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NITRATE REMOVAL BY DENITRIFICATION USING 'CAPTOR' MEDIA

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ABSTRACT:

In many areas throughout the U.S. groundwater supplies are contaminated by nitrates in excess of the standard of 10 mg/L (as N)mandated by the Safe Drinking Water Act of 1974 and its subsequent amendments. The nitrate standard is based on the fact that nitrates can cause infant methemoglobinemia and it also may lead to the possible formation of nitrosoamines, which are known carcinogens. Economic methods for the removal of nitrates from water supplies are needed to mitigate the problems caused by this pollutant. The research results presented herein used an attached growth biological denitrification process using a new media called 'captor'. 'Captor' media denitrification was determined in a packed column and compared with a conventional packing media; e.g., 1" flexiring. The synthetic feed simulating ground water quality had nitrate levels varying from 10-30 mg/L. Methanol was added as a carbon source with NO_3:methanol ratio of 1:4. At all loading rates (0.2 to 1.2 $Kg/m^3/d$) the 'Captor' media performed better than the flexiring media. The percent NO_3^--N removal decreased exponentially for both systems as the loading rates were increased. Even at NO_3^--N loading rate of up to 0.7 $Kg/m^3/d$, the 'Captor' column removed greater than 80% of the incoming NO_3^--N . The reduction of empty bed contact time (EBCT) from 60+ minutes to 20+ minutes reduced the NO_3^--N removal efficiency markedly, even though the loading rate was reduced from 0.7 to 0.4 $Kg/m^3/d$. Thus, it seems that EBCT is a very important parameter for evaluating the removal efficiency of attached growth denitrification process.

Introduction

In many areas throughout the U.S., ground water supplies are contaminated by nitrates in excess of the standard of 10 mg/L (as N) mandated by the Safe Drinking Water Act of 1974 and its subsequent amendments. The nitrate standard is based on the finding that nitrates can cause infant methemoglobinemia (blue baby syndrome). Methemoglobinemia occurs when nitrite, which is formed in the stomach from ingested nitrate, reacts with hemoglobin in blood, converting hemoglobin into methemoglobin, which cannot carry oxygen to cell tissue (1,2). Nitrates may also lead to the possible formation of nitrosoamines, which are known carcinogens (3). In addition, it has been reported that nitrates have caused heart and behavioral problems in laboratory animals (4).

A recent publication (5) on ground water contamination reported that many wells in Illinois and Nebraska had nitrate levels in excess of 10 mg/L(as N). This same publication also reported high nitrate levels in wells in Long Island, N.Y. McDonald and Splinter reported that long-term trends of nitrate levels in Iowa surface streams and shallow aquifers is on the increase (6). The major sources of nitrates in surface and ground water are said to be animal waste, septic tank seepage and excess nitrogen fertilizer use for agriculture (5,6).

The economic methods for the removal of nitrates from water supplies are needed to mitigate the problems caused by this pollutant. Presently there are many methods available for the removal of nitrates from wastewater and agricultural drainage but very few from water supplies. Available treatment alternatives for nitrate pollution control and treatment include anion exchange, reverse osmosis, biological denitrification, electrodialysis, distillation, and possibly chemical reduction (7-9). A comparison of these alternatives concluded that only the first three processes are economically viable (10). The reverse osmosis and ion exchange processes are not very economical in small scale systems. However, biological denitrification is an economical process even for small systems.

Biological denitrification has been used successfully in the removal of nitrates from wastewaters. Nitrates are converted into harmless nitrogen gas and small concentrations of nitrous and nitric oxides. In this process, denitrifying bacteria use nitrate in place of dissolved oxygen. This anoxic reaction requires that organic carbon be added to the water to provide the necessary energy for the bacteria. Most denitrifying systems use methanol as the carbon source for economical and operational reasons (low solids production).

Biological denitrification has been carried out very successfully in both attached and suspended growth systems (11-16). Attached growth systems include packed-bed reactors that are packed with highly porous matrices through which influent water is passed. Biological growth is supported on the surface of the porous medium or within its pore spaces or voids (17).

The biological denitrification process research reported herein developed the methodology and procedures for small scale units using a new media called 'Captor'. The 'captor' media consisted of small cubes of sponge material that can support a large amount of attached biological growth. This media was developed in the U.K. by Ashbrook-Simon-Hartley Co. (18). The removal of biological growth from the media can be easily accomplished by squeezing the sponge material; therefore, separate settling tanks are not needed. The large surface area of the 'captor' media and the ease of collection of the bio-solids makes this media superior to rock media or plastic media used previously for denitrification studies. Use of this media should cut down the size of the units considerably.

This study investigated the potential of using biological denitrification in 'captor' reactor for nitrate removal from contaminated drinking water supplies with moderate nitrate concentrations. The specific objective of the research was to determine the feasibility of using 'captor' media for attached growth denitrification.

Denitrification Stoichiometry

The bacteria cultivated in the reactor are heterotrophic organisms, that is they require an organic source of carbon to carry out their metabolism. Because there is an insufficient amount of soluble carbon available to these bacteria in most waters, an external source of carbon must be introduced into the treatment system. Methanol has been used widely because of its low cost, availability, and low bacterial cell yield.

Most of these bacteria are also facultative because they will thrive in both aerobic and anaerobic environments. In fact many of these bacteria prefer to use elemental oxygen rather than nitrate as an energy source. Therefore, if anaerobic conditions are maintained, the high level of nitrate reduction can be obtained.

The chief mechanism for nitrate removal is through this respiratory action rather than bacterial synthesis. Some nitrate may be used for bacterial synthesis, but the nitrate serves primarily as an energy source to these microbes. Because the reactions are respiratory, the system produces a low sludge yield. Overall, the chemical reactions for the nitrogen reduction proceed as follows:

Overall energy reaction:

$$NO_3^{-}\text{-}N + 0.833\ CH_3OH \rightarrow 0.5\ N_2 + 0.833\ CO_2 + 1.167\ H_2O + OH^{-} \qquad \text{(Eq. 1)}$$

Bacterial synthesis reaction:

$$NO_3^{-} + 4.667\ CH_3OH + CO_2 + H^{+} \rightarrow C_5H_7O_2N + 6.333\ H_2O \qquad \text{(Eq. 2)}$$

In practice, however, 25 to 30% of the methanol required is used for bacterial synthesis. On the basis of experimental laboratory studies, the following empirical equation was developed to describe the overall nitrate removal reaction (13):

$$NO_3^{-} + 1.08\ CH_3OH + H^{+} \rightarrow 0.065\ C_5H_7O_2N + 0.467\ N_2 + 0.76\ CO_2 + 2.44\ H_2O \qquad \text{(Eq. 3)}$$

Equation 3 can be used to determine the overall methanol requirement. However, if nitrate and dissolved oxygen are present, the methanol requirement is correspondingly higher.

Materials and Methods

Reactor design and operation

Denitrification 'captor' reactor consisted of a Plexiglass vertical column which was followed by filtration column for further treatment as shown in Figure 1. Figure 2 shows a schematic drawing of the system. The active liquid volume of the reactor was 24 L (0.84 ft^3), while the total empty bed volume was 296 (1.01 ft^3). The reactor was filled with 680 pieces of 'captor' media (2.5 cm x 2.5 cm x 1.3 cm) for biofilm growth which were held in place by a stainless steel wire screen. The Koch flexiring reactor was identical to the 'captor' reactor in terms of physical dimensions. However, the active reactor volume had 500 of Koch flexiring media. Each flexiring was 2.5 cm (1 in.) in diameter and length, with a surface:volume ratio of 213 m^2/m^3 (65 ft^2/ft^3). Media details are shown in Table 1.

