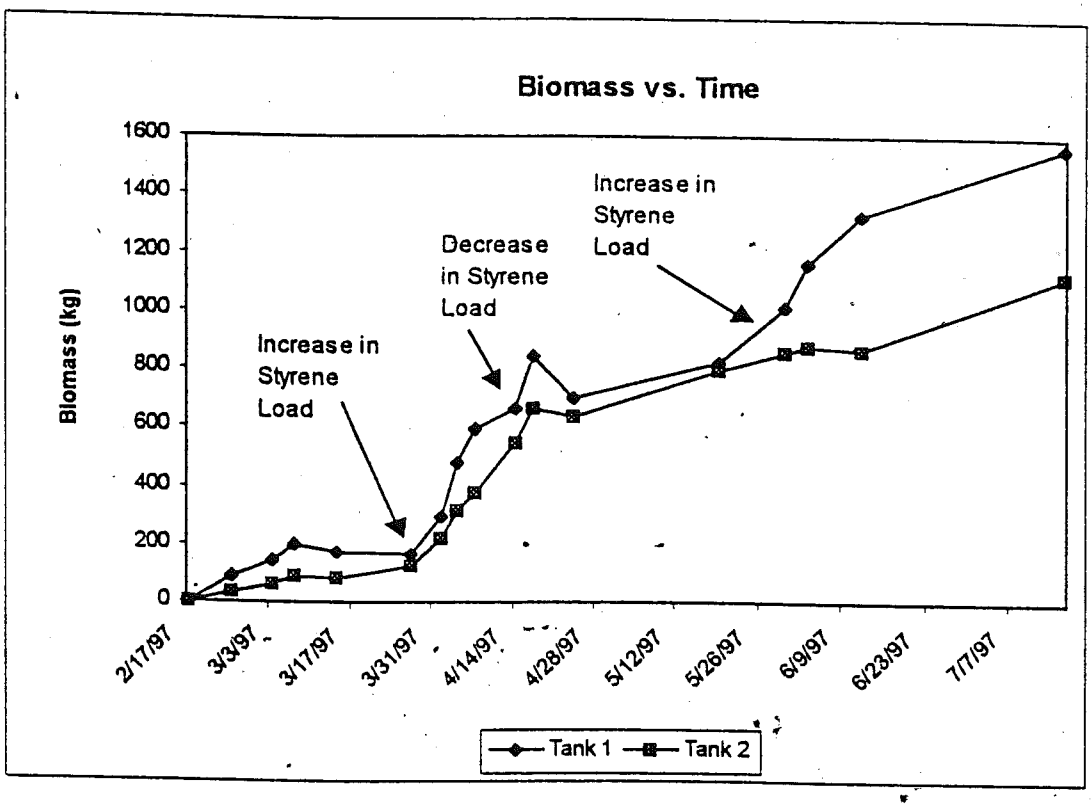


Figure 6. Biomass increase during artificial styrene load.

7. Heating Element Turned Off

The heating element that maintained the recirculating water temperature range of 30-34°C was turned off because of the warmer weather. This had no effect on elimination capacity or removal efficiency.

8. Water Flow Rate Experiment Was Performed

It was unknown how the flow rate of water trickling through the filter bed effected wettability of the biofilm, and thus the biodegradation of styrene. An experiment was performed to measure removal efficiency and elimination capacity of the first tank as a function of water flow rate.

The only way to vary the flow rates of water into the tanks is by way of opening or closing a ball valve on the water pipe going to the top of each tank. In this experiment, only the inlet ball valve for tank 1 and the pumping capacity (either one or two pumps

were working during the experiment) were manipulated. Because of work breaks at the Lasco plant, the styrene inlet concentration varied considerably. For more accurate results, the plant styrene load was shut off and an artificial styrene load of the same average inlet concentration (150 ppmv) was maintained. This was done by using a peristaltic pump to draw liquid styrene from a drum into the inlet air dilution port. The small amount of liquid styrene required to attain a 150 ppmv concentration allowed for almost instantaneous vaporization. The water flow rates were changed and allowed to run for an hour while the FID reported inlet, between tanks, and outlet styrene concentrations. On the first day of the experiment, the tank 1 flow rates were changed in the following order: 38 L/min, 189 L/min, 367 L/min and finally 427 L/min. The 427 L/min flow rate required the use of both pumps whereas all the other flow rates required only one pump. On a following day, the flow rates were changed to 95 and 284 L/min, again for one-hour periods each.

Figure 7 is the graph of elimination capacity and removal efficiency versus flow rate. The graph shows that a slight increase in performance occurred as the flow rate increased. The standard deviation for the removal efficiency was about +/- 2% and +/- 1.5 for the elimination capacity. These values may have come from the inaccuracy of the FID. Given the upward trend of Figure 7, the result show that despite a moderate standard deviation, enough points were gathered to discount the probability that the upward trend was just noise. The increased removal efficiency and elimination capacity was the result of more dispersion of water throughout the filter bed. Presumably, the wetting of the biofilm eliminated channeling and allowed for a better environment in which VOC degradation could occur. Increasing the flow rate beyond what was tested was not possible due to the lack of pumping capacity.

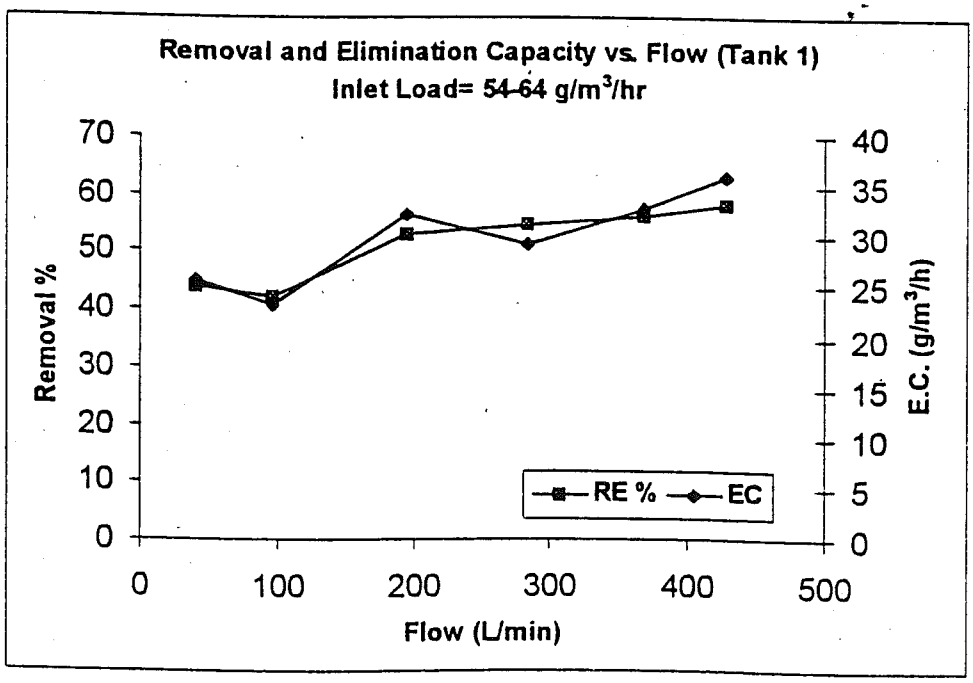


Figure 7. Reactor performance as a function of water flow rate.

9. Tracer Experiment Performed

A putrid smell was observed coming from the reactor. The smell was most likely the byproduct of anaerobic respiration. As mentioned before, anaerobic respiration is a less efficient mode of cellular respiration and will only occur if there is no oxygen present. If certain portions of the filter bed were under anaerobic conditions, the elimination capacity would be significantly reduced because anaerobic degradation is very slow. Air and water may not be trickling evenly throughout the reactor as a result of biomass buildup. This is known as channeling. A dry filter bed has a large void fraction and channeling is at a minimum. However as biomass increases and biofilm thickness increases, the void spaces that previously allowed for free flow of water and air are filled. The channeling that results may cause anaerobic conditions. To test if channeling was occurring, a tracer experiment was performed. In the tracer experiment, the air residence time of tank 1 was measured. A comparison to the empty bed residence time and a measure of the amount of space not being utilized in the filter bed was determined. This test will identify if channeling was prevalent.

To perform the tracer experiment, the contaminated air supplied by the plant was shut off. A pulse of propane at the inlet of the reactor system was applied. The pulse basically traveled through the reactor as the contaminated air would travel. The computer system on the reactor took FID measurements every 2 seconds to measure the progress of the pulse through the system. A plot of concentration versus time as measured at the midpoint sampling port was prepared. The retention time of the pulse was determined and the experimental void was compared to the calculated void. This comparison revealed the amount of space not being utilized in the filter bed.

Three tests were performed to ensure accurate results. Figure 8 shows the concentration of the propane over time. The shape of the curve shows the system had considerable mixing. That is, the pulse did not travel as a plug through the system. The retention time was determined to be 36.94 seconds. The flow rate through the system was 357 m^3/s; thus the experimental void was determined to be 3.66 m^3. From the geometry of the piping, the liquid holdup, the packing material, and the biofilm present in the first filter bed the calculated void was determined to be 4.05 m^3. From these values, the dead void or the space in which air is not traveling through, was calculated to be 0.386 m^3. Roughly 9.5% of the filter bed tank 1 was not being utilized. At first glance, this may appear to be a significant amount. However, if this space were utilized in the reactor, the performance of the reactor would not likely improve very much. This test demonstrated that enough of the filter bed was being used to conclude that there was not a major problem with channeling in the system.

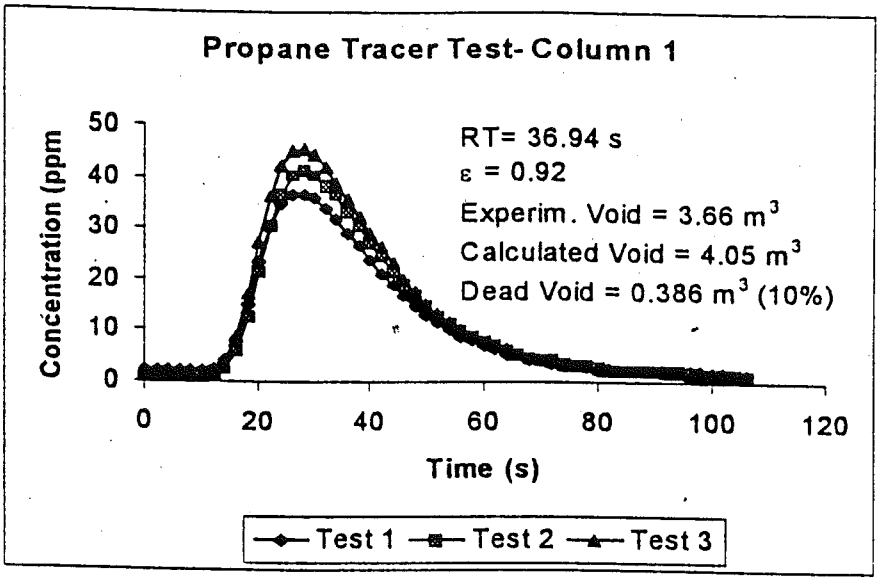


Figure 8. Pulse of propane through Tank 1.

10. Biological Oxygen Demand (BOD) Test Performed/Water Flow Rate Increased

A BOD test was performed on the wastewater effluent water that was being discharged from the reactor. The 5-day BOD was found to be 460 mg/l. This is considered a low to moderate BOD level. Discharge of such water to the local POTW may not require an additional permit if other wastewater from the Lasco plant is low in BOD. This is most likely the case since Lasco's manufacturing process does not produce large quantities of organic matter in the liquid phase.

The water flow experiments (timeline item 8) suggested that higher water flow rates might promote better wetting of the packing. Hence, the water flow was increased over both tanks to 380 l/min.

11. Water Flowrate Reduced; Styrene Load Increased

The elimination capacity was generally not improving, so the water flowrate was returned from 380 l/min to 208 l/min. Additionally, the styrene load was once again artificially increased to 66 g/m^3 h in hopes of increasing the biomass further and improving elimination capacity of the system (Figure 6). After 6/9/97, for the continuance of the experiment, the styrene load was artificially increased and decreased for short periods of time during various experiments.

12. Styrene Removal and Temperature Measurements Along Tank 1

Concern over the low elimination capacity in tank 1 prompted an experiment to review the contaminant degradation along the reactor length. It may be possible that the majority of the contaminant was being removed in a small portion of the bed.

The experiment was performed by connecting sampling ports along the length of tank 1. As in the water flow rate experiment, inlet contaminant air was supplied artificially. The concentrations from the inlet, three ports along tank 1, and the outlet of tank 1 were measured. The inlet and outlet were measured as usual. Using an extra sampling line available (normally a line which supplies blank air to the FID), sample air was drawn from the three ports (at different times) through a 250 ml glass flask (to catch any water vapor) and into the FID. Results of the experiment can be seen in figure 9.

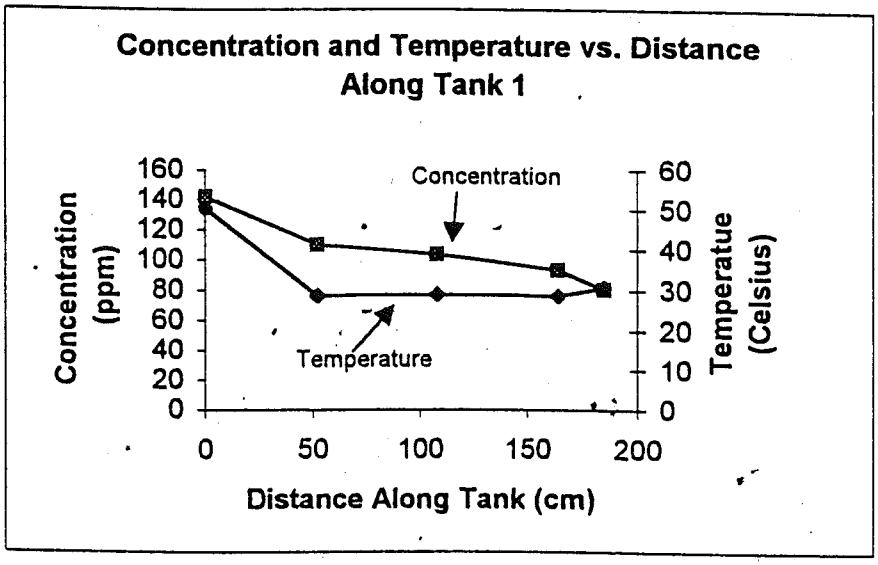


Figure 9. Concentration and temperature along tank 1.

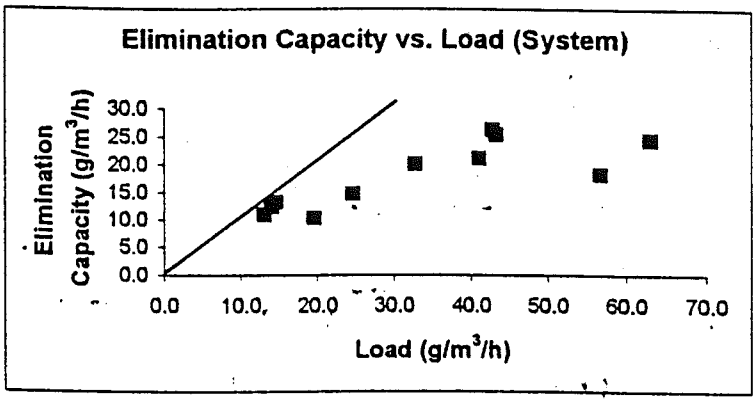
Results show that the predominant amount of degradation in tank 1 occurs near the inlet of the tank, with moderate degradation occurring along the remainder of the filter bed. At the inlet, tremendous biomass may have accrued because this is where the load was the largest. Experiments were also conducted to study if the samples obtained along the length of the reactor were representative across the bed radially (not shown). Such experiments demonstrated no observable differences between air samples obtained along the wall of the bed and up to 40 cm radially into the bed.

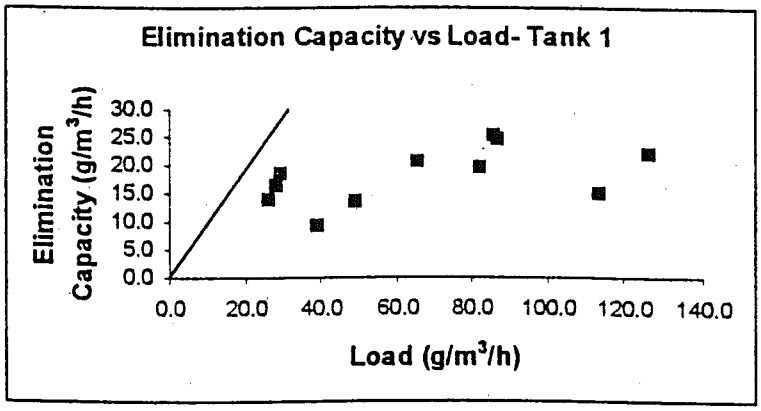
13. Sampling System Malfunction

Over a week's period, the sampling system malfunctioned because water and sludge entered the sampling lines and sampling pump. Backpressure caused by biofouling of the knock-out pod at the end of the system caused the water and sludge to contaminate the sampling system. This disturbance to the sampling pump prevented accurate data from being collected.

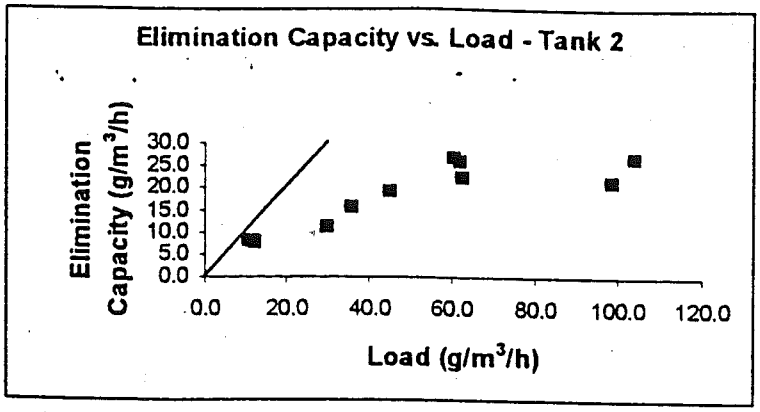
14. Load Modification Experiment

The empty bed residence time per tank was 45 seconds. An experiment was set up so that larger retention times could be tested at similar loading rates (by increasing the concentration), with the hope that possibly better removal could be demonstrated. The flowrate (as well as the load) was halved to 179 m^3/h. After a few days, the load was brought back to the original value by doubling the inlet concentration artificially. The experimental conditions were modified to then double the flow and halve the concentration. Finally, the flow and concentration were both doubled to double the load on the system to 56 g/ m^3 h. As the concentrations and airflow rates were frequently modified over a seven-day period, difficulties were encountered in establishing steady-state conditions. Results should be viewed with caution (Figures 10,11,12).





Figures 10 and 11. Elimination capacity vs. load for tank 2. Straight line represents 100 % removal.



Figures 12. Elimination capacity, vs. load for tank 2. Straight line represents 100 % removal.

From the previous figures, it can be seen that at the lower loading rates (less than 15 $g/m^3/h$), the removal efficiency is fairly high for all tanks (>80%). These low loading rates were established by halving the flow and keeping the concentration constant. In other words, the best removal efficiencies were seen when the residence times were lengthened. This was to be expected. However, at higher loading rates, removal efficiency severely dropped off and the maximum elimination capacity occurred at about 25-30 $g/m^3/h$ for the overall system, tank 1 and tank 2. These values are considerably lower than the 65 $g/m^3/h$ seen for biofilters treating styrene (Cox et al., 1995). Higher elimination capacities (up to 70 $g/m^3/h$) were seen earlier in the experimental operation (3/31-4/14) by simply increasing the concentration in the system. For this reason, the results from the load modification experiments should be viewed with caution and may not be representative of the maximum ability of the system. The lower elimination seen during these experiments may be a function of the rapidly changing conditions imposed on the system during the seven day experiment. More time between modifications in the experiment may have enhanced the performance level. When the system was allowed to operate at higher loading rates after this experiment was completed, elimination capacities as large as 50 $g/m^3/h$ were seen. Such an experiment accents the need to allow suitable time between reactor condition modifications.

15. Specific Oxygen Uptake Rate Experiments/Species Identification

Based on the poorer elimination capacities experimentally determined in the load modification studies, it was postulated that a biological limitation may be occurring in the reactor system. For this reason, both suspended and fixed biofilm samples were studied at the UCR laboratory. These studies included developing the Michaelis-Menton constants for both sample types, as well as speciating the microbes which are responsible for the degradation of the styrene in both the suspended and immobilized phases.

