Full-scale treatment of chemical process wastes using anaerobic filters

James C. Young, Harley W. Young

James Young H.W. Young

ABSTRACT: A full-scale anaerobic filter system has been used to treat industrial wastewater having flow rates and CODs ranging from 400 to 1500 m^3/d and 10 000 to 30 000 mg/L, respectively. The reactors were of the hybrid configuration and contained corrugated, modular, cross-flow plastic media having a specific surface of 98 m^2/m^3. Facilities were included to store and feed nutrients and trace minerals, and equalization was provided to attenuate variations in waste strength.

After seeding and subsequent removal of specific waste streams that were found to be inhibitory to anaerobic microorganisms, the COD removal efficiency stabilized at about 80%. After 1 year, the reactors were converted to series operation as a first cycle in a two-stage, cyclic mode. During the second year of operation, the COD removal performance stabilized at 93 to 95%. No sludge was wasted from the reactors during 600 days of operation. *Res. J. Water Pollut. Control Fed.*, **63**, 153 (1991).

KEYWORDS: anaerobic filter, anaerobic treatment, chemical waste, filters, industrial waste, methane, wastewater treatment.

In 1982, the NutraSweet Division of G.D. Searle Co. (now a subsidiary of the Monsanto Corp.) commissioned a study of methods to treat wastewater from its new aspartame production facility located in Augusta, Georgia.[1] This study included a review of four alternatives: discharge to the municipal sewerage system, transfer to a nearby wastewater treatment plant, aerobic treatment, and anaerobic treatment. The first two alternatives were ruled out because of limited local treatment capacity. Aerobic treatment was eliminated because of large reactor volumes, high energy costs, and high sludge production, leaving anaerobic processes as the most economical treatment alternative. Because of the relatively low strength, suspended solids concentration, and biological solids yield anticipated for the wastewater, upflow anaerobic filters were determined to present the most appropriate process alternative.

This paper presents a summary of the design basis and performance history of the system through the first 2 years of operation.

Waste Characteristics

Wastewater production rates and characteristics could not be determined before construction of the Augusta manufacturing plant. Consequently, wastewater samples collected from existing sites that produced raw products and finished aspartame were used to estimate the characteristics of wastewater from the new plant. Flow rates were also estimated using wastewater production records from existing separate processes. Analytical tests indicated that the combined plant wastewater would be highly soluble and contain components that should be readily treated using anaerobic processes (Table 1). One question did arise, however, concerning the amount of sulfate that would be present. Preliminary tests suggested that the sulfate concentration in the combined wastewaters would be at or near the threshold for inhibition of anaerobic digestion. This problem, if it arose, could be handled by removing one or more low-flow, high-sulfate waste streams.

The treatability of the anticipated combined wastewater was confirmed using laboratory-scale, mixed anaerobic treatment units.[1] A 0.2-m^3 anaerobic filter pilot plant was used to further confirm treatability. No major problems were encountered as indicated by gas production and COD removal. Based on the projected flow rates, waste loads, and treatability measurements, the full-scale anaerobic filter process was designed to operate at an organic loading of 8 $kg/m^3 \cdot d$ when receiving 3000 m^3/d mixed wastewater having an influent COD of 10 000 mg/L. The design average COD removal efficiency was 85%. Variations in flow, load, and wastewater composition were not known but were expected to be substantial at times. Equalization was provided to attenuate these variations.

Actual flow rates were only 400 to 1500 m^3/d and the waste strength was usually found to be 10 000 to 30 000 mg/L soluble COD. The resulting COD loading varied from 2 to 4 $kg/m^3 \cdot d$ (Table 1). Small amounts of methanol were expected; actual values were as high as 5000 mg/L but were erratic. Organic solvents occasionally appeared in higher-than-expected concentrations, and phenolic compounds occasionally ranged from 100 to 450 mg/L. The system was designed for operation at 35 to 37°C, and this temperature was maintained throughout the 2-year study period.

Treatment Plant Description

The full-scale wastewater treatment plant included an equalization tank, two anaerobic filters with effluent recirculation, a waste gas burner, and a steam boiler (Figure 1). A clarifier, solids thickener, and filter press were included to remove excess suspended solids from individual influent wastewater streams. Polymer, liquid sodium hydroxide, and calcium chloride storage and feed facilities were included to be used as needed for these operations and to help start up and stabilize the operation of the anaerobic reactors. Facilities were also included to store and feed ammonium phosphate, phosphoric acid, ferric chloride, cobalt chloride, and nickel chloride. These chemicals provided the nutrients and trace minerals needed to support biological reactions.[2]

The equalization tank consisted of a 3000-m^3 cylindrical tank. This unit was operated at a constant volume to provide maximum equalization of load and concentration. No flow equalization was provided with this mode of operation.