The surface area:reactor volume ratio did not take into account the surface area of the reactor walls.

Table 1. Specifications of the media

Media	Specific Surface Area, m^2/m^3 (ft^2/ft^3)	Packed % Void Volume
'Captor' (orange pad)	1180 (360)	97.2
Koch flexiring	213 (65)	93.0

Operation of denitrification reactors was continuous during the study. Feed was continuously pumped in at the top of the reactor through a distribution manifold and effluent was withdrawn from the bottom for further treatment. The liquid level was maintained 2 cm above the top of the biofilm support media to keep the biofilm surface wet. These reactors were located in a room of ambient temperature. Denitrification can be carried out successfully over a wide temperature range, so temperature was not an important parameter in this study (16).

The effluent from the first column passed through a sand filter to remove any microbial solids sloughed off from the denitrifying reactor. The sand filter was backwashed with aeration periodically to keep it functional.

Substrate

The feed solution simulated ground water with normal range of nitrate concentrations, and was fortified with trace elements and a buffer. The basic makeup of the feed solution is shown in Table 2. Potassium nitrate was used as the nitrate source. Methanol was added as carbon source according to the stoichiometric relationships as in Equation 3. All of the experiments were conducted at a NO_3-N:methanol ratio of 1:4 to obviate any possible carbon limitations while examining nitrate removal characteristics.

Table 2. Synthetic Feed Solution Composition*

Component	Concentration, mg/L
$MgSO_4$-$7H_2$)	200.0
K_2HPO_4	600.0
KH_2PO_4	400.0
$MnSO_4$-$4H_2O$	1.0
Na_2MoO_4-$2H_2O$	1.5
$CaCl_2$	40.0
$FeSO_4$-$7H_2O$	5.5
Citric Acid (monohydrate)	5.4

*KNO_3 level was 7.22 g/L

Experimental plan

Both reactors were started with 5 L of an equal volume mixture of anaerobic sludge taken from Columbia Municipal Wastewater Treatment Plant. The balance of the reactor volume was made up with tap water. This ensured that both reactors were started with the same biomass quantity and quality.

After inoculation, the reactors were operated on batch basis with the effluent recycle to allow microorganism attachment to the packing media for three days. After batch operation, continuous flow feed was started with a gradual increase from a three-hour hydraulic retention time (HRT) to an HRT of about one hour which was followed by the change of nitrate concentration from 5 ppm to 10 ppm. Startup took approximately 30 days.

Following startup, each reactor was operated at three different steady state nitrate concentrations between 10 and 30 ppm. Because the design of both experimental reactors caused continuous biomass accumulation, the results are for pseudo-steady states (PSS). PSS data was obtained by operating each reactor for a minimum of two days at each concentration, which corresponds to 50 change overs in reactor volume for each PSS. After two operating days at one PSS, samples were then taken several times, and the average of the data points was reported. At the conclusion of the particular experiment, reactor feed rates were increased to an HRT of about 15 minutes, and then an HRT of about 30 minutes. Data for these runs was obtained as described above.

Analysis

In order to attain the objectives described previously, it was necessary to measure and keep a record of several variables which affect the magnitude of the substrate removal rate. These variables are the following: nitrate concentration (NO_3-N), dissolved oxygen concentration (DO), pH, temperature, soluble chemical oxygen demand (sCOD) and alkalinity in the influent and effluent streams. Samples were analyzed just after collection. The procedures in the 16th Edition of Standard Methods for the Examination of Water and Wastewater were followed for every analysis (19).

Operational problems

After 60 days from startup some of 'Captor' media began to float with nitrogen (NO_2) gas formation, and after 90 days all of the 'Captor' media floated which caused some clogging of the media. It often caused the overflow of the reactor due to the head loss, and the high rate of nitrate removal was never obtained after that period. Overflow of the Koch flexiring reactor was observed also. But the accumulation of the sloughed biomass in the reactor was regarded as the primary reason for clogging in the latter system.

Results

General operating results

The daily results of the influent and effluent NO_3-N concentrations are given in Figure 3. During the study, an attempt was made to maintain the CH_3OH:NO_3-N ratio at approximately 4.0. Because of the difficulty in setting a proper flow rate of the chemical feed pump, the proper ratio was not always maintained (See Table 3). As a result, there was sometimes insufficient methanol fed to the system to allow high removal of the influent nitrogen. Also, biofilm growth inside the feed tubing resulted in fluctuation of flow rates at higher flow rate study.

As may be seen from the data, the 'Captor' system showed a good performance at the early period of operation compared with the flexiring system. Even though same quantity and quality of biomass inoculation was used for both reactors, removal efficiency of the 'Captor' system was much higher than that of the flexiring system. Appendix A contains daily operating data of the two columns which include flow rates, temperature, pH, alkalinity, D.O., etc.

Nitrate-alkalinity relationship

According to the chemical equations for the denitrification reaction, 3.57 mg/L of alkalinity should be produced for 1 mg/L of nitrate nitrogen removed. Figure 4 shows that the actual ratio obtained during this work was about 3.21. Table 3 shows the fluctuation of this ratio in the system. The reason for the difference is that the stoichiometric equation does not truly represent all of the reactions that occur. For example, some of the influent nitrate may be assimilated into cell mass and therefore would not be reduced according to the denitrification equations.

Nitrate removal

Figure 5 shows the relationship of Nitrate-N removed and COD removed. The theoretical ratio of COD removal:NO_3^--N removal from equation 3 is about 3:702. The observed ratio from Figure 5 is 5.25, which indicates that some heterotrophic growth was occurring which provided some COD removal without any denitrification. This should be expected since even at the highest loading rate there was some D.O. present in the system (see Appendix A for D.O. data).

Figure 6 shows the NO_3^--N removal rate for the 'Captor' and Koch flexiring media at different NO_3-N loading rates. It can be seen that, as loading rate increases, the percent NO_3^--N removal decreases exponentially. Also, at all loading rates the 'Captor' media performed better compared to the flexiring media. It should be noted that the temperature for the systems was 20 ± 2°C. Table 4 shows the details of the data at different loading rates.

Table 5 compares the performance of the two columns on the basis of empty (EBCT) bed contact time. It can be seen from this table that EBCT has a major impact on the performance of these columns. For the same loading rate, the decrease of EBCT from 60+ minutes to 20+ minutes dropped the percent NO_3-N removals from about 80% to 30-40%. Therefore, it appears EBCT is one of the main design factors for denitrification column design.

Conclusions

1. The 'Captor' media removed NO_3^--N better than conventional flexiring media at all loading rates tested.

2. The percent NO_3-N removal rate decreased exponentially as the NO_3 loading rates were increased for both the systems.

3. The reduction of empty bed contact time (EBCT) from 60+ minutes to 20+ minutes decreased the percent NO_3-N removal from 80% to 30-40%. EBCT appears to be a more sensitive parameter compared to NO_3-N loading rate.