Michaelis and Menton formulated a rate equation for enzyme-substrate reactions:

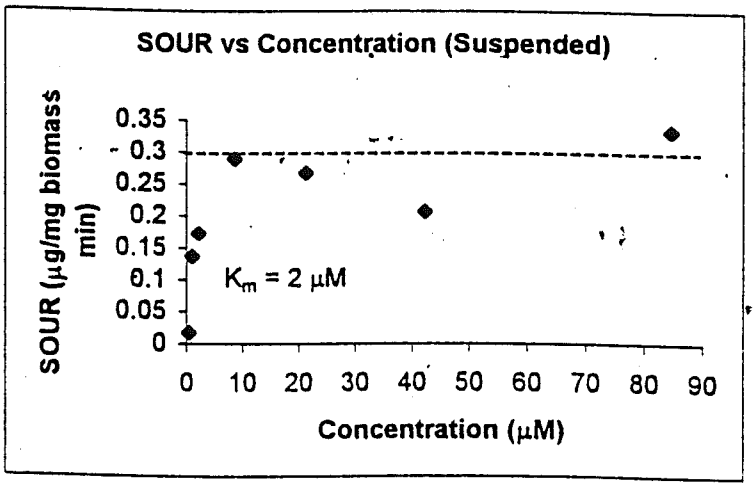
$$v = v_m S / (K_m + S) \qquad (5)$$

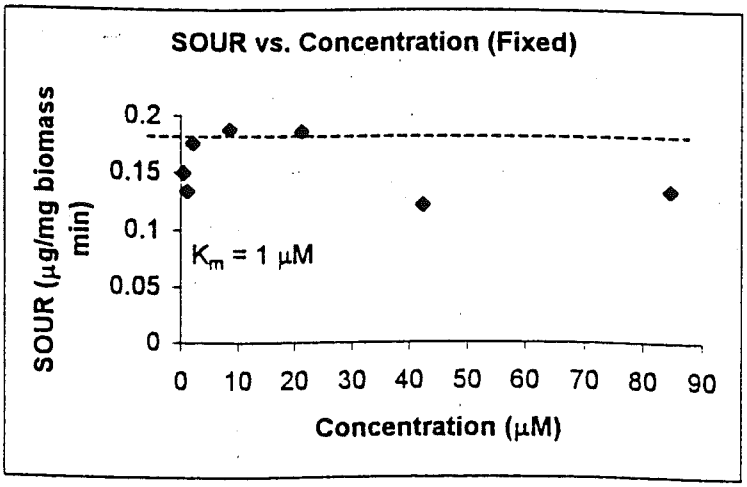
Where

v	=	enzyme reaction rate constant, $time^{-1}$
v_m	=	maximum enzyme rate constant, $time^{-1}$
S	=	concentration of substrate in solution, mg/L
K_m	=	half saturation constant, mg/L

Two extreme cases are of interest in the application of equation 4 to biotrickling filters. In the case where the concentration of the limiting substrate is in excess, or $S >> K_m$, then the enzyme reaction rate constant v is roughly equal to v_m. The Michaelis-Menton equation becomes zero-order and is independent of substrate concentration. In the opposite case, where the system is substrate limited, or $S << K_m$, the enzyme reaction rate becomes first-order. By establishing the value of K_m of both the suspended and fixed biofilms, knowledge will be gained on the substrate uptake order. In knowing this order, reasonable assumptions may be made as to why there is a limitation in substrate uptake in the reactor.

The specific oxygen uptake rates were determined for both sample types by adding known quantities of styrene in liquid form to a cell suspension of suspended or fixed biomass. Using an oxygen probe, depletions in oxygen were measured as the substrate was consumed and the amount of oxygen consumed per mass of biomass per time could be calculated. In plotting these values against the liquid concentrations, the half-saturation constants could be determined (Figures 13 and 14).





Figures 13 and 14. Specific Oxygen Uptake Rates for suspended and fixed biomass.

Results from both graphs show small K_m values (2 and 1 μM for suspended and fixed biomass, respectively), indicating that the substrate uptake rates are zero order (independent of concentration). A low K_m value is good because it indicates that the substrate uptake rate will be close to v_m, down to low concentrations. Though it is difficult to extrapolate these results directly to what is occurring in the reactor, it can be postulated that the maximum elimination capacity may be correlated to the maximum substrate uptake rates. What this essentially means is that the microbes in the system may not be able to remove more styrene simply because they do not have sufficient styrene oxidizing enzymes or the enzyme turnover is too low. The microbes in the reactor may not be the best microbes to remove styrene, so they do not perform as well as other microbes seen in other experiments (Cox et al., 1997). If this were the case, then establishing the identity of these microbes would assist future researchers in avoiding the low eliminations seen in this experiment.

The suspended and fixed biomass was cultured on styrene in the laboratory and inoculated on Biolog Identification Plates. Specific results of these enrichment cultures are still being identified, but gram-negative bacilli and cocci appear to dominate the microbial consortium.

16. High Styrene Load Experiments and Nutrient Load Increase

High styrene load experiments were conducted to determine a maximum elimination capacity obtainable in the system. Essentially, the inlet concentration was increased artificially to give a system load of 95 $g/m^3/h$. Based on this high load, results for the maximum elimination capacity of the system were 32 $g/m^3/h$. This value compares well to the modified load experimental results but not with previous maximum elimination capacity results. Difficulty exists in explaining such a phenomena, but a likely answer may be because of system upset and frequent shut-down. This experiment was conducted during a period when system malfunctions constantly occurred, often stopping the system completely. For a day, or possibly two, the system would have no air passing through it and anaerobic conditions would persist. After system restart, contaminant removal performance appears to have been affected.

During the high styrene load experiment, increases in nutrient loads were also performed. The nutrient load was increased to 1.3/2.2/1.4 lbs/day. No increase in system performance was seen.

System Problems in an Industrial Setting

Many system problems dealing with the proper operation of the reactor were encountered. One potential problem was the fluctuating styrene load that occurred over

Lasco's workweek. Lasco operation hours were Monday through Friday, 24 hours a day. They stop manufacturing on Saturday and Sunday, and thus the microorganisms have to rely on other carbon sources besides styrene. In cases like this, microorganisms will resort to predation and endogenous respiration. On the Mondays before the artificial styrene load was increased (timeline item 5), the elimination capacity and the removal efficiency of the system were poor as the styrene degrading microorganisms rebounded from the starvation occurring over the weekends. Generally, at least a day would be required to bring removal performance back to previously seen levels the week before. After the styrene load was increased, the biomass was sufficient to reduce the performance effects brought about by the short periods without styrene. In this case, only a few hours were needed for effective system rebound.

There were also problems with the equipment on the reactor. Due to faulting wiring, one of the pump's relay switches did not shut off during a power surge. The relay switch and the pump had to be replaced as a result, but not before the system was wired correctly. Alga growth occurred on all clear plastic tubing, flowmeters, and the water level indicators. Black plastic was wrapped around these pieces of equipment to inhibit photosynthesis. Despite this, the level indicators had significant functioning problems. The float within the indicator stuck to the rails that guide it due to biomass growth. The level indicator is the measuring device for the controller of the water inlet and outlet solenoids. As a result of this sticking, the controller did not know the water level was low and water was not added to the system. Several reactor shut downs took place because the reservoir of water at the bottom of the column dropped to the point where air was being drawn into the water pump. Periodic cleaning had to be performed or the float would not fall as the water level fell. The level indicator currently being used was not suited for a biotrickling filter with such a turbid, organic liquid. A capacitance level switch would be better if the floating switch were to be replaced. The nutrient supply system also had problems. The nutrients form precipitates at the injection port, causing clogging conditions. Cleaning of the injection port of the nutrient system had to be performed weekly to prevent these clogs from forming.

Conclusions and Possible Application to Lasco Bathware

This study provided some preliminary information about the application of a biotrickling filter reactor at an industrial site such as Lasco Bathware. Because of the capacity limitations of the blower, higher loading rates provided by larger flows could not be experimentally tested. It would be in this regime that a more effective assessment of the technology could be made for the Lasco plant. However, based on the loads that were obtained through the experiments, the size of a reactor to treat 50% of the off-gases would be:

Assuming,

Flow= 51000 m^3/h (30000 scfm)
Inlet Concentration = 0.6 g/m^3 (150 ppmv)
Average Elimination Capacity = 40 $g/m^3/h$
Pollutant Removal Efficiency = 60 %

$$Load = (51000\ m^3/h) \times (0.6\ g/m^3) = 30600\ g/hr$$

$$Volume = (30600\ g/hr)/(40\ g/m^3/h) = 765\ m^3$$

If the diameter of the tank was 7 meters, four tanks in parallel of 5 meters high would be required. This is a fairly large system and most likely would not be cost effective. It is also based on the maximum amount of pollutant removal and not based on removal efficiency. If high removal efficiency were needed, then the system would need to be much larger. Overall, this simple calculation points out the need for more studies on this technology to effectively enhance the degradation performance of the biotrickling filter reactor.

Numerous steps were taken to experimentally determine the causes of the low elimination capacity seen in this particular biotrickling filter reactor. Originally, simple parameters such as temperature and nutrients were modified, believing that there was some sort of inhibition or limitation occurring. During the first 60 days of operation, the biomass was not increasing as rapidly as expected. During this period, the amount of nutrients supplied to the system was increased to ensure the microorganisms were not being deprived of the essential non-carbon compounds needed to survive. This had no effect on the biomass increase or the elimination capacity.

To increase the biomass, and thus the biofilm thickness on the packing material, the styrene load was doubled by means of artificial styrene addition. The amount of biomass increased five times over a period of three weeks. From this observation, it is obvious that the nutrients are not limiting in the system. After the artificial styrene load was halted, the biomass increase once again became very gradual. The elimination capacity increased slightly, yet performance was still insufficient.

The investigation then turned to assessing if an engineering problem may be a factor. Tracer test studies, water recirculation rate tests, and load modification experiments were conducted. To determine if the filter bed was being used effectively a tracer test was performed. The results of the test showed that approximately 10% of the filter bed was not being used, due possibly from channeling. However, the performance of the reactor would not improve dramatically if this 10% were recovered. A flow rate experiment was performed to determine how the wettability of the biofilm effected the elimination capacity. As expected, at higher flow rates, the wettability of the biofilm increased and subsequently the elimination capacity slightly increased. However, the water recirculation rate was not the primary reason why the performance of the system was low. Though some insight was gained into the system performance, little improvement resulted.

Finally, tests to determine the robustness of the biology of the system were performed. Evidence of a slow growing microbial consortium with low styrene uptake rates was determined. Hence, it is believed that this particular system was encumbered by a slow growing styrene degrading organism that could not degrade the styrene easily. It is not known if another strategy to stimulate the species or if a different inoculation of another microbial population would have significantly improved removal performance. Future tests on such a concept are warranted.

Because the reactor is a prototype system and Lasco was the first test site, system malfunctions frequently interrupted reactor operation. Presumably, if these system malfunctions could have been eliminated, the continuous operation of the reactor would only have enhanced the reactor performance by providing a constant load to the system and preventing short times where anaerobic conditions were allowed to exist.

Acknowledgments

Major funding for this project was provided in by the University of California Toxics Substance Research and Teaching Program. Additional support came through Lasco Bathware, Inc. and the South Coast Air Quality Management District (SCAQMD). Special thanks to Isidro Pe and Pete Dennis for their assistance in implementing the project at the Lasco site. Additional thanks to Larry Walkins and Mohan Balagopalan of the SCAQMD for their assistance in permitting the reactor.

References

1. Cox, H.H.J., Moerman, R.E., van Baalen, S., van Heiningen, W.N.M., Doddema, H.J., and Harder, W., Performance of a Styrene-Degrading Biofilter Containing the Yeast *Exophiala jeanselmei*, Biotechnology and Bioengineering, 53(3). 259-266.

Resolving Operational and Performance Problems Encountered in the Use of a Pilot/Full-Scale Biotrickling Filter Reactor

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A pilot/full-scale biotrickling filter reactor experiment was performed at an industrial site to treat styrene laden waste gas. The engineered system consisted of two stainless steel tanks in series, each with filter bed volumes of 4.0 m^3, filled with 3.5-inch plastic spheres. The system treated 340 $m^3\ h^{-1}$ of air laden with styrene concentrations ranging up to 0.8 g m^{-3}. Over the five-month study, styrene elimination was demonstrated up to 24 g $m^{-3}\ h^{-1}$ (35 g $m^{-3}\ h^{-1}$ across the first tank in series) with 70 to 85% removal. Operational and performance problems were identified that differ from those developed under controlled, laboratory set-ups. Operational problems typically involved equipment malfunctions, with the most prone to failure pieces of equipment being the air sampling system and water level sensors. Performance problems were identified that possibly limited the styrene removal. The transient operation of the plant, producing discontinuous, unsteady-state concentrations, made it difficult to establish a stable biofilm on the packing material. Experiments were performed indicating both biological and mass transfer limitations may have occurred.

INTRODUCTION

The treatment of industrial air phase contaminants has predominantly been performed through the use of incineration and/or carbon adsorption. Incineration is effective for concentrated waste streams that require a minimal fuel source. However, this technology becomes increasingly expensive when treating dilute waste streams, requiring the addition of supplemental fuel. Incineration also generates secondary pollutants such as nitrogen oxides. Carbon adsorption is effective for both dilute and concentrated waste air streams, but the technology simply transfers the contaminant from the air phase to the solid phase. This solid phase is a hazardous waste and must be treated as such. Alternative technologies that have recently gained more interest in the United States are the use of biofiltration and biological trickling filtration [4, 6, 13]. With biological trickling filtration technology, a stream of contaminated air and water is passed through an inert filter bed on which a consortium of microorganisms lives. As the air passes through the bed, aerobic oxidation of the contaminant is performed and carbon dioxide, water, and additional biomass are produced. In comparison to a biofilter, a primary advantage of the biotrickling filter is the better system control of environmental conditions affecting removal performance (e.g., pH, nutrients, salts, etc.).

The treatment of air phase contaminants with the use of a biological trickling filtration reactor is relatively new in the United States. Hence, a paucity of knowledge is available detailing problems associated with the technology operating in an industrial setting. Recent papers have explored nutritional limitations and bioclogging problems associated with biotrickling filters [8, 10, 11, 12]. However, these studies have been performed in laboratory or controlled environments. This article describes some of the necessary problem solving and "trouble-shooting" required in the operation of a pilot- or full-scale biotrickling filter reactor at an industrial facility. Two types of problems are detailed in length: operational and performance problems. Operational problems involve those instances where system operation is impeded or halted. This type of problem is a function of system equipment malfunctions, operator error, and site-specific malfunctions. Performance problems are those that lead to inadequate system contaminant removal. Performance may be affected by nutrient limitations, temperature fluctuations, transient operating conditions, channeling of air, microbiological limitations, as well as a result of operational problems. Both prob-

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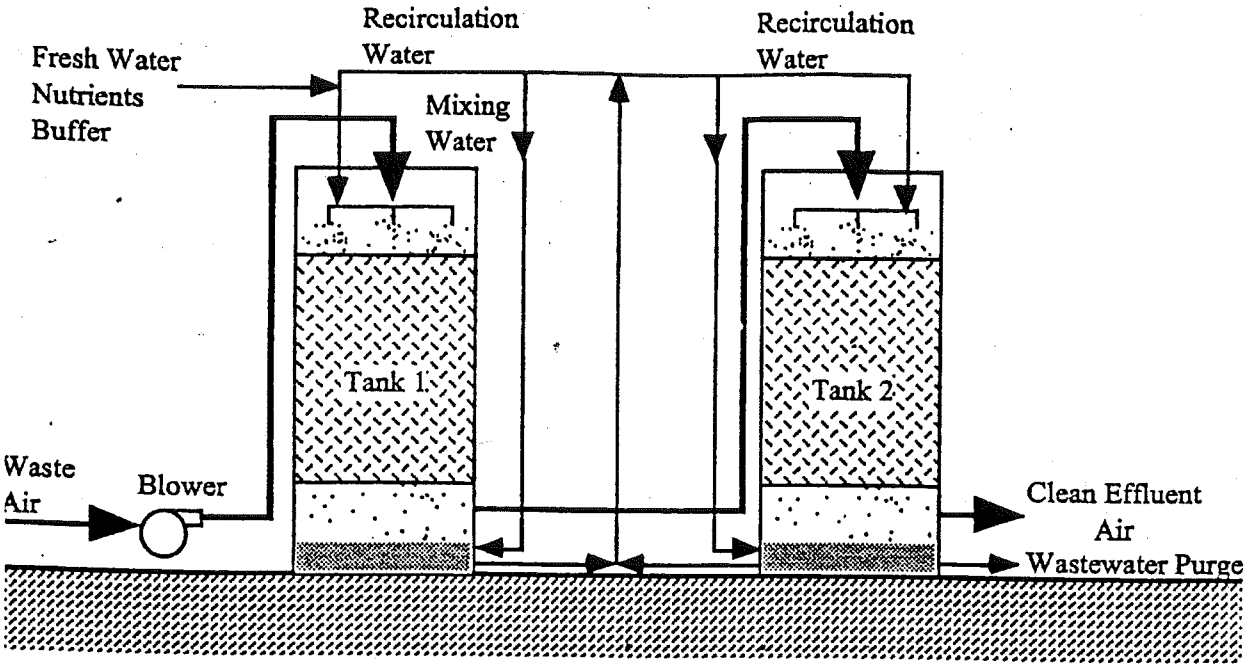

FIGURE 1. Schematic of the biotrickling filter system. For this cocurrent system, air is passed through the two tanks in series and water is applied in parallel.

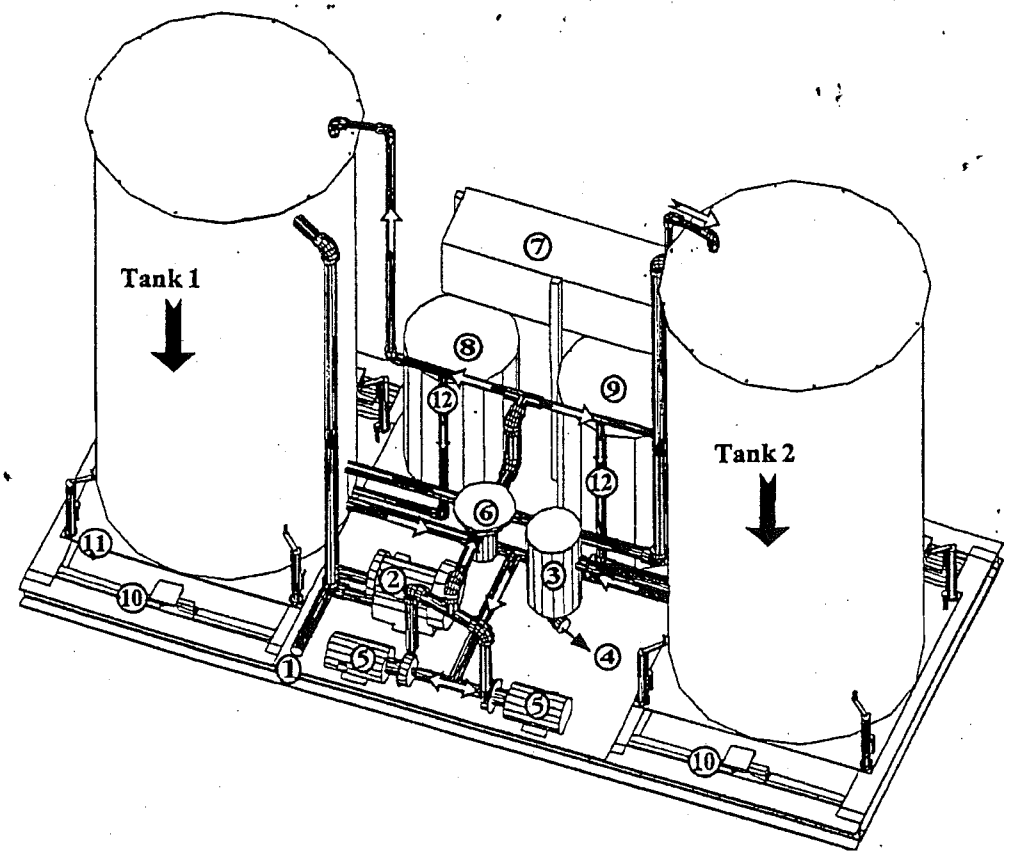

FIGURE 2. Design drawing of the pilot-scale biotrickling filter reactor. Open arrows: water flow; filled arrows: air flow. (1) contaminated inlet air; (2) blower; (3) knock-out pod; (4) purified outlet air; (5) water pumps; (6) strainer basket; (7) computer control box; (8) nutrient tank; (9) caustic tank; (10) sliding load cells (outside position); (11) jacks; (12) water return to tank bottoms (for mixing).

lem types are explained and resolutions noted where improvements might or have been implemented.

Process Description

In an air phase biological trickling filter reactor, waste gas contaminants are absorbed in a flowing liquid phase and biodegraded by suspended and immobilized microorganisms (Figure 1). Depending on the specific operation, the reactor operates with either co- or countercurrent movement of the air and water phases. The flowing water phase benefits the biotrickling filter by providing a continuous supply of nutrients, removing possible degradation by-products, suspending biomass for continual reseeding of the system, and aiding in the diffusion of hydrophilic pollutants into the biofilm. As the water is recirculated over the packing material, an operator or computer may add nutrients, acids, or bases to aid in regulating the environment for optimal contaminant removal. It is essential for the system to host a thriving microbial population while avoiding clogging conditions.

