A PREDICTIVE MODEL
FOR ANAEROBIC FILTERS
TREATING LOW STRENGTH
DOMESTIC WASTEWATERS*

SETH DAVID ABRAMSON, PH.D.
530½ N. San Vincente Blvd.
Los Angeles, California

ABSTRACT

The anaerobic filter pilot plant was operated for two years using low strength domestic wastewater. The pilot plant used two upflow reactors filled with a PVC packing material which supported the growth of submerged microbial films. A mathematical model was developed using first order mass balances of the major components produced both biologically and chemically, including CH_4, CO_2, and N_2. The model used characteristics of the influent stream to predict characteristics of both the effluent liquid and gas phases, and was programmed using the Crank-Nicolson algorithm. Predicted results were consistent with experimental data. Using optimized parameters of dispersion, velocity, and a first order reaction constant, the model predicted effluent treatment levels to within 5 percent of the data, with treatment efficiencies of 40-90 percent TOC removal, depending on influent concentrations and retention times. Operation of the model would determine conditions necessary for achieving secondary treatment standards of <30 mg/1 effluent BOD_5 and TSS on a monthly average for a variety of biodegradable substrates. Future applications would eliminate lengthy pilot plant studies to predict anaerobic filter performance.

INTRODUCTION

Anaerobic filters, first developed by Coulter [1], Schroepfer [2], Young and McCarty [3] and Pretorius [4], have been used to treat medium and high strength wastes using domestic raw sewage as influent substrate. Recently Chung [5] and Kobayaski [6] have investigated the use of anaerobic filters for low strength waste treatment, reporting favorable results. This investigation used

---

anaerobic filter pilot plants to treat low strength raw domestic wastewater, with the goal of demonstrating the filter's ability to achieve secondary treatment standards.

The reactors ran continuously for over two years and were sampled daily for liquid and gas phase data. Treatment efficiencies and biogas production rates at various retention times were investigated. Each reactor was filled with a PVC packing material which supported the growth of submerged microbial films. The packing material was corrugated with 1 inch openings and had a specific surface area of greater than 99 percent. Effluent drained near the top of each upflow reactor, leaving a one-half foot space for the gas phase. Gas production was measured through wet test meters while gas composition was analyzed by gas chromatography. Influent and effluent wastewaters were analyzed for pH, TOC, TSS, alkalinity, sulfides and ammonia every two days, for a total of 679 days of experimental data collection.[1] Other analyses were made less frequently, including conductivities, oil-grease and volatile fatty acid determinations.

The data were used to develop and verify a first-order kinetic model considering dispersion and reaction. The dispersion equation was solved using Crank-Nicolson. Mass balances were derived from the ionic-equilibrium of the liquid phase along with solubility characteristics of the gas phase and were used to predict effluent water quality and gase phase purity. A dispersion coefficient was determined experimentally through tracer studies. The optimized dispersion coefficient was obtained using the influence coefficient method. The velocity constant was calculated from flow rates, while the first-order reaction constant was estimated from treatment efficiency.

Results have shown that gas phase composition was primarily N_2, with CH_4 never composing more than 20 percent of the total, due in part to the highly soluble CH_4 escaping with the effluent as well as N_2 being present at saturation levels. This was to be expected because lower effluent substrates levels usually mean lower CH_4 gas levels. Ammonia concentrations in the influent ranged from 5 to 25 ppm, with a 10-20 percent increase in the effluent. Losses of less than 10 percent may have occurred in the analyses of ammonia and methane during the time samples were taken and the time the analyses were made, due to the highly volatile nature of these gases, although precautions were taken to prevent this. Influent alkalinity levels ranged from 100 to 200 ppm, while sulfides varied from 0.5 to 5.0 ppm, with higher levels in the effluent due to bacterial reduction of sulfates to sulfides and hydrogen sulfide under anaerobic conditions. All these data are within the range of what has been reported for domestic wastewaters.

The completed model with optimized parameters predicted effluent TOC treatment levels to within 5 percent of experimental data, dependent on the

---

[1] TOC analysis was substituted for BOD_5 (BOC_5/TOC ratio varies from 1.0 to 1.6 for untreated domestic wastewaters).

value of the first order reaction constant. Thus, the model will help design anaerobic filters for the treatment of low strength substrates, predicting treatment efficiencies as a function of retention time as well as determining effluent water quality and gas phase purity.

MATERIALS AND METHODS

Anaerobic Filter Pilot Plant

The anaerobic filter pilot plant is shown in Figure 1. The sewage was pumped from a street pipeline to a holding tank on the 4th floor roof. The pipeline contained a grinding pump which broke up larger particles while the tank was equipped with a mixing rake and served as a settling tank. A second pump sent substrate directly to the bottom of the upflow reactors.

The reactors were 8 feet and 7.5 feet high, respectively, and had diameters of just under 2 feet, with sampling ports installed at regular intervals to study the effects of treatment verses height up the reactor column. Treated effluent drained one-half foot from the reactor top, while the remaining top space was used for gas collection.

Gas collected above the effluent drain was measured through wet test meters. The meters required pressures of at least two inches of water to operate. A manometer was attached to each reactor to carefully monitor pressure due to the high combustibility of methane (average tank pressures were in the range of 3 to 6 inches of water). Gas taken for GC analysis was sampled before being measured through the meters to avoid the possibility of contamination with either previous gases collected in the meters or with the meters themselves, which tended to corrode after several months and needed to be taken apart and cleaned. After passing through the meters, gas was vented to the atmosphere.

The plant originally consisted of a single anaerobic reactor, but was later expanded to include a second reactor operating in parallel. Both were packed with the corrugated PVC material for submerged film growth. Each reactor was seeded with digested sludge from the Hyperion Wastewater Treatment Plant in Los Angeles, a process which lasted approximately four weeks. Five gallons of seeding material was siphoned to each reactor, which were then filled to capacity with domestic sewage pumped from the street. Reactors were considered operational when pressures and gas production increased to consistent daily levels. A schedule of retention times during the course of the study is given in Figure 2.

Reactor Number 1 was operational for over a year before Reactor Number 2 was brought on-line. This study began at day 373 after the start-up of Reactor Number 1.
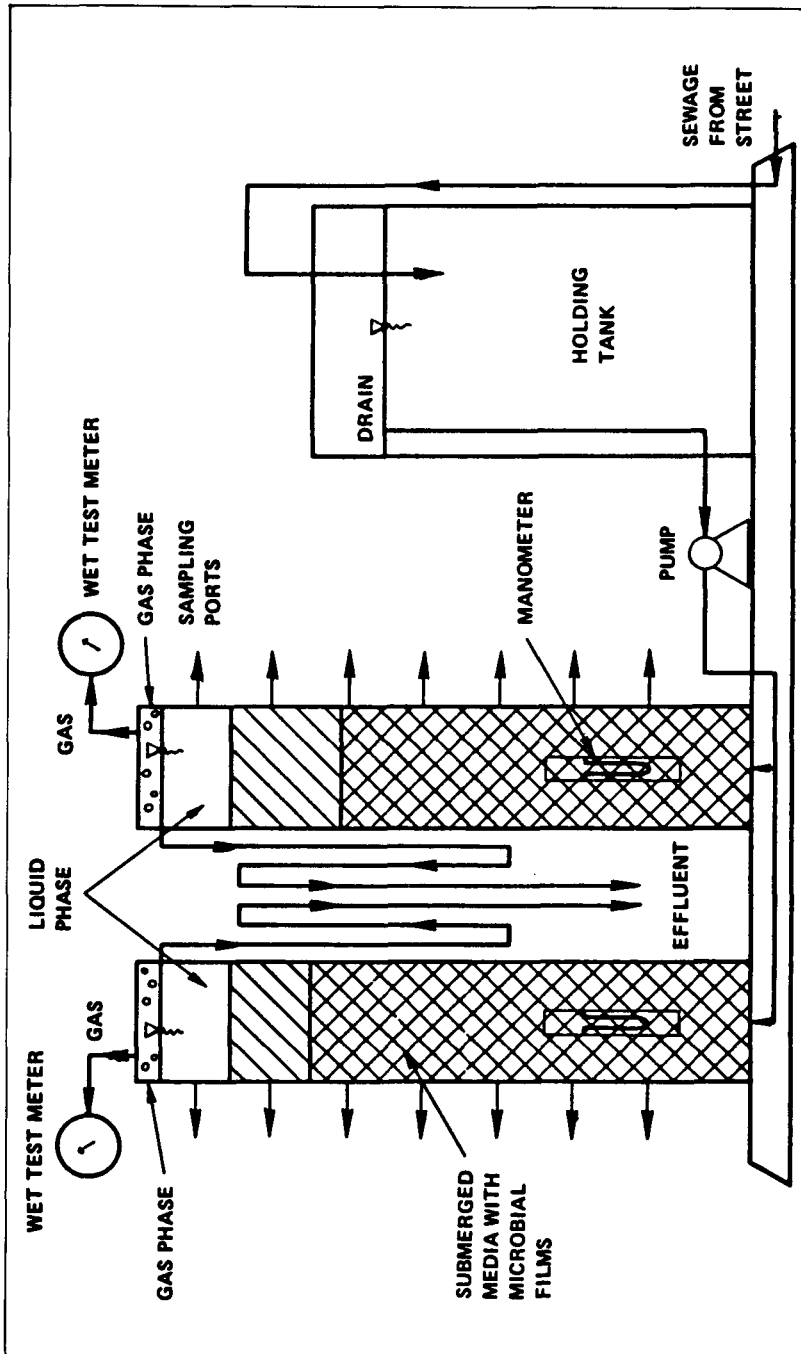
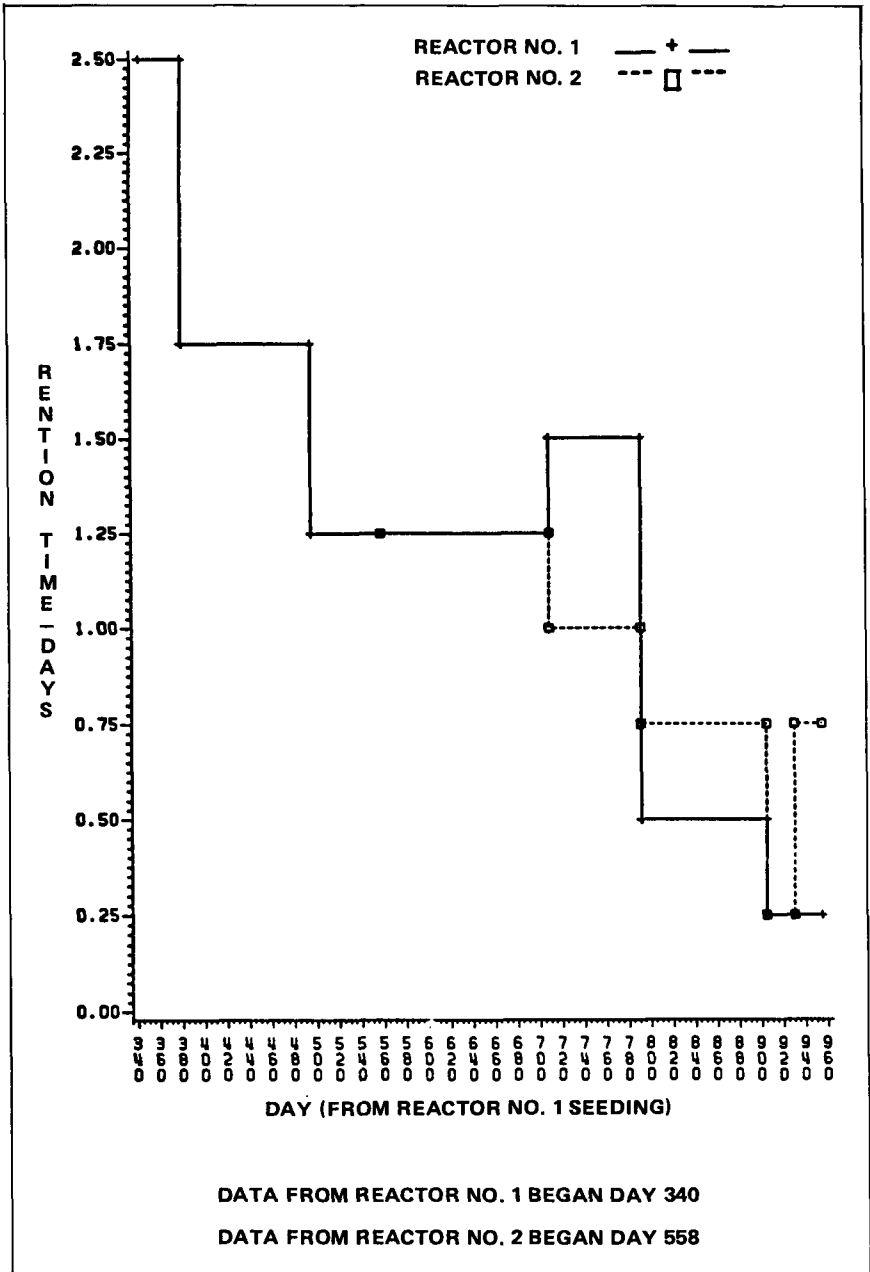Figure 1. Schematic diagram of the anaerobic filter pilot plant.