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Appendix A

Figure 1. Denitrification and Filter Column Details

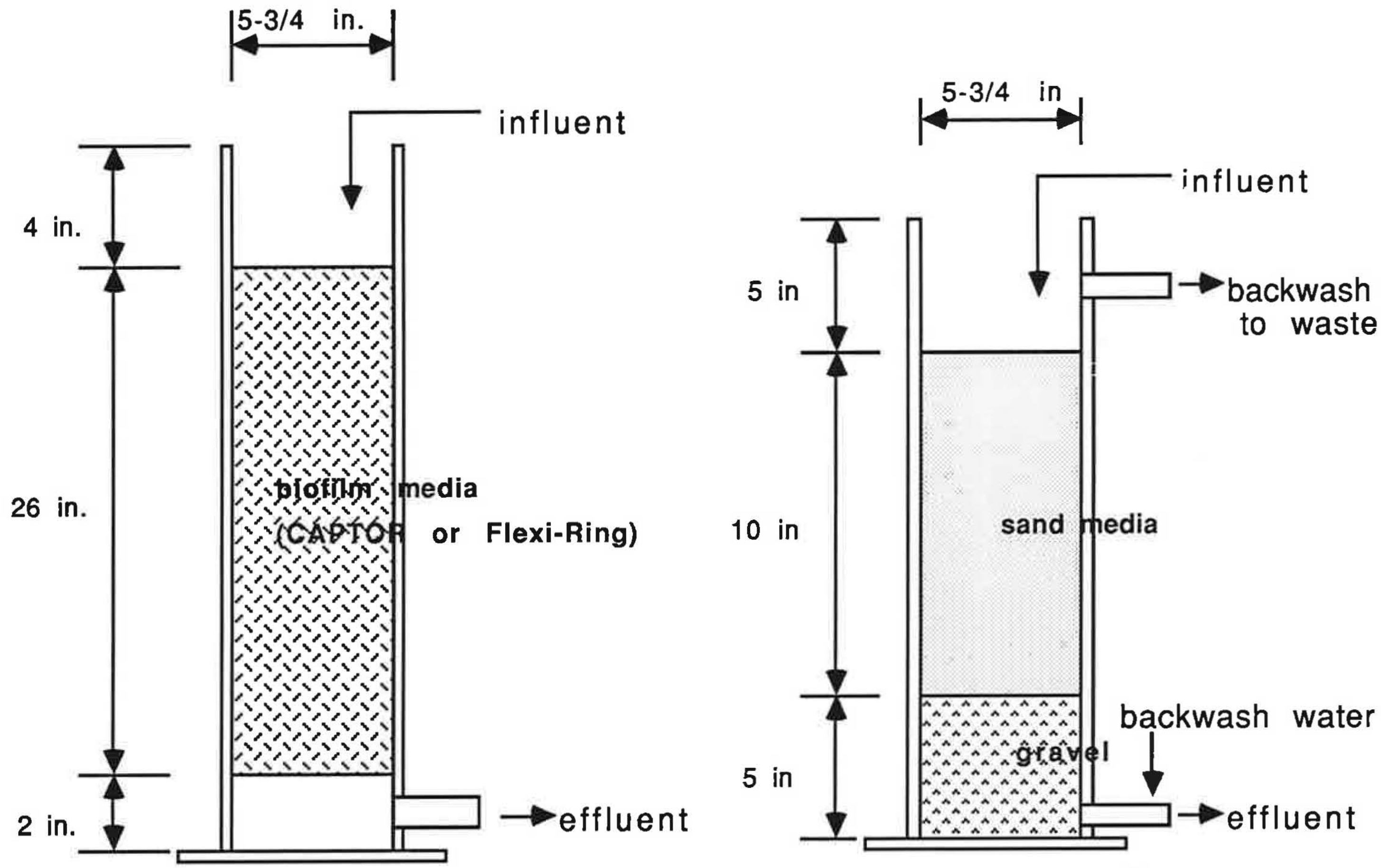

Figure 2. Experiment Setup for Denitrification Using 'CAPTOR' Media

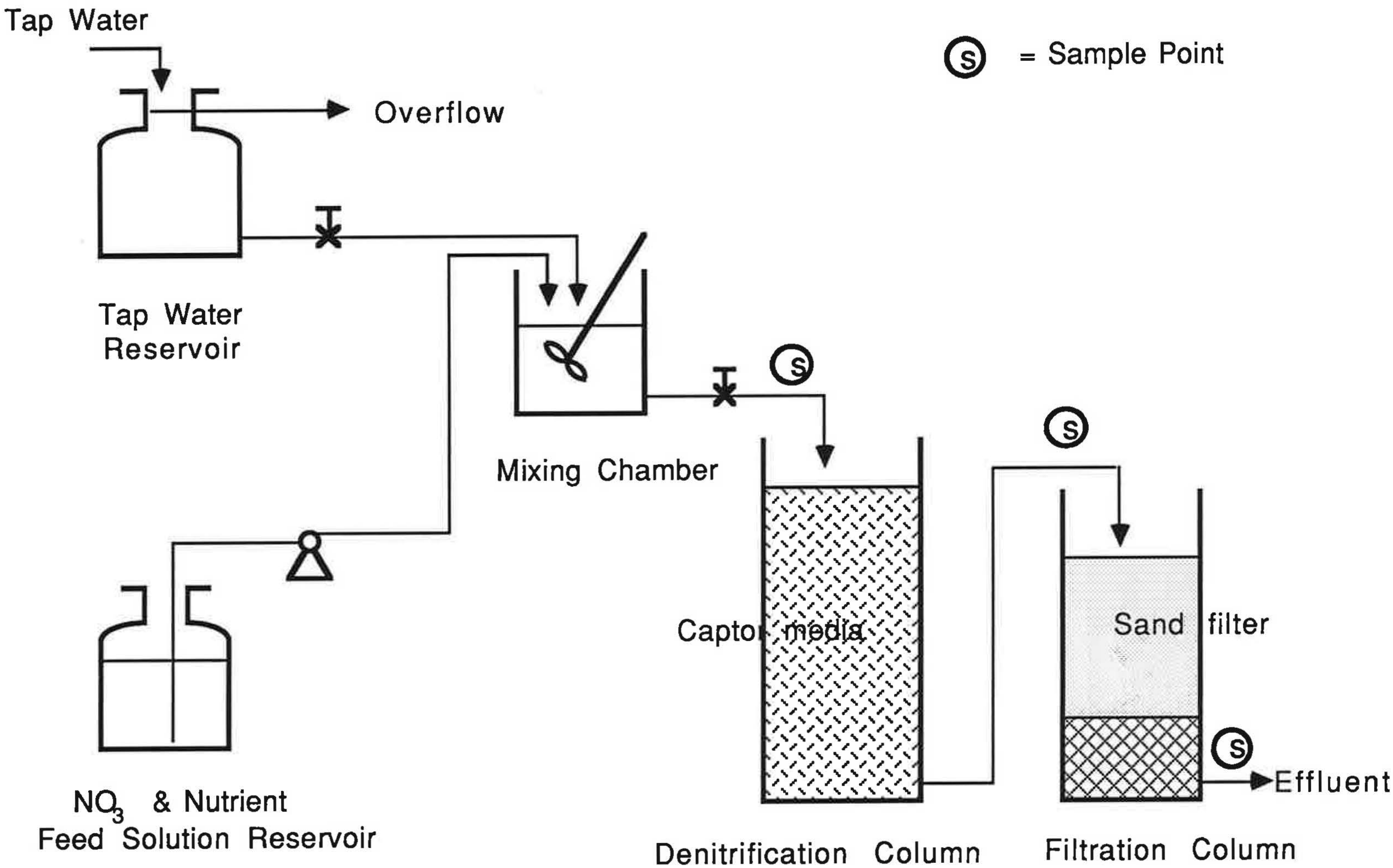

Figure 3 Daily Results on Nitrate Removal

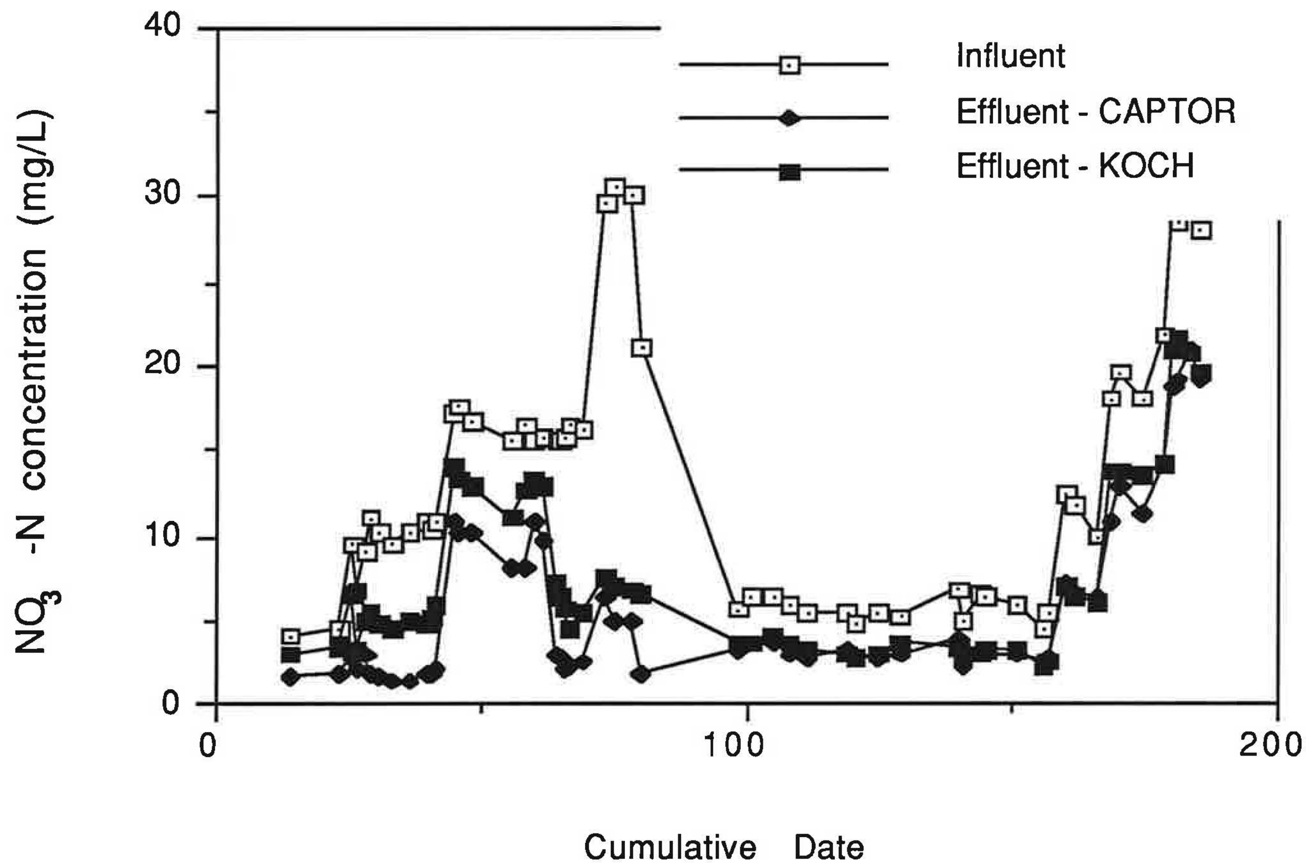

Figure 4 Relationship of nitrate nitrogen and alkalinity

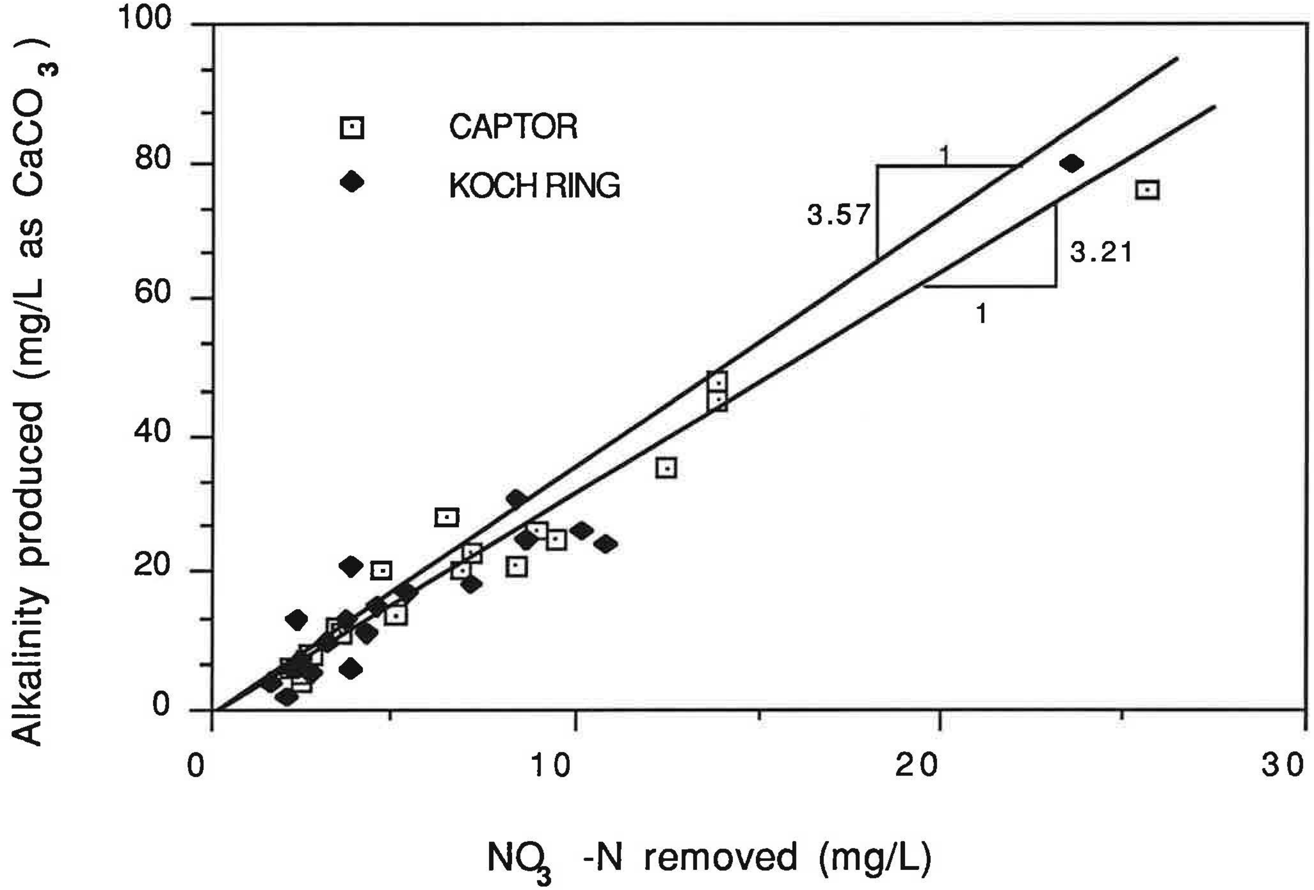

Figure 5 Relationship of nitrate nitrogen and COD

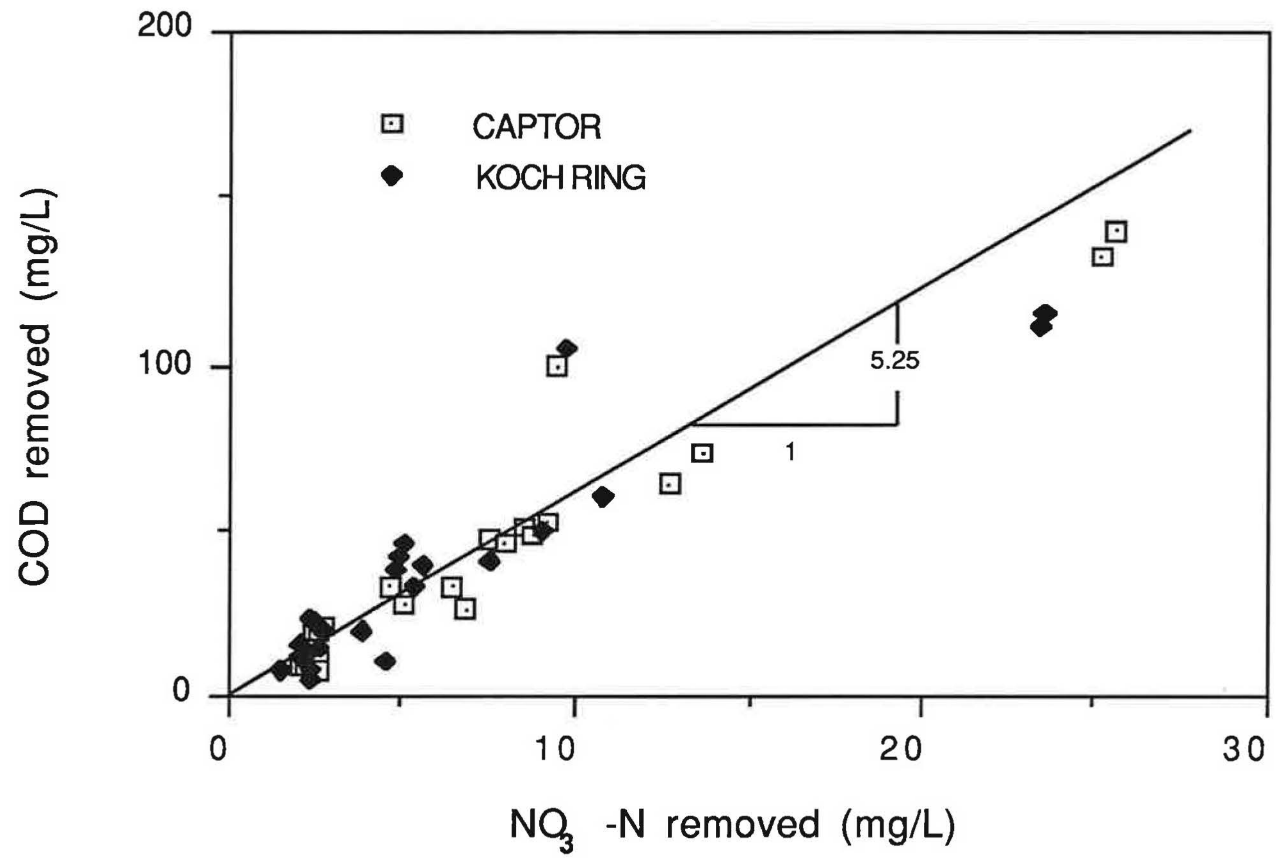

Figure 6 Loading vs. removal % at steady state

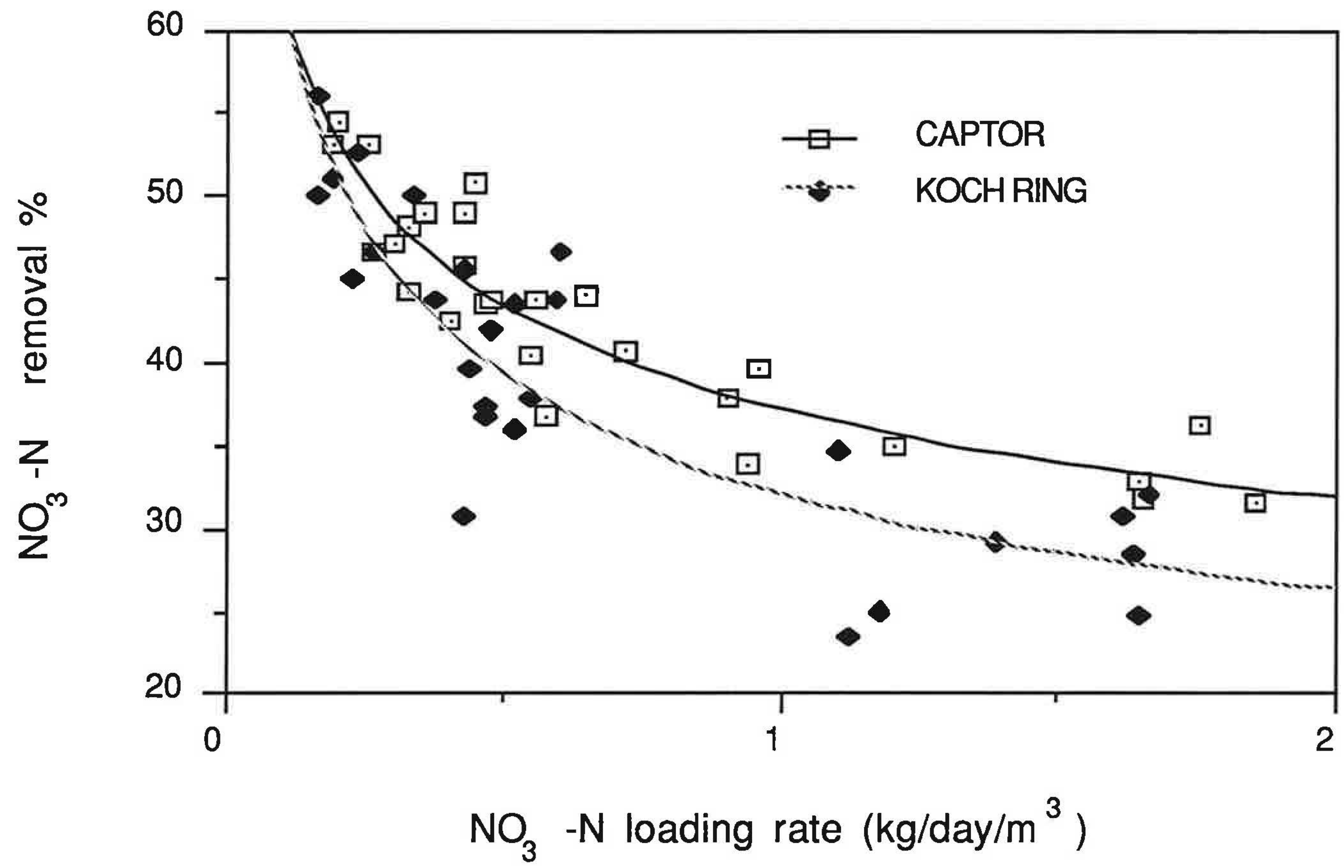

Table 3. "Captor" Column Denitrification Results

Cumulative date	CH3OH : NO3-N ratio in influent	COD removed : NO3-N removed ratio		Alkalinity removed : NO3-N removed ratio	
		Captor	Plastic	Captor	Plastic
1					
14					
23					
26					
27					
28					
29					
31	3.87	5.64	6.98		
33					
37	4.36	5.70	7.94		