Removal of the contaminant in the reactor occurs by microbial catabolic reactions within the fixed biofilm, and to some smaller degree, in the liquid phase by the suspended microbial consortium. Contaminants enter in the gas phase and are absorbed into the biofilm attached to the inorganic packing material. The microbes convert the contaminant, along with oxygen, to carbon dioxide, water, and additional biomass. Because some contaminants are more recalcitrant, complete oxidation may not occur and intermediates may form. These intermediates may pass through the remainder of the system untreated. Additionally, some compounds can form end products that are harmful to the sustainability of the microbes. For instance, during the degradation of some chlorinated or reduced sulfur compounds, acidic metabolites may form and cause the pH of the recirculating water to rapidly decline. This rapid decline will inhibit the performance of the microbes if not properly resolved. Biotrickling filtration is an effective technology for those contaminants that are considered biodegradable. For those contaminants which can not be completely oxidized or resist any degradation whatsoever, further physico-chemical treatment may be required.

EXPERIMENTATION AND METHODS

Site Description

The test site was located at a fiberglass bathtub manufacturing facility (LASCO Bathware, Anaheim, CA). The pilot-scale biotrickling filter was operated for five-months. Styrene vapors were emitted from the plant during the manufacturing process through a stack at a flowrate of 51,000 $m^3\ h^{-1}$ and at concentrations up to 0.8 $g\ m^{-3}$. The waste gas was emitted at a temperature of 25°C and did not contain other contaminants. All particulates were removed prior to entering the stack by a filter screen. The plant generally operated continuously Monday morning through Saturday morning. It was shutdown over the weekend.

Reactor Design

The pilot-scale reactor design was based on three successful years of operation of a bench-scale biotrickling filter at the Swiss Federal Institute of Technology [14]. The prototype system, designed and constructed by the University of California at Riverside and Environmental Biosystems (Sandwich, MA), included two side-by-side tanks constructed of 304 stainless steel, each with an internal diameter of 1.6 m and height of 3.4 m (Figures 1 and 2). Each tank had filter bed height of 2.0 m, consisting of Jaeger Tri-Pack® (Houston, TX) spheres with a diameter of 8.9 cm and a specific surface area and void space of 125 $m^2\ m^{-3}$ and 95%, respectively. The bed volume per tank was 4.0 m^3.

Standard Operation

The biotrickling filter reactor was set up to withdraw a side stream (340 $m^3\ h^{-1}$) of styrene-contaminated air from one of the facility stacks for treatment, giving an empty bed retention time of 43 seconds per tank. The flow remained constant throughout the experimental study. The reactor system utilized one blower (pressure), two water pumps, and two water heaters to deliver air, water, and heat, respectively. The blower supplied the waste gas through stainless steel piping (3 inches in diameter) to the tops of the two tanks in series.

The pumps sprayed water in parallel to the two tanks through Schedule 40 and 80 PVC piping (diameters of 1 to 3 inches) at flowrates up to 400 liters per minute each. A portion (114 liters per minute) of the total recirculating water was directed to the base of each tank to provide adequate mixing of the tank bottom. A volume of 0.8 m^3 of water was maintained in the base of each tank. This served as a water reservoir to control pH and other water parameters. A water level observation tube was connected with vinyl tubing to two separate locations outside each reactor tank. One of the connections was to the base of the tank (below the water line), while the other was connected above the water line. Float level sensors inside the tube detected changes in the tank water level. The reactor also contained a water strainer basket to remove large particulates from the recirculated water and a knockout pod to remove air phase particulates and water from the effluent air.

The nutrient and caustic were stored in 757 liter tanks and supplied periodically through 1.3 cm ports on the pressure side of the water piping. Using two diaphragm nutrient feed pumps, a GrowMore hydroponic premixed fertilizer (Gardena, CA) containing 12/9/11 mass percentage of N/P/K and the trace elements iron, magnesium, calcium, zinc, copper, manganese, and sulfur, was added to the recirculation water at a feed concentration of 0.7/0.5/0.6 $g\ l^{-1}$ of N/P/K. Two diaphragm feed pumps metered a caustic solution of 5% NaOH into the recirculation water to maintain the pH between 6 and 8.

A programmable logic controller (PLC) unit, programmed using Labview Software (National Instruments, Austin, TX), was implemented to monitor and control important parameters such as inlet and outlet concentrations, air and water flowrate, nutrient and caustic addi-

TABLE 1. Biotrickling Filter Operational and Performance Parameters Measured Using a Programmable Logic Controller Computer With Feedback Control Capabilities.

Parameter to Be Measured	Type of Instrument	Notes
Air Flowrate	Orifice Plate (Differential Pressure)	Differential pressure used to calculate flowrates. Located downstream of blower before tank 1.
Air Phase Concentration	Flame Ionization and Direct Electrolytic Conductivity Detectors (FID/DELCD Detectors)	Air measured at inlet, between, and outlet of two tanks. Also, set up to measure concentration along the length of each tank.
Air Pressure	Pressure Gauges (Electronic)	Measured across both tanks, the blower, and the entire system.
Air Temperature	Thermocouples	Air measured at inlet, between, and outlet of two tanks. Also, set up to measure temperature along the length of each tank.
Tank Weights	Load Cells	Three load cells per tank.
Water Conductivity	Conductivity Probe	Measured after water pumps.
Water Flowrate	Paddlewheel Flow Sensors	Measured at the inlet of both tanks.
Water Level Indicators	Water Float Sensors	Measured outside of each tank in a water level observation acrylic tube.
Water pH	pH Probes	Measured directly in each tank.
Water Pressure	Pressure Gauge (Electronic and Analog)	Measured in-line on pressure side of pumps.
Water Temperature	Thermocouples	Measured at the outlet of both tanks.

tion, water addition and removal, pressure drop, temperature, pH, and conductivity. The PLC used feedback control logic to maintain the operating parameters of the reactor to within specified input limits. Specific methods used to measure many of the parameters are listed in Table 1.

The system was inoculated with a concentrated mixed culture of microbes extracted from a dissolved air flotation unit from a publicly owned treatment works. This culture was added to the recirculating water along with a nutrient solution to promote growth. The reactor recycle liquid was initially operated in a batch mode of operation for two weeks to promote bacterial attachment to the packing. Contaminated styrene vapors from the stack were supplied to the system at an average mass load of 26 g m^{-3} h^{-1} (during initial month of operation the average load was 20 g m^{-3} h^{-1}). During the batch mode of operation, the system performance was monitored. Continuous, improving performance indicated sufficient biological activity and provided evidence to operate the recycle liquid in a continuous mode. The continuous mode of operation involved the hourly removal of 10 liters of recirculation water and the replacement with 10 liters of a fresh nutrient solution.

The focus of the experiment was to optimize pollutant removal while assessing various operational and performance problems under an industrial setting. Over a five-month period, operational problems that created system malfunctions were noted and solutions were engineered. The effects of environmental reactor conditions, transient operating conditions, air channeling problems, and microbiological limitations were assessed to improve reactor performance.

RESULTS AND DISCUSSION

Resolving Operational Problems

In general, problems of a newly operating biotrickling filter can be numerous. These operating problems cause or lead to component malfunction or complete system shutdown. System shutdown is detrimental to performance and can have grave economic impacts at the full-scale level. Hence, assessment of the problems that cause system shutdown is warranted. The most common operational problems observed during the experiment and their frequency have been classified under system component malfunctions and industrial site upsets (Tables 2 and 3).

System Component Malfunctions

System component malfunctions occurred numerous times during the progression of the experiment. Though some problems were attributable to design or construction constraints, others were simply maintenance problems that every large system is bound to have. Of the system component malfunctions, three notable problems that were not foreseeable in the

TABLE 2. System Component Malfunctions, Their Effect on the System, and Resolution of the Problems (Over a Period of Five Months).

Component Malfunction	Frequency	General Problem	Result/Effect On System	Resolution
Water Level Indicators	6	Mechanical float level indicators often were impeded by biomass build up on the float.	Created a situation where PLC system failed to recognize the water level declining. Eventually (approximately 2 days), the water level in the reactor declined below the tank water outlet, causing air to be pumped in the line and the system to shut down.	Level indicators were frequently cleaned. Surface contact area for the float was reduced. Suggest capacitance based level indicators for better effective control of turbid water levels.
Sampling System (FID Flame Out)	6	As a result of large backpressure generated by the knockout pod, water and biomass became entrained in sampling lines and entered the sampling system and FID.	Caused sampling system failure (constant FID flameouts) and prevented reliable concentration data acquisition for over two weeks.	Sampling pump diaphragms were cleaned and lines manually cleared. Sampling pump operated at less capacity compared to prior operation. Diaphragms needed replacement. Lines should be visually inspected for water on a daily to weekly basis.
Nutrient Pumps	5	Pumps failed to prime when air was in line. Nutrients would precipitate and clog inlet port to reactor.	The system failed to receive nutrients for short periods of time (1-2 days).	Ports were manually cleaned and nutrient solution was adequately mixed to enhance solubility. Ports and lines should be checked on a weekly basis.
Unknown System Problems	5	Unknown problems caused low water pressure alarms to be set off. May have been facility electrical problem.	System shut down.	System restarted.
Water Level Observation Tube-Air Inlet Line Clogged	3	A water level observation tube is connected by two lines to the side of each tank. The differential presure between the line at the bottom (filled with water) and top (filled with air) physically moves the water level. Water from the tank would get into the air line. Biomass accumulated and eventually clogged the line (in 2-3 days).	When the upper air line became clogged, a huge differential pressure developed in the observation tube. This caused the water level to quickly rise and give a false reading of a high water level situation to the PLC. The PLC shut the system down.	A long tube was attached to the air line and inserted downward into the sidewall of the tank. Water (or biomass) trickling down the inside of each tank could not enter the tube that was also pointed downward.
Knockout Pod	3	Pod would collect water and biomass slowly grew on filter over time. Backpressure in the system increased to maximum levels.	System shut down because of large pressure differentials.	Knockout pod should be checked and cleaned on a weekly basis. Filter will need replacement every four to five months.
Air flowrate miscalculated by PLC	1	A pressure line used to measure differential pressure across an orifice plate broke.	The air flowrate was erroneously calculated to be much lower than the actual flowrate. The PLC acknowledged this low flowrate phenomenon to be a mechanical failure in the system and correctly shut the system down (3 days).	The pressure line was replaced and the air flowrate was once again calculated correctly by the PLC.
Water Pump/Relay	1	Faulty electrical wiring hook-up caused a short with the water pump relay, causing an electrical overload on the water pump.	System shut down.	The second pump was used alone, temporarily. Defective pump was removed and repaired. Wiring was replaced.
Piping Cracked	1	Schedule 40 PVC inlet water line cracked.	Water was discharged for a small period of time on reactor, but had no effect on operation of reactor.	Part replaced and no further piping problems observed.

TABLE 3. Industrial Site Specific Upsets, Their Effect on the System, and the Resolution of the Problems (Over a Period of Five Months).

Site Upsets	Frequency	General Problem	Result/Effect On System	Resolution
Resin Development in Line	3	Unknown source of resin somehow entered air inlet line to blower.	No effect. Resin did not appear to reach blower but could be a problem if not detected	Remove resin from line before it enters the blower. Check for resin development once a week.
Electrical Malfunction	2	Power outages and site-employee mistakes caused electrical system to be disconnected.	System shutdown	System restarted and signs added to electrical lines to warn employees against disconnecting electrical lines.
Water Addition Malfunction	1	Site employees mistakenly disconnected water line to reactor.	System failed to get fresh replacement water for lost evaporative water. Eventually (approximately 2 days), the water level in the reactor declined below the tank water outlet, causing air to be pumped in the line and the system to shut down.	Water turned back on.

design phase of the system occurred during operation. The first operational problem was that the water level float sensors, used to indicate the level of the water in the biotrickling filter reactors, consistently failed because of suspended biomass. The suspended biomass caused the floats to stick to the observation tube wall. The floats required regular cleaning, but the procedure was time consuming. Capacitance based level sensors could potentially be a better choice, since they eliminate the need for a float.

Another component malfunction developed with the system knockout pod located at the end of the treatment train. The purpose of this pod was to collect and return water that exited the reactor vessel in the effluent air, as well as to filter any particulates that may have been emitted in the process. Little to no particulates were observed on the filter, but humidified air created a suitable environment on the knockout pod filter for microbial growth. This growth caused large pressure drops (increased 25 to 50% compared with the clean pod pressure drop) over the entire reactor system, eventually shutting the system down. From the detection of this problem, it is advisable to clean the filter once a week and replace it every three to four months. Even so, knockout pods present large pressure drops (can increase system pressure drop 25% for a clean pod) and depending on the reactor setup, their use may not be required or other systems (demisters) may be better suited.

The gas sampling system with the FID had numerous problems near the end of the experiment (Day 120). The system was designed so that if small amounts of water condensed in the sampling lines, the gas-sampling pump would remove this condensation by backflushing the sampling lines every fifteen minutes. Such a procedure was regulated through the PLC computer and was effective. However, a rare case occurred where some large backpressures were caused in the air distribution lines by the clogged knockout pod. These large backpressures forced sludge and water into the gas sampling lines and through the gas sampling system. The operator cleaned the sampling system, but the gas-sampling pump was damaged and the capacity was significantly reduced. This reduction in capacity limited its backflushing capacity as well, allowing condensation to enter the FID, causing repeated flameouts. The diaphragm in the pump required replacement. A sampling system that can draw sample gas into the FID and then backflush the line is very effective if not hindered by other problems. If the reactor is in cold climates, using heated sampling lines may also be used to prevent condensation. For a more effective condensation prevention system, incorporation of both heated lines and backflushing is advisable. In order to prevent significant operational problems from occurring, sampling lines should be checked regularly (once a week) for water condensation and biomass build-up.

Numerous system components, whether water, air, or sampling, demonstrated some problems during the five month study. As is the case with most prototype

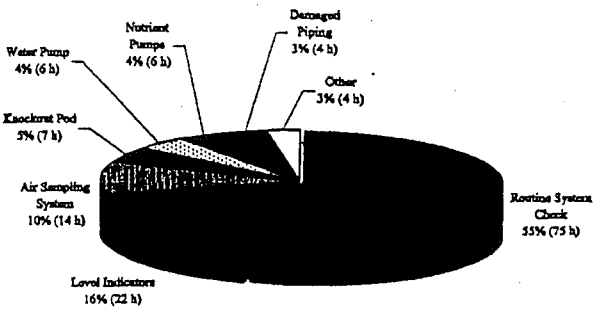

FIGURE 3. The distribution of time (% and hours) required for routine system checks and maintenance on different malfunctioning systems over a five-month operating period. Total hours = 138 h.

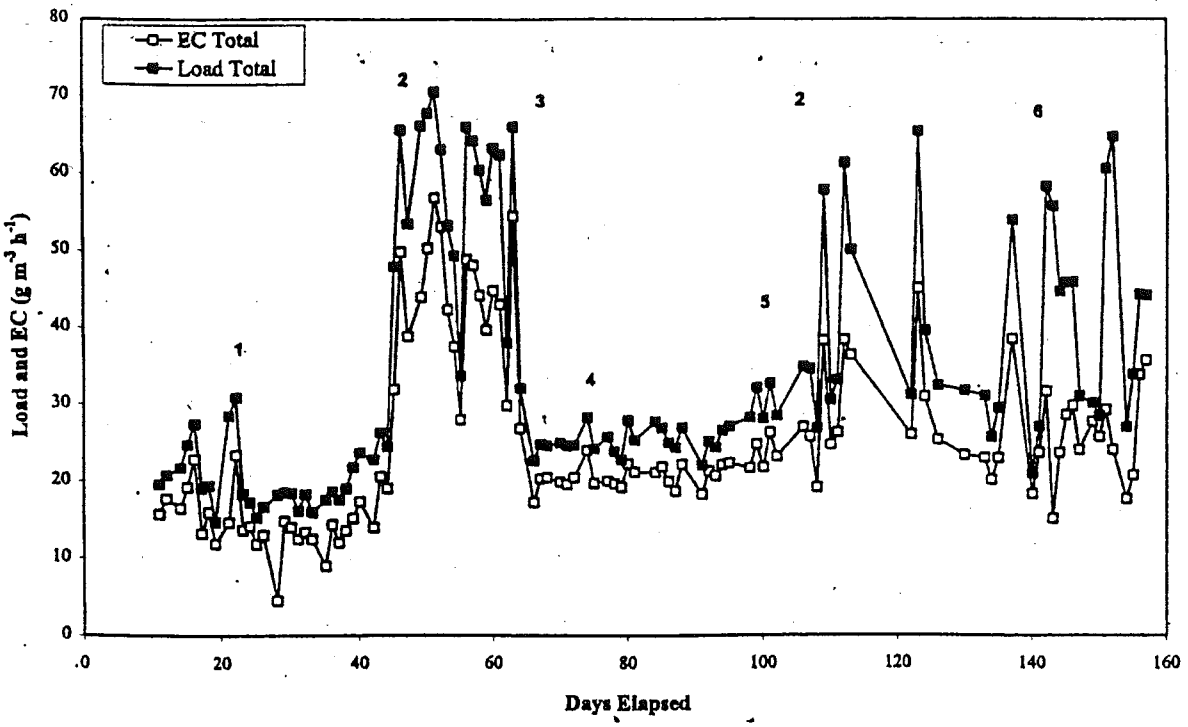

FIGURE 4. Total load and elimination capacity for biotrickling filtration system. System experiments occurred: (1) nutrient concentration in water doubled; (2) styrene load artificially increased; (3) artificial styrene load decreased; (4) heating element turned off; (5) tracer test performed; (6) microbiological substrate uptake rate study performed.

a large percentage of operator time involved routine system checks and resolving system component operating problems. In general, the system required 75 hrs (6.9 h per week) of operator attention. Of this time, 55% was dedicated to routine checks and 45% to resolving component malfunctions and operating problems (Figure 3). Typically, no one component was the sole reason for every system upset. Instead, a combination of component problems and malfunctions lead to other component problems. Such findings demonstrate the need for the implementation of an effective maintenance program with weekly equipment checks [6]. Items requiring weekly checks include the air sampling system (including all waste gas delivery lines), nutrient delivery system, caustic delivery system, and knockout pod filter. Monthly checks may include inspection of the conductivity probes, pressure gauges, pH probes, and flowmeters for proper calibration and operation.

Industrial Site Specific Upsets

System upsets can also be caused by specific problems associated with a particular site. In general, upsets that occurred at the bathtub manufacturing facility were unavoidable and caused by plant personnel with little knowledge about the operation of the biotrickling filter reactor. Such problems included personnel unknowingly disconnecting the power and water supplies, as well as unexpected power surges or outages from the main plant power. Such problems are difficult to alleviate at a plant where activity is high near the reactor. Appropriate signs, warnings, and barricades (fences) may be set up near or around the reactor to prevent such problems. However, space is often limited and such preventive measures may affect plant operation.

Additional problems may be generated at an industrial plant which are specific to its operation. The generation of dusts and particulates from the plant may slowly affect the system components. Though this prototype reactor was operated for a fairly short period of time, some corrosion and wearing of the system components was evident. In general, the environment where the reactor will be placed is of great importance. The system should be in an area highly accessible to water and electricity, but not such to be a nuisance to plant personnel. Care should also be noted about the surroundings of the plant. Rodents, snakes, lizards, and spiders thrive in damp areas; they had a tendency to converge under or near the biotrickling filter reactor in this study. Such conditions may seem obvious, but are noteworthy because of their great importance to the safety of the system and operator alike.

Resolving Performance Problems

After the initial start-up phase, when continuous operation began, early system performance demonstrated sustained elimination capacities of 15 g m^{-3} h^{-1} with 70% overall removal efficiency (50% removal efficiency and 20 g m^{-3} h^{-1} across the first tank in series). After a more stable biomass was established on the

packing material by artificially increasing the styrene load to the system (discussed below), elimination capacity increased to sustained levels of 24 g m^{-3} h^{-1} (35 g m^{-3} h^{-1} across the first tank in series) with 70 to 85% overall removal (Figure 4).

For biofilter technology, numerous research studies have been performed on the treatment of styrene. Sabo et al. (1993) and Arnold et al. (1997) demonstrated sustainable styrene elimination capacities of approximately 12 g m^{-3} h^{-1}. Hartmans et al. (1990) reported styrene elimination rates of 50 g m^{-3} h^{-1} but could only maintain 100% conversion at a maximum load of 15 g m^{-3} h^{-1}. Though results from this five-month biotrickling filter study were comparable or higher to those previous biofilter studies, the testing of possible system problems and operating conditions was warranted in an attempt to enhance reactor performance. Nutrient supply was increased, reactor water temperatures were decreased, and organic loading was artificially supplied during times when the plant was not operating to create more steady state like conditions (Figure 4). In addition, experiments were performed to establish if reactor performance was hindered by poor air distribution through the filter bed or by biological uptake limitations.

Environmental Conditions

Environmental conditions found in a biotrickling filter reactor require optimization in order to host a thriving microbial population. Conditions such as water temperature, nutrient concentration, pH, and conductivity affect microbial growth and metabolism.

The liquid recycle water temperature was significantly altered in an attempt to enhance removal performance. Initially, the temperature of the water passing over the filter bed was maintained between 30-34°C using a water immersion heater. The test-site location ambient conditions generally ranged from 26°C (at night) to 36°C (during hot summer days). Based on this narrow temperature range of ambient conditions, it was speculated that substantial operational cost savings could be incurred by turning off the heating element without a correlating loss in removal performance. On day 73 (Figure 4, Point 4) of the experiment, the heating element was turned off and little to no correlation was established between reactor recycle liquid temperature and removal performance. It has been suggested that such behavior is an indication of a mass transfer limitation because biological kinetics usually has greater temperature sensitivity than transfer kinetics [2]. However, in the absence of specific information on the activation energy of styrene biodegradation, such a conclusion may be too expeditious.