The anaerobic filter system consisted of two concrete tanks, each 9.15 m wide, 25.6 m long, and 8.5 m high, with a 2000-m^3 volume (Figure 2).[3] Vertically these units consisted of a 2.1 m open zone at the bottom followed by a 4.9-m section of

Table 1—Anticipated and actual characteristics of the anaerobic filter influent wastewater.

Parameter	Anticipated value	Actual value
Flow rate, m^3/d	3 000	400–1 300
COD, mg/L	10 000	10 000–30 000
BOD_5, mg/L	5 800	7 000–20 000
SS, mg/L	—	200–2 000
Organic acids, mg/L (as acetic)	5 000	0–3 000
Methanol, mg/L	—	500–3 000
Phenols, mg/L	—	0–450
Solvents, mg/L	—	0–400
NH_3, mg/L	900	50–100
SO_4, mg/L	3 050	0–300
pH	—	4–5
HRT, days	1.3	1.4–4
Organic loading, $kg/m^3 \cdot d$	8	2–4
COD removal efficiency, %	85	80–93

corrugated, modular, cross-flow plastic media having a specific surface area of 98 m^2/m^3 and a porosity of 95%. This design configuration is commonly referred to as a "hybrid" reactor.[4] A 1.5-m open section was provided above the media for placement of effluent collection launders and for gas–liquid separation. A 2.5 × 2.5 m elevated hatch was placed in the center of a concrete roof to provide access for media placement and to serve as a pressure relief vent. The two anaerobic filters were initially piped to operate in parallel with effluent recirculation to either or both units. Later, the piping was changed to permit the units to be operated in a two-stage mode.[5] The distribution system consisted of a primary header and six secondary laterals in each reactor with distribution outlets placed 2 m apart and 0.2 m above the floor of the reactor. A separate piping system was provided for removal of excess sludge solids.

Plate-and-frame heat exchangers were installed to heat the influent stream. Steam also could be injected directly to the inlet and effluent recycle sump to maintain reactor performance during abnormally cold periods. Heat economizers were included in the original design to capture waste heat from the reactor effluent, but these were found to be ineffective because of frequent plugging and were removed from service.

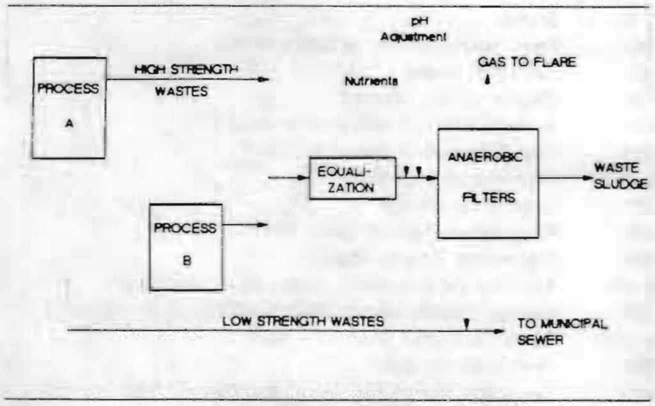

Figure 1—Schematic diagram of industrial wastewater treatment system, including equalization and anaerobic filter process.

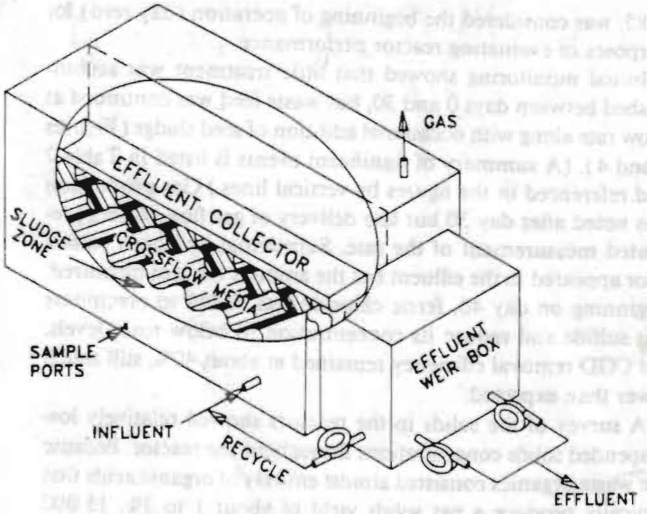

Figure 2—Schematic illustration of two concrete anaerobic filter reactors.