40					
41					
42	4.26	6.04	8.86		
45	3.97	5.53	8.55		
46					
48				4.31	5.53
56	3.64	5.08	5.05		
58				2.53	1.58
60				4.26	5.65
62	4.01	6.94	10.22		
64				2.82	3.73
65					
66	4.00	4.98	5.53	3.47	2.55

Table 3. (Continued)

Cumulative date	CH3OH : NO3-N ratio in influent	COD removed : NO3-N removed ratio		Alkalinity removed : NO3-N removed ratio	
		Captor	Plastic	Captor	Plastic
67					
69				3.27	2.22
73	3.93	5.31	5.52		
75					
78	3.73	5.46	4.90	3.02	3.41
80	3.71	5.25	4.76		
98				1.60	0.95
101	3.68	3.44	5.71		
105	4.12	5.12	5.73	2.86	2.61
108					
112					
119	4.61	4.58	7.24	2.50	2.80
121	4.45	8.42	8.68		
125					
129	4.06	3.04	3.61	2.79	2.58
140	4.30	4.47	5.16		
141				2.68	2.71
144	4.62	7.28	5.16		
145				3.53	3.13
151					
156	4.74	7.68	7.15		
157	4.04	4.52	2.30	2.00	1.79
160					
162				2.75	3.15
166	4.40	5.47	6.04	3.06	3.51

Table 3. (Continued)

Cumulative date	CH_3OH : NO_3-N ratio in influent	COD removed : NO_3-N removed ratio		Alkalinity removed : NO_3-N removed ratio	