Another environmental condition, the nutrient concentration, was changed and the effects on performance were monitored. The nutrient concentration of the recycled water was doubled (to 1.4/1.0/1.2 g l^{-1} of N/P/K) during the course of the experiment to determine whether a nutrient limitation was occurring. Once again, no correlation of increasing nutrient content to reactor performance was established (Figure 4, Point 1). Possible nutrient limitations were also dismissed as biomass growth increased rapidly during high styrene load experiments (See Transient Operating Conditions). All other environmental conditions appeared to be suitable for microbial growth (i.e., pH, conductivity), so further investigation into possible enhancements in contaminant removal performance turned to potential problems caused by site specific operating conditions.

Transient Operating Conditions

The bathtub manufacturing facility operated in a transient state. The plant would generally operate Monday morning through Saturday morning and shut down over the weekend. During this plant downtime, liquid recycle and ambient air continued to be supplied to the biotrickling filter reactor to avoid anaerobic conditions from developing in the reactor and malodorous emissions occurring during system restart. However, no substrate (styrene) source was supplied to the microbial population. Under such starving conditions, the microbes in the system quickly reverted to endogenous respiration. Inevitably, through measurements made with the load cells, attached biomass weight in the reactors declined over the weekend. When the plant restarted operations on Monday morning and styrene was supplied to the microbes, system performance was very poor (0 to 30 % removal). The reduction in cell viability and loss of active biomass over the weekend likely contributed to the initial poor removal. In addition, because of the low solubility of styrene, an initial mass transfer limitation may have occurred once styrene was reintroduced into the reactor. After a day of plant operation passed, gradual improvement to pre-weekend performance levels was achieved. This slow recovery made it difficult to achieve rapid biofilm growth on the media bed (Figure 5). Generally, in the laboratory, it is the opposite problem. Previous research in the laboratory has demonstrated the problem of excessive biomass growth for systems where loading was high and a steady supply of contaminant existed [10, 11]. However, in the field, at low loadings and discontinuous operation, it could be a problem to achieve a stable and sufficient density of biomass.

To test the possible theory of reaction limitations in the biofilm, styrene removal was studied at higher concentrations. A metered stream of liquid styrene was directly injected into the air stream prior to entering the blower (the air flow remained constant). Combined with the load from the plant (26 g m^{-3} h^{-1} during the week), a total average load of 66 g m^{-3} h^{-1} was applied to the reactor continuously for approximately two weeks (days 44 to 60). This steady state, high load condition caused biofilm to generate rapidly on the packing material (Figure 5). Elimination capacity also improved to values of 45-50 g m^{-3} h^{-1} (55-65 g m^{-3} h^{-1} across the first tank in series). Such results possibly indicate that the actual styrene uptake kinetics in the biofilm was of a positive order and the biofilm was not saturated during normal operating conditions. Consequently, raising the substrate concentration could increase biological kinetics.

When the styrene load was reduced and transient conditions continued, performance declined (but was

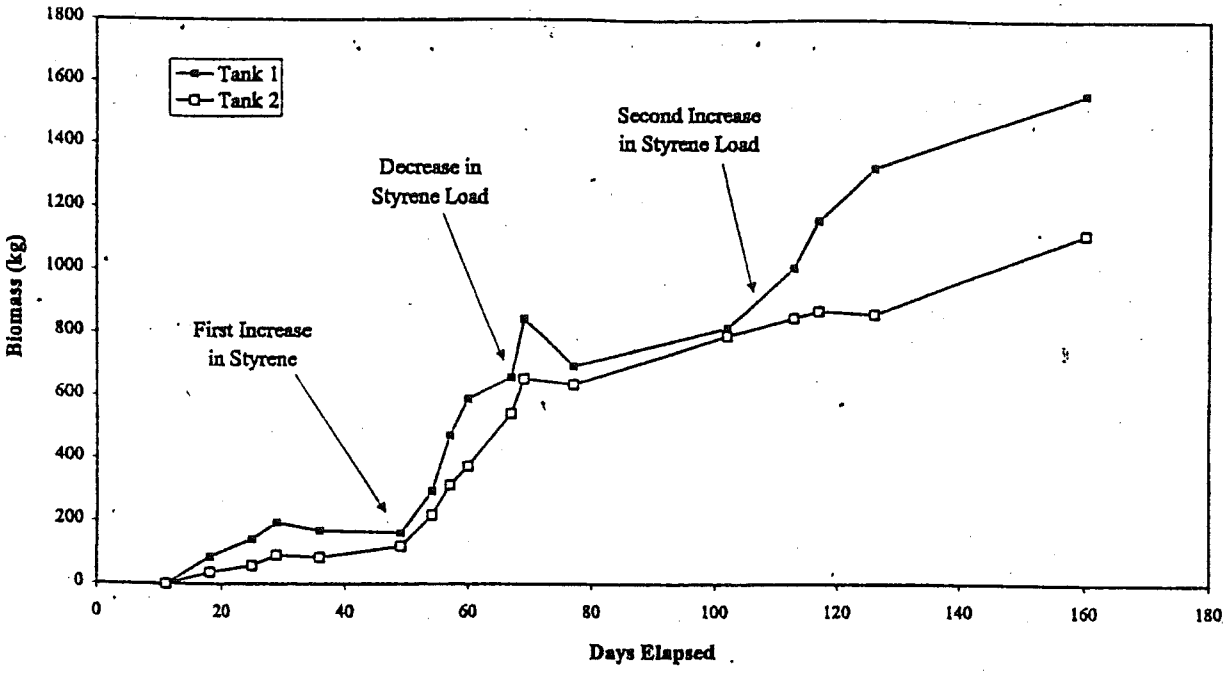

FIGURE 5. Biomass accumulation after styrene load additions to the system. Secondary load increase not discussed in paper.

still better than previous levels) to sustained levels of 20-24 g m^{-3} h^{-1} (33-35 g m^{-3} h^{-1} across the first tank in series). The increase in biomass was approximately 500 kg per tank (400% increase compared with prior levels before the increase in load), but performance only increased 25-30%. A rough estimate of the biofilm thickness based on the additional biomass formed (500 kg), assuming a packing surface area to volume ratio of 125 m^2 m^{-3}, wet biomass density of 1000 kg m^{-3}, and 100% coverage, was calculated to be 700-900 µm in thickness. Despite the large increase in biomass, the small moderate increase in elimination capacity suggests that most of the biomass that accumulated was inactive and that future research efforts should be placed in the optimization of the amount of active biomass. Cox (1995) was able to sustain 60 g m^{-3} h^{-1} of styrene removal with efficiencies greater than 80% using a packing material in a biofilter with a surface area to volume ratio of 860 m^2 m^{-3}. The Jaeger Tri-Pack® used in this study had a surface area to volume ratio of only 125 m^2 m^{-3}. This caused poorer biofilm density distribution and possibly explains the lower styrene elimination. Such a thick biofilm could have created mass transfer limitation problems or oxygen diffusion limitations, limiting performance. Even so, in the absence of more detailed information, it is difficult to conclude whether the performance could be attributed to biological reaction limitation or mass transfer limitation. The low influent concentrations and the intermittent operation encountered at the test site suggest the former, but it is possible that both types of limitation occurred at different locations in the reactor. Further investigation of possible problems with air distribution in the reactor and microbiological limitations were warranted.

Channeling of Air and Packing Material Surface Area

Though some improvement in removal was seen with the system after the biomass increased, a continued increase in removal performance was not noted. Heterogeneities in the biomass distribution possibly caused channeling of air or dead zones of activity. The packing material utilized for the filter bed had a fairly high void space (95%), but problems with air channeling were suspected and required testing. A tracer test was performed to determine if any portion of the bed was unutilized. The styrene load was completely halted and a pulse of propane was injected into the inlet pipe leading to the first tank of the system (downstream of the blower). The pulse injection experiment was repeated three times. The PLC and FID continuously monitored the air along a port on the outlet piping from tank 1. From these measurements, a retention time of the pulse was experimentally determined. The triplicate runs were averaged. Using this experimentally determined retention time and knowing the flow through the reactor, an experimental void volume was calculated to be 3.7 m^3. From the geometry of the piping, the tank, the liquid holdup (estimated), the packing material, and the biofilm present in the first filter bed, the calculated total void volume was determined to be 4.1 m^3. A dead void volume was then calculated from the difference in the calculated void volume and the experimentally determined void volume:

(1) Dead Volume = (Inlet Pipe Volume + Tank 1 Volume + Outlet Pipe Volume - Bare Packing Volume - Biomass Volume - Dynamic Hold-up Volume) - (Experimentally Determined Residence Time of Tracer x Air Flow Rate)

The dead void volume was 0.4 m^3, roughly 10 % of the filter bed. This amount of dead void volume is moderately significant, but it does not constitute a

major portion of the bed. Hence, limited styrene removal could not be attributed solely to channeling of air. Such pulse tests provide a quick and easy assessment of bed usage (and performance), and should be performed with all pilot- and full-scale reactors at least twice a year.

Biological Limitations

The final phase of the experiment investigated possible biological limitations with the microbial populations. Specific oxygen uptake rates were determined for cells immobilized in the biofilm by adding styrene to a suspended biofilm sample. Using an oxygen probe in a respirometry flask (YSI, Yellow Springs, CO), depletions in oxygen were measured as the substrate was consumed. In addition, controls were set up to establish the amount of endogenous respiration that occurred without styrene addition. Knowing the oxygen consumption based on the styrene degradation and correcting for oxygen consumption from endogenous respiration, the amount of oxygen consumed per mass of dry biomass per time was calculated. Maximum uptake rates were calculated to be 0.2 μg of oxygen mg^{-1} dry biomass min^{-1}. Such uptake rates are 3 to 10 times lower than uptake rates measured for the styrene-degrading fungus Exophiala jeanselmei used in a biofilter experiment treating styrene gases [5]. By isolating pure cultures through streak plating and inoculating Biolog® GN Identification Plates (Biolog, Hayward, CA), the dominant fixed-film microbes performing the degradation in the reactor were tentatively identified as Pseudomonas diminuta and Pseudomonas mendocina. Though difficult to correlate batch-scale experiments in the laboratory with actual pilot-scale results, such uptake measurements provide another possible explanation as to why contaminant removal in the biotrickling filter was limited. These particular Pseudomonas sp. may not have had the constitutive enzymes, or proficient inductive enzymes, necessary for effective styrene treatment, or the enzyme turnover may have been too low. Contrary to compost biofilters, where a large indigenous population is present on the medium at the start and where inoculation is often needless, biotrickling filters do need an efficient inoculation to establish a thriving process culture. Such experimental results indicate a possible weakness with inoculating a biotrickling filter with activated sludge and then assuming a suitable degrading population will develop. Instead, these findings magnify the importance of inoculating a biotrickling filter reactor that is treating a pure stream of styrene with highly proficient styrene degrading microbes.

CONCLUSIONS

The use of a biotrickling filter reactor in an industrial setting posed many additional challenges not seen at the bench-scale level in the laboratory. Both operational and performance problems unique to the particular reactor design and its site location constantly surfaced. Operational problems included the malfunction of water pumps, poor performance of water level sensing equipment, sampling system malfunctions, and plant power outages. Some problems were quickly alleviated, while others were more difficult to control and caused repetitive system upsets. Throughout the experiment, the need for more reliable, advanced equipment (float sensors, nutrient pumps, etc.) was evident. More advanced equipment requires higher capital costs. In some instances, these higher costs are warranted to prevent frequent system upsets that contribute negatively to reactor performance. In designing this type of system, a balance exists between the capital and the operational costs needed to maintain the system so that upsets are minimal.

The biotrickling filter reactor performed well and provided a sustained styrene elimination capacity of up to 24 g m^{-3} h^{-1} (35 g m^{-3} h^{-1} across the first tank in series) with 70 to 85 % removal. Possible performance problems were assessed to enhance the system's overall pollutant removal capacity. The surface area to volume ratio of the packing may have limited the effective biofilm density in the system. This created large quantities of inactive biomass and possibly led to some mass transfer limitation. Minimal effect on pollutant removal was demonstrated when the environmental conditions of water temperature and nutrient concentration were varied inside the reactor. Transient operation of the plant made it difficult to establish an effective, active biofilm on the packing material. This fact alone contradicts many results from research efforts of continuous, steady state systems operated in the laboratory, for which biomass overgrowth is a common problem. Therefore, additional work is needed in the laboratory to assess the varying effects of transient operation of biotrickling filter reactors. Focussing on the design, possible problems of air channeling were dismissed by results of a propane tracer study that determined more than 90% of the bed of the first tank in series was effectively being utilized. Microbial limitations were investigated and preliminary results described a microbial consortium of styrene degraders, dominated by Pseudomonas sp., with low maximum substrate uptake rates compared with other laboratory research results of pure styrene-degrading cultures. Such a problem points to the need for better defined inoculation procedures of biotrickling filtration reactors.

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LITERATURE CITED

1. Arnold, M., Reittu, A., von Wright, A., Martikainen, and P. J., Suihko, M.L., "Bacterial degradation of styrene in waste gases using a peat

filter," Appl. Microbiol. Biotechnol.,48, pp. 738-744 (1997).
2. Barton, J.W., Klasson, T., and Davison, B.H., "Extended operation and control of biomass overgrowth in biofilters designed for VOC removal," Proceedings of the 1997 Annual Meeting of the Air & Waste Management Association, Toronto, Canada (June 1997).
3. Cox, H.H.J., "Styrene removal from waste gas by the fungus Exophiala jeanselmei in a biofilter," Ph.D Thesis, University of Groningen, The Netherlands (1995).
4. Cox, H.H.J., and Deshusses, M.A., "Biological waste air treatment in biotrickling filters," Current Opinion in Biotechnology, 9(3), (June 1998).
5. Cox, H.H.J., Moerman, R.E., van Baalen, S., van Heiningen, N.M., Doddema, J., Harder, W., "Performance of a styrene-degrading biofilter containing the yeast Exophiala jeanselmei," Biotechnology and Bioengineering, 53(3), pp. 259-266 (February 1997).
6. Devinny, J.S., Deshusses, M.A., and Webster, T.S., Biofiltration for Air Pollution Contr ol, First Edition. CRC Press, Inc., Boca Raton, FL, (September 1998).
7. Hartmans, S., Tramper, J., and de Bont, J.A.M., "Biological waste air treatment," Proceedings of the Fifth European Congress on Biotechnology2, pp. 659-662 (1990).
8. Holubar, P, Andorfer, C., and Braun, R., "Prevention of clogging in trickling filters for purification of hydrocarbon-contaminated waste air," Proceedings of the 1995 Conference on Biofiltration, eds. Hodge, D. and Reynolds, F. E. Jr., Los Angeles, California (October 1995).
9. Sabo, F., Fisher, K., and Baumeister, R., VDI Berichte NR'1034, pp. 521-539 (1993).
10. Sorial, G., Smith, F.L., Suidan, S.T., Biswas, P., "Evaluation of trickle bed biofilter media for toluene removal," J. Air & Waste Management Association, 45, pp. 801-810 (October 1995).
11. Togna, A.P., and Folsom, B., "Removal of styrene from air using bench-scale biofilter and biotrickling filter reactors," Proceedings of the 85th Annual Meeting & Exhibition of the Air & Waste Management Association, Kansas City, MO, (June 1992).
12. Weber, F.J., and Hartmans, S., "Toluene degradation in a trickle bed reactor- Prevention of clogging," VDI-Berichte NR 1104, pp. 161-168 (1994).
13. Webster, T.S., Togna, A.P., Yang, Y., and Guarini, W. J., "From bench- to pilot-scale experimentation: The Treatment of volatile organic compound emissions from spray paint booth applications using a biological trickling filtration reactor," Proceedings of the 1998 Annual Meeting & Exhibition of the Air & Waste Management Association, San Diego, California, (June 1998).
14. Zuber, L., Dunn, I.J., and Deshusses, M.A., "Comparative scale-up and cost estimation of a biological trickling filter and an air lift reactor for the removal of methylene chloride from polluted air," J. Air & Waste Management Association, 47, pp. 969-975 (1997).

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Evaluating Design Options for Biofilters

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ABSTRACT

Biofilters are now increasingly offered and accepted in North America for air pollution control. However, prospective buyers often lack the technical and economic criteria to select a suitable biofilter design for their applications. This paper summarizes past experiences with full-scale biofilters and emerging design trends. Since control of the filter media's moisture content is essential for effective pollutant removal, the processes affecting moisture content are reviewed and ranges for evaporation rates and dry-out periods are estimated. High VOC concentrations and elimination rates cause high moisture removal and require additional irrigation; excessive irrigation or condensation of moisture from hot off-gases routinely cause overwatering and poor performance. Consequently, an application's moisture balance should be evaluated carefully prior to selecting a biofilter design. High VOC loadings and the need for low maintenance and verifiable pollutant removal favor fully enclosed vessels with automatic moisture control. Open biofilters with a low level of moisture control are suited for dilute off-gases, e.g., in non-critical odor control applications. Typical cost ranges for biofilter installations in North America are presented. Other design selection criteria, including choice of media, space demands, and monitoring requirements are reviewed. Three case examples of full-scale biofilters for VOC control illustrate our findings.

IMPLICATIONS

Biofilters treating VOC concentrations >0.5 g/m^3 and achieving elimination capacities >50 gm^{-3}h^{-1} are prone to rapid bed dry-out. Biofilter applications in chemical and other manufacturing industries often fall in this category. Estimates of moisture gains and losses should be established before selecting a biofilter design and moisture control strategy. At even higher VOC elimination capacities, heat-up and evaporation make it increasingly difficult to maintain optimum moisture content, even with automatic moisture control. Thus, the difficulty of controlling moisture in a large, heterogeneous reactor constitutes a major nonbiological limitation to high volumetric VOC removal in biofilters.

INTRODUCTION

Since the mid-1980s, biofiltration technology for treatment of off-gases containing odors or low concentrations of volatile organic compounds (VOC) and hazardous air pollutants (HAPs) has been established in Europe as an often cost-effective and environmentally benign alternative to combustion and sorption technologies. Following two decades of very limited use of open biofilters for odor control, they are now also more widely accepted, researched, and applied in North America. Domestic suppliers of biofilters have carried out pilot tests in a wide range of emitting industries. Since the late 1980s, approximately thirty, usually enclosed, large full-scale systems (more than 100 m^3 of filter material) for VOCs, HAPs, and advanced odor control have been built. Another estimated 50-100 simpler open biofilters were installed for odor control at wastewater treatment, composting, and food processing operations. More than 50 small enclosed biofilters (<20 m^3 of media) are used to treat off-gas from soil vapor extraction operations and small odorous gas streams.[1-5]

Prospective buyers are faced with a diverse selection of biofilter systems that vary with respect to reactor design, composition and projected life of filter media, level of process control, and consequently, performance and price. Most buyers still lack field experience with this emerging technology and the criteria for selecting the appropriate design. This article reviews the major technical, economic, and operational aspects to be considered in the selection. Because of its particular relevance to filter performance, the balance and control of media moisture is discussed in more detail. Three examples of full-scale biofilters illustrate our conclusions.

OPERATING EXPERIENCES AND DESIGN TRENDS

Early biofilters built in Europe and the U.S. in the 1960s consisted of perforated pipes for off-gas distribution that were covered with mineral soils as filter media. These systems often achieved sufficient control of odors, but operational problems such as clogging of the air distribution systems, uneven off-gas distribution, and dry-out of the beds were common.[6,7]

In the 1970s, more advanced, open biofilters were developed in Europe. They have been widely used for odor control, and typically consist of one or more open beds at ground level enclosed by concrete walls, with an air distribution/media support system based on molded concrete plates or blocks of various designs. The filter material consists typically of a mixture of compost or peat with a structural support medium (heather, branches, wood chips, bark, or mineral granulates) that reduces the risk of compaction, and the resulting increase in pressure drop and potential for channeling of untreated off-gas.

With the emergence of these systems, biofilters became increasingly popular in Germany and the Netherlands because of their often lower capital cost and energy demand compared to competing technologies. Most installations were for odor control, but emerging regulatory requirements to remove VOCs or HAPs also stimulated interest in their treatment by biofilters. A growing number of installations also demonstrated operational and performance problems. Common problems included dry-out and over-watering of the filter material, rapid media compaction, and acidification by degradation products, causing insufficient pollutant removal, increased pressure drop and energy cost, and a shorter bed life.

