

Mechanism for Simultaneous Nitrification/Denitrification and Biological Phosphorus Removal in Orbal Oxidation Ditches and Their Full-Scale Application

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ABSTRACT

The operating characteristics of six full-scale wastewater treatment plants using the staged, closed loop bioreactor process known as orbal were evaluated to determine the degree of simultaneous biological nutrient removal (SBNR) occurring. Low effluent total nitrogen concentrations indicate that simultaneous nitrification and denitrification occurs reliably in these facilities. The use of SRT values sufficient long to allow nitrifiers to grow and the maintenance of low DO concentrations in channel 1 of the process encourage nitrogen removal. Environmental conditions are relatively uniform throughout each channel, and distinct anoxic and aerobic zones do not appear to form. This suggests that the anoxic conditions necessary for denitrification may be developing within the biological flocs. Biological nitrogen removal in these facilities could be characterized using the International Association on Water Quality (IAWQ) Activated Sludge Model number 1 (ASM1). Effluent total phosphate data, and observed phosphorus removal relative to process BOD₅ loadings, suggest that biological phosphorus removal may be occurring. Distinct anaerobic zones were not observed. It is possible that the anaerobic zones needed for enhanced biological phosphorus removal may have developed inside the biological flocs. These systems are good candidates for further study of SBNR.

This research was conducted in the context of an overall research project directed at better understanding and controlling SBNR in full-scale wastewater treatment plants. The basic hypothesis of this research is that three general mechanisms are responsible for SBNR and that all three can operate, to different degrees, within any biological nutrient removal (BNR) system. The three mechanisms are: (1) bioreactor mixing patterns that allow the anoxic and/or anaerobic zones necessary for BNR to develop, referred to as the bioreactor macro-environment, (2) the development of anoxic and/or anaerobic zones within the floc, referred to as the micro-environment, and (3) the presence of novel microorganisms. System design and operating parameters will determine the relative importance of each mechanism. The objective of the overall research project is to identify the factors affecting the relative contributions of the three mechanisms identified above to SBNR, thereby allowing SBNR to be implemented and controlled more effectively in full-scale plants.

KEYWORDS

Nutrient removal, biological, nitrogen, phosphorus, nitrification, denitrification, simultaneous, closed loop reactor, staged.

INTRODUCTION

Background

Activated sludge is an aerobic biological wastewater treatment process used to bio-oxidize biodegradable organic matter and to convert ammonia- and organic nitrogen to nitrate-nitrogen via the biological process of nitrification. The activated sludge process can also be configured to remove the nutrients nitrogen and phosphorus by providing mixed and non-aerated zones and internal process recycle streams to create the anoxic and anaerobic environments needed to achieve biological nitrogen and phosphorus removal, respectively. Grady, Daigger, and Lim¹ define the functions occurring in each zone, and which ones are required to achieve different degrees of nutrient removal. The design and operation of biological nutrient removal (BNR) activated sludge systems using these well defined anoxic and anaerobic zones has evolved over about the past 20 years, to the point where it is a widely applied wastewater treatment technology.

At the same time, nutrient removal has been observed numerous times in activated sludge facilities that do not possess explicitly defined anoxic and anaerobic zones. Nitrogen losses from aerated facilities have been observed frequently.²⁻⁶ This phenomenon has been referred to as simultaneous nitrification and denitrification since it was surmised that these two biological processes were occurring simultaneously in the same aerated bioreactor. Biological phosphorus removal has also been observed in aerated bioreactors where no formal anaerobic zone is available.^{7,8} Simultaneous nutrient (nitrogen and/or phosphorus) removal (referred to hereafter as SBNR) offers the potential to reduce the cost and simplify the implementation of BNR, as illustrated in Table 1. However, because the mechanisms responsible for SBNR are not well understood, it is not a simple matter to design and operate such systems. If the operating mechanisms could be better characterized, SBNR could be used in a wider range of applications thereby reducing the cost of implementing BNR and making it possible to implement it more easily at existing facilities.

Table 1. Advantages and Disadvantages of Simultaneous Biological Nutrient Removal (SBNR).

Advantages	Disadvantages
<ul style="list-style-type: none"> • Does not require baffles to create anoxic and/or anaerobic zones. • Mixing of separate anoxic and/or anaerobic zones not required. • Mixed liquor recycle not required. • Can be implemented at some existing facilities without construction. 	<ul style="list-style-type: none"> • Operating mechanisms not well understood. So, not clear how to implement. • Process control may be more complex.