		Captor	Plastic	Captor	Plastic
168				3.24	2.62
170					
174				2.94	3.33
178	4.48	3.75	2.44		
180	4.18	6.26	5.48		
181				2.66	2.54
183					
185	5.28	10.53	10.82	2.92	2.91

Table 4. NO_3-N Loading Rate and % Removal Data

Cumulative date	NO3-N (ppm)			% Removal		NO3-N Loading Rate (lb/day/1000CF)		NO3-N Loading Rate (kg/day/CM)		Flux rate (gpm/SF)	
	Influent	Captor	Plastic	Captor	Plastic	Captor	Plastic	Captor	Plastic	Captor	Plastic
1											
14	4.0	1.5	3.0	62.5	25.0	4.88	5.86	0.078	0.094	0.220	0.264
23	4.4	1.7	3.3	61.4	25.0	5.73	6.44	0.092	0.103	0.235	0.264
26	9.4	2.7	6.5	71.3	30.9	13.00	13.00	0.208	0.208	0.249	0.249
27	6.7	2.0	3.1	70.1	53.7	9.26	9.26	0.149	0.149	0.249	0.249
28	9.1	3.0	5.0	67.0	45.1	12.58	12.58	0.202	0.202	0.249	0.249
29	11.0	1.8	5.4	83.6	50.9	15.21	15.21	0.244	0.244	0.249	0.249
31	10.2	1.6	4.7	84.3	53.9	14.10	14.10	0.226	0.226	0.249	0.249