Figure 2. Schedule of retention times for Reactor No. 1 and Reactor No. 2.

Laboratory Analyses

Laboratory analyses were performed following procedures in *Standard Methods for Water and Wastewater Analysis* [7]. Gas composition including percent CH_4, CO_2, and N_2 was measured with a Varian 920 series chromatograph equipped with a thermal conductivity detector, using a 3.6 meter stainless steel column packed with activated carbon. TOC measurements were made with an Ionics Model 1270 Analyzer, which vaporized organic carbon contained in aqueous samples to CO_2. Measurement of resulting CO_2 was made by IR spectrophotometry to determine total organic content.

Tracer experiments were performed using a Perkin Elmer Atomic Absorption System Model 303 with a lithium lamp to read pulses of LiCl. Tracer curves were integrated for determination of dispersion and velocity coefficients.

Operational characteristics, including gas and liquid phase flow rates, hydraulic retention times and reactor pressures were measured on-line.

MATHEMATICAL PREDICTIVE MODEL

Dispersion Equation

The dispersion equation with diffusion, convection, and reaction terms was used to model flow in the liquid phase.

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} + V\frac{\partial c}{\partial x} - kc \tag{1}$$

It was solved analytically with no reaction for verification with the numerical solution. The solutions agreed with each other to greater than 98 percent after the first few time steps.

Analytical Solution

For the analytical solution, boundary conditions were set at constant flux (Danckwerts B.C.) for the influent boundary and no flow at the exit boundary, with zero initial condition.

$$D\frac{\partial c}{\partial x} + Vc = \text{Constant Flux @ Influent} \tag{2}$$

$$\frac{\partial c}{\partial x} = 0 \text{ @ Exit} \tag{3}$$

The procedure was to change variables and reduce the dispersion equation to the heat equation, which could be solved by separation of variables.

Numerical Solution

The Crank-Nicolson algorithm was used for the numerical solution of the computer based model. A stability analysis showed ΔX of 0.077 meters and Δt of 0.25 hours to be the most stable. After the programmed solution was confirmed, coefficients of dispersion and velocity were determined.

Dispersion Coefficient

Dispersion coefficients were determined from tracer studies analyzed by the methods of Levenspeil [8] and Van der Laan [9], and were optimized along with velocity constants by the method of constrained pattern search [10]. Figure 3 gives a plot of dispersion coefficient versus retention time.
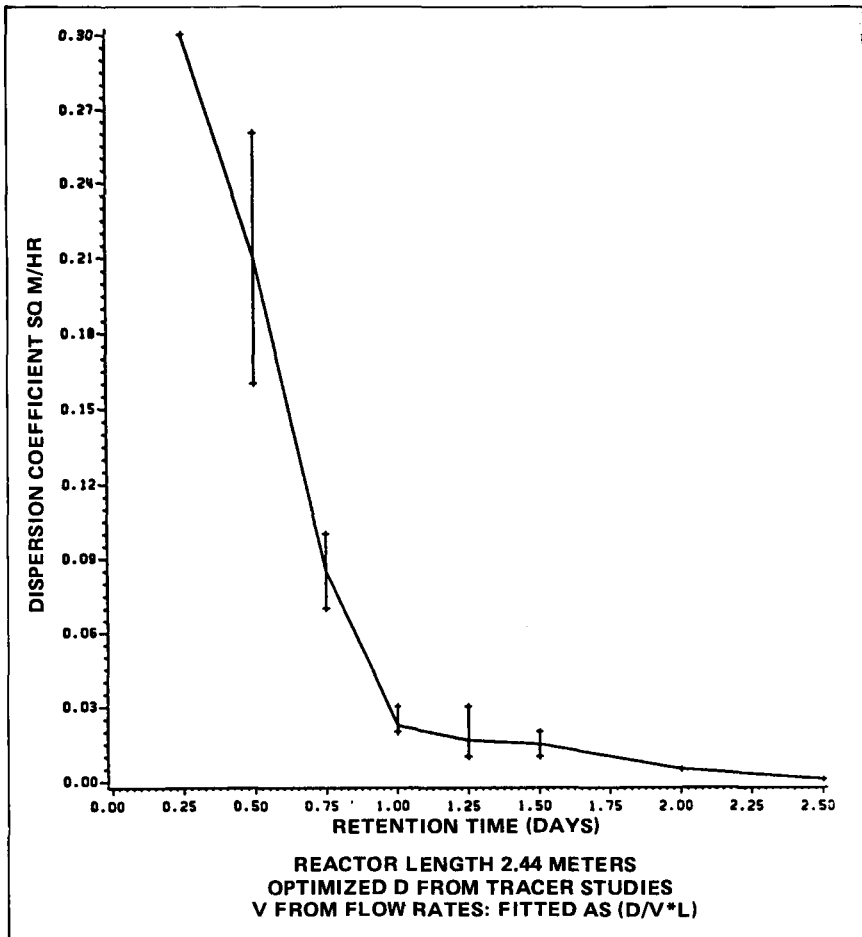
Figure 3. Dispersion coefficient standard curve in square meters/hour.

Velocity Coefficient

Figure 4 gives the flow rate curves for both reactors made shortly after the initial seeding process.