In the 1980s, these problems and the increasing desire of regulatory agencies to ascertain biofilter performance (particularly for VOC and HAP control applications) stimulated the development of a new generation of biofilters. They are usually fully enclosed, use a more porous media that involves slowly degradable or inert support material, and often provide for automatic monitoring and control of the media's moisture content. After a decade of development and full-scale demonstration in a variety of applications, these systems are now accepted by regulatory agencies and industry in several European countries. They are generally considered a reliable, cost-effective, and environmentally benign control option for off-gases containing low concentrations (typically several hundred parts per million measured as carbon [ppmC], of gaseous, biodegradable air pollutants. Open systems of various designs also continue to be built for odor control. More recent operational experiences and design trends in North America are similar. More detailed discussions concerning various design concepts and the performance of full-scale biofilters can be found in the literature.[8-14]

Because of the higher capital cost of fully enclosed, more controlled biofilters, simple, open systems are routinely considered for the removal of VOCs and HAPs from process off-gases. Unfortunately, their use in unsuitable applications, particularly for the treatment of higher concentrations and loads of VOCs without proper moisture control, has repeatedly resulted in media dry-out and poor performance, and given biofiltration the reputation of a somewhat unreliable technology. Yet despite the obvious importance of moisture control, there has been little quantitative evaluation of th affecting media moisture and the suitability of varic able control strategies.[15]

THE MOISTURE BALANCE OF A BIOFILTER

The moisture content of a biologically active filter the operating parameter most relevant to performa most sensitive to changes. Insufficient moisture prev mation on the filter particles of a wet "biofilm" tl ports microbial growth and respiration. Excessive m on the other hand, reduces mass transfer of hydr substances, clogs available pore space, and thereby biofilm surface available for pollutant transfer; it also i pressure drop, contributes to slime formation, and m irreversible, structural damage to the media throug out of small particles. The optimum moisture conte given installation depends primarily on media comp and physical characteristics of the target VOC. Literat the authors' experience with pilot and full-scale biofi VOC control suggest that for most applications, the m content at which optimum, sustained performance is a is between 40 and 60% by wet weight. For compact, drained media and for the treatment of hydrophobic V moisture content at the lower end of this range is de Lighter, highly porous media treating hydrophilic VO have an optimum moisture content above 60%. Wh moisture content by weight is only an indirect indic the moisture actually available to microorganisms, it measured gravimetrically and constitutes a reasonab trol parameter for a given off-gas and media.[11,16]

Due to the availability of moisture in the biofilter the presence of large surfaces for moisture transfer be media and off-gas, and their comparatively long res time, off-gases usually become saturated in filter mec exit at relative humidities near 100%. The resulting exi ture load may differ from that of the incoming off-gas moisture transfer by evaporation or condensation, wh timately affect media moisture content and perfor unless it is controlled. A review of the thermodynar biofilters suggests that such moisture exchange is cau five major processes. They are summarized in Table 1 fundamentals, quantitative impacts, and moisture c strategies are reviewed in the following sections.

Incomplete Prehumidification

An off-gas entering the filter media at less than 100 tive humidity (RH) evaporates moisture from the filte trance zones until it reaches full saturation. In a psychro chart, the endpoint of this change in off-gas state is sented by its adiabatic saturation temperature. The corres ing rate of moisture removal from the bed varies witl temperature, initial RH, and (empty bed) residence ti off-gases are vented to a biofilter without (or with inade

prehumidification, this rate becomes substantial. For example, an off-gas with wet- and dry-bulb temperatures of 20 and 13.8 °C, respectively (RH = 50%), and a 30 second residence time removes moisture primarily from the biofilter inlet at a rate of 350 grams per cubic meter of media per hour ($gm^{-3}h^{-1}$). This reduces the moisture content in the initial 20% of the media from 60% to its lower acceptable level of 40% in less than six days.

Industrial off-gases are commonly not moisture-saturated at their point of collection. To avoid an otherwise rapid dry-out at the filter inlet, most open and enclosed biofilter systems now provide off-gas prehumidification for such off-gases. A relative humidity of 90-95%, which is routinely achieved during prehumidification, reduces the rate of dry-out to a level where it no longer causes rapid changes in bed moisture and can be controlled by overbed spraying. A somewhat less than complete prehumidification is also desirable for control purposes, since it provides a limited capability for drying out media that has intentionally or inadvertently received excessive moisture. In installations where the off-gas fan is located between the humidifier and filter bed, off-gas compression by the blower effects an increase in temperature, a corresponding decrease in relative humidity, and additional moisture loss from the biofilter inlet. In case of a high media pressure drop this loss may become substantial. Table 1 compares typical moisture removal rates for unsaturated and prehumidified off-gas.

Exothermic Biooxidation

As in other combustion processes, the enzymatic biooxidation of organic off-gas constituents in a biofilter is an exothermic process. The resulting increase in off-gas enthalpy causes an increase in off-gas temperature and consequently, evaporation of moisture to maintain complete off-gas saturation. Evaporation rates increase as concentration and heating value of VOC species increase in the raw gas. In a psychrometric chart, this change in state corresponds to a shift along the RH = 100% line. The enthalpy of the endpoint equals that of the starting point plus the total enthalpy of combustion. The latter equals the sum, over all VOC species, of raw gas concentration (in kg of VOC per kg of wet air) times their respective upper heating value (in MJ/kg). Net moisture removal per off-gas volume, or weight of dry air, is calculated as the difference in off-gas moisture between biofilter inlet and outlet, minus moisture formed from oxidation of VOCs. The latter typically provides 10-20% of the total moisture demand

Table 1. Impact of processes occurring during biofiltration on off-gas temperature (ΔT), enthalpy (Δh), and moisture content (Δmc).

Process	ΔT(°C)	Δh_{total}[a] (kJ/m^3)[c]	Δh_{evap}[b] (kJ/m^3)[c]	Δ_{mc} (g/m^3)[d]	Response Time (days)[e]
Humidification/Adiabatic Cooling					
T_{dry} = 20 °C:rH = 50% -> 95%[f]	-5.8	0	6.7	2.7	3.5-7
rH = 95% -> 100%[g]	-0.6	0	0.7	0.3	35-70
T_{dry} = 40 °C:rH = 50% -> 95%[f]	-9.8	0	10.3	4.3	2.5-5
rH = 95% -> 100%[g]	-0.8	0	1.0	0.4	20-40
Biooxidation (@ 20 °C)					
C_{in} = 0.1 g VOC/m^3[h]	0.7	2.8	1.6	0.7	15-30
C_{in} = 0.5 g VOC/m^3[h]	3.2	14	9.3	3.8	3-6
C_{in} = 1.0 g VOC/m^3[h]	6	28	17	7	1.5-3
Condensation Losses/Heat Gains[i]					
Change in T_{wet} from 20 <-> 19 °C	+/- 1	4.0	2.6	+/- 1.1	10-20
Change in T_{wet} from 40 <-> 39 °C	+/- 1	8.9	6.8	+/- 2.9	3.5-7
Media Degradation	0.1-0.2	0.5-1	0.35-0.7	0.14-0.28	75
Flower (Δp: 1-2 kPa, 4-8" wg)	0.25-0.5[k]	1-2	0.75-1.5	0.3-0.6	17-70

[a] Change in total off-gas enthalpy effected by a process.
[b] Amount of evaporative enthalpy involved in a process.
[c] m^3 refers to wet off-gas volumes at actual temperatures.
[d] Difference in absolute off-gas moisture before and after process in g/m^3 of moist air.
[e] Period in which respective process increases or reduces average media moisture content by 30 liters/m^3, thus requiring operator response. Boundaries correspond to residence times of 30 (low figure) to 60 seconds.
[f] Adiabatic cooling of off-gas (initial T_{dry} = 20 °C), concurrent increase in RH from 50 to 95%.
[g] Complete saturation of a prehumidified off-gas.
[h] Off-gas contains oxygenated solvent, UHV: 27.5 MJ/kg (11,800 BTU/lb).
[i] Moisture gains or condensation losses realized by off-gas undergoing the respective temperature change in bed as a result of heat exchange between vessel and environment.
[k] ΔT after complete re-saturation of off-gas in bed entrance.

resulting from exothermic biooxidation. Upper heating values for VOCs commonly treated in biofilters range from 22.6 MJ/kg (9,700 BTU/lb) for methanol to 50 MJ/kg (21,500 BTU/lb) for alkanes and alkenes. Table 1 indicates that moisture removal due to biooxidation becomes significant as VOC inlet concentration and volumetric elimination capacity approach 0.5 g/m³ and 50 grams of VOC per cubic meter of media ($gm^{-3}h^{-1}$), respectively.

Heat Exchange with the Environment and Media Degradation

The above discussion assumes implicitly that filter media do not exchange thermal energy with the environment, that heat produced by the gradual biodegradation of media is negligible, and that off-gas and media are always in thermal equilibrium. While heat exchange with the environment can theoretically be eliminated, economic constraints limit the extent of thermal insulation, particularly for larger systems. Thus, in practice, even fully enclosed, well insulated filter vessels gain or lose some heat. This causes temperature differences between off-gas and media and results in net energy and moisture transfer. For enclosed, well insulated biofilters, short-term fluctuations in off-gas temperature and humidity are more important and result in local moisture exchange.

Off-gases entering at wet-bulb temperatures below the bed temperature will heat up and remove moisture from the media. This may be the case for biofiltration of air-conditioned ventilation off-gases in hot climates. On the other hand, warm and saturated off-gases (for example from baking and drying operations) with wet-bulb temperatures above the bed temperature add mist or condensate to the bed, particularly in colder climates. This effect is particularly pronounced during start-up. Since condensation may result in over-watering of the media, it may have to be controlled by forced cooling or by adding dry dilution air.

Some biofilter installations rely on condensation to provide additional moisture to the biofilter inlet by raising the wet bulb temperature to above the bed temperature during prehumidification. However, since the amount of condensate thus produced varies with the rate of heat loss to the environment, i.e., with ambient temperature, it is difficult to control. Undesirable condensation losses are highest, during the cold season after weekend shutdowns. Heat exchange with the environment and its impact on off-gas moisture are strongest in small, open, and poorly insulated filter vessels and at long residence times.

Finally, the gradual exothermic biodegradation of media may add heat to bed and off-gas, thus causing additional evaporation loss. Its rate varies primarily with media composition and age, and with bed temperature. Higher temperatures increase the rate of mineralization, particularly of wood materials that generally degrade only slowly in the mesophilic temperature range. Media degradation has been identified as one of the factors affecting the carbon balance in a biofilter. Table 1 suggests that it is of comparatively low importance to bed moisture balance. It also indicates that changes in the off-gas saturation temperature by 1 °C in poorly insulated beds cause considerable condensation gains or evaporation

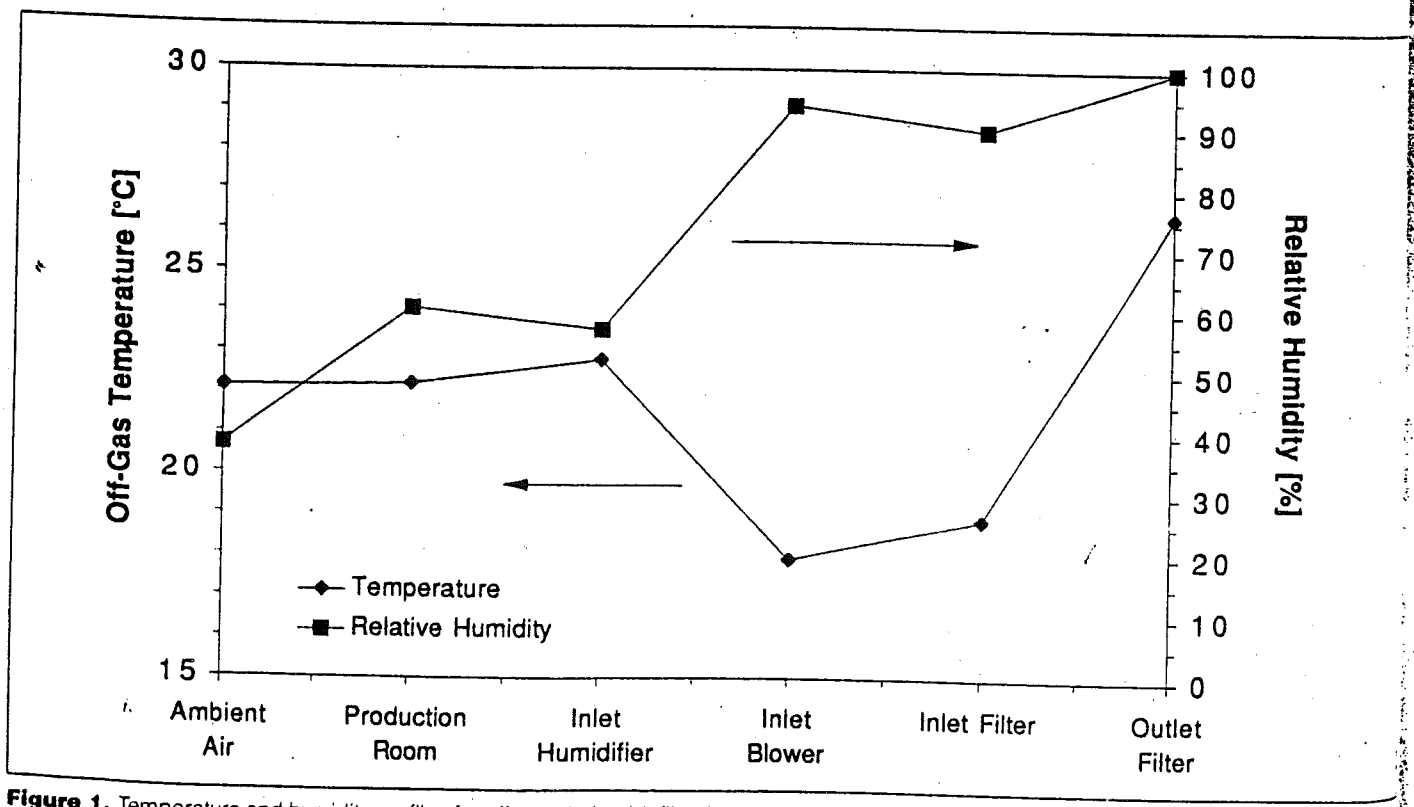

Figure 1. Temperature and humidity profiles for off-gas during biofiltration.

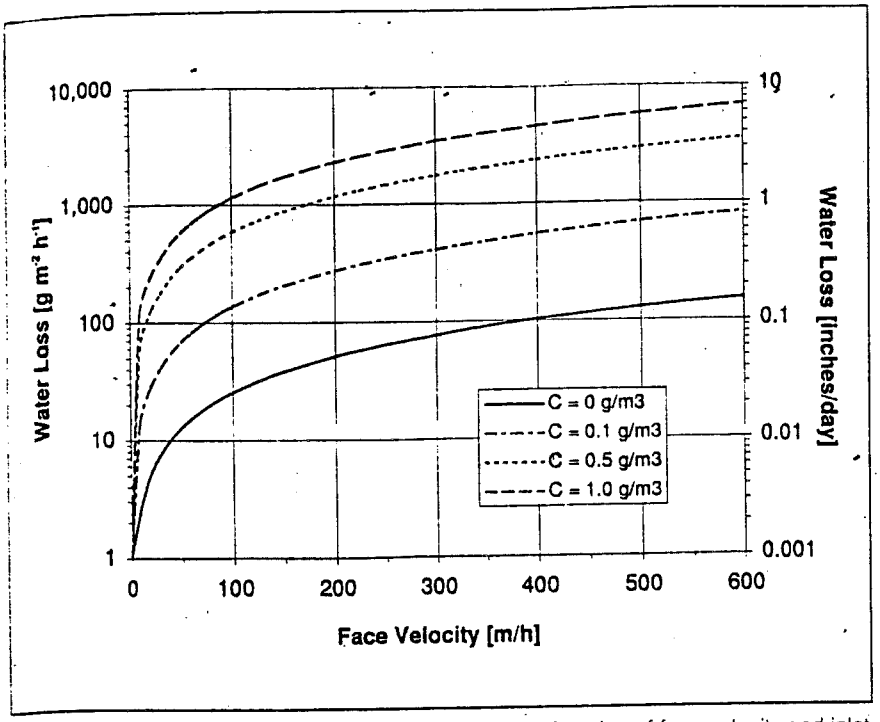

Figure 2. Estimated moisture losses from biofilters as a function of face velocity and inlet VOC concentration.

losses in the media. However, since the impacts of these processes vary strongly with vessel design (insulation), off-gas temperature, relative humidity, ambient temperature, and media status, they are not considered in the following calculations.

Table 1 indicates that non-prehumidified off-gases and those containing VOC concentrations approaching 0.5 g/m³ may cause rapid dry-out of filter media. As an example, Figure 1 illustrates the impacts of adiabatic cooling during prehumidification, heat-up by off-gas fan, and biooxidation in the media on energy and moisture balance of an existing full-scale biofilter.[10] It shows profiles of dry-bulb temperature and relative humidity taken at various locations in the path of an off-gas with an average concentration of 1.3 g/m³ of VOCs, primarily ethanol. Figure 2 allows initial estimation of moisture losses due to incomplete prehumidification and exothermic biooxidation. They are expressed as the weight of the corresponding moisture column (10,000 gm⁻²h⁻¹ equals a loss rate of 1 centimeter per hour or 10 inches per day). Assumptions include a wet-bulb temperature of 20 °C, raw gas prehumidification to 95% RH, an upper heating value of 27.5 MJ/kg (11,800 BTU/lb) for VOCs, and complete VOC removal in the biofilter. In addition, 20-70% of the applied irrigation water may be typically lost as drainage. Shorter and more frequent spraying generates less drainage losses than long spray cycles. These losses must be added to evaporation losses when estimating actual irrigation demand. Two examples illustrate the range of typical evaporation losses and the use of Figure 1 in estimating them. Discrepancies between text and graph are due to differences in biofilter inlet temperature.

Case A. An off-gas entering the biofilter at 35 °C and 95% RH and containing 1 g/m³ of an easily degradable VOC may require a 45 second residence time for complete VOC removal, corresponding to a face velocity of 80 m/h at a 1-m bed height. The high temperature and organic load result in a net evaporation loss of 650 gm⁻²h⁻¹, corresponding to an irrigation demand of 1.6 cm/day, assuming no drainage loss.

Case B. A cold off-gas (15 °C) with low concentrations of odorous compounds (0.1 g/m³) and a residence time of only 15 seconds, corresponding to a face velocity of 240 m/h, may cause bed moisture to evaporate at a rate of 0.5 cm/day.

It is suggested that the reader estimate moisture removal rates for other off-gas conditions with a psychrometric chart. This will provide a better understanding of the mechanisms affecting moisture balance and a sense of their quantitative effects.

MOISTURE CONTROL OPTIONS

Our estimate suggests that the rate of moisture removal from filter media varies considerably between applications. Even for a given source, moisture demand will fluctuate with off-gas temperature, VOC loading, and ambient conditions. Considering the significance of moisture content for microbial activity and filter performance, effective bed irrigation must involve some form of monitoring and control of bed moisture. Figure 2 suggests that the required monitoring frequency and accuracy of the control approach increase with increasing VOC load. The four most commonly used monitoring and control strategies for bed moisture are listed in Table 2. Their suitability for a given application depends on the extent of moisture loss and the acceptable level of monitoring and maintenance activity. These strategies are best distinguished by whether monitoring of media moisture is performed manually or automatically.

Manual Monitoring

Manual sampling involves perforation of the media by an auger, or similar sampler, and the recovery of several representative samples from various locations in the bed. It is followed by visual or gravimetric evaluation of moisture content and the determination of irrigation needs, if any. Irrigation is administered by rainfall, manually (spray hose), by an installed overbed spray system with manual control valve, or by a timer-controlled, semi-automatic spray system. Systems relying on manual moisture monitoring are suitable

where moisture removal by the off-gas is slow and allows for monitoring at reasonably long intervals, i.e., weeks to months, without risking loss of performance. More than 90% of all large biofilter systems built to date rely on one of these three control approaches involving manual moisture monitoring.

Manual monitoring of filter of material for moisture is time-consuming. The number of samples required to establish a representative moisture profile depends on the spatial variability of bed irrigation patterns, with five samples per 200 m^3 of filter material as a typical value. Considering that the medium often dries out preferentially at the filter inlet, samples should be obtained from different heights in the bed. Sampling usually involves walking on the media and its perforation by the sampling device. It is to be conducted carefully to minimize compaction and the formation of channels. The recently more common bed heights of 1.5 m make sampling from the bottom zone increasingly difficult. Thus, where moisture removal rates are high and variable, and where monitoring efforts are to be minimized without risking impaired performance, automatic moisture monitoring and control become desirable.

Automatic Monitoring and Control

Biofilter suppliers use two approaches to automatic moisture monitoring. Some systems obtain spot measurements from one or more locations in the bed(s), e.g., by measuring electric conductivity or capacity. The accuracy of this approach is limited by the small area represented by a spot measurement, the typically large filter volume and nonhomogeneity of filter media, and by the low sensitivity of these methods in the target moisture range. More commonly used is the measurement of bulk moisture content by weighing all or sections of the filter material continuously with load cells. This approach is offered by several biofilter vendors in the U.S. and provides for the registration and control of bulk weight gains or losses attributed to irrigation or evaporation. For accuracy, this control method requires even bed coverage by the irrigation system, and that variations in the total weight of the filter material reflect only changes in its moisture content. This limits its applicability to fully enclosed systems, since the growth of weeds, snowfall, and wind affect weight measurements in open systems. Periodic recalibration may be required to adjust for media decomposition and for losses of filter material into the drainage. Data obtained from both spot and bulk monitoring methods are usually processed in a programmable logic controller (PLC) that determines irrigation needs and controls the duration and frequency of spraying. Uneven spraying patterns are known to contribute to considerable spatial variations in bed moisture content. They impair performance and affect how representative moisture measurements are, particularly spot measurements. Thus, even coverage of the beds by a carefully designed irrigation system is paramount for producing meaningful moisture content data.