Sampling and Analysis

Samples were collected routinely at the inlet and outlet to each reactor and periodically at sample ports located at 0.15-, 0.9-, 1.5-, 3.7-, 5.2-, and 7-m heights on the reactor walls. Chemical oxygen demand (COD) was used as the primary measure of treatment performance with periodic supplemental measurements of 5-day BOD, volatile and total suspended solids (VSS and TSS), alkalinity, and organic acids. Measurements of heavy metals, methanol, organic solvents, and other specific compounds were made when necessary. Wet chemistry methods[6] were used to determine COD, BOD, VSS, TSS, alkalinity, organic acids, and nutrients. Atomic absorption spectroscopy was used to determine the levels of cobalt, nickel, and toxic metals in the waste stream. Gas chromatography was used to measure methane and carbon dioxide in the digester gas, to detect methanol and organic solvents in liquid samples, and to measure and identify organic acids.

Performance

Start-up and operation. Construction was completed in late 1984; wastewater was added to one reactor in November 1984 and to the second in March 1985. Seeding was accomplished using anaerobically treated sludge trucked from a nearby municipal anaerobic digester. Initially, 19 cu m were added to each reactor to condition the units. After about a week of conditioning, 130 m^3 of seed sludge was added, followed by feeding of wastewater at a loading rate of about 1 $kg/m^3 \cdot d$. Liquid sodium hydroxide (15% feedstock concentration) was used to maintain a pH of 6.8 to 6.9 at the top of the sludge zone in each reactor. Ammonium phosphate was added as a nutrient feed. The initial effluent recycle rate was set at 2.5 times the influent rate. As the reactor approached stable performance, the recycle rate was reduced to between 0.5 and 1.0 times the influent flow rate. Nickel and cobalt chlorides were added to the reactor influent at 3-month intervals to provide a batch dose of about 5 mg/L of each within the reactors.

Operation during the first 4 months was characterized by highly variable waste composition, flow, and load because of production plant start-up variations. Consequently, March 20, 1985, was considered the beginning of operation (day zero) for purposes of evaluating reactor performance.

Initial monitoring showed that little treatment was accomplished between days 0 and 30, but waste feed was continued at a low rate along with occasional addition of seed sludge (Figures 3 and 4). (A summary of significant events is listed in Table 2 and referenced in the figures by vertical lines.) Gas production was noted after day 30 but late delivery of gas flow meters prevented measurement of the rate. Substantial hydrogen sulfide odor appeared in the effluent but the amount was not measured. Beginning on day 40, ferric chloride was added to precipitate this sulfide and reduce its concentration to below toxic levels, but COD removal efficiency remained at about 40%, still much lower than expected.

A survey of the solids in the reactors showed relatively low suspended solids concentrations throughout the reactor. Because the waste organics consisted almost entirely of organic acids that typically produce a net solids yield of about 1 to 3%, 15 000 mg/L influent COD, if it were all degraded, would only produce about 150 to 450 mg/L of volatile suspended solids. The level of effluent suspended solids escaping the reactor exceeded this limit so that some method had to be found to retain the synthesized biological solids, at least until the desired accumulation was achieved.

Beginning on day 80, a wastewater stream containing high concentrations of biological cell solids was added to the reactor. This action did not produce a measurable increase in COD removal but did cause a major increase in effluent suspended solids (Figure 5). On day 125, the organic load was essentially doubled. A corresponding decrease in efficiency occurred although the mass of COD removed remained essentially constant. Starting on day 140, 3.5 mg/L of aluminum chloride and 0.5 mg/L of cationic polymer were added to the wastewater stream to help flocculate the biological solids. Microbiological examination of influent and effluent solids concentrations indicated that most of the solids leaving the system in the effluent were, in fact, the same inert cell solids that were being added to the system. However, this practice did seem to enhance the buildup of solids in the system and also may have provided nutrients that otherwise were not present.

This prolonged period of low efficiency prompted a survey and analysis of the individual waste streams contributing to the system influent. One of these streams seemed to contain one or more substances inhibitory to the anaerobic reaction. While no specific inhibitory chemical was identified, sulfides produced at the time of sulfate reduction were suspected to contribute to the problem. Consequently, a low-volume, high-sulfate stream was isolated from the main wastewater flow on day 183, and operation continued with lower peaks in influent sulfate concentrations (Figure 6). However, no significant improvement occurred in COD removal efficiency.

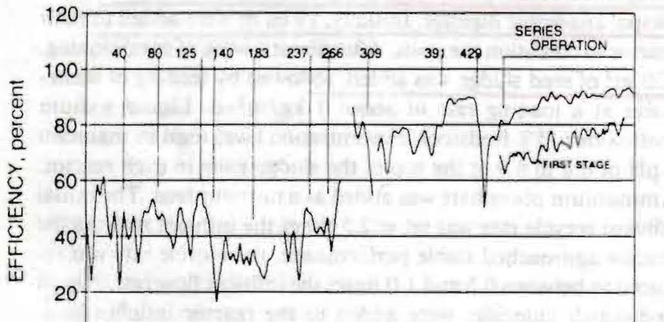

Figure 3—COD removal efficiency of anaerobic filters over a 600-day operating period.