These curves represent flow through the reactors with no microbial films attached to the submerged media. Both lines are exponentially decreasing curves with increasing retention time, and do not reflect the effects of microbial film growth on flow rate over time at similar pumping rates. Although velocity coefficients were determined with dispersion coefficients through integration of
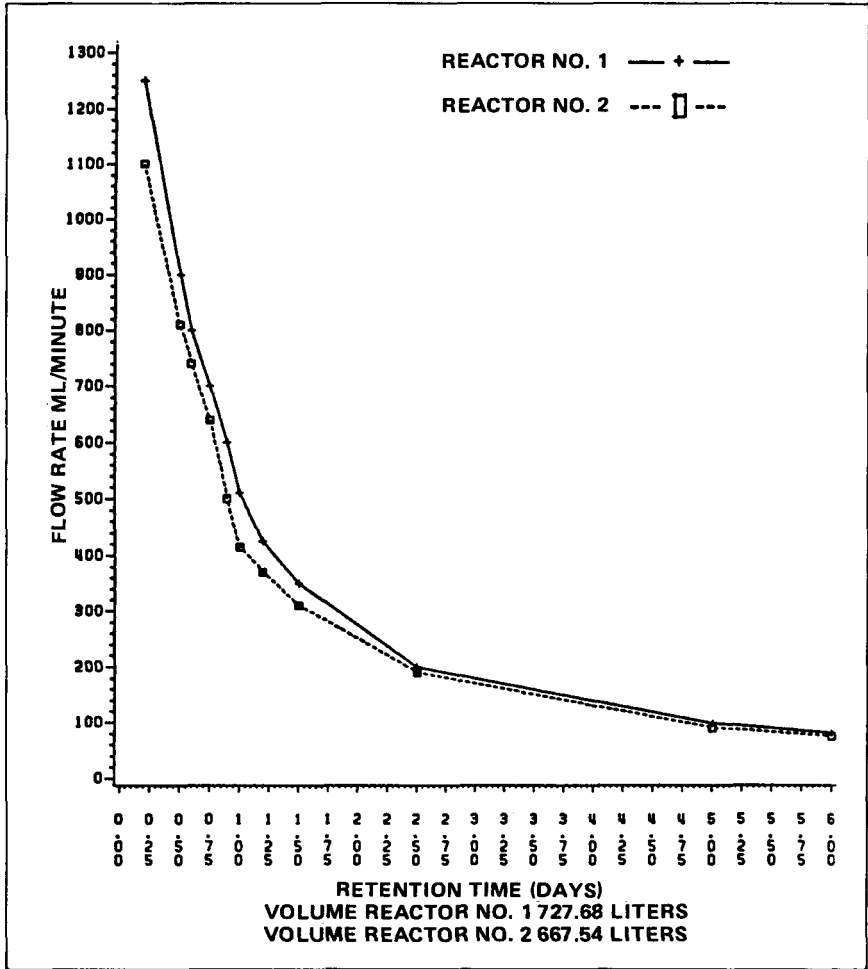
Figure 4. Pilot plant flow rate curves for Reactors No. 1 and No. 2.

the tracer curves, it was not possible to continuously calibrate pumps to maintain exact flow rates at similar pump settings.

A more reliable standard curve was used based on the relationship

$$[Theta] = [V/Q] = [[L*A]/Q] = [L/V] \tag{4}$$

Figure 5 is a plot of [V] versus [L/Theta] and was used to derive the velocity coefficients for the liquid phase model.
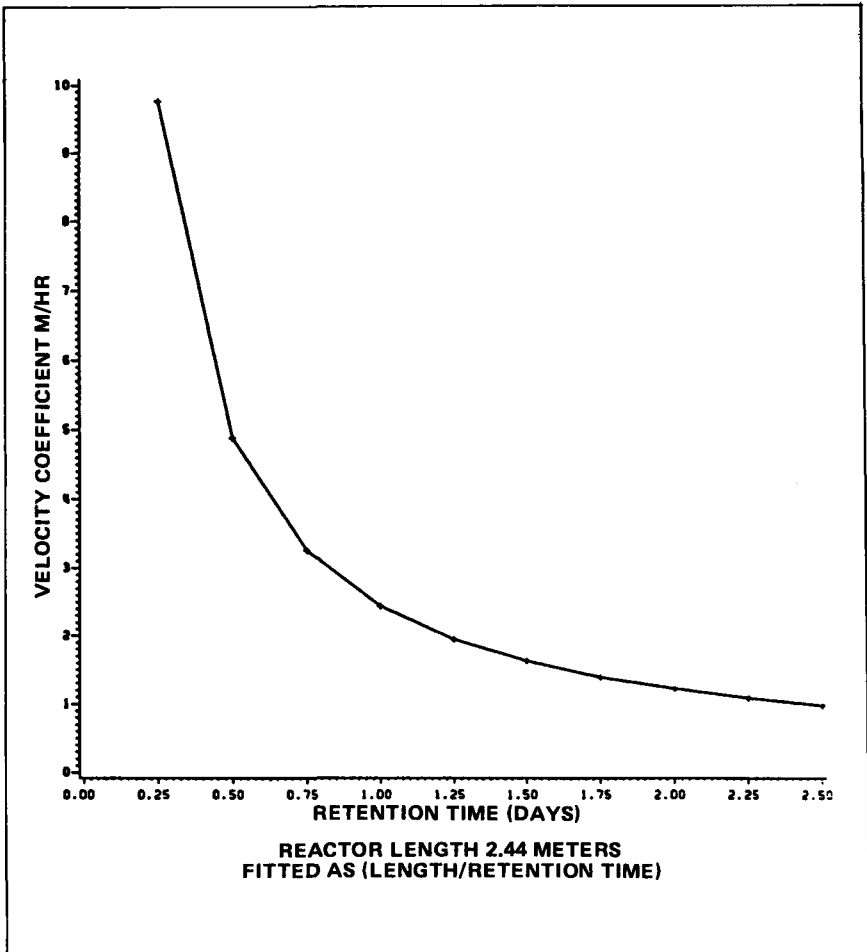
Figure 5. Velocity coefficient standard curve in meters/hour.

Optimization of Dispersion and Velocity Coefficients

Optimized dispersion and velocity coefficients were determined by using the influence coefficient method. The procedure used concentration data derived from tracer experiments along with a first approximation of each coefficient, and is defined mathematically when the jth row of the Jacobian matrix transpose is approximated by

$$\frac{\partial c_i}{\partial \alpha} = \frac{C_i(\alpha + \delta \alpha_j e_j) - C_i(\alpha)}{\delta \alpha}, i = 1, \ldots m \tag{5}$$

where: e_j = the jth unit vector
         $\delta \alpha_j$ = small increment of α_j

Liquid Phase First Order Reaction Constant

The optimal first order reaction constant for the reduction of organic matter to carbon dioxide and methane was derived using experimental data with the equation for reactors in series.

$$\text{Organic Matter} \rightarrow \text{Volatile Acids} \rightarrow CO_2 + CH_4 \tag{6}$$
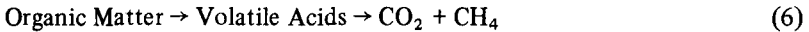
The equation was solved for up to five reactors, optimizing the reaction constant where the sum of squares error was minimized. Figure 6 gives the results of treatment efficiency using the experimental data as well as the predictive model with several of the reaction constants. The graph shows the optimal reaction constant to be 0.048/hour for one reactor and was used in the predictive model for all retention times. Equilibrium constants for the carbonate and bicarbonate reactions were taken from the literature [11]. Stoichiometric relationships of equations (7)-(11) were also included.

$$\text{Organic Nigrogen} \rightarrow NH_4^+ \rightarrow NH_3 + H^+ \tag{7}$$

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO_3^- + H^+ \rightarrow CO_3^{-2} \tag{8}$$

$$CO_3^{-2} + Ca^{+2} \rightarrow CaCO_3 \tag{9}$$

$$SO_3^{-2} + \text{Organic Matter} \rightarrow S^{-2} + H_2O + CO_2 \tag{10}$$

$$S^{-2} + 2H^+ \rightarrow H_2S \tag{11}$$
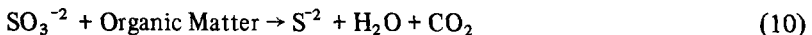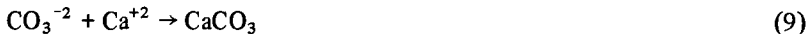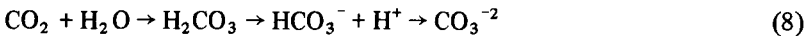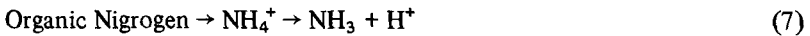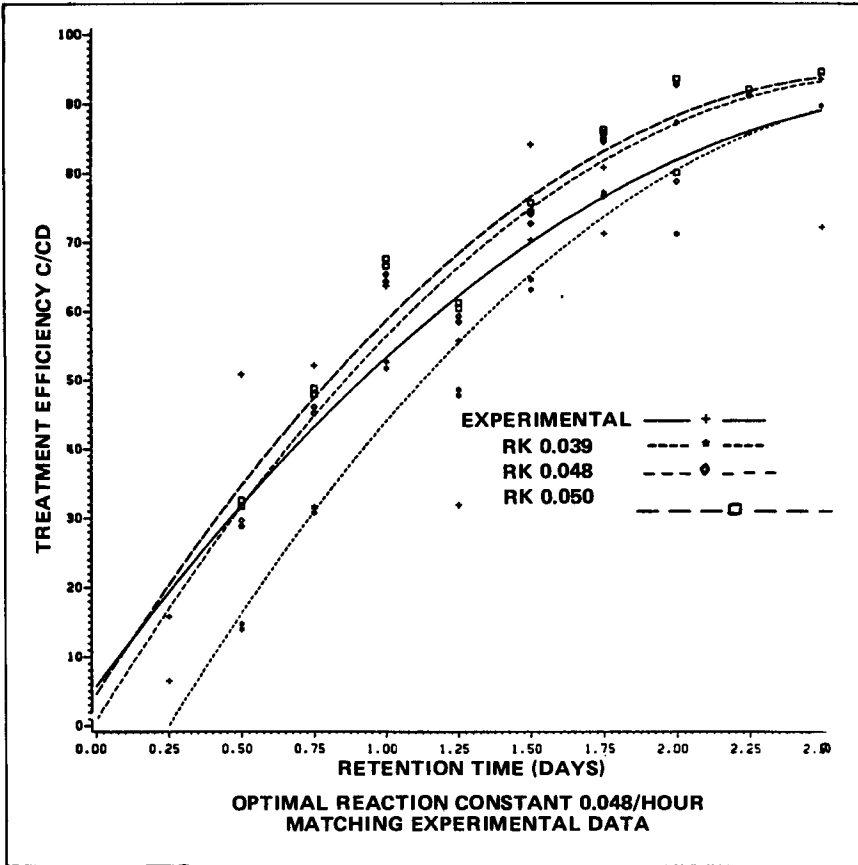
Figure 6. TOC efficiency versus Theta (experimental and modeled)
reaction constants: 0.0390, 0.048 and 0.050/hour.