Table 2. Moisture control options for biofilters.

Method	*Description*
Automatic	The moisture content of the filter material is measured automatically by bulk or spot methods. The monitoring results control an automatic media spraying system. Excessively high or low moisture content may trigger an alarm or cause shutdown.
Semi-Automatic	Spraying frequency and duration are controlled by a timer which is adjusted periodically based on media sampling or automatic moisture monitoring.
Manual/Periodic	A bed spraying system with a manual valve is installed. Spraying is conducted periodically based on periodic media sampling.
Manual/Ad hoc	No spraying system is installed. The moisture content of the media is monitored several times per year and, if necessary, adjusted manually with a spray hose.

Other Moisture Control Features

In addition to these active measures for moisture monitoring and control, several passive control features are commonly employed. Enclosed biofilters are now increasingly built for downflow operation. This allows preferential irrigation of the bed inlet (i.e., those zones frequently subject to moisture removal and dry-out). For off-gases containing acidifying compounds (reduced sulfur and nitrogen compounds or chlorinated VOCs), upflow may be preferable since it allows for more efficient flushing of acidic degradation products.[20] The use of more porous, well drained filter media reduces the risk of over-watering and formation of moisture saturated zones and channels, and constitutes another passive moisture control measure. Such media, for example those composed of coarse, chipped root wood, are now frequently used in European applications. Their inherently low sensitivity to overwatering allows application of conservatively high watering rates, thus minimizing the risk of dry-out. Their main trade-off is lower pollutant removal per volume of media.[21]

As an alternative to measuring bed moisture directly, the calculation of moisture demand based on continuous monitoring of temperature and relative humidity in biofilter inlet and outlet has been considered. The limited accuracy of relative humidity measurements in off-gases close to saturation and the partial, unavoidable discharge of irrigation water to drainage following bed irrigation limit the reliability of this approach.

Selecting Moisture Control Options

The previous discussion suggests that moisture evaporation rates and corresponding dry-out periods provide useful screening criteria for the four moisture control options in Table 2. The objective of any moisture control strategy is to avoid fluctuations in media moisture that are sufficiently large to impair performance or damage the media. It has been found that deviations from the optimum media moisture content by as much as 30 liters of water per m^3 of filter material do not cause a significant loss in performance. For a given difference in off-gas moisture content across the filter media (Δ mc, measured in grams per cubic meter of off-gas) caused by the processes listed in Table 1, and a given residence time τ, measured in minutes, the total evaporative loss Q_e ($gm^{-3}h^{-1}$) from the media can be calculated as:

$$Q_e = \Delta mc * 60 / \tau \quad (1)$$

Assuming Q_e represents an average evaporation rate, beds should be watered at a minimum frequency, or within a typical response period n, measured in days, of:

$$n = 1{,}250 / Q_e \quad (2)$$

to avoid a reduction in moisture content by more than 30 l/m^3. This simple model assumes even moisture loss from the media. In practice, media close to biofilter inlets tend to dry out more rapidly, and the required response times may be shorter.

Table 3 suggests ranges of evaporative losses for which each of the four control options provides a sufficiently fast response. Off-gases with high VOC concentrations and face velocities—i.e., those with high organic loadings, insufficient prehumidification, and/or high temperatures—require frequent monitoring and spraying and are preferably controlled automatically. Dilute off-gases with low face velocities absorb less moisture, and occasional manual watering or even moisture control by precipitation may suffice. Whether an open biofilter can be operated without any overbed spraying depends on local precipitation rates and the extent of condensation losses or additional heat gains. For a quantitative evaluation, dry season precipitation and the fact that up to 70% of the rainfall may be lost as drainage must be considered.

The four control options are technically downward compatible; i.e., fully automatic systems are also appropriate for off-gases which cause lower evaporation rates. If properly designed and installed, they require less maintenance and improve the operational reliability of a biofilter. They also result in higher capital cost for the fully enclosed vessel, monitoring and control systems, and possibly for the integration into an existing facility control system. These considerations on moisture balance in filter media suggest that the need for its accurate maintenance may pose nonbiological limitations on the suitability of biofiltration for treatment of high VOC concentrations and volumetric loadings. At VOC elimination capacities of more than 100 $gm^{-3}h^{-1}$, the high corresponding evaporation rates and short response times of less than one day make maintenance of an even moisture content increasingly difficult, even with an automatic moisture control system. The relative compactness of filter media and reliance of moisture transport on gravity contribute to this difficulty.

OTHER DESIGN AND CONTROL OPTIONS

Other available biofilter design options relate to reactor design, media selection, and other process monitoring and control features.

Biofilter Reactor

The biofilter reactor consists of an air distribution system contained in a partially open or fully enclosed vessel or reactor, with one or more layers (beds) of the biologically active filter material, and possibly an overbed humidification system. Open and fully enclosed vessels are best distinguished by whether they can be operated under both pressure and vacuum. The walls of open biofilters are most commonly made from concrete, either precast or poured on site. Walls of coated or stainless steel or wood have also been used. In the U.S.,

Table 3. Recommended moisture control methods for biofilters as a function of evaporative loss.

Evaporation Loss $[gm^{-3}h^{-1}]$	*Response Time [days]*	*Recommended Method of Moisture Control*
<50	>25	Manual / Ad hoc method
50-180	7-25	Manual irrigation / periodic media monitoring for moisture content
180-400	3-7	Semi-automatic (timer controlled) method.Requires routine manual media monitoring and timer adjustment.
>400	<3	Semi-automatic method and the use of coarse, well drained media or fully automatic moisture control

open systems for odor control are also frequently installed in excavations without separate walls. Enclosed vessels are usually built as steel frames with insulated sheet metal walls, or as pre-cast or poured on-site concrete structures. Smaller systems (<60 m^3) often involve standardized steel transportation containers, and tanks made from polyethylene or fiberglass-reinforced epoxy resin. Designs of air distribution systems cover the range from slotted PVC pipes with a rock cover to precast concrete plates or blocks accessible to heavy equipment, and with metal grids and support mats made from synthetics.

On a per-volume basis, open biofilters are generally less expensive to build than fully enclosed vessels. They also provide for easier access and loading and unloading of the filter material. Since multi-story design diminishes some of these advantages, almost all open biofilters have been built on a single level. Fully enclosed vessels are predominantly used in recent VOC and HAP control applications in Europe and the U.S. They provide for better insulation and control of media temperature and eliminate the impact of rainfall and plant growth on the media. They also allow for accurate, single point monitoring of the treated off-gas and for better dispersion of residual pollutants. Finally, they are preferred where space constraints dictate the use of a reactor with two or more stacked beds.

Process Monitoring and Control

In addition to bed moisture, the rate of media compaction, temperature, nutrient availability, and pH must be controlled actively or passively in order to maintain a biofilter's mechanical and biological performance. The following approaches are now commonly applied.

Pressure drop and selection of filter material. Rapidly compacting media may require mechanical turning or even replacement after less than one year. To limit pressure drop passively and increase media life, many vendors now employ designed filter materials that involve composted organic matter supported by a larger volume of inert or slowly degradable constituents, such as ceramic, plastic, granular activated carbon, or wood chips. Such media achieve lower pressure drop and longer bed life but are also more expensive than mixtures of unprocessed compost.

Nutrient supply and pH. Most microorganisms capable of degrading VOCs show optimum growth at pH values in the biofilm of between 6.5 and 7.5. To buffer acidic by-products in the media and maintain a neutral pH, most suppliers of biofilters add alkaline buffers to the filter material, usually calcium carbonate lime. The use of a biotrickling filter which allows for active pH control should be considered where high loads of acidifying compounds would otherwise limit the useful bed life.[16] Compost-based media usually supply sufficient quantities of inorganic nutrients for film growth, primarily nitrogen, potassium, and phosphorus. Since some loss of biomass with drainage occurs, particularly in nutrient-poor filter materials, i.e., those with a high fraction of inert or wood based ingredients, these may require the addition of nutrients, preferably poorly water-soluble synthetic fertilizers. Since it may result in excessive biofilm growth, nutrient addition to media or spraying with nutrient solution must be conducted carefully.

Relative humidity and temperature. Off-gas prehumidification by spray nozzle humidifiers, packed bed towers, and steam injection is provided in most recent full-scale biofilters. Selection criteria include their respective space requirements, energy consumption, and sensitivity to particulates and high pollutant loads. For the mesophilic microorganisms that are almost exclusively used, bed temperatures between 10 and 42 °C (50-108 °F) are acceptable, with an optimum range for biological activity of 30-35 °C (85-95 °F). Bed temperatures outside of the 10-42 °C range generally result in reduced pollutant removal and may require off-gas preheating or precooling, which results in additional capital and operating costs. Heating by steam injection or in-duct burners has been practiced in some installations to improve volumetric performance. Adiabatic cooling by prehumidification allows for cooling of hotter off-gases with wet-bulb temperatures below 40 °C. Cooling with ambient dilution air is feasible but generally increases biofilter size and capital cost. Active cooling by heat exchangers and refrigeration is rarely practiced. In some installations, particularly in the tobacco industry, bed temperatures between 45 and 50 °C have been maintained without causing a significant loss in performance. Further research is required into the microbiological mechanisms and the potential applicability for other off-gases with elevated temperatures. Finally, the use of thermophilic microorganisms for treating off-gases with wet bulb temperatures in excess of 50 °C is currently being investigated.[21, 22]

Process monitoring. Biofilter systems may include instrumentation for monitoring off-gas temperature, relative humidity, pressure drop, off-gas flow, moisture content of the filter material, and pH of the drainage. Depending on the number of parameters monitored and the sophistication of data display and logging, the corresponding costs vary considerably. For example, the inlet off-gas temperature may be displayed by an analog thermometer, monitored and recorded continuously or connected to an alarm or shut-down switch. If required by regulation, biofilter inlet and outlet may also be monitored continuously for total organic carbon, using a flame ionization detector (FID). This allows for a more representative evaluation of VOC removal, particularly from streams with fluctuating loads. Screen displays of system status, trends, and alarms are also used in more recent installations. Designs in

which neither the temperature and relative humidity of the raw gas nor the pressure drop across the filter beds are measured are becoming increasingly rare in Europe, since they do not provide even minimal diagnostic information on a system's status and potential performance problems.

COST AND OPERATIONAL CONSIDERATIONS

Capital Cost

For a given application, total installed capital cost (TIC) may vary considerably among designs. Their costs can be compared on a per-volume or a performance basis. Figure 3 shows the typical range of TIC per volume of media installed for systems larger than 100 m^3 that have been proposed and/or installed in the U.S. since 1990. On a per-volume basis, open systems rank at the low end, with enclosed and controlled multi-level biofilters at the high end. Enclosed concrete vessels with a 1.5-m bed height fall in between.

A cost comparison between systems on a per-volume basis is only meaningful if they achieve the same volumetric VOC removal, thus requiring the same residence time and media volume. In practice, many open systems involve less efficient off-gas distribution systems, non-optimized filter materials, and little moisture and temperature control and routinely require longer residence times than fully enclosed, controlled systems, which improves the competitiveness of the latter. The impact of residence time on TCI per installed flow (in $/cfm) is shown in Figure 4. The required cost per media figures were assumed to be the average of the range shown in Table 3. Figure 4 suggests that biofilters become increasingly competitive with the capital costs of incineration systems at residence times of less than one minute. For large open biofilters, TICs of less than $3/cfm have been reported.[4] An accurate cost comparison between competing technologies and designs for a specific application usually requires pilot testing or experience-based vendor information. With the still small number of fully enclosed systems installed in North America, the biofilter market is not yet mature and prices reflect not only differences in technological sophistication, but also the current competitive marketplace and the suppliers' generally low level of full-scale experience.

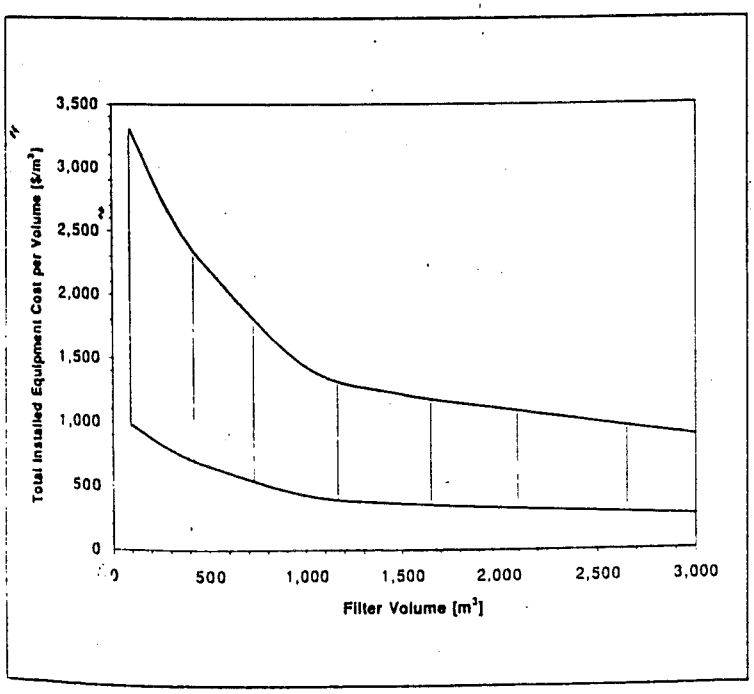

Figure 3. Estimated range of capital cost for biofilters >100 m^3.

Operating Cost

Operating cost items for a biofilter include charges for electricity, replacement of spent media, consumption of water, monitoring, and maintenance and repairs. A brief assessment of how filter design may affect these items follows.

Energy consumption. This is primarily due to off-gas transport through ducts, humidifier, and media beds. Pumps and controls contribute smaller amounts. Bed pressure drop depends on structure and moisture content of filter material, off-gas face velocity, and bed depth. It is routinely higher for open filters, where non-optimized media with a higher specific pressure loss are more common because of their lower initial costs. For a given residence time and media, single-bed biofilters show the lowest pressure drop. Systems with two beds in series have twice the face velocity and effective bed height and at least four times the pressure drop of a single layer system. This mandates the use of designed filter materials with a low specific pressure drop and media life. Total bed pressure drops in full-scale applications may range from 50 to more than 3,000 Pa (0.2-12 inches of water column, "wg). Corresponding power demand for a 30,000 m^3/h (18,000 cfm) stream varies from 0.7 to 41 kW, indicating a potentially considerable impact of media selection and bed design on energy cost.

Water consumption. Due to their inherently higher condensation gains and heat-up losses, the water balance of open systems may differ considerably from that of enclosed systems treating the same off-gas. Also, some of their water demand is provided by natural precipitation. However, the corresponding cost savings are insignificant, typically less than $200 per year for a 1,000 m^2 bed.

Operation and maintenance. For a biofilter performing well, monitoring and control of its moisture content and checking and recording other basic operating parameters constitute the major routine maintenance requirements. Respective labor requirements depend on the system's moisture balance, choice of moisture control, data monitoring, and control systems. An

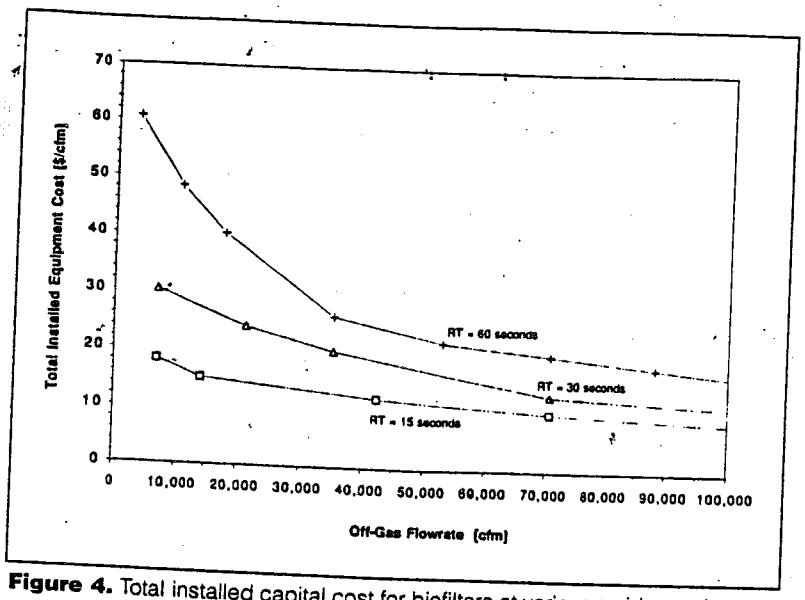

Figure 4. Total installed capital cost for biofilters at various residence times.

open filter of several hundred m² which treats off-gas with fluctuating VOC concentrations frequently exceeding 1 g/m³ may require as much as several person hours per day to maintain the proper moisture content. Biofilters with an effective automatic moisture control system, and well designed open biofilters treating low pollutant loadings for odor control, typically require five to ten minutes of maintenance per day. Performance problems with full-scale biofilters due to media dry-out or compaction have routinely caused additional demand for inspection, maintenance and repair work.

Media replacement. Replacing the filter media is the most arduous biofilter maintenance item. Depending on its initial composition and operating conditions, replacement is typically required every 2 to 7 years when the bed pressure drop has become unacceptably high and performance decreases. At typical media loading rates of 50-200 m³/day, replacement may require several days. In open systems using cast concrete air distribution elements, easier access to the filter material facilitates its replacement and its periodic fluffing with frontloaders to extend useful life. Since the latter is impractical for enclosed systems, their vendors usually employ the already mentioned designed media with a targeted useful life of 4 to 7 years.

Annualized filter material replacement costs depend on the media's useful life, media volume, and cost per volume. Open systems are more likely to use less processed media, usually obtained from local composting facilities. Tradeoffs for their lower cost, typically $30-$50/m³ excluding installation, may include a shorter useful life and lower performance, resulting in a larger required filter volume. Designed media routinely achieve bed lives of more than five years while maintaining a low pressure drop,[23] but at a total replacement cost of typically $100-$300/m³. Cost savings from extended life and lower energy cost may only partly justify their higher initial cost. Their generally higher performance and reliability, and longer periods between bed replacements, argue in their favor.

OTHER CRITERIA FOR SYSTEM SELECTION

Operational Reliability

Because of their limited control of temperature and moisture, open beds are more sensitive to loss of performance in applications with short dry-out and response times; i.e., they are inherently less reliable. Enclosed systems with automatic moisture control and more durable filter material are intended to minimize this risk. A lower level of control may suffice for dilute off-gases in climates without extreme temperatures and precipitation, or if regulatory requirements need not be met consistently and some variation in performance is acceptable. The latter situation is common for odor sources without immediate residential neighbors, generally lower odor levels and seasonal emission patterns.

Siting Considerations

Footprint and volume of biofilters are large compared to competing air pollution control systems. To date, most biofilters have been installed at ground level. Where a biofilter competes with other facility operations or expansions for space, rooftop installations are common. They may also allow for siting directly above the emitting source, thus reducing ducting cost. Since existing buildings can rarely support concrete biofilters, rooftop installations usually involve steel or plastic reactor vessels. They are predominantly built as enclosed systems, although some open rooftop installations have been built in Europe.[12]

Off-Gas Monitoring and Dispersion

If biofilters are applied for VOC or HAP control, their compliance with quantitative regulatory standards must be verifiable by monitoring pollutant concentrations in the raw and or treated off-gas. In open systems, the lack of a single discharge point and the common spatial variations in filter performance, including channeling, impair the reliability of performance measurements with monitoring hoods. Closed systems discharge the entire treated stream from a stack and allow potentially continuous single-point monitoring for total VOC or selected organic species.

Stack discharge from closed systems also provides for better off-gas dispersion, typically by a dilution factor of 50-250 at the facility boundary. Thus, residual odors in the off-gas from a properly functioning biofilter, which are typically in the range of 50-100 odor units, are rarely noticed by neighbors. Open systems emit such odorous residues at lower exit velocities and at ground level. As a result, poor performance of an open system is more likely to cause odor nuisances in

its vicinity, which have been experienced in some cases. The same applies to distribution of the moisture plume typically emitted by biofilters, particularly during cold weather.

CASE EXAMPLES

Three case examples of full-scale biofilters for VOC and HAP control illustrate the relationship between off-gas characteristics, moisture balance, system design and maintenance needs. The systems were installed in the early 1990s for the control of VOC or air toxics from industrial processes, one in the Netherlands, the others in the U.S.

Case example 1. A two-level open biofilter is used to treat 17,000 m^3/h (10,000 cfm) of off-gas from the mold production at an investment foundry in Los Angeles. As a function of production rates, the off-gas contains often high (up to 3 g/m^3) and strongly fluctuating concentrations of VOC, predominantly ethanol. At a residence time of ~60 seconds and an inlet wet-bulb temperature of ~20 °C, temperature increases across the bed of more than 5 °C and moisture losses of more than 500 $gm^{-3}h^{-1}$ are common. A typical humidity and temperature profile for this unit is shown in Figure 1. Although a timer-based, semi-automatic sprinkler system controls spray humidification, it has been difficult to maintain proper bed moisture at these evaporation rates. The considerable need for irrigation, typically 2 cm/day, also caused flush-out of fine particles which were present in excess in the original bark and sewage-sludge compost based filter material. Subsequently, compaction and an increase in bed pressure drop to more than 3,000 Pa (12" wg) required replacement with a less compact, wood-chip based media after two years of operation. Moisture monitoring of the filter material and adjustment of irrigation patterns were labor-intensive but did not avoid repeated dry-out, particularly in the bottom zones. Three years of operating experience support the suggestion made in Table 3 of using automatic moisture control for evaporative losses exceeding 400 $gm^{-3}h^{-1}$.