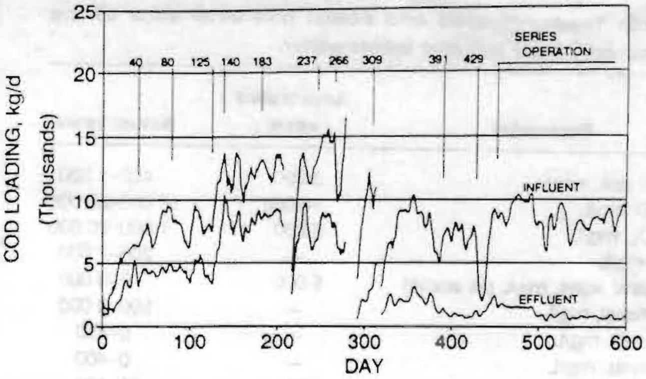

Figure 4—Influent and effluent organic load for the anaerobic filter process over the 600-day evaluation period.

The lower-than-expected efficiency continued through day 208 when the system was shut down for maintenance. After restart on day 217, the efficiency was rapidly reestablished at the same level as before the maintenance break. The efficiency then seemed to increase until day 237 when an inadvertent upstream spill resulted in 50 to 100 mg/L of organic solvent being added to the reactors. This event was followed by a sharp rise in effluent suspended solids (Figure 5) and any improvement in efficiency seemed to stop (Figure 3). Removal of a second high-sulfate stream on day 246 seemed to cause no decrease in influent sulfate and no obvious improvement in COD removal efficiency (see Figures 3 and 6).

Table 2—Summary of critical events during operation of anaerobic filters.

Day	Action
0	Startup
40	Ferric chloride added for sulfide control
80	Cell solids added
125	Organic loading doubled
140	Aluminum chloride and polymer added
183	High-sulfate waste stream removed
208–217	Maintenance shut-down
237	Organic solvent spill
246	Remove second high-sulfate stream
266	Magnesium chloride added
280–292	Maintenance shut-down; modify equalization tank
309	Calcium chloride added, soluble COD used for monitoring
315–319	Solvent spill, shut down for 4 days
391	First series operation
429	Cell solids, aluminum chloride, and polymer feed stopped, dilute process stream added
435	Reactors to parallel operation
453	Reactors back to series operation

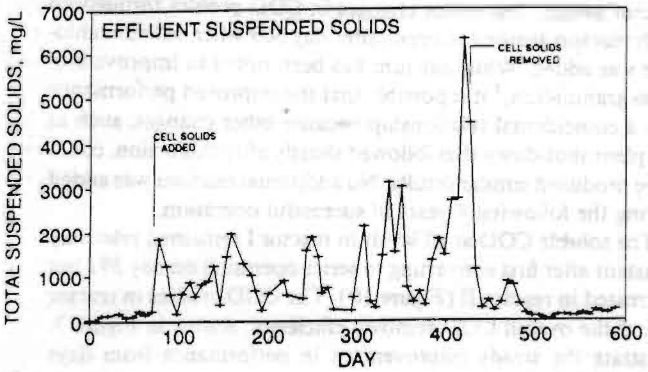

Figure 5—Total suspended solids concentration in anaerobic filter effluent.

On day 266, 45 kg of magnesium chloride was added daily for 3 days. A significant improvement in efficiency was noted almost immediately, but at the same time the influent load was decreased, so that it is not possible to attribute the improvement entirely to the addition of magnesium.

On day 280 the plant was shut down for maintenance. During this break the inlet to the equalization tank was modified to help reduce a suspected problem with short-circuiting. After restart on day 292, the COD removal efficiency was immediately higher than at any time in the past and continued to increase to about 80% over a 20-day period. Because there was no major reduction in the variations in influent load and concentrations of specific waste constituents (Figures 4, 5, and 6), all the improvement in COD removal efficiency was not considered to be attributable to the modifications in the equalization tank. While no cause-and-effect relationships were obvious, the combination of the resting period and the previous actions on days 246 and 266 were considered to be the more likely contributors to the improved performance.

On day 309, 730 kg of calcium chloride was added to the waste stream in an attempt to improve granulation of the sludge.[7] Also on day 309, and thereafter, soluble COD was used as the measure of waste strength and reactor performance. The next day, significant foaming occurred, but it is not certain that this phenomenon was caused by the addition of calcium. On day 315, a spill of organic solvent caused the reactors to be shut down for 4 days until the upstream problem was solved. After restart on day 319, the previous COD removal efficiency of 75 to 80% was achieved almost immediately and continued through day 390.