Gas Phase

Mass balances of CH_4, CO_2, and N_2 between the liquid and gas phases were based on the rates of biological and chemical production (equations (12), (13), and (14)). From the experimental data and the literature [12], it was determined that N_2 production was always present at saturation levels. Therefore, although the rates of production of CH_4 and CO_2 were a function of influent TOC concentrations, growth and yield rates, N_2 production was considered a constant 15.3 mg/1 (saturated).

$$[Y*u] *X*VCH_4 = FL*HKCH_4 *P_p CH_4 *16000 +$$
$$Fg*P_p CH_4/P_t *(16000/22.4) \tag{12}$$

$$[Y*u] *X*VCO_2 = FL*HKCO_2 P_pCO_2 *44000 + \\ Fg*P_pCO_2 /P_t *(44000/22.4) + [TERM\ 1] + [TERM\ 2] \quad (13)$$

$$SATN_2 = FL*HKN_2 *P_pN_2 *(0.79)*(1)*28000 + \\ Fg*P_pN_2 /P_t *(28000/22.4) \quad (14)$$

$$P_t = P_pCH_4 + P_pCO_2 + P_pN_2 + P_pH_2O\ P_pCO_2 + \quad (15)$$

where:

FL = flow of liquid (liters/time)
Fg = flow of gas (liters/time)
P_pCH_4 = partial pressure CH_4 (mmHg)
P_pCO_2 = partial pressure CO_2 (mmHg)
P_pN_2 = partial pressure N_2 (mmHg)
P_pH_2O = partial pressure H_2O (mmHg)
P_t = total pressure (mmHg)
$HKCH_4$ = Henrys constant CH_4 (moles/liter atm)
$HKCO_2$ = Henrys constant CO_2 (moles/liter atm)
HKN_2 = Henrys constant N_2 (moles/liter atm)
$[VCH_4]$ = volume CH_4 (liters)
$[VCO_2]$ = volume CO_2 (liters)
Y = percent yield
u = growth rate (1/days)
$[X]$ = influent substrate concentration (mg/l)
$[TERM\ 1]$ = concentration of $[HCO_3^-]$ (mg/l)
$[TERM\ 2]$ = concentration of $[CO_3^{-2}]$ (mg/l)

Incorporating the partial pressure law and setting P_pN_2 equal to $P_t-(P_pCH_4 + P_pH_2O)$, mass balances were equated through the flow of gas term (Fg), then solved for P_pCO_2.

Experimental Results

Experimental data and a statistical analysis for each reactor at all retention times are presented in Tables 1, 2, and 3.

The model used ionic equilibrium present in the liquid phase to predict effluent pH. TSS levels were not mathematically modeled because they were a function of the influent stream and would vary randomly and therefore, could not be fitted by a first order reaction constant. The low strength suspended solids were significantly reduced by passing through the porous media present in the upflow reactors. Any instance where the effluent TSS were higher than the influent TSS was caused by decayed material inside the reactor being washed out with the effluent and was not due to a failure of the filter. This could be avoided

Table 1. Reactors No. 1 and 2: All Retention Times

Variable	N	Mean	Standard Deviation	Minimum Value	Maximum Value	Standard Error of Mean	Sum	Variance	C.V.
					COLM = 1				
DATE	598	641.60033445	172.94770988	343.00000000	953.00000000	7.07235779	383677.00000	29910.910352	26.956
THETA	598	1.26170569	0.56197644	0.25000000	2.50000000	0.02298093	754.50000	0.315818	44.541
TOCI	111	67.43153153	52.07926473	5.00000000	200.00000000	4.94314505	7484.90000	2712.249815	77.233
TOCE	109	18.88348624	12.88241346	1.00000000	69.00000000	1.23391142	2058.30000	165.956577	68.221
TSSI	31	100.11935484	68.23938950	8.70000000	292.80000000	12.25615616	3103.70000	4656.614280	68.158
TSSE	30	26.70666667	40.64350424	1.80000000	152.30000000	7.42045470	801.20000	1651.894437	152.185
SULI	25	1.89600000	1.61180024	0.00000000	5.70000000	0.32236005	47.40000	2.597900	85.011
SULE	26	2.22692308	1.34983190	0.50000000	5.50000000	0.26472381	57.90000	1.822046	60.614
ALKI	24	102.46666667	23.12368759	53.00000000	137.80000000	4.72010296	2459.20000	534.704928	22.567
ALKE	24	150.17083333	30.61957997	98.10000000	206.70000000	6.25019559	3604.10000	937.558678	20.390
AMMI	27	6.43928571	3.68463670	1.20000000	12.50000000	0.69633088	180.30000	13.576548	57.221
AMME	28	12.51428571	6.49117431	2.90000000	29.00000000	1.22671664	350.40000	42.135344	51.870
GAS	108	0.27805556	0.25584552	0.00000000	1.00000000	0.02461875	30.03000	0.065457	92.012
N_2	7	0.82571429	0.02760262	0.79000000	0.87000000	0.01043281	5.78000	0.000762	3.343
CH_4	7	0.11571429	0.03408672	0.05000000	0.15000000	0.01288357	0.81000	0.001162	29.458
CO_2	7	0.01285714	0.00487950	0.01000000	0.02000000	0.00184428	0.09000	0.000024	37.952
OTH	7	0.04714286	0.02563480	0.01000000	0.08000000	0.00968904	0.33000	0.000657	54.377
TDSI	9	424.22222222	117.40291497	303.00000000	650.00000000	39.13430499	3818.00000	13783.44444	27.675
TDSE	9	419.77777778	60.53878463	328.00000000	510.00000000	20.17959488	3778.00000	3664.94444	14.422
TEMP	28	81.34714286	6.69557226	64.00000000	89.00000000	1.26534422	2278.00000	44.830688	8.230

COLM = 2

DATE	387	751.21963824	112.24180885	558.00000000	954.00000000	5.70557179	290722.00000	12598.223655	14.941
THETA	387	0.96770026	0.28383136	0.25000000	1.25000000	0.01442796	374.50000	0.080560	29.331
TOCI	66	31.02121212	23.89839721	4.00000000	99.80000000	2.94168934	2047.40000	571.133389	77.039
TOCE	65	17.74153846	16.83547122	1.00000000	85.00000000	2.08818320	1153.20000	283.433091	94.893
TSSI	11	57.75454545	44.18858141	8.70000000	149.80000000	13.32335860	635.30000	1952.630727	76.511
TSSE	11	19.63636364	43.89180499	1.80000000	151.70000000	13.23387714	216.00000	1926.490545	223.523
SULI	23	1.96521739	1.66367848	0.00000000	5.70000000	0.34690094	45.20000	2.767826	84.656
SULE	25	3.35600000	1.64673414	0.50000000	7.10000000	0.32934683	83.90000	2.711733	49.068
ALKI	23	102.54347826	23.74025508	53.00000000	137.80000000	4.92933394	2358.50000	558.861660	23.054
ALKE	23	149.09130435	34.80231070	95.40000000	206.70000000	7.25678342	3429.10000	1211.200830	23.343
AMMI	27	6.63333333	3.60608460	1.20000000	12.50000000	0.69399131	179.10000	13.003846	54.363
AMME	27	12.50000000	5.91289334	3.30000000	25.00000000	1.13793685	337.50000	34.962308	47.303
GAS	80	0.28512500	0.28118643	0.00000000	1.45000000	0.03134760	22.81000	0.079066	98.619
N_2	7	0.84428571	0.03457222	0.78000000	0.88000000	0.01306707	5.91000	0.001195	4.095
CH_4	7	0.07571429	0.04117327	0.01000000	0.14000000	0.01556203	0.53000	0.001695	54.380
CO_2	7	0.01142857	0.00377964	0.01000000	0.02000000	0.00142857	0.08000	0.000014	33.072
OTH	7	0.07000000	0.02449490	0.04000000	0.10000000	0.00925820	0.49000	0.000600	34.993
TDSI	9	424.22222222	117.40291497	303.00000000	650.00000000	39.13430499	3818.00000	13783.444444	27.675
TDSE	9	423.77777778	62.19280058	330.00000000	520.00000000	20.73093353	3814.00000	3867.944444	14.676
TEMP	28	81.35714286	6.69557226	64.00000000	89.00000000	1.26534422	2278.00000	44.830688	8.230