33	9.4	1.4	4.6	85.1	51.1	13.00	13.00	0.208	0.208	0.249	0.249
37	10.1	1.4	4.9	86.1	51.5	13.96	13.96	0.224	0.224	0.249	0.249
40	10.7	1.7	4.8	84.1	55.1	14.79	14.79	0.237	0.237	0.249	0.249
41	10.3	1.8	5.2	82.5	49.5	14.24	14.24	0.228	0.228	0.249	0.249
42	10.8	2.1	5.9	80.6	45.4	15.81	14.93	0.253	0.239	0.264	0.249
45	17.1	10.8	14.0	36.8	18.1	23.64	23.64	0.379	0.379	0.249	0.249
46	17.6	10.2	13.2	42.0	25.0	22.90	26.48	0.367	0.425	0.235	0.271
48	16.7	10.2	12.9	38.9	22.8	23.09	21.73	0.370	0.348	0.249	0.235
56	15.4	8.1	11.0	47.4	28.6	21.29	21.29	0.341	0.341	0.249	0.249
58	16.3	8.0	12.5	50.9	23.3	23.86	22.54	0.383	0.361	0.264	0.249
60	15.5	10.8	13.2	30.3	14.8	22.69	20.80	0.364	0.333	0.264	0.242
62	15.8	9.7	12.8	38.6	19.0	23.13	21.84	0.371	0.350	0.264	0.249
64	15.4	3.0	7.1	80.5	53.9	22.54	20.04	0.361	0.321	0.264	0.235
65	15.4	2.6	6.4	83.1	58.4	22.54	20.04	0.361	0.321	0.264	0.235
66	15.8	2.0	5.6	87.6	64.6	23.77	19.92	0.381	0.319	0.271	0.227

Table 4. (Continued)