Case example 2. Two single-level open biofilters were installed in 1992 to treat similar off-gas streams from polymer manufacturing facilities in Springfield, MA and Trenton, MI. The off-gas flow rate is about 35,000 m^3/h (20,000 cfm) and the off-gas contains between 0.4 and 0.7 g/m^3 of total VOC, predominantly ethanol plus aldehydes and esters. Biofilter VOC removal efficiency is measured every few months at between 90 and 95%. It is limited by several high molecular weight VOCs which are present in low concentrations in the inlet off-gas but are the primary compounds in the treated exhaust gas.

Just prior to entering the biofilter, the off-gas is saturated by spray nozzles and the gas temperature is controlled between 30 and 35 °C, i.e., above average ambient temperature. The residence time of the off-gas in the biofilter is about 100 seconds and the elimination rate for total VOC is 15-25 $gm^{-3}h^{-1}$. The filter material, a compost/wood chip mixture, is sampled in several locations every few months for moisture content and other attributes. The compost moisture content has varied between 50 and 70% by weight, somewhat higher than the 40-60% optimum. Initially, water spray systems were not installed on either biofilter. For moisture control, media relied on rainfall and temporary condensation of moisture from the warm off-gas. This has been adequate with the exception of two extended periods of hot, dry weather when water was manually sprayed to prevent dry-out of the filter material. A manual bed spraying system has recently been installed on one of the biofilters to improve the moisture distribution compared to spray hose. Experiences with these two open biofilter demonstrate that rainfall and condensation may provide sufficient moisture to open beds not equipped with additional spray, if VOC concentrations in the raw gas are low, its wet bulb temperature exceeds the ambient temperature, and the off-gas is humidified just prior to entering the bed. They also indicate the potential for dry-out in case of extended hot dry periods and for condensation of moisture in the filter material during colder periods.

Case example 3. A fully enclosed biofilter with two stacked beds operated in series (total media volume: 1200 m^3) is used to treat 140,000 m^3/h (80,000 cfm) of easily degradable solvents. VOC concentrations in the raw gas are fairly constant and typically average 500 ppmC. The wet-bulb temperature is 20 °C. At the designed residence time of 30 seconds, the biofilter achieves 90% VOC removal, sufficient to meet regulatory standards which limit organic carbon concentrations in the treated off-gas. The biofilter is equipped with an automatic moisture control system which consists of load cells, overhead sprays, and a PLC control system, and maintains a constant bulk moisture content in the filter material.

The unit has been in operation with the initial batch of filter material for more than six years. At a face velocity of 240 m/h (13 fpm), the total pressure drop across the beds has gradually increased by ~25% to 500 Pa (2" wg). The system achieved reliable moisture control of the beds, required little maintenance, and demonstrated the advantages of an enclosed system with automatic moisture control for treating off-gases with high face velocities and medium VOC concentrations. It also provided several lessons on the compatibility of biofilters with sophisticated industrial processes. First, it demonstrated that biofilters are suitable as an add-on control technology for production processes which require that negative pressure at the production side be maintained within tight limits. Second, after several years of operation, bed irrigation had caused some compaction of the surface layer. Raking of the top 10 cm of filter material in the top bed, which typically requires three person shifts of labor, decreased the

pressure drop to previous levels. Raking is now performed on an annual basis. Finally, in order to maintain an even moisture content across the height of the beds, minimum and maximum spraying duration had to be adjusted to changes in average VOC concentration. For the same total irrigation rate, longer and less frequent spraying achieves better bed penetration and brings relatively more water into the lower levels of the media. This is typically required at higher VOC inlet concentrations.

CONCLUSIONS

This review of biofilter thermodynamics, general operational experience, and several full-scale case examples illustrated the relevance of moisture balance and control to biofilter performance. In a biofilter, evaporation and condensation rates are determined by the VOC concentration in the off-gas, face velocity (or residence time), degree of prehumidification, inlet temperature, heat and moisture exchange of the media with the environment, and media degradation. These parameters and the resulting evaporation rates vary widely in full-scale biofilters, typically 1-30 mm of water column per day. Considering drainage losses, actual irrigation demand will be higher. The period in which detrimental dry-out of the media occurs and the appropriate moisture control varies accordingly. This is illustrated by the following two typical cases.

Open systems without an installed irrigation system maintain acceptable moisture content and performance if moisture losses are sufficiently low to be replaced by spraying on less than a monthly basis, by rain, or by condensation gains. This is the case for off-gases with wet bulb temperatures at or above ambient levels and VOC concentrations of <0.1 g/m^3, typical for many odor control applications. In those applications, their lower capital cost compared to fully enclosed, controlled systems make open biofilters attractive.

VOC concentrations and elimination capacities exceeding 0.5 g/m^3 and 50 gm^{-3}h^{-1}, respectively, cause high evaporation rates and require increasingly sophisticated moisture control systems, typically involving fully enclosed filter vessels. Over the last decade, these systems have achieved a reasonably accurate and reliable control of media moisture. The necessary monitoring, control, and data-logging equipment may add considerably to system cost. As VOC elimination capacities exceed 100 gm^{-3}h^{-1}, the resulting moisture removal rates make maintaining the proper moisture content in large, heterogeneous reactors increasingly difficult, even with automatic moisture control. This constitutes a major nonbiological limitation to high volumetric VOC removal in a biofilter.

REFERENCES

1. Leson, G.; Winer, A. "Biofiltration: an innovative air pollution control technology for VOC emissions," *JA&WMA* 1991, *41*, 1045.
2. Leson, G.; Dharmavaram, S. "A status overview of biological air pollution control," *Proceedings of the 88th Annual Meeting of A&WMA*, A&WMA: Pittsburgh, PA, 1995.
3. Williams, T. "Biofiltration for the control of odorous and volatile organic compound emissions in municipal and industrial applications," *Proceedings of the 88th Annual Meeting of A&WMA*, A&WMA: Pittsburgh, PA, 1995.
4. Williams, T. E&A Environmental Consultants, Cary, NC. Personal communication, 1996.
5. Singleton, B. EG&G Biofiltration, Saugerties, NY. Personal communication, 1996.
6. Gethke, H.G. "Positive und negative Erfahrungen mit grosstechnischen Biofilteranlagen," *VDI Berichte 1034;* VDI Verlag, Düsseldorf, 1993.
7. Heslinga, D.C. "Biofiltration technology," *VDI Berichte 1104;* VDI Verlag, Düsseldorf, 1994.
8. Bohn, H.L. "Soil and compost filter of malodorant gases," *JAPCA* 1975, *25*, 953.
9. Eitner, D.; Gethke, H.-G. "Design, construction and operation of biofilters for odor control in sewage treatment plants," *Proceedings of the 80th Annual Meeting of APCA*, APCA: Pittsburgh, PA, 1987.
10. Leson, G.; Chavira, R.; Winer, A.; Hodge, D. "Experiences with a full-scale biofilter for control of ethanol emissions," *Proceedings of the 88th Annual Meeting of A&WMA*, A&WMA: Pittsburgh, PA, 1995.
11. van Lith, C. "Design criteria for biofilters," *TransIChemE* 1990, *68* (Part B), 127.
12. Paul, H. "Biofiltereinsatz zur Reduzierung der Geruchsemission aus einem Giessereibetrieb," *VDI Berichte 1104*, VDI Verlag, Düsseldorf, 1994.
13. *VDI Guideline 3477: Biological Waste Gas/Waste Air Purification Biofilters;* VDI Verlag, Düsseldorf, 1991.
14. Knuth, M. "Beseitigung von Riechstoffen und Hexan im Abgas einer Ölmühle mit einem Biofilter," *VDI Berichte 1104*, VDI Verlag, Düsseldorf, 1994.
15. Plas, C.; Holubar, P.; Moser, K.; Ploder, W.; Braun, R. "Die Bilanzierung von Wasser und Kohlenstoff bei der Biofiltration," VDI *Berichte 1104*, VDI Verlag, Düsseldorf, 1994.
16. Ottengraf, S.P.P; Diks, R.M.M. "Process technology of biotechniques," *Biotechniques for Air Pollution Abatement and Odour Control Policies* (Dragt, A.J.; van Ham, J., Eds:); Elsevier: Amsterdam, London, 1992.
17. Seed, L.P.; Corsi, R. "Biofiltration of benzene, toluene, and o-xylene: substrate effects and carbon balancing," *Proceedings of the 89h Annual Meeting of A&WMA*, A&WMA: Pittsburgh, PA, 1996.
18. Lee, B.D; Apel, W.A.; Walton, M.R.; Cook, L.L. "Treatment of methanol contaminated air streams using biofiltration," *Proceedings of the 89h Annual Meeting of A&WMA*, A&WMA: Pittsburgh, PA, 1996.
19. Nichols, K. Weyerhaeuser Co., Federal Way, WA. Personal communication, 1995.
20. Yang, Y.; Alibeckoff, D. "Biofiltration for control of CS_2 and H_2S vapors," *Proceedings of the USC/TRG Conference on Biofiltration.*
21. Knauf, S. "Biofiltration bei Ablufttemperaturen über 40 °C," *Staub-Reinhaltung der Luft* 1994, *54*, 41.
22. van Groenestijn, J; Harkes, M.; Cox, H.; Doddema, H. "Ceramic materials in biofiltration," *Proceedings of the USC/TRG Conference on Biofiltration.*
23. van Lith, C. "Long term experiences with biofilter material stabilized with inert additives," *Proceedings of the 89th Annual Meeting of A&WMA*, A&WMA: Pittsburgh, PA, 1996.

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INSTALLATION, OPERATION AND MAINTENANCE MANUAL

Prepared by:
Environmental BioSystems

November, 1996

Company Description

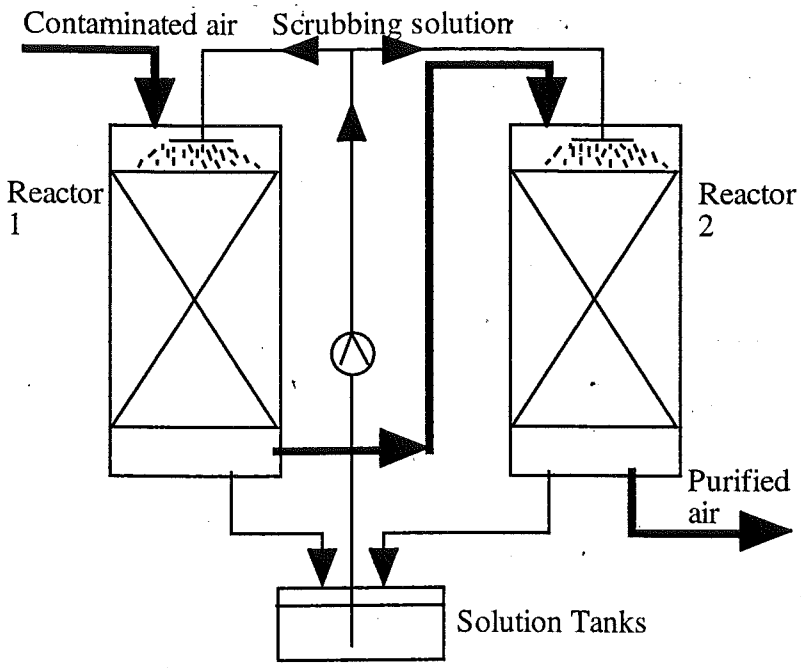
Environmental BioSystems is an environmental biotechnology company dedicated to discovering and commercializing biological based treatment technologies for use in pollution prevention and hazardous waste site remediation. Specifically, Environmental BioSystems develops, designs, and fabricates computer controlled treatment systems for air, water, and solid waste streams. The staff consists of leading researchers in the environmental arena, several of whom are affiliated with University programs throughout the US. Projects include the design and fabrication of both biofilters and biotrickling filters for treating waste streams contaminated with diehloromethane (DCM), styrene, methyl isobutyl ketone (MIBK), JP4 fuel, and other petroleum base hydrocarbons. The company has worked for federally funded research programs, the department of defense, and several industrial companies.

Two Stage Biotrickling Filter

Environmental BioSystems, along with the University of California at Riverside, has designed and fabricated a pilot-scale *BIOTRICKLING FILTER* for demonstrating the technologies effectiveness at treating both industrial waste streams and contaminants from remediation sources. *The BIOTRICKLING FILTER* utilizes biological processes to remove the contaminants from the waste air streams and subsequently convert them into carbon dioxide and water.

Process Description

The *BIOTRICKLING FILTER* consists of a two-stage columnar reactor containing a media that serves as an attachment surface for the retention of microorganisms. The reactor maintains high concentrations of biomass, thereby providing high volumetric efficiency.



The system works in a down flow mode. The contaminated air stream enters the top of the first reactor, passes through the packing media, and exits at the bottom. The stream is then channeled into a second reactor, where it undergoes the same treatment as in the first reactor. As the air stream passes through the reactor, contaminants in the air phase solubilize in a liquid/biomass phase and are degraded by the microorganisms. The microorganisms utilize the contaminants for energy and growth purposes. The end-products of the degradation are carbon dioxide, water, heat, and newly synthesized microorganisms. In addition, pumps recirculate water through the system in a downflow mode. The recirculating water enables the addition of inorganic nutrients, controls the pH, maintains constant temperature throughout the systems, and removes harmful metabolites.

Process Control

The system is controlled by a graphics-based computer program which uses a pentium computer equipped with data acquisition and control boards. The computer control system simultaneously monitors 30 input sensors and controls 18 output devices. Input parameters including temperature, pressure, flowrate, pH, conductivity, reactor weight, water level, and air contaminant concentration are measured and assimilated by the process control program. To maintain optimal operating conditions, the process control system interprets the input parameters and adjusts the output control devices. The output devices include water pumps, air blowers, water heaters, nutrient and caustic metering pumps, and water and air solenoid valves. In addition, the control systems statistically manipulates the input data from the sensors and stores values in output files that can be subsequently download. The graphical program allows continuous monitoring of all sensors and other devices through a specially designed control interface. The graphical

interface displays measured values from the sensors, identifies status of output parameters, and allows equipment to be turned on and off and calibrated with the simple click of a mouse. All control can be accomplished from the control system at the testing site, or from anywhere in the world via modem and phone line.

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Manufacturer's Equipment Manuals

Components List

Design air flowrate	180 cfm
Design water flowrate	240 gpm
Maximum air operating pressure	40 inches of water
Maximum water operating pressure (at pump heads)	45 psi
Designed operating water temperature	100 deg. F
Spray Nozzles	Bete TF full cone, 3/4 inch, 170 deg, 10 psi
Nutrient and NaOH Tanks	Polyethylene
Bioreactor Tanks	Stainless Steel 304
Chassis (computer control system)	SCXI-1000, 4-slot, National Inst.
Analog and Digital I/O Board	Model AT-MIO-16E-10, National Inst.
I/O Connector Box	Model CB 150, National Inst, used with the level switches
Input Signal Conditioning Device	Model SCXI-1102, National Inst, 32 channel
Output Power Modules	Model SCXI-1161, National Inst, 8 channel
Software	Labview windows 95, National Inst.
Gas Detector	FID and DELCD, SRI instruments
Sampling air pump	Model TD-4X2, two headed, 24 volt power, 2 L/min at 2psi, maximum pressure is 5 psi, Brails-Ford
Water pumps	Model (AB) D, Series, 3000, 5 hp, 60 Hz, 230 volt, 3 phase, 120-140 gpm at 80 feet of water head,R.S. Corcoran
Air Blower	Model DR707K72X, 3 Hp, 60 Hz, 230 volt, 3 phase, 180 cfm at 50 inches of water head, EG&G Rotron
Water flowmeters	Model 8510, 24 volt, 0-180 gpm in 2 inch

	diam. pipe, Signet
Conductivity probe	Model 2820, 24 volt, 0-100,000 µS, Signet
pH meters	Model 8710, 24 volt, 0-14 range, Signet
Thermocouples	Model CF-090-T-4-60-2, mV signal, SS construction
Water level switches	Model LV10-1201, 2 mm accuracy, polypropylene, Flowline Inc.
Air Pressure Gauges	Series 630A, 24 volt, 0-20 inches of water & 0-100 inches of water, Dwyer
Water Pressure Gauge	Series 634A, 24 volt, 0-60 psi, Dwyer
Metering Pumps	Series C/LC04SA-PTT1, 115 volt, 12 & 22 gpd, Harrington
Water Immersion Heaters	Model ST122261,60 Hz, 240 volt, 29 amp, 12,000 watt, Process Technology
Overload Relays	Model 100-A18ND3, 240 volt, 3 phase, 15 amps, Orange County Electric
Air flowrate orifice plate	Model 4150, 304 ss, 0-300 cfm in 3 inch diam. pipe, Lambda Square, Inc.
Load cells	Model SB-5000s, max cap: 5000 lbs, 15 VDC excitation, Cardinal Scale Manufacturing CO.
Water visual flowmeters	Model F-440, 0-10 gpm & 0-40 gpm, Blue White Industries
Air Soleniod Valves	Model 6013, 24 volt,brass, Burkert
Water Solenoid Valves	Brass body, 3/4 inch adapters, 110 volt, Superior Globe Valve
24 Volt Power Supply	Model SPWS-2436, 110 volt input power, Acme Electric Corporation
Computer	Pentium chip, 125 mHz, 1.6 gigbyte hard drive, 16 megabyte internal ram, disk drive, color monitor

Particulate Knock out	Model CSL-335P-300, 3-inch adapters, steel construction, Solberg Manufacturing
Strainer Basket	PVC construction, 3-inch adapters, Harrington Plastics

Basic System Components

The two stage biotrickling reactor is constructed from rugged 304L stainless steel, steel, and PVC. It is designed to handle extreme operating conditions associated with treating dichloromethane vapors. Prior to operating this system, the operator must have a full understanding of the many components involved with the system. The operator should have a solid understanding of water and air process flow, electricity, and technical problem solving. We recommend that the new operator go through a mentoring program with the current operator to obtain hands on instruction. In addition to this manual, we have also created an instructional video that should be viewed.

In addition to the descriptions provided below, information from manufacturers of the individual components on the system are included in the appendix under "Manufacturer's Equipment Manuals".

Water Pumps

The system uses two water pumps, installed in parallel, to provide water flow through the system at a maximum rate of 240 gpm. Each pump provides 120 gpm. This flowrate probably will only be required while treating chlorinated compounds such as DCM. For most other compounds, the system will require a much lower flowrate that should be able to be achieved with just one pump. With one pump operating, the headloss through the system is less, with a maximum flow of approximately 150 gpm can be achieved.

The water pumps are manufactured by R.S. Corcoran (Model (AB) D, series 3000). They are 5 hp pumps requiring 60 Hz/230 volt 3 phase power. They can operate with pressures not exceeding 110 feet of water head. Pressures above this will damage the pumps or the electrical system.

Important notes:

- Before turning on pumps, make sure that all water passageways are clear and water pipe valves are open. Turning on pumps with clogged pipes or closed valves will damage the system and pumps.
- Never turn pumps on without water in the system (or run pumps dry). This will destroy pumps within a few seconds and void the warranty.
- When installing the system at a new site, check to see if pumps are rotating in the right direction. Installing electrical lines incorrectly will change the rotation of the pumps.
- Read R.S. Corcoran instruction manual before operating pumps.

Blower

The blower on the system is designed to provide a maximum flow of 210 cfm. The blower is a EG&G Rotron Model DR707K72X, 3Hp, that operates with 60 Hz/230 volt/ 3 phase power. Pressures should not exceed 80 inches of water with this blower.

Important notes:

- Before turning on blower, make sure that all air passageways are clear and air pipe valves are open. Turning on blower with clogged pipes or closed valves will damage the system and blower.

- When installing system at a new site, check to see if blower is rotating in the right direction. . Installing electrical lines incorrectly will change the rotation of the blower.

- It is critical that water does not enter the blower housing while the blower is operating; this will damage the blower and void the warranty. The control system prevents this from happening by first starting the blower and then the water pumps. However, in manual operating mode, this safety procedure is not present and precautions should be taken to avoid water entry.

- Read Rotron's operating instruction manual before operating blower.

Metering pumps

Four metering pumps are installed on the reactor. This pumps supply the nutrients and pH adjusting solutions to the reactor. The metering pumps are supplied by Harrington (Series C/LC04SA-PTTI) and operate off of 115 volt/60 Hz/single phase power. The pumps handle a range of flowrate between 2 - 22 gpd. Specific flowrate ranges are listed on the pumps. The pumps capacity is controlled by means of the stroke length adjusting knob. Therefore, a range between 0 - 100 % stroke length will have to be correlated with the desired flowrate (see metering pump operating manual for details).

Important notes:

- Before turning on pumps, make sure that all water passageways are clear and water pipe valves are open. Turning on pumps with clogged pipes or closed valves will damage the system and pumps.

- Read Harrington's operating instruction manual before operating pumps.