Table 2. Reactor No. 1: Individual Retention Times

Variable	N	Mean	Standard Deviation	Minimum Value	Maximum Value	Standard Error of Mean	Sum	Variance	C.V.
				COLM = 1	THETA = 0.25				
DATE	30	920.63333333	9.05722548	906.00000000	939.00000000	1.65361557	27619.000000	82.0333333	0.984
TOCI	10	19.25000000	12.12721916	7.50000000	43.00000000	3.83496342	192.500000	147.0694444	62.999
TOCE	10	18.00000000	11.17536974	6.00000000	37.00000000	3.53396221	180.000000	124.8888889	62.085
TSSI	3	26.46666667	5.84836159	21.10000000	32.70000000	3.37655314	79.400000	34.2033333	22.097
TSSE	3	52.93333333	85.62250483	3.00000000	151.80000000	49.43417621	158.800000	7331.2133333	161.755
SULI	3	0.60000000	0.55677644	0.00000000	1.10000000	0.32145503	1.800000	0.3100000	92.796
SULE	3	4.03333333	0.80829038	3.10000000	4.50000000	0.46666667	12.100000	0.6533333	20.040
ALKI	2	116.60000000	7.49533188	111.30000000	121.90000000	5.30000000	233.200000	56.1800000	6.428
ALKE	2	166.95000000	3.74766594	164.30000000	169.60000000	2.65000000	333.900000	14.0450000	2.245
AMMI	5	4.60000000	2.34520788	2.20000000	7.80000000	1.04880885	23.000000	5.5000000	50.983
AMME	5	7.48000000	3.98710421	2.90000000	11.50000000	1.78308721	37.400000	15.8970000	53.304
GAS	3	0.02000000	0.00000000	0.02000000	0.02000000	0.00000000	0.060000	0.0000000	0.000
N_2	0	.	.	.	.	.	.	.	.
CH_4	0	.	.	.	.	.	.	.	.
CO_2	0	.	.	.	.	.	.	.	.
OTH	0	.	.	.	.	.	.	.	.
TDSI	0	.	.	.	.	.	.	.	.
TDSE	0	.	.	.	.	.	.	.	.
TEMP	2	84.00000000	0.00000000	84.00000000	84.00000000	0.00000000	168.000000	0.0000000	0.000

COLM = 1   THETA = 0.5

DATE	118	853.24576271	37.93673015	793.00000000	953.00000000	3.49235909	100683.00000	1439.1954947	4.446
TOCI	19	31.10526316	22.29572639	5.00000000	90.00000000	5.11499043	591.00000	497.0994152	71.678
TOCE	19	15.31578947	10.96992166	3.00000000	45.00000000	2.51667263	291.00000	120.3391813	71.625
TSSI	5	57.32000000	62.6329419C	8.70000000	149.80000000	28.05502451	286.60000	3935.4220000	109.443
TSSE	5	7.26000000	6.25043998	1.80000000	16.60000000	2.79528174	36.30000	39.0680000	86.094
SULI	6	1.13333333	0.34448028	0.70000000	1.50000000	0.14063349	6.80000	0.1186667	30.395
SULE	6	3.26666667	1.45005747	2.10000000	5.50000000	0.59198348	19.60000	2.1026667	44.390
ALKI	6	114.83333333	16.98206897	100.70000000	137.80000000	6.93290063	689.00000	288.3906667	14.788
ALKE	6	150.16666667	38.60884182	106.00000000	206.70000000	15.76199367	901.00000	1490.6426667	25.711
AMMI	7	5.10000000	4.46840762	1.20000000	11.50000000	1.68889933	35.70000	19.9666667	87.616
AMME	7	9.48571429	6.35175266	2.90000000	17.00000000	2.40073685	66.40000	40.3447619	66.961
GAS	39	0.27923077	0.21603344	0.00000000	0.84000000	0.03459304	10.89000	0.0466704	77.367
N$_2$	0	.	.	.	.	.	.	.	.
CH$_4$	0	.	.	.	.	.	.	.	.
CO$_2$	0	.	.	.	.	.	.	.	.
OTH	0	.	.	.	.	.	.	.	.
TDSI	0	.	.	.	.	.	.	.	.
TDSE	0	.	.	.	.	.	.	.	.
TEMP	8	84.00000000	4.34248119	77.00000000	89.00000000	1.53529895	672.00000	18.8571429	5.170

Table 2. (Cont'd)

COLM = 1   THETA = 1.75

Variable	N	Mean	Standard Deviation	Minimum Value	Maximum Value	Standard Error of Mean	Sum	Variance	C.V.
DATE	117	438.00000000	33.91902121	380.00000000	496.00000000	3.13581462	51246.000000	1150.5000000	7.744
TOCI	38	116.05263158	37.57726985	33.00000000	196.00000000	6.09583812	4410.000000	1412.0512091	32.380
TOCE	38	22.31578947	14.33405558	5.00000000	69.00000000	2.32529087	848.000000	205.4651494	64.233
TSSI	13	148.33846154	64.69723769	69.00000000	292.80000000	17.94378522	1928.400000	4185.7325741	43.615
TSSE	12	42.50833333	45.54227723	9.90000000	152.30000000	13.14692301	510.100000	2074.0990152	107.137
SULI	0	.	.	.	.	.	.	.	.
SULE	0	.	.	.	.	.	.	.	.
ALKI	0	.	.	.	.	.	.	.	.
ALKE	0	.	.	.	.	.	.	.	.
AMMI	0	.	.	.	.	.	.	.	.
AMME	0	.	.	.	.	.	.	.	.
GAS	31	0.40903226	0.30227311	0.01000000	0.95000000	0.05428985	12.680000	0.0913690	73.900
N_2	0	.	.	.	.	.	.	.	.
CH_4	0	.	.	.	.	.	.	.	.
CO_2	0	.	.	.	.	.	.	.	.
OTH	0	.	.	.	.	.	.	.	.
TDSI	0	.	.	.	.	.	.	.	.
TDSE	0	.	.	.	.	.	.	.	.
TEMP	0	.	.	.	.	.	.	.	.

COLM = 1   THETA = 2.5

DATE	37	361.00000000	10.82435525	343.00000000	379.00000000	1.77951304	13357.000000	117.1666667	2.998
TOCI	11	96.50000000	60.27146920	30.00000000	200.00000000	18.17253172	1061.500000	3632.6500000	62.457
TOCE	9	27.00000000	9.63068014	18.00000000	50.00000000	3.21022671	243.000000	92.7500000	35.669
TSSI	6	88.55000000	46.50616088	29.80000000	157.00000000	18.98606068	531.300000	2162.8230000	52.520
TSSE	6	8.58333333	7.81880212	2.30000000	24.00000000	3.19201260	51.500000	61.1336667	91.093
SULI	0	.	.	.	.	.	.	.	.
SULE	0	.	.	.	.	.	.	.	.
ALKI	0	.	.	.	.	.	.	.	.
ALKE	0	.	.	.	.	.	.	.	.
AMMI	0	.	.	.	.	.	.	.	.
AMME	0	.	.	.	.	.	.	.	.
GAS	12	0.16750000	0.26451070	0.01000000	1.00000000	0.07635766	2.010000	0.0699659	157.917
N₂	0	.	.	.	.	.	.	.	.
CH₄	0	.	.	.	.	.	.	.	.
CO₂	0	.	.	.	.	.	.	.	.
OTH	0	.	.	.	.	.	.	.	.
TDSI	0	.	.	.	.	.	.	.	.
TDSE	0	.	.	.	.	.	.	.	.
TEMP	0	.	.	.	.	.	.	.	.

Table 2. (Cont'd)

Variable	N	Mean	Standard Deviation	Minimum Value	Maximum Value	Standard Error of Mean	Sum	Variance	C.V.
				COLM = 1	THETA = 1.25				
DATE	213	603.00000000	61.63197222	497.00000000	709.00000000	4.22295315	128439.00000	3798.500000	10.221
TOCI	20	44.89500000	26.98247921	10.00000000	99.80000000	6.03346577	897.90000	728.054184	60.101
TOCE	20	19.86500000	12.46854041	2.30000000	40.30000000	2.78805039	397.30000	155.464500	62.766
TSSI	0								
TSSE	0								
SULI	9	3.21111111	2.02758751	0.50000000	5.70000000	0.67586250	28.90000	4.111111	63.143
SULE	8	1.75000000	0.58309519	0.50000000	2.10000000	0.20615528	14.00000	0.340000	33.320
ALKI	8	96.72500000	26.57419532	53.00000000	132.50000000	9.39539686	773.80000	706.187857	27.474
ALKE	8	133.50000000	34.45539560	98.10000000	201.40000000	12.18182194	1068.00000	1187.174286	25.809
AMMI	8	9.55000000	2.92379401	4.60000000	12.50000000	1.03371729	76.40000	8.548571	30.616
AMME	8	17.22500000	6.62953349	10.40000000	29.00000000	2.34389404	137.80000	43.950714	38.488
GAS	11	0.23454545	0.21430649	0.01000000	0.60000000	0.06461584	2.58000	0.045927	91.371
N_2	6	0.83166667	0.02483277	0.80000000	0.87000000	0.01013794	4.99000	0.000617	2.986
CH_4	6	0.11500000	0.03728270	0.05000000	0.15000000	0.01522060	0.69000	0.001390	32.420
CO_2	6	0.01333333	0.00516398	0.01000000	0.02000000	0.00210819	0.08000	0.000027	38.730
OTH	6	0.04166667	0.02316607	0.01000000	0.07000000	0.00945751	0.25000	0.000537	55.599
TDSI	9	424.22222222	117.40291497	303.00000000	650.00000000	39.13430499	3818.00000	13783.444444	27.675
TDSE	9	419.77777778	60.53878463	328.00000000	510.00000000	20.17959488	3778.00000	3664.944444	14.422
TEMP	18	79.88888889	7.55286380	64.00000000	88.00000000	1.78022707	1438.00000	57.045752	9.454