On day 391, the two reactors were converted to series operation as the first cycle of a two-stage, cyclic mode.[5] This change was accompanied by a rapid increase in COD removal efficiency of about 8% (Figure 3). This improved efficiency continued through day 428.

On day 429, two major changes in influent conditions were imposed on the reactors. First, the addition of cell solids, polymer, and aluminum chloride was stopped. Second, a dilute process stream was added to the wastewater flowing into the reactors. This stream not only reduced the influent waste COD from 22 000 mg/L to 10 000 mg/L, but it also contained significant amounts of phenolic compounds. This action caused the COD removal efficiency to decrease, no doubt as a consequence of the decreased HRT and an increase in phenolic compounds. As soon as this occurrence was detected, the load to the reactors was decreased, and on day 435 the reactors were converted back to parallel operation. By day 453, full load was restored and the reactors were again converted to series operation.

The first conversion to series operation on day 391 was accompanied by a surge in the effluent suspended solids concentration (see Figure 5). Removal of cell solids from the influent stream on day 429 and the conversion to parallel operation on day 435 produced a sharp decline in the effluent suspended solids concentration (see Figure 5). The effluent TSS concentration increased only slightly after restarting series operation on day 453 and by day 480 was less than 200 mg/L. The increase in effluent TSS after day 80, when cell solids were first added, and the sharp decrease after day 429, when the addition of cell solids was stopped, strongly suggest that large amounts of the influent cell solids were passed through the reactor with little or no change.

By day 500, the COD removal performance reached 90% and increased gradually thereafter to above 93% on day 600 (Figure 3). Throughout this period, the organic loading ranged from 1.5 to 2.5 kg/m^3·d (Figure 4). This excellent performance continued throughout day 713 when the anaerobic filter system was taken out of service for a change in the manufacturing process. The reactors were restarted in February 1987 at a loading of 1 kg/m^3·d. The COD removal efficiency immediately averaged about 70% and increased rapidly to an average in excess of 95% at HRTs of 48 to 60 hours and organic loadings approaching 5 kg/m^3·d.

Methanol. Because methanol is soluble and highly biodegradable and is not produced by anaerobic reactions, its presence in the reactor effluent could be used to indicate short-circuiting; any pass-through would indicate poor contact with the biological solids in the reactor. As indicated in Figure 7, essentially complete methanol removal was accomplished in the lead reactor when operating in the two-stage mode. Consequently, short-circuiting did not seem to be occurring in the reactors.

Concentration profiles. Beginning on day 175 and extending through day 600, suspended solids, soluble COD, and volatile fatty acids (VFA) concentrations were measured throughout the reactor height. Initially, the solids concentration at all heights was below 12 000 mg/L, but the greater concentrations occurred at the lower heights (0.9 to 1.5 m) and the lower concentrations remained above 3.7 m (Figure 8). A change in the solids distribution pattern began to take place after days 208 to 217 when the plant was first shut down for maintenance. This action, or

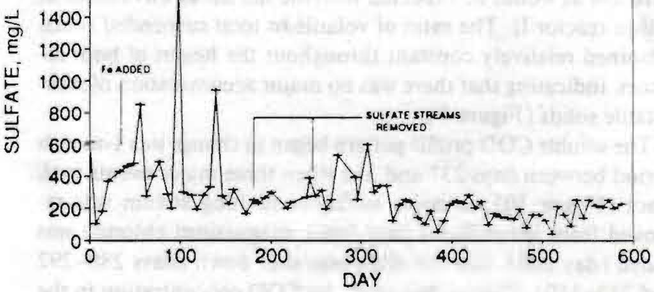

Figure 6—Sulfate ($SO_4^=$) concentration in influent to anaerobic filters.

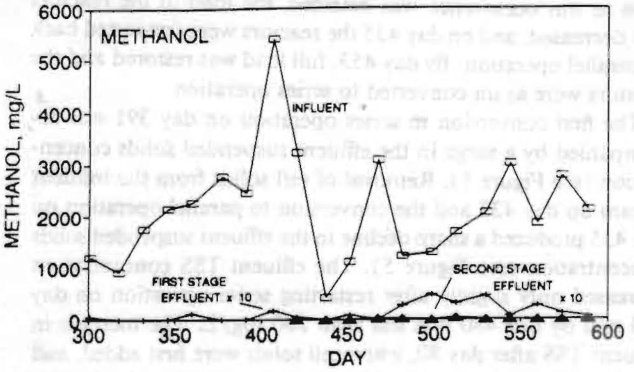

Figure 7—Methanol concentration in influent to anaerobic filters and effluent from the first and second stages.

the solvent influx on day 237 seemed to cause the suspended solids concentrations at the 1.5- and 3.7-m heights to decrease in both reactors.