Cumulative date	NO3-N (ppm)			% Removal		NO3-N Loading Rate (lb/day/1000CF)		NO3-N Loading Rate (kg/day/CM)		Flux rate (gpm/SF)	
	Influent	Captor	Plastic	Captor	Plastic	Captor	Plastic	Captor	Plastic	Captor	Plastic
67	16.3	2.3	4.4	85.7	73.0	25.19	19.89	0.404	0.319	0.279	0.220
69	16.2	2.4	5.4	84.9	66.7	21.08	23.72	0.338	0.380	0.235	0.264
73	29.6	6.2	7.4	79.1	75.0	40.93	40.93	0.656	0.656	0.249	0.249
75	30.5	4.9	7.0	83.9	77.2	39.69	44.65	0.636	0.716	0.235	0.264
78	30.2	5.0	6.8	83.4	77.6	45.44	35.62	0.729	0.571	0.271	0.213
80	21.2	1.8	6.6	91.5	68.8	17.24	41.38	0.276	0.663	0.147	0.352
98	5.7	3.2	3.6	43.9	36.8	29.67	29.21	0.476	0.468	0.938	0.923
101	6.2	3.7	3.6	40.3	41.9	34.29	29.75	0.550	0.477	0.997	0.865
105	6.4	3.6	4.1	43.8	35.9	34.88	32.27	0.559	0.517	0.982	0.909
108	5.9	2.9	3.7	50.8	37.3	27.83	29.27	0.446	0.469	0.850	0.894
112	5.3	2.7	3.2	49.1	39.6	26.73	27.59	0.428	0.442	0.909	0.938
119	5.5	3.1	3.0	43.6	45.5	29.08	26.84	0.466	0.430	0.953	0.880
121	4.8	2.6	2.7	45.9	43.9	26.60	23.47	0.426	0.376	0.997	0.880
125	5.3	2.7	3.0	49.1	43.4	21.99	32.33	0.352	0.518	0.748	1.099
129	5.1	2.9	3.5	42.6	30.7	25.06	26.70	0.402	0.428	0.894	0.953
140	6.8	3.8	3.4	44.3	50.1	20.52	21.08	0.329	0.338	0.542	0.557
141	4.9	2.3	2.7	53.2	45.0	15.97	14.38	0.256	0.230	0.586	0.528
144	6.6	3.0	2.9	54.5	56.1	12.35	10.20	0.198	0.164	0.337	0.279
145	6.4	3.0	3.2	53.1	50.0	11.97	10.41	0.192	0.167	0.337	0.293
151	5.8	3.0	3.1	48.3	46.6	20.76	16.51	0.333	0.265	0.645	0.513
156	4.5	2.4	2.2	46.7	51.1	16.47	12.08	0.264	0.194	0.660	0.484
157	5.3	2.8	2.5	47.2	52.8	18.97	15.09	0.304	0.242	0.645	0.513
160	12.3	7.3	6.9	40.7	43.9	45.02	37.02	0.722	0.593	0.660	0.542
162	11.6	6.5	6.2	44.0	46.6	40.57	37.74	0.650	0.605	0.630	0.586
166	9.8	6.2	6.1	36.7	37.8	35.87	34.28	0.575	0.549	0.660	0.630

Table 4. (Continued)

Cumulative date	NO3-N (ppm)			% Removal		NO3-N Loading Rate (lb/day/1000CF)		NO3-N Loading Rate (kg/day/CM)		Flux rate (gpm/SF)	
	Influent	Captor	Plastic	Captor	Plastic	Captor	Plastic	Captor	Plastic	Captor	Plastic
168	17.9	10.8	13.7	39.7	23.5	59.69	69.88	0.957	1.120	0.601	0.704
170	19.5	12.9	13.8	33.8	29.2	58.68	86.44	0.941	1.386	0.542	0.799
174	18.0	11.2	13.5	37.8	25.0	56.37	73.20	0.904	1.174	0.564	0.733
178	21.7	14.1	14.2	35.0	34.6	75.01	68.84	1.203	1.104	0.623	0.572
180	29.2	18.6	20.9	36.3	28.4	109.25	102.13	1.751	1.637	0.674	0.630
181	28.6	19.2	21.5	32.9	24.8	102.35	102.35	1.641	1.641	0.645	0.645
183	30.3	20.8	20.6	31.4	32.0	115.83	103.51	1.857	1.659	0.689	0.616
185	28.1	19.2	19.5	31.7	30.6	102.85	100.56	1.649	1.612	0.660	0.645

Table 5. Column Performance at Different Empty Bed Contact Times (EBCT)

Cumulative Days	NO_3-N Loading Rate Kg/day/CM		NO_3^-% Removal		EBCT	
	Captor	Plastic	Captor	Plastic	Captor	Plastic
64	0.361	0.321	80.5	53.9	61.1	68.8
65	0.361	0.321	83.1	58.1	61.1	68.8
73	0.656	0.656	79.1	75.0	64.7	64.7
75	0.636	0.716	83.9	77.2	68.1	61.1
78	0.729	0.571	83.4	77.6	59.5	75.9
125	0.352	0.518	49.1	43.4	21.6	14.7
129	0.402	0.428	42.6	30.7	18.0	16.9
151	0.333	0.265	48.3	46.6	25.0	31.4
156	0.264	0.194	46.7	51.1	24.4	33.3
170	0.941	1.386	33.8	29.2	29.7	20.2
174	0.904	1.174	37.8	25.0	28.6	22.0
181	1.641	1.641	32.9	24.8	25.0	25.0
183	1.857	1.659	31.4	32.0	23.4	26.2

Table 6. Column Denitrification Operating Data

Cumulative date	Flowrate (mL/min)		Temperature (°C)			pH			Alkalinity (mg/L as CaCO3)		
	Captor	Plastic	Air	Influent	Effluent	Influent	Captor	Plastic	Influent	Captor	Plastic
1											
14	150	180	17.8	20.4	20.8						
23	160	180	16.7	20.8	21.0						
26	170	170	16.7	20.5	21.5						
27	170	170	17.2	21.0	22.0						
28	170	170	18.9	20.7	20.8						
29	170	170	18.1	20.3	21.0						
31	170	170	17.6	20.5	20.7						
33	170	170	17.9	20.9	21.3						
37	170	170	17.4	20.4	20.7						
40	170	170	18.0	19.9	20.6						
41	170	170	17.9	20.6	20.9						
42	180	170	18.3	21.3	21.7						
45	170	170	17.2	20.5	21.6						
46	160	185	17.7	20.7	21.8						
48	170	160	17.2	21.2	21.5				256	284	277
56	170	170	17.2	20.3	21.4						
58	180	170	15.6	20.5	19.9				247	268	253
60	180	165	16.1	20.9	20.6	7.62	7.42	7.52	264	284	277
62	180	170	17.2	21.2	21.2						
64	180	160	16.7	21.0	21.0	7.77	7.14	7.53	247	282	278
65	180	160	15.6	18.7	18.5	7.56	7.81	7.22			
66	185	155	16.1	20.0	19.5	7.45	6.58	7.07	250	298	276

Table 6. (Continued)

Cumulative date	Flowrate (mL/min)		Temperature (°C)			pH			Alkalinity (mg/L as CaCO3)		
	Captor	Plastic	Air	Influent	Effluent	Influent	Captor	Plastic	Influent	Captor	Plastic
67	190	150	16.4	20.8	20.2	7.43	6.65	6.96			
69	160	180	17.1	20.5	20.0	7.68	6.90	7.31	245	290	269
73	170	170	15.8	20.1	19.2	7.59	6.96	7.11			
75	160	180	15.9	19.9	18.7	7.62	7.00	7.08			
78	185	145	14.2	18.2	17.5	7.63	6.92	7.11	276	352	356
80	100	240	15.6	19.0	19.0	7.62	6.61	7.18			
98	640	630	16.6	17.6	17.8	7.58	7.38	7.40	258	262	260
101	680	590	16.7	18.4	18.4	7.44	7.38	7.41			
105	670	620	15.7	16.8	16.9	7.62	7.55	7.57	249	257	255
108	580	610	14.9	17.3	17.5	7.37	7.29	7.30			
112	620	640	15.4	17.0	17.1	7.52	7.48	7.49			
119	650	600	15.7	18.5	18.8	7.49	7.46	7.46	240	246	247
121	680	600	13.8	17.3	17.3	7.45	7.40	7.40			
125	510	750	14.4	18.6	18.9	7.51	7.50	7.50			
129	610	650	11.4	17.0	17.0	7.23	7.22	7.22	240	246	244
140	370	380	18.9	19.6	19.7	7.36	7.25	7.25			
141	400	360	16.1	17.0	17.6	7.10	7.03	7.01	232	239	238
144	230	190	22.0	18.5	18.5	7.00	6.90	6.80			
145	230	200	15.0	15.0	15.0	7.10	6.90	6.80	246	258	256
151	440	350	19.2	19.2	19.9	7.70	7.30	7.30			
156	450	330	12.8	16.6	17.0	7.87	7.54	7.51			
157	440	350	15.0	18.2	18.4	7.46	7.42	7.39	242	247	247
160	450	370	15.6	18.4	17.9	7.38	7.16	7.15			
162	430	400	16.5	19.1	18.4	7.53	7.39	7.34	248	262	265
166	450	430	15.9	19.3	19.0	7.61	7.46	7.46	254	265	267