	N								
DATE	83	751.00000000	24.10394159	710.00000000	792.00000000	2.64575131	62333.000000	581.00000000	3.210
TOCI	13	25.53846154	20.98259352	7.00000000	80.00000000	5.81952437	332.000000	440.26923077	82.161
TOCE	13	7.61538462	5.59074327	1.00000000	23.00000000	1.55059319	99.000000	31.25641026	73.414
TSSI	4	69.50000000	29.62543952	41.00000000	109.00000000	14.81271976	278.000000	877.66666667	42.627
TSSE	4	11.12500000	4.92975659	7.00000000	17.00000000	2.46487829	44.500000	24.30250000	44.312
SULI	7	1.41428571	0.64917530	0.30000000	2.30000000	0.24536520	9.900000	0.42142857	45.901
SULE	9	1.35555556	0.89597867	0.50000000	3.30000000	0.29865956	12.200000	0.80277778	66.097
ALKI	8	95.40000000	23.53240926	58.30000000	127.20000000	8.31996308	763.200000	553.77438571	24.667
ALKE	8	162.65000000	15.82998962	132.50000000	180.20000000	5.59674650	1301.200000	250.58857143	9.733
AMMI	8	5.65000000	2.75317998	2.00000000	10.50000000	0.97339612	45.200000	7.58000000	48.729
AMME	8	13.60000000	4.57415098	5.80000000	20.00000000	1.61720659	108.800000	20.92285714	33.633
GAS	12	0.15083333	0.12324833	0.02000000	0.42000000	0.03557873	1.810000	0.01519015	81.712
N₂	1	0.79000000	.	0.79000000	0.79000000	.	0.790000	.	.
CH₄	1	0.12000000	.	0.12000000	0.12000000	.	0.120000	.	.
CO₂	1	0.01000000	.	0.01000000	0.01000000	.	0.010000	.	.
OTH	1	0.08000000	.	0.08000000	0.08000000	.	0.080000	.	.
TDSI	0	.	.	.	.	.	.	.	.
TDSE	0	.	.	.	.	.	.	.	.
TEMP	0	.	.	.	.	.	.	.	.

Table 3. Reactor No. 2: Individual Retention Times

Variable	N	Mean	Standard Deviation	Minimum Value	Maximum Value	Standard Error of Mean	Sum	Variance	C.V.
				COLM = 2	THETA = 0.25				
DATE	25	918.00000000	7.35980072	906.00000000	930.00000000	1.47196014	22950.000000	54.166667	0.802
TOCI	7	23.28571429	12.36546651	8.00000000	43.00000000	4.67370703	163.000000	152.904762	53.103
TOCE	7	19.64285714	10.93432777	7.50000000	34.00000000	4.13278743	137.500000	119.559524	55.666
TSSI	2	23.35000000	3.18198052	21.10000000	25.60000000	2.25000000	46.700000	10.125000	13.627
TSSE	2	78.80000000	103.09616870	5.90000000	151.70000000	72.90000000	157.600000	10628.820000	130.833
SULI	1	0.90000000	.	0.70000000	1.10000000	0.20000000	1.800000	0.080000	31.427
SULE	2	4.80000000	0.98994949	4.10000000	5.50000000	0.70000000	9.600000	0.980000	20.624
ALKI	1	111.30000000	.	111.30000000	111.30000000	.	111.300000	.	.
ALKE	1	153.70000000	.	153.70000000	153.70000000	.	153.700000	.	.
AMMI	2	6.90000000	1.27279221	6.00000000	7.80000000	0.90000000	13.800000	1.620000	18.446
AMME	2	10.40000000	2.26274170	8.80000000	12.00000000	1.60000000	20.800000	5.120000	21.757
GAS	1	0.03000000	.	0.03000000	0.03000000	.	0.030000	.	.
N$_2$	0	.	.	.	.	.	.	.	.
CH$_4$	0	.	.	.	.	.	.	.	.
CO$_2$	0	.	.	.	.	.	.	.	.
OTH	0	.	.	.	.	.	.	.	.
TDSI	0	.	.	.	.	.	.	.	.
TDSE	0	.	.	.	.	.	.	.	.
TEMP	1	84.00000000	.	84.00000000	84.00000000	.	84.000000	.	.

COLM = 2   THETA = 0.75

DATE	127	859.42519685	42.96205777	793.00000000	954.00000000	3.81226616	109147.00000	1845.7384077	4.999
TOCI	26	25.17307692	21.48624784	4.00000000	90.00000000	4.21379988	654.50000	461.6588462	85.354
TOCE	26	12.03846154	9.58115137	3.00000000	44.00000000	1.87901838	313.00000	91.7984615	79.588
TSSI	5	62.12000000	62.12000000	58.88278186	149.80000000	26.33318059	310.60000	3467.1820000	94.789
TSSE	5	6.34000000	3.20749123	1.80000000	10.70000000	1.43443369	31.70000	10.2880000	50.591
SULI	6	0.91666667	0.56005952	0.00000000	1.50000000	0.22864334	5.50000	0.3136667	61.097
SULE	6	4.13333333	2.64247359	1.30000000	7.10000000	1.07878533	24.80000	6.9826667	63.931
ALKI	6	118.36666667	15.60277753	100.70000000	137.80000000	6.36980725	710.20000	243.4466667	13.182
ALKE	6	161.65000000	33.47821680	127.20000000	206.70000000	13.66742478	969.90000	1120.7910000	20.710
AMMI	9	4.85555556	3.86008779	1.20000000	11.50000000	1.28669593	43.70000	14.9002778	79.498
AMME	9	9.14444444	5.67408828	3.30000000	18.00000000	1.89136276	82.30000	32.1952778	62.050
GAS	45	0.29355556	0.27466637	0.02000000	1.09000000	0.04094485	13.21000	0.0754416	93.565
N₂	0	.	.	.	.	.	.	.	
CH₄	0	.	.	.	.	.	.	.	
CO₂	0	.	.	.	.	.	.	.	
OTH	0	.	.	.	.	.	.	.	
TDSI	0	.	.	.	.	.	.	.	
TDSE	0	.	.	.	.	.	.	.	
TEMP	9	84.00000000	4.06201920	77.00000000	89.00000000	1.35400640	756.00000	16.5000000	4.836

Table 3. (Cont'd)

Variable	N	Mean	Standard Deviation	Minimum Value	Maximum Value	Standard Error of Mean	Sum	Variance	C.V.
					COLM = 2 THETA = 1				
DATE	83	751.00000000	24.10394159	710.00000000	792.00000000	2.64575131	62333.000000	581.00000000	3.210
TOCI	13	25.53846154	20.98259352	7.00000000	80.00000000	5.81952437	332.000000	440.26923077	82.161
TOCE	13	9.23076923	6.58475317	1.00000000	24.00000000	1.82628194	120.000000	43.35897436	71.335
TSSI	4	69.50000000	29.62543952	41.00000000	109.00000000	14.81271976	278.000000	877.66666667	42.627
TSSE	4	6.67500000	3.57339708	4.40000000	12.00000000	1.78669854	26.700000	12.76916667	53.534
SULI	7	1.41428571	0.64917530	0.30000000	2.30000000	0.24536520	9.900000	0.42142857	45.901
SULE	9	2.72222222	1.35441664	0.50000000	5.30000000	0.45147221	24.500000	1.83444444	49.754
ALKI	8	95.40000000	23.53240926	58.30000000	127.20000000	8.31996308	763.200000	553.77428571	24.667
ALKE	8	172.25000000	15.51681116	153.70000000	196.10000000	5.48602120	1378.000000	240.77142857	9.008
AMMI	8	5.65000000	2.75317998	2.00000000	10.50000000	0.98339612	45.200000	7.58000000	48.729
AMME	8	13.21250000	5.62175303	5.20000000	22.00000000	1.98758985	105.700000	31.60410714	42.549
GAS	34	0.28147059	0.29429044	0.00000000	1.45000000	0.05047039	9.570000	0.08660686	104.555
N$_2$	1	0.78000000	.	0.78000000	0.78000000	.	0.780000	.	.
CH$_4$	1	0.14000000	.	0.14000000	0.14000000	.	0.140000	.	.
CO$_2$	1	0.01000000	.	0.01000000	0.01000000	.	0.010000	.	.
OTH	1	0.07000000	.	0.07000000	0.07000000	.	0.070000	.	.
TDSI	0	.							
TDSE	0	.							
TEMP	0	.							

COLM = 2   THETA = 1.25

DATE	152	633.50000000	44.02272141	558.00000000	709.00000000	3.57071421	96292.000000	1938.000000	6.949
TOCI	20	44.89500000	26.98247921	10.00000000	99.80000000	6.03346577	897.900000	728.054184	60.101
TOCE	19	30.66842105	23.11747902	3.80000000	85.00000000	5.30351341	582.700000	534.417836	75.379
TSSI	0	.	.	.	.	.	.	.	
TSSE	0	.	.	.	.	.	.	.	
SULI	8	3.50000000	1.95959179	0.50000000	5.70000000	0.69282032	28.000000	3.840000	55.988
SULE	8	3.12500000	0.61817704	2.10000000	3.70000000	0.21855859	25.000000	0.382143	19.782
ALKI	8	96.72500000	26.57419532	53.00000000	132.50000000	9.39539686	773.800000	706.187857	27.474
ALKE	8	115.93750000	27.53049932	95.40000000	174.90000000	9.73350138	927.500000	757.928393	23.746
AMMI	8	9.55000000	2.92379401	4.60000000	12.50000000	1.03371729	76.400000	8.548571	30.616
AMME	8	16.08750000	5.45014744	10.30000000	25.00000000	1.92691811	128.700000	29.704107	33.878
GAS	0	.	.	.	.	.	.	.	
N_2	6	0.85500000	0.02167948	0.83000000	0.88000000	0.00885061	5.130000	0.000470	2.536
CH_4	6	0.06500000	0.03271085	0.01000000	0.11000000	0.01335415	0.390000	0.001070	50.324
CO_2	6	0.01166667	0.00408248	0.01000000	0.02000000	0.00166667	0.070000	0.000017	34.993
OTH	6	0.07000000	0.02683282	0.04000000	0.10000000	0.01095445	0.420000	0.000720	38.333
TDSI	9	424.22222222	117.40291497	303.00000000	650.00000000	39.13430499	3818.000000	13783.444444	27.675
TDSE	9	423.77777778	62.19280058	330.00000000	520.00000000	20.73093353	3814.000000	3867.944444	14.676
TEMP	18	79.88888889	7.55286380	64.00000000	88.00000000	1.78022707	1438.000000	57.045752	9.454

with proper design of tubing or media traps. Alkalinity was modeled through ionic equilibrium and ammonia levels were related to influent TOC concentrations as previously stated.