As indicated previously, no major change in total COD removal performance took place until days 266 to 309 when magnesium and calcium chloride were added to each reactor and the reactors experienced two additional downtime periods. One or more of these actions seemed to cause the suspended solids concentrations to begin increasing at the lower heights, especially at 0.9 and 1.5 m in reactor II. Since there was no accompanying increase in effluent suspended solids, the solids must have settled to lower levels. Unfortunately, suspended solids data were collected infrequently at the 0.15-m height in both reactors, and no suspended solids data were collected at this height in either reactor from day 210 to day 380. (Data in Figures 8 through 11 represent three-point moving averages except at the 0.15-m height.)

A major shift in suspended solids distribution occurred in both reactors during conversion to series operation on day 391. TSS concentrations at the 0.15-m height in the first stage (reactor I) decreased sharply while less dramatic changes occurred at higher levels. This shift in solids concentrations indicates that the solids blanket moved upward.

An increase in TSS concentrations occurred at the 0.15-m height in reactor II after conversion to a two-stage operation (Figure 8). This suggests that biological solids carried over from reactor I were accumulating at the lower levels in reactor II. A substantial amount of biomass was washed from reactor II during this time as discussed previously and as illustrated in Figure 5. The relatively stable suspended solids profiles and low effluent SS concentrations after day 453 show that the biomass yields were low as would be expected with the net decay environment within reactor II. The ratio of volatile to total suspended solids remained relatively constant throughout the height of both reactors, indicating that there was no major accumulation of nonvolatile solids (Figure 9).

The soluble COD profile pattern began to change in a 1-month period between days 237 and 315 when three major events took place (Figure 10): a major sulfate-containing stream was removed from the influent (day 246), magnesium chloride was added (day 266), and the plant was shut down (days 280–292 and 315–319). During this time, the COD concentration in the lower levels began to decrease dramatically so that after day 325 the COD concentration was essentially the same throughout the reactor height. The major changes in COD profiles throughout both reactors seemed to occur after day 309 when calcium chloride was added. While calcium has been noted to improve biomass granulation,[7] it is possible that the improved performance was a coincidental relationship because other changes, such as the plant shut-down that followed shortly after this action, could have produced similar results. No additional calcium was added during the following 4 years of successful operation.

The soluble COD at all levels in reactor I remained relatively constant after first converting to series operation on day 391 but decreased in reactor II (Figure 10). The COD profiles in reactor II and the overall COD removal efficiency, shown in Figure 3, illustrate the steady improvement in performance from days 435 through 600.

Major changes in organic acid concentration profiles preceded the improvements in COD reduction (Figure 11). From day 246, when high-sulfate streams were removed from the waste, through day 391, when series operation was first initiated, the organic acid concentration decreased from 3000 mg/L to 600 mg/L throughout the reactors. Further reduction in organic acid concentrations occurred in the lead reactor for more than 150 days after the second conversion to series operation with effluent organic acids concentrations rapidly decreasing to less than 200 mg/L. The similarity of profiles for soluble COD and VFAs at all heights throughout both reactors supports experimental observations that show the liquid phase of upflow anaerobic filters is essentially completely mixed.[8]

Solids granulation. The long SRT required for satisfactory performance in anaerobic filters is made possible in part by granulation of the biological solids within the reactors. These granules consist of active microorganisms bound in a dense ma-

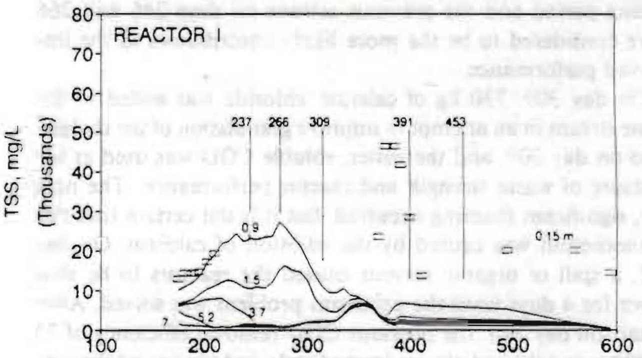

Figure 8—Total suspended solids concentrations at various heights throughout reactors I and II.

trix of inert and fibrous solids and often incorporating filamentous strains of microorganisms.[7,9,10] Such granules have settling velocities that exceed the upflow velocity within the reactor and consequently remain in the system. With many carbohydrate wastes, the granules range from 1 to 4 mm in diameter, but with protein or organic acid wastes the granules more closely resemble large flocculant masses. Granules were evident early in the operation of the NutraSweet reactors, but they were small (<1 mm) or consisted of loosely bound flocs of bacteria.