Air Sampling Pump

Air samples are collected via a small two headed membrane pump. The pump is designed for a maximum flowrate of 3 lpm and has special membranes made of vitron

that are resistant to most chemicals. The pump is manufactured by Brails-Ford (Model TD-4X4) and requires only 24 volt power. Its maximum operating pressure is 5 psi.

Important notes:

- Never turn air pump on with all air solenoids in the closed position. This will immediately cause membrane failure and void the warranty.
- Make sure pressure gage downstream of the air pump is set correctly at approximately 3 psi. Higher pressures will cause damage to the pump.
- The pump membranes only have a limited life time expectancy and will have to be replaced every 7 or 8 months, if system operates continuously.
- Read metering pump operating manual before using pumps.

Water Immersion Heaters

To maintain optimal operating water temperatures, the system is equipped with two water immersion heaters, one in each reactor. The heaters are manufactured by Process Technology (Model ST122261, stainless steel 316) and required 230 volt/60 Hz/230 volt power. They draw a significant amount of power at approximately 12,000 watts/each or 29 amps/each. For treatment of DCM, both heaters may be required to maintain temperatures. However, other compounds should only required one heater.

Important notes:

- Never turn on heaters when they are not submerged in water. The water level in the reactors should be at least 6" above the heating elements. If the elements are not properly submerged they will overheat, damaging the elements, posing a fire hazard.
- Keep water temperature below 105^0 F. Higher temperatures may adversely affect microorganisms, increase evaporative losses, and cause condensation problems in the sampling lines.
- Heater sheath should be cleaned once a month to prevent excessive buildup of biomass and other debris. Accumulation of this material will shorten heater life.
- Read Process Technology's operating manual before using heaters.

Load Cells

The accumulation of biomass in the two reactors is measured by the use of load cells placed beneath each reactor. Three load cells per reactor are used. The cells are

manufactured by Cardinal Scale Manufacturing Company (Model SB-5000s). They require 15 volts of direct current (DC) for excitation. The maximum capacity for each load cell is 5000 lbs, allowing a total reactor weight of 15,000 lbs to be measured. The load cells are mounted on a unique removal system for transportation and alignment purposes. Jacks mounted on the bottom plate of the reactor are used to elevate the reactors and remove the jacks for maintenance or transportation purposes.

Important notes:

- Remove load cells from beneath the reactors before transportation of the unit. Transportation of the systems with full load on the cells will damage the cells and void the warranty.

- During installation of the system, the load cell support system, consisting of two square steel beams 5 feet in length, should be supported with redwood wedges. Wedges should be placed between the ground surface and the beams. This will prevent flexing of the beams that would cause inaccuracies with the measurements and irreversible damage to the beams.

- During transportation of the system, tie the support structures for load cells to the skid of the reactor unit to prevent movement and damage. This may be accomplished with rope or elastic lock down devices.

- Read Cardinal's instruction manual before operating load cells.

Air Pressure Gauges

The system utilizes four very sensitive air pressure transmitters for headloss measurements across the blower, across the two reactors, and differential measurements across an orifice plate. The pressure transmitters are manufactured by Dwyer Instruments (Model 630A) and require 24 volts DC to operate. Three of the transmitters measure between 0-20 inches of water while the fourth measures between 0-100 inches of water (for the blower). The transmitters convert the pressure readings to ampere output signals between 4-20 mA DC. The ampere signals are sent to the computer control system for interpretation and collection. The computer control system uses measurements as a safe guard for clogging problems, shutting down the system if pressures deviated from an established ranged.

Important notes:

- Never exceed the maximum differential pressures. This will destroy the membrane in the gauges and void the warranty. The maximum differential pressures are twice that of the range pressures. Therefore, 40 inches and 200 inches for the two different range gauges. The maximum pressures are easily

exceed if one of the pressure lines is removed from the gauges during system operation (BE AWARE OF THIS).

- Note that the LED reading on the transmitters is percent of the calibrated range and not inches of water. Therefore, for the 0-20 inch transmitters, a LED reading of 50 corresponds to a pressure differential of 10 inches of water.

- Prevent water accumulation in the air pressure lines.

- Read Dwyer operation manual before using gauges.

Water Flow Meters

The system measures water flowrate with two digital water flowmeters located near the entrance of the inflow water line to the reactors. The flowmeters are a combination of a paddlewheel and a meter that interprets the paddle wheel signal and converts it to flowrate. Each flowmeter can measure flows between 0 and 180 gpm in a two water line. The flowmeters are manufactured by Signet (Model 8510) and require 24 volt DC power. The flowmeters convert the flow to ampere output signals between 4-20 mA DC. The ampere signals are sent to the computer control system for interpretation and collection. Flowrate readings are also displayed on the LED screen of the transmitter. Flowrates are monitored by the computer control system which automatically shuts down the system if rates deviate from an established range.

Important notes:

- Make sure paddle wheel is installed correctly. Slight deviations in alignment cause significant inaccuracies in measurements.

- The paddle wheel assembly should be checked and cleaned once a month.

- Read Signet instruction manual before operating flowmeters.

Orifice Plate

Air flowrates are measured with a highly reliable device called an orifice plate. The 3 inch stainless steel orifice plate measures flowrates between 0-300 cfm. The basic concept is to measure, with a pressure transmitter, the differential pressure across the plate. This differential pressure varies with changing flowrates. The orifice plate is manufactured by Lambda Square, Inc. (Model 4150). Flowrates are monitored by the computer control system which automatically shuts down the system if rates deviate from an established range.

Important notes:

- Check pressure lines and adapter locations once a month for potential clogging.

- Read Lambda Square's instruction manual before operating orifice plate.

Water Pressure Gauge

Water pressures are measured with a Dwyer Series 634A pressure transmitter which converts water pressures between 0-60 psi to 4-20 mA signals that can be subsequently interpreted by the computer control system. The system uses just one water pressure transmitter, located downstream of the water pumps. This gauge serves several purposes. First it monitors pressures in the water lines and detects increases in pressures due to biomass accumulation in the water filter. Secondly, it is used by the computer control system as a safe guard for pump failure, shutting down the system if pressures deviated from an established ranged.

Important notes:

- Check calibration of the pressure gauge on a month basis with the manual pressure gauge hook to the system.

- Monitor changes in water pressure closely. Increase or decreases in the water pressure signify changes in flowrate of backpressures in the line that may have to be rectified (e.g. increase in backpressure may suggest that the strainer basket needs to be cleaned).

Visual Water Flowmeters

Recirculation water used to mix fluids in the bottom of both reactors passes through visual flowmeters prior to entering the reactors. In addition, inlet and outlet water supplies for the reactor pass through visual flowmeters. Blue White Industries manufactures the flowmeters (Model F-440) and their range is 0-40 and 0-10 gpm, respectively.

Important notes:

- These flowmeters will need to be cleaned on a monthly basis to remove accumulated biomass and other debris.

- Flowmeters should be checked once a week. They do have a tendency to lock in one position, therefore inaccurately displaying the flowrate.

- Read Blue White Industries instructional manual before using flowmeters.

pH Meters

The systems uses two pH meters to monitor pH levels in both reactors. The meters consist of three separate components: the pH probe, an amplifier, and a transmitter. Signet manufactures the pH system (Model 8710) which requires 24 volt DC power. The probe and amplifier are mounted at a 25 degree angle on the reactor wall with a specially designed removal system for easy maintenance and calibration. The pH system measures values between 0 and 14. The transmitter receives signals from the probe/amplifier, calibrates the signal and sends a 4-20 mA signal to the computer control system. pH values are displayed on the LED screen of the transmitter. The pH values are used by the control system to adjust the pH in the system through NaOH addition via the metering pumps.

Important notes:

- The pH probes are very sensitive instruments and should be handled with care.
- The tip of the probe should always be in solution and never be allowed to become dry. Therefore, during transportation of the system, probes should be removed from reactors and shealths with pH 7 solution placed over the tip.
- The calibration of the probes should be checked on a weekly basis.
- Read Signet's instructional manual before using pH system.

Conductivity Probe

The conductivity of the recirculated water is measured just downstream of the water pumps and is used to monitor the accumulation of salts. The system consists of a probe and a transmitter manufactured by Signet (Model 2820) that has a range of 0-100,000 μS. As with the other Signet devices, it uses 24 volt DC power. The transmitter displays the reading and sends a 4-20 mA signal to the computer control system. Based on the readings, the control system adjusts the conductivity of the water by adding and withdrawing water, therefore removing the accumulated salts. If conductivity adjustment procedures fail and values increase beyond a critical level, the control system will shut down the reactor system.

Important notes:

- The tip of the probe should be cleaned and calibrated on a monthly basis.
- When removing probe from PVC line, take care in not rotating the flexible all that much. Over rotation may damage wiring.
- Read Signet's instructional manual before using conductivity system.

Thermocouples

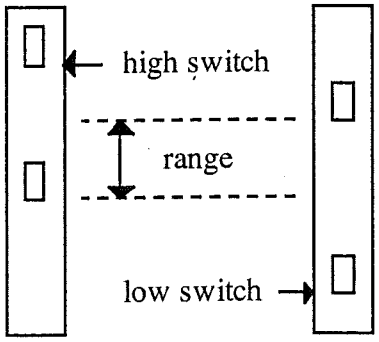
The treatment system is equipped with five thermocouple probes, two installed in the water lines and three installed in the air lines. Omega manufactures the probes (Model CF-090-T-4-60-2) which have a stainless steel shealth that is resistant to most chemicals. The probes are mounted on the water and air lines with swagelock fittings for easy removal. The probes measure the inlet, middle, and outlet air temperature through the reactor and the water temperatures in each reactor. mV signals are sent to the computer control system for temperature correlations. The water heaters are adjusted based on the water temperature in the system.

Important notes:

- Clean probes once a month.
- The thermocouple wires are sensitive and should be handle with care.

Water Level Switches

Water levels in both reactors are maintained at an establish range through the use of water level switches mounted in clear sight tubes, adjacent to the reactors. The level control system uses two sights, each containing two level switches. The switches are manufactured by Flowline Inc. (Model LV10-1201) and are made of polypropylene. Their accuracy is +/- 2 mm.



The diagram identifies the position of the switches in relation to each other. The switches are used by the computer control system for a number of important purposes. Under proper operating conditions, the water level in the sight tubes should be between the two switches identified with the range arrow. If the water level drops below the bottom range switch, the computer adjusts the water level upwards by adding fresh water to the system. If the water level exceeds the top range switch, the control system reduces the water level by dumping water out of the reactors. Therefore, the water level should never deviate from this range. However, two safety switches were also installed in case Murphy's Law comes into play. If the water level drops below the "low switch" or rises above the "high

switch", the control system will shut off the entire system, therefore preventing potential damage to the pumps and blower.

Important notes:

- Switches should be checked on a weekly basis for accumulation of biomass, algae, or other debris. This material may abstruct the sliding action of the switch, therefore making the switch ineffective.

- Take special care when removing the switches from the sight tube. The cord attached to the switches tends to twist when removing the switches, potentially damaging the current flow in the cord lines.

- To prevent algae growth in the sight tubes, tubes should be covered with either foil or cloth, preventing sunlight from entering the sight tubes.

- Read Flowline's operating manual before using the switches.

Water and Air Solenoids

Six air and two water solenoids are used by the system. The air solenoids are used only for air sample collection purposes while the water solenoids control the fresh and waste water flow streams. The air solenoids are manufactured by Burkert (Model 6013) and are brass bodied. They used 24 volt DC power. The water solenoids are manufactured by Superior Globe Valve (Model 950) and also have a brass body but are powered by 110 volt AC power. The solenoids are controlled by the computer control system and a red light is visible on the air solenoids when they are activated and "on".

Important notes:

- Read Burkert's operating manual before using solenoids and understand the ramifications of manually turning valves on and off. Air solenoids have the potential of damaging the air pump if all are closed while the pump is on.

Particulate Drop Out

After the air stream passes through both reactors it enters a particulate dropout device that removes particulates from the air stream before the air exits the treatment system. The particulate dropout is manufactured by Solberg MFG (Model CSL-355p-300) and consists of a steel container with a plastic internal mesh. Water removed from the dropout device is funneled back to the second reactor.

Important notes:

- The plastic mesh screen that removes the water particles requires cleaning on a weekly basis. Failure to clean mesh will cause increase in back pressures throughout the entire reactor system potentially cause shutdown.

Water Filter/Strainer Basket

To remove excess debris from the water stream, the system is equipped with a strainer basket downstream of the water pumps. The basket is manufactured by Harrington Plastics and consists of PVC enclosure, 3 inch inlet and outlet ports, and a plastic mesh basket. Debris is caught in the basket as the water passes through the system.

Important notes:

- The basket requires weekly cleaning to prevent clogging.
- If excessive backpressures occur in the water system, it will most likely be attributed to the strainer basket so initiate problem solving there.

Main Disconnect Switches

There are two main disconnect switches on the system that remove power to the system. One switch for 110 volt power supply and another switch for the 220 volt power supply. A disconnect is required by the National Electric Code (NEC).

Important notes:

- Make sure that a qualified licensed electrician installs the power lines to the disconnect boxes during the installation of the system at a new site.
- When working with any electrical component on system, proper safety procedures should be followed with regard to turning on and off the power with the disconnect switches.
- Don't attempt to solve electrical problems if you do not fully understand and appreciate electricity. Have a licensed electrician help you.

Overload Relays

Overload relays are used between the disconnect box for the 220 volt power supply and the pumps and blowers. Three relays are located in an enclosure next to the disconnect box. The purpose of the relays are to protect the pumps and blowers from excess current surges, to allow variable current to the motors during start-up, and to allow the computer to turn the motors on/off. The relays are manufactured by Orange County Electric (Model 100-A18ND3) and are for 230 volt, 3 phase AC power. The relays are rate for approximately 15 amps.

Important notes:

- If the pumps and blower do not start-up, check the relays first to see if they have been tripped.

- Read the Orange County Electric operations manual for the relays first before using system.

24 Volt Power Converters

Many of the sensors and solenoids on the system require 24 volt DC power. The system is equipped with two 24 volt power converters that convert 110 volt AC power to 24 volt DC. The converters are located in the main control box above the air solenoids. The power converters are manufactured by Acme Electric Corporation (Model SPWS-2436).

Important notes:

- When handling the power converters, turn the 110 volt power off at the disconnect box. The converters have exposed wires that should be avoided.

Spray Nozzles

To provide uniform water distribution at the tops of both reactors, special spray nozzles are used that are attached to a manifold system inside the reactors. Five nozzles are used per reactor. Bete Nozzles manufactures the nozzles (Model TF full cone) that adapt to a 3/4 inch female pipe fitting on the manifold system. Each nozzle spreads the water out at a 170 degree angle, providing a very uniform distribution of water. They are designed to pass a significant amount of solids without clogging.

Important notes:

- Nozzles should be checked monthly for potential clogging.

Nutrient and Caustic Tanks

Nutrients and caustic materials are stored in two separate 100 gallon polyethylene black tanks located beneath the main control box. The size of the tanks should enable the system to run for at least two weeks before refilling is required.

Important notes:

- When adding nutrients or caustic materials to tanks, make sure chemicals are completely mixed and solubilized before running system.

- Prior to transport, completely empty the tanks of all fluids.

Stainless Steel Reactors

The two reactors on the system are made of 304 stainless steel which is resistant to the majority of chemicals. The tanks were custom welded by Environmental BioSystem to meet the exact design criteria of the project. The thickness of the walls are 12 gauge. The internal dimensions are as follows: height = 11 ft, diameter = 5 ft, foot print = 19.64 sq ft, total volume = 215.98 cu ft. A support structure for the packing material is also made of stainless steel and is located approximately 2.5 ft above the bottom of the reactor. The approximate depth of the packing material above the support structure is 7.5 ft. There are numerous adapters and sampling ports located on the walls of the reactor and the top lid is fitted with a 2 ft diameter manhole for entry into the reactor. In addition, the top of the reactor is flanged for easy removal. A more detailed description of the reactors is provide in the design drawing section of this manual.

Important notes:

- VERY IMPORTANT: All fluids and biomass must be removed from the reactors before transporting unit. The axial system can only support the dry weight of the system.

Air Sampling and Detector System

The air sampling system incorporates six solenoid valves, a diaphragm air pump, a pressure relief regulator, a flowrate control system, a FID detector, and a DELCD detector. The detector system was manufactured by SRI Instruments. It was specially designed and manufactured for this project so when speaking with SRI personnel, mention the project name and possibly Doug HODGE'S name. The system collects air samples from air lines before the first reactor, between the first and second reactors, after the second reactor, and from ambient air. The sampling system is computer controlled. Samples are collected and analyzed one at time. It takes three minutes to sample from each location. After all four samples are collected, the system back flushes the lines for three minutes prior to starting sampling sequence over again. Therefore, the entire sequence takes fifteen minutes to complete (Figure I).

The four solenoids used to open and close air lines are *normally closed.* Normally closed solenoids require electrical excitation to open. During sampling of the four locations, air is drawn through the Teflon sampling lines by action of a two headed air pump. This pump is rated at approximately 3 L/min. at 3 psi. Pressure in the air lines should not exceed 5 psi. Permanent damage may occur to the diaphragms if maximum pressure limits are exceed. After air passes through the pump, it enters a three way solenoid. During the *sampling mode*, air passes through the three way valve and into a pressure relief regulator. This regulator dumps excess air not used by the detectors. The flowrate entering the regulator is approximately 3000 ml/min. 10 ml/min. passes onto the detector

systems and 2990 ml/min. is dumped. This process enables the sampling lines to be continually flushed with high flows, reducing lag time between sampling locations. The 10 ml/min. flow then enters the flowrate control system located inside the detector unit. The flowrate control system consists of a pressure restrictor device and a digital pressure gauge. The two devices are monitored and controlled by the detector unit in order to maintain the line pressure in the system at exactly 2 psi. If line pressure departs from 2 psi, the control system opens and closes the pressure restrictor, correcting the pressure. Air flow through the detector system is maintained at 10 ml/min. as long as pressure is set a 2 psi. Higher and lower flowrates may be obtained by adjusting the line pressure.

After passing through the flowrate control system, the sample air is analyzed by both a FID and DELCD, operated in series. The entire 10 ml/min. is used by the detectors. Therefore, changes in the flowrate will linearly effect response of both the detectors. Under this arrangement, doubling the flowrate will double the response of the detectors.

Every fifteen minutes, sampling lines are flushed by reversing the flow through the lines. This is accomplished by switching the three way valve and one additional valve located between the outlet and ambient valves. Air is drawn through the ambient sampling line, through the pump and three way valve, and back to the between the tank valve and outlet valve. The flushing retards the accumulation of water in the lines.

Important notes:

- Be very careful during manual operation of the solenoids so you do not close all the solenoids while the pump is on. The pump will be damaged.
- The pressure relief regulator should be checked once a week and set a 3 psi.
- The detectors should be calibrated once a week.
- Maintenance of the detectors should be done at least once every three months.
- Read the SRI operating manual before using the detectors.

Computer Control System

The system is controlled by a graphics-based computer program which uses a pentium computer equipped with data acquisition and control boards. The computer control system simultaneously monitors 30 input sensors and controls 18 output devices. Input parameters including temperature, pressure, flowrate, pH, conductivity, reactor weight, water level, and air contaminant concentration are measured and assimilated by the process control program. To maintain optimal operating conditions, the process control system interprets the input parameters and adjusts the output control devices. The output devices include water pumps, air blowers, water heaters, nutrient and caustic metering pumps, and water and air solenoid valves. In addition, the control systems statistically

manipulates the input data from the sensors and stores values in output files that can be subsequently download. The graphical program allows continuous monitoring of all sensors and other devices through a specially designed control interface. The graphical interface displays measured values from the sensors, identifies status of output parameters, and allows equipment to be turned on and off and calibrated with the simple click of a mouse. All control can be accomplished from the control system at the testing site, or from anywhere in the world via modem and phone line (modem and phone line not included).

The computer control system consists of a pentium computer, a chassis that holds one input board and three output boards, a I/O connector block for the level switch control, and an analog and digital I/O board that fits into the computer. The control system was programmed using Labview software. All equipment and software was purchased from National Instruments.

Important notes:

- The control system is complex and should be fully explained through a mentoring program that allows hands on instruction.

Transportation of System

The system has been designed with a trailer hitch and extendible wheels for transportation. This section describes the step by step procedures to follow in preparing the system for transport. We recommend that this process be explained in the field in depth by someone familiar with the process before the feat is undertaken for the first time:

- VERY IMPORTANT - All fluids must be removed from the entire system before transport. This includes any biomass that may have accumulated on the packing material. The axial is only designed to handle the load of the dry reactor.

- After fluids have been removed from the reactors, load cells should be placed into the transportation position. Use jacks to move load cells from under the reactors to the sides of the skid. Latch load cell support structures to the skid with rope or elastic bands.

- Lower reactors and associated platforms to the transportation position, flush with skid. Lock down platforms with the eight 3/4 inch screws.

- Disconnect 110 and 230 volt power lines at the disconnect boxes. Turn disconnect boxes to the off position. Squire latches on the boxes so they cannot open during transport.

- Place protective shealth over pH probes so they do not dry up.

- Make sure particulate dropout is securely fastened to the skid.

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COMPONENT LIST

COMPONENT INFORMATION

COMPUTER PROGRAM

DESIGN CALCULATIONS

DESIGN DRAWINGS