Gas phase analysis was primarily concerned with the quantity of biogas production as well as the composition of the resulting gas phase. From Tables 1, 2, and 3, there were discrepancies between the composition of gas by-product derived experimentally and that which was predicted by the model. Although the flow of gas was relatively consistent, the decrease in methane and overabundance of nitrogen could be attributed to leaks either in the gas traps themselves or leaks occurring during the sampling process. As previously noted, some researchers have reported very high nitrogen levels with corresponding low levels of methane and not attributed this to leaks. It is a point which needs to be tested further in a more controlled environment.

Retention Times to Achieve Secondary Treatment

Figure 7 was derived from Figure 6 and shows the required retention times necessary for achieving secondary treatment standards at a variety of influent TOC concentrations.

The other requirements for secondary treatment standards, including pH monthly averages of 6.0-9.0 and TSS monthly averages of 30 mg/l, were inherently achieved when dealing with these low strength influents. The system was sensitive enough that it would fail if pH or TSS levels were significantly out of range and could not be brought back to secondary levels. This was also found to be true for fluctuations in temperature, for which this study averaged 81°F. During colder periods, gas production decreased to almost nothing while treatment efficiencies fell off accordingly.

DISCUSSION

The primary objectives of this research were to build and operate an anaerobic filter pilot plant using low strength influent, then develop, calibrate and verify a computer based model to evaluate the performance of the filter and to demonstrate the ability of the system to achieve secondary treatment standards.

The model was calibrated using experimental data. Table 4 demonstrates the calibration at 1.5 days retention time and 100 ppm influent TOC.

Results show that at approximately 140-150 time steps (0.25 hours each) secondary standards were achieved, matching the experimental results previously presented in Figure 7. Figure 8 summarizes the operational characteristics between the most important parameters modeled in this study, and was based on a similar diagram developed for anaerobic treatment using medium to high strength substrates [13].
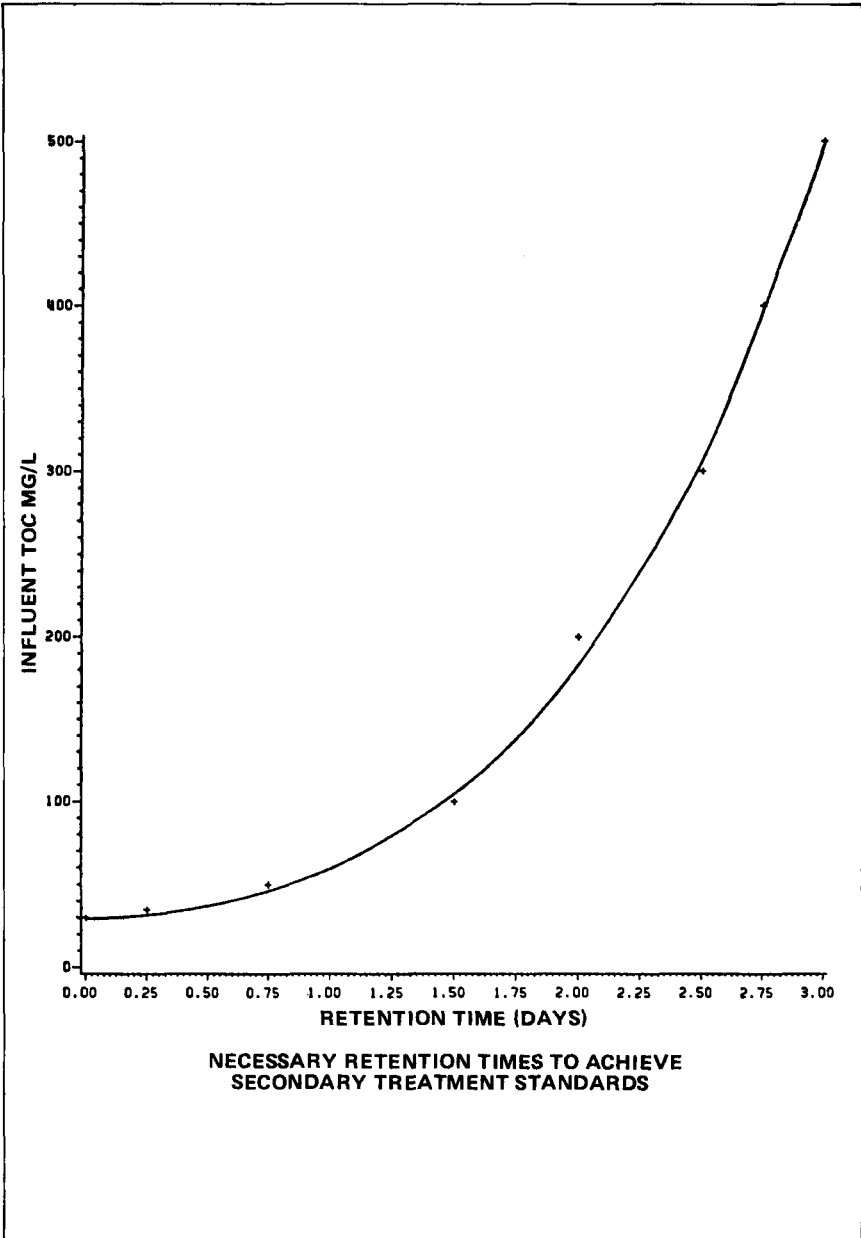
Figure 7. Secondary treatment with low strength influent. Influent Concentrations from 30-500 mg/l TOC.
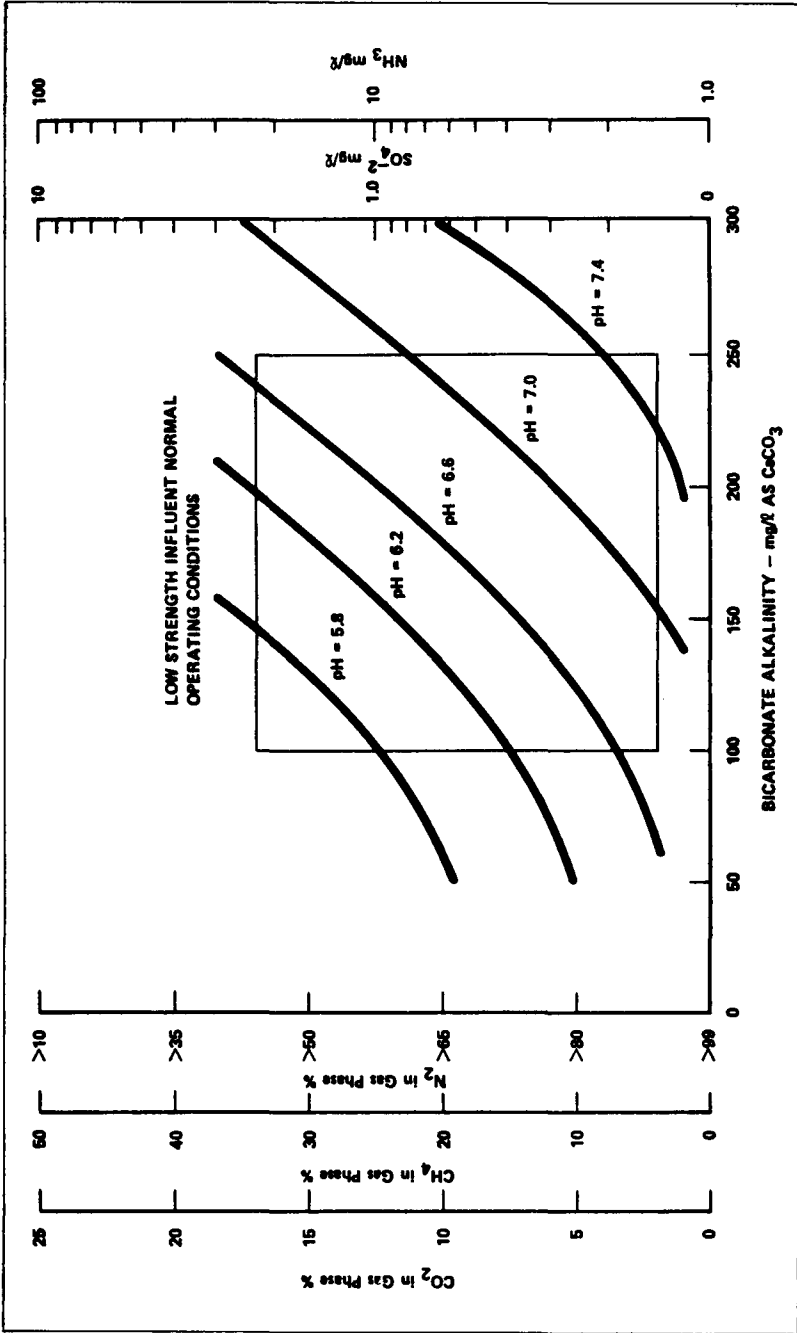
Figure 8. Normal operating conditions treating low strength influent.