Problems Encountered

Sulfates. High sulfate and its subsequent reduction to sulfide was considered to be a potential problem at the time of design. While the average sulfide concentration would have been less than 150 mg/L which would not have been toxic, occasional sulfate concentrations in excess of 800 mg/L were observed (see Figure 6). These events caused frequent, high sulfide concentrations, which seemed to be inhibitory to the microorganisms during start-up. These concentrations were controlled initially using ferric chloride starting day 40. Removal of two low-volume, high-sulfate streams from the wastewater flow further reduced the problem so that after day 200 high sulfide concentrations were not observed.

Solvents. The entry of organic solvents to the waste stream was expected to cause dispersion of flocculated biomass and an increase in effluent suspended solids. While effluent suspended solids measurements did show some evidence of this (Figure 5), no definite correlation was shown between effluent suspended solids and a decrease in COD removal efficiency. Nevertheless,

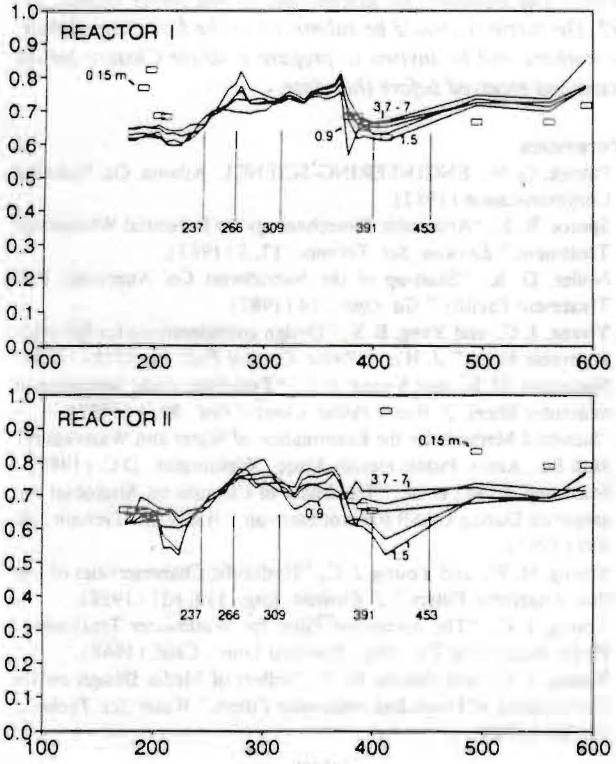

Figure 9—Ratio of volatile to total suspended solids throughout the height of reactors I and II.

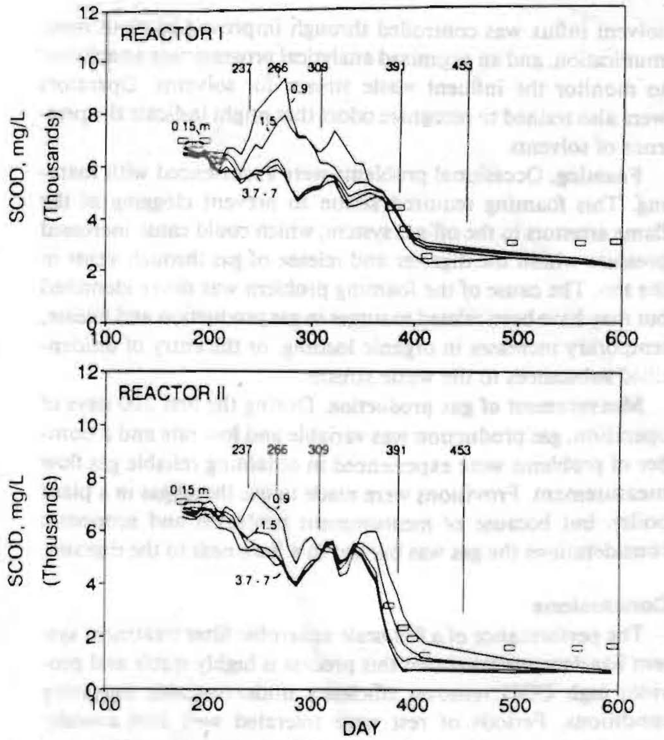

Figure 10—Soluble COD concentrations throughout the height of reactors I and II.