Table 6. (Continued)

Cumulative date	Flowrate (mL/min)		Temperature (°C)			pH			Alkalinity (mg/L as CaCO3)		
	Captor	Plastic	Air	Influent	Effluent	Influent	Captor	Plastic	Influent	Captor	Plastic
168	410	480	16.8	18.5	18.4	7.46	7.33	7.28	260	283	271
170	370	545	16.3	18.9	18.3	7.65	7.51	7.50			
174	385	500	21.3	18.5	19.1	7.55	7.38	7.29	262	282	277
178	425	390	23.0	19.3	19.8	7.49	7.37	7.38			
180	460	430	22.9	19.4	19.1	7.61	7.46	7.44			
181	440	440	20.4	18.2	18.1	7.64	7.47	7.39	276	301	294
183	470	420	20.1	18.7	18.8	7.53	7.24	7.31			
185	450	440	18.2	17.4	17.5	7.59	7.27	7.30	288	314	313

Table 7. Column Denitrification Data - DO, COD, NH_3-N and NO_3-N

Cumulative date	D.O. (ppm)			COD (ppm)			NH3-N (ppm)			NO2-N (ppm)		
	Influent	Captor	Plastic	Influent	Captor	Plastic	Influent	Captor	Plastic	Influent	Captor	Plastic
1												
14												
23												
26												
27												
28												
29				63.9	12.0	24.8					0.5	0.3
31												
33				61.5	15.9	23.4						
37												
40												
41				65.8	14.5	20.6					0.7	0.4
42				64.3	16.2	22.4						
45												
46											1.0	0.3
48				91.2	58.2	72.0						
56												
58											0.7	0.3
60				93.2	60.6	69.7					0.7	0.2
62												
64												
65				92.4	28.7	42.6					0.3	0.2
66												

Table 7. (Continued)

Cumulative date	D.O. (ppm)			COD (ppm)			NH3-N (ppm)			NO2-N (ppm)		
	Influent	Captor	Plastic	Influent	Captor	Plastic	Influent	Captor	Plastic	Influent	Captor	Plastic
67												
69				95.5	22.5	35.9					0.6	0.4
73												
75				170.6	30.8	55.1						
78				168.1	35.8	56.4					1.0	0.5
80												
98	9.30	5.50	3.40	31.5	22.9	19.5						
101	9.00	5.80	4.70	38.3	25.5	23.4						
105	9.50	6.20	4.40									
108	8.90	5.50	4.10									
112	9.30	5.90	3.60	36.6	24.7	21.4						
119	9.10	5.70	2.00	36.7	16.5	15.0						
121	9.30	5.20	4.30									
125	9.00	5.60	5.10	32.3	24.4	24.0						
129	8.00	5.05	5.65	32.6	23.0	24.6						
140	8.40	6.00	5.30									
141	9.60	5.70	4.80	34.0	15.0	22.6	0.3	0.2	0.3			
144	9.10	5.00	3.60									
145	10.20	5.10	4.20									
151	8.55	4.00	4.00	41.2	19.7	21.9						
156	9.40	5.05	3.20	27.3	17.8	22.0	0.3	0.3	0.3			
157	9.20	5.30	4.60									
160	9.15	4.65	4.00				0.5	0..4	0.5			
162	8.95	5.25	4.25	76.6	48.7	44.0						
166	8.60	5.10	4.45									

Table 7. (Continued)

Cumulative date	D.O. (ppm)			COD (ppm)			NH3-N (ppm)			NO2-N (ppm)		
	Influent	Captor	Plastic	Influent	Captor	Plastic	Influent	Captor	Plastic	Influent	Captor	Plastic
168	8.45	4.80	3.75									
170	5.75	3.45	2.65								0.5	0.5
174	6.80	3.80	3.35	121.0	95.5	110.0						
178	7.05	3.65	2.40	136.1	88.5	95.0	0.7	1.0	0.9			
180	7.90	4.45	3.90								0.6	0.6
181	8.70	5.10	4.25									
183	9.00	5.40	4.25	240.0	140.0	135.0	0.8	0.8	0.8		0.8	0.6
185	8.80	5.25	3.90									

Table 8. Denitrification Columns - Empty Bed Contact Time Data for the Two Columns

Cumulative date	Empty Bed Contact time (min) Captor	Plastic	Remarks
1			1. Empty bed volume = 0.39 CF (11.0 L)
14	73.3	61.1	
23	68.8	61.1	2. Cross sectional area = 0.18 SF
26	64.7	64.7	
27	64.7	64.7	3. CH_3OH : NO_3-N = 4 : 1
28	64.7	64.7	
29	64.7	64.7	
31	64.7	64.7	
33	64.7	64.7	
37	64.7	64.7	
40	64.7	64.7	
41	64.7	64.7	
42	61.1	64.7	
45	64.7	64.7	
46	68.8	59.5	
48	64.7	68.8	
56	64.7	64.7	
58	61.1	64.7	
60	61.1	66.7	
62	61.1	64.7	
64	61.1	68.8	* Nutrition was added from the 63rd day.
65	61.1	68.8	
66	59.5	71.0	

Table 8. (Continued)

Cumulative date	Empty Bed Contact time (min) Captor	Plastic	Remarks
67	57.9	73.3	
69	68.8	61.1	
73	64.7	64.7	
75	68.8	61.1	
78	59.5	75.9	
80	110.0	45.8	
98	17.2	17.5	* Change Fluxrate (from 0.25 to 1.0) on 97th day.
101	16.2	18.6	
105	16.4	17.7	
108	19.0	18.0	
112	17.7	17.2	
119	16.9	18.3	
121	16.2	18.3	
125	21.6	14.7	
129	18.0	16.9	
140	29.7	28.9	* Change Fluxrate (from 1.0 to 0.6) on 134th day.
141	27.5	30.6	
144	47.8	57.9	
145	47.8	55.0	
151	25.0	31.4	
156	24.4	33.3	
157	25.0	31.4	* Change Conc. (from 5 to 10ppm) on 157th day.
160	24.4	29.7	
162	25.6	27.5	
166	24.4	25.6	* Change Conc. (from 10 to 20ppm) on 167th day.

Table 8. (Continued)

Cumulative date	Empty Bed Contact time (min)		Remarks
	Captor	Plastic	
168	26.8	22.9	
170	29.7	20.2	
174	28.6	22.0	
178	25.9	28.2	* Change Conc. (from 20 to 30ppm) on 179th day.
180	23.9	25.6	
181	25.0	25.0	
183	23.4	26.2	
185	24.4	25.0	* Reactor was shut-down on April 4th.