227

Table 4. Predictive Model Output Related to Influent Data

	Delta-t: 0.25 hours		Influent Concentrations:	
	D: 0.012 sq meters/hour		TOC: 100 ppm	
	V: 1.90 meters/hour		Ammonia: 4.65 ppm	
	K: 0.0148/hour		Alkalinity: 116.6 ppm	
			Sulfides: 1.5 ppm	

#Dt's	Percent Treated	Sulfides	Alkalinity	Ammonia
0.00	0.45	0.00	0.00	0.00
10.00	14.82	3.09	233.32	5.45
20.00	26.35	4.33	233.31	6.07
30.00	35.59	5.33	233.31	6.56
40.00	43.00	6.12	233.31	6.96
50.00	48.95	6.76	233.31	7.28
.	.	.	.	.
.	.	.	.	.
120.00	67.89	8.80	233.30	8.30
130.00	68.91	8.91	233.30	8.35
140.00	69.73	9.00	233.30	8.40
150.00	70.38	9.07	233.30	8.43
160.00	70.91	9.12	233.30	8.46
170.00	71.33	9.17	233.30	8.48

Although similar trends are apparent between operation at high and low strength substrates, differences do occur in the composition of the gas phase, where percent CH_4 was expected to be lower due to a lower concentration of influent TOC from which most CH_4 was derived. Consequently, the remaining components of the gas must make up for this reduced CH_4, with a corresponding reduction in the percent CO_2. N_2, therefore, becomes the major gas component at reduced influent TOC levels, at retention times of less than two and a half days, coming from saturation levels present in the influent stream and any negligible amounts produced through biological production.

The range of pH was consistent with the range for anaerobic treatment of medium to high strength wastes, while the ammonia, alkalinity and sulfide concentrations in the effluent were decreased due to lower influent levels.

TOC treatment efficiency using low strength influent substrate was shown in Figure 6 for both the experimental data and the predicted model. The curves approximate each other to greater than 95 percent dependent on k, indicating an accurate determination of parameters and a correct solution of the dispersion equation.

Measurements of TOC were thought to be a better indicator of water quality with regards to secondary treatment standards for several reasons. First, the availability of the automatic TOC analyzer meant that more samples and standard curves could be measured to insure that all samples were read correctly. Also, samples could be read in hours instead of days. Second, unlike BOD or COD, TOC is independent of the individual oxidation states of each organic particulate present in wastewater. Furthermore, TOC does not measure other organically bound elements, such as nitrogen or hydrogen, which might incorrectly influence a BOD or COD analysis.

Total suspended solids data were derived from filterable residue and did not include non-filterable residue. The term *total suspended solids* (TSS) should, therefore, not be confused with *total residue*, which would have included both the filterable and non-filterable residue, and would have increased the reported concentrations. Secondary treatment standards are reported as TSS.

Sulfides were considered to be a combination of what is referred to as *total sulfides*. This includes the concentrations of $[H_2S]$ and $[HS^-]$, but does not include the remaining concentration of $[S^{-2}]$ which has been shown to be negligible [7].

Alkalinity data, which is the quantitative capacity of a wastewater to react with a strong acid $[H_2SO_4]$ to a designated pH, was within the limits of what should be expected for low strength domestic wastewaters. The measurement reflects the aggregate property of the wastewater, including primarily carbonate $[CO_3^{-2}]$, bicarbonate $[HCO_3^-]$ and hydroxide $[OH^-]$ ions, as well as possibly including any of the alkaline earth metals, such as phosphates, borates or silicates. Only carbonate, bicarbonate and hydroxide ions were included in this model to calculate pH, assuming most alkaline earth metals are converted to salts and will have little or no effect on alkalinity or the normal operation of the anaerobic filter.

Influent ammonia was considered to be derived from any organically bound nitrogen in the tri-negative oxidation state. Ammonia nitrogen $[NH_3-N]$ was produced by deamination of organic nitrogen containing compounds. In the case of domestic wastewaters, it is also produced by the hydrolysis of urea. It was assumed that both methods of producing ammonia were present in this anerobic filter pilot plant, and extreme care was taken to prevent loss of ammonia to the atmosphere during the time the samples were taken and the time they were analyzed.

The effects of temperature variation were not critical here due to the temperate climate of Los Angeles. Temperatures averaged in the low 80s, which meant that microbial growth rates were never seriously affected by severe changes in temperature. In addition, the columns received direct sunlight and acted as solar heaters during the day to keep the filters warm.

The most difficult problem encountered during the data collection was that domestic sewage tended to reflect the seasonal events of the university. During

the holidays, the TOC concentration decreased significantly, while at the beginning of a new quarter the TOC concentration increased. Diurnal variation was also quite dramatic due to shock loading into the sewer system.

For these reasons, changes in retention time did not consistently reflect increases or decreases in treatment efficiencies, because effluent concentrations could decrease or increase dramatically at any moment. The problem also influenced the ability to derive accurate velocity constants from integration of tracer study data. This problem was overcome by using superficial velocities to plot a standard curve to derive V's for the computer model.

The ability of the anaerobic filter to achieve secondary treatment standards makes future applications very promising. Small filters could effectively treat local wastewaters which would otherwise flow away untreated. Larger systems could be used where operation and maintenance costs had to be conserved due to the relative simplicity of this system. In addition, the anaerobic filter is aesthetically acceptable to most urban, agricultural or residential areas. It does not cause the order problems of lagoons or other open-air treatment systems, and can be located in any area on a smaller tract of land. For all of these advantages, further applications of this system could be evaluated with the computer based predictive model and implemented where the model results were interpreted as favorable.

CONCLUSION

The results of this study demonstrate the anaerobic filter to be capable of achieving secondary treatment standards using low strength domestic wastewaters. Hydraulic retention times of 0.25 to 2.5 days resulted in less than 30 mg/l TOC as influent TOC concentrations varied from 30 to 500 mg/l, respectively. TSS levels at these TOC concentrations were also within the 30 mg/l standard when considering domestic wastewaters. Effluent pH values ranged between six and eight during normal operations.

Mathematical modeling of the system showed hydraulic retention times and reaction constants to be the most important parameters to estimate to accurately design a treatment plant for achieving secondary standards. Applying the dispersion equation to describe flow patterns showed dispersion and velocity constants to be less influential in determining concentrations at each time step.

The calibration process used experimental data for dispersion, velocity and reaction constants to model treatment at specific retention times. The example in Table 4 calibrated the system in one and a half days retention time, the time needed to treat a 100 ppm influent TOC substrate to the secondary standard of 30 ppm.

In conclusion, the complete predictive model will produce effluent characteristics of the liquid and gas phases knowing the primary constituents of

the influent substrate, including TOC, pH, alkalinity, sulfides and ammonia. The flow may be modeled over a wide range of retention times and can demonstrate treatment levels, gas production and gas composition at any time during the treatment period.

The predictive model should be used where low strength domestic wastewaters are to be treated with the anaerobic filter. The analysis would begin with a determination of constants for dispersion, velocity and reaction for each reactor and substrate under consideration. Operation of the completed model would produce treatment patterns at all retention times and demonstrate the ability of the filter to successfully treat the influent substrate.

REFERENCES

1. J. B. Coulter, S. Soneda, and M. B. Ettiger, Preliminary Studies of Complete Anaerobic Sewage Treatment, *Journal of Sanitary Engineering Division*, (ASCE), *82*, SA5, 1956.
2. G. J. Schroepfer, W. J. Fullen, A. S. Johnson, N. R. Ziemke, and J. J. Anderson, The Anaerobic Contact Process as Applied to Packinghouse Wastes, presented at the 27th Annual Meeting, *Federation of Sewage and Industrial Waste Associations*, Cincinatti, Ohio, October 11-14, 1954.
3. J. C. Young and P. McCarty, The Anaerobic Filter for Waste Treatment, *Stanford University Technical Reports*, Report No. 87, Stanford, California, 1969.
4. W. A. Pretorius, Anaerobic Digestion of Raw Sewage, *Water Research, 5*, pp. 681-687, 1971.
5. A. P. Y. Chung and M. K. Stenstrom, *Anaerobic Filteration of Low Strength Wastewater*, Water Resources Program, University of California at Los Angeles, SEAS-ENGR-82-27, Los Angeles, California, 1982.
6. H. A. Kobayashi, M. K. Stenstrom, and R. A. Mah, Treatment of Low Strength Domestic Wastewater Using the Anaerobic Filter, *Water Research*, 1981.
7. Standard Methods for the Examination of Water and Wastewater, 14th Edition, APHA-AWWA-WPCF, 1975.
8. O. Levenspiel and W. K. Smith, Notes on the Diffusion-Type Model for the Longitudinal Mixing of Fluids in Flow, *Chemical Engineering Science, 6*, pp. 227-233, 1957.
9. E. T. van der Laan, Letters to the Editor, *Journal of Chemical Engineering Science, 7*:187, 1958.
10. L. Becker and W. W.-G. Yeh, Identification of Parameters in Unsteady Open Channel Flow, *Water Resources Research, 8*:4, pp. 956-965, 1972.
11. J. N. Butler, *Ionic Equilibria: A Mathematical Approach*, Addison-Wesley Publishing Company, Inc., 1964.

12. J. A. Oleszkiewicz, *et al.*, Low Temperature Anaerobic Biofiltration in Upflow Reactors, *Journal of Water Pollution Control Federation, 54*:11, November 1982.
13. P. L. McCarthy, Anaerobic Waste Treatment Fundamentals: Part II, *Public Works*, pp. 123-126, October 1964.

Direct reprint requests to:

Seth David Abramson, Ph.D.
530½ N. San Vincente Blvd.
Los Angeles, CA 90048