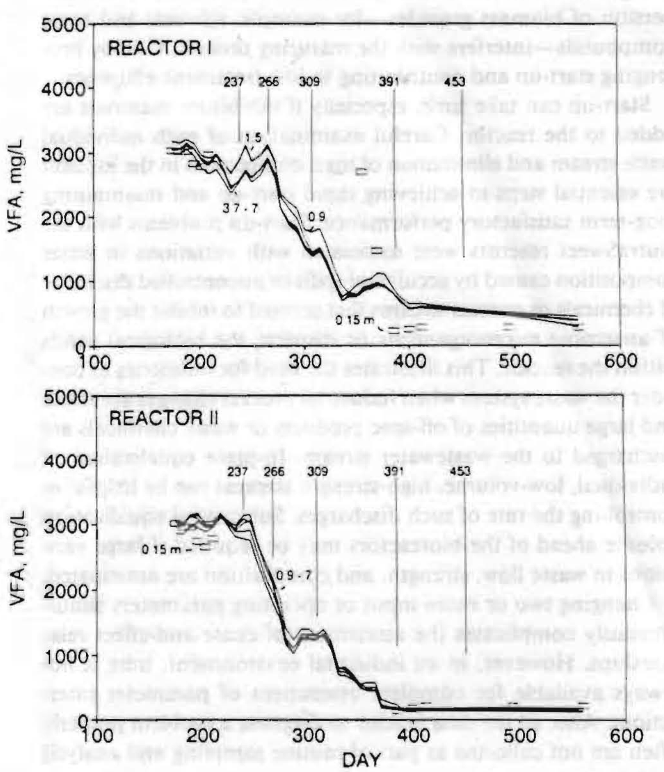

Figure 11—Organic volatile fatty acids concentrations throughout the height of reactors I and II versus time of operation. Concentrations are expressed as total acetic acid equivalents.

solvent influx was controlled through improved in-plant communication, and an organized analytical program was established to monitor the influent waste stream for solvents. Operators were also trained to recognize odors that might indicate the presence of solvents.

Foaming. Occasional problems were experienced with foaming. This foaming required action to prevent clogging of the flame arrestors in the off-gas system, which could cause increased pressure within the digester and release of gas through vents in the top. The cause of the foaming problem was never identified but may have been related to surges in gas production and release, temporary increases in organic loading, or the entry of unidentified substances to the waste stream.

Measurement of gas production. During the first 200 days of operation, gas production was variable and low rate and a number of problems were experienced in obtaining reliable gas flow measurement. Provisions were made to use the offgas in a plant boiler, but because of measurement problems and economic considerations the gas was burned in a flare next to the digester.

Conclusions

The performance of a full-scale anaerobic filter treatment system has demonstrated that this process is highly stable and provides high COD removal efficiency under variable operating conditions. Periods of rest were tolerated well and actually seemed to improve the performance. The treatment performance continued to improve with time. This "maturing" effect seems to be related to the enhanced retention of biomass made possible in part through physical actions such as improved flocculation and granulation of the biological solids. Agents that cause dispersion of biomass granules—for example, solvents and toxic compounds—interfere with the maturing process, thereby prolonging start-up and contributing to low treatment efficiency.

Start-up can take time, especially if inhibitory materials are added to the reactor. Careful examination of each individual waste stream and elimination of toxic compounds in the influent are essential steps in achieving rapid start-up and maintaining long-term satisfactory performance. Start-up problems with the NutraSweet reactors were associated with variations in waste composition caused by accidental spills or uncontrolled discharge of chemicals or process streams that seemed to inhibit the growth of anaerobic microorganisms or disperse the biological solids within the reactor. This illustrates the need for industries to consider the waste system when industrial process changes are made and large quantities of off-spec products or waste chemicals are discharged to the wastewater stream. In-plant equalization of individual, low-volume, high-strength streams can be helpful in controlling the rate of such discharges. Substantial equalization volume ahead of the bioreactors may be required if large variations in waste flow, strength, and composition are anticipated.

Changing two or more input or operating parameters simultaneously complicates the assessment of cause-and-effect relationships. However, in an industrial environment, time is not always available for complete assessment of parameter interactions. Also, all the data needed to diagnose a problem properly often are not collected as part of routine sampling and analysis programs.

Flexibility in system operation, especially to allow different modes of operation and the recycle of reactor effluent, is desirable. The NutraSweet reactors seemed to perform best in the two-stage mode, which helped to improve biological solids retention and provided improved COD removal efficiency. Because disposal of the waste through alternative methods is so costly, a strong argument can be made for having two or more independent reactors with one serving as a backup when one unit requires maintenance or repair. In this case, the appurtenances needed to operate the reactors in series adds little to the cost of the system.

A major advantage of anaerobic systems is the low biological solids yield. This advantage is enhanced by anaerobic filters that provide long solids retention times. Because of these factors, no sludge was wasted from the NutraSweet reactors during the 600 days of operation reported in this paper.

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Authors. James C. Young is Professor and Head of Civil Engineering at the University of Arkansas in Fayetteville. Harley W. Young is an environmental engineer with the Department of Environmental Regulation of the State of Florida at the Fort Myers Office. Correspondence should be addressed to Dr. James C. Young, Civil Engineering Department, University of Arkansas, Fayetteville, AR 72701.

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