Due to the significant potential for SBNR systems to reduce cost and improve the performance of BNR systems, a research program has been initiated to better understand and characterize the mechanisms operating in such systems. Analysis of systems accomplishing SBNR suggests that three principal mechanisms may be responsible for SBNR, as follows:

1. **Mixing Patterns.** Anoxic and/or anaerobic zones may develop within the bioreactor as a result of the mixing pattern caused, for example, by the oxygen transfer device. This could be referred to as the bioreactor macro-environment.
2. **Floc Micro-Environment.** Anoxic and/or anaerobic zones may develop inside the activated sludge flocs.
3. **Novel Microorganisms.** Recent advances in microbiological have revealed a range of previously not recognized microorganisms and biochemistries that could account for nutrient removal in aerated bioreactors.

It is well known that full-scale bioreactors do not provide an entirely uniform environment throughout. Examples of such bioreactors include oxidation ditches and plants with oxygen transfer devices (such as mechanical surface aerators) that cause large-scale recirculation of the mixed liquor.^{1,3,4,5,6,7,9} In such facilities, intense oxygen transfer occurs in one portion of the bioreactor, limited oxygen transfer occurs throughout the rest of the bioreactor, and mixed liquor is recycled between the aerated and non-aerated zones. This bioreactor flow pattern is characteristic of BNR systems with defined anoxic, anaerobic, and aerobic zones. Thus, it is not surprising that BNR would be observed in such systems.

It is also recognized that dissolved oxygen concentration gradients occur within biological flocs.^{4,10} The anoxic and/or anaerobic zones necessary to achieve BNR may form inside the biological flocs. Thus, SBNR would be observed in bioreactors where formal, identifiable anoxic and/or anaerobic zones do not form.^{11,12,13} In fact, the performance of a SBNR process accomplishing nitrogen removal has been characterized mathematically based upon such a mechanism.²

Over the past several years a number of novel nitrogen biochemistries have been identified that may, at least partially, account for SBNR. These include denitrification by autotrophic nitrifiers (the so-called AMANMOX process) and heterotrophic nitrification – aerobic denitrification. The interested reader is referred to the recent review by van Loosdrecht and Jetten for more detail.¹⁴ Our understanding of the biochemistry and microbiology of the biological phosphorus removal process is

also incomplete and evolving.¹⁵ Thus, future discoveries may reveal how biological phosphorus removal can occur in aerated bioreactors.

It is the basic hypothesis of the SBNR research program mentioned above that all three of these mechanisms could operate simultaneously in any system accomplishing SBNR. But, it is logical that the relative contributions of each mechanism may vary, depending upon system design and operating parameters. Thus, a key to understanding, and controlling, SBNR is to understand how process design and operating parameters affect SBNR. This is the basic objective of the overall SBNR research program.

Objectives

This paper is the first report from the overall SBNR research program described above. The objective of this paper is to characterize SBNR in some representative full-scale activated sludge plants that are either known to or are thought to be capable of SBNR. The focus is on plants of the orbital configuration, as described below. The orbital process bioreactor consists of three closed loop reactors in series. Oxygen input to each stage can be, and is, varied to allow the creation of different environments.¹¹ As a result, spatially varying environments can be created through the bioreactor, thereby allowing the first mechanism described above (mixing patterns) to operate. Moreover, because all three bioreactor stages are aerated and bulk dissolved oxygen concentrations are controlled, the potential exists to develop anoxic and/or anaerobic micro-environments within the biological floc (the second mechanism described above). This makes the orbital configuration ideal to study SBNR. Moreover, focusing on plants with a specific configuration allows the affects of other design and operating parameters on SBNR to be specifically characterized. The specific objectives of this paper are as follows:

1. Characterize the degree of simultaneous nitrogen and/or phosphorus removal occurring in selected full-scale Orbital plants.
2. Characterize how process operating parameters affect the nature (nitrogen removal, phosphorus removal, or both) and extent of SBNR.
3. Record any other observations that may be helpful in selecting specific plants for more detailed study.

Several plants were evaluated to obtain an overall assessment of the performance capabilities of the orbital plants evaluated in this research. Selected plants were then evaluated in more detail based on the special circumstances at that plant.

METHODS AND MATERIALS

Orbal Process Description

Figure 1 provides a schematic of a typical three channel orbital facility. Influent wastewater enters channel 1 (the outer channel) and flows from there to channel 2 and finally to channel 3 (the inner channel) before the mixed liquor flows to the secondary clarifier. Return activated sludge (RAS) from the secondary clarifier is also added to channel 1. Oxygen transfer is accomplished using disc aerators. They also provide mixed liquor recirculation within each channel to maintain settleable solids in suspension. Like in other closed loop bioreactors, on average the mixed liquor will circulate around each channel many times before it passes into the next channel. An interesting feature of the disc aerators is that the number of discs placed on each shaft can be varied, along with their orientation (“Base Forward” or “Apex Forward”), thereby allowing the relative distribution of oxygen supply to each channel to be varied. Shaft speed and aerator submergence can also be adjusted to adjust oxygen input. Channel 1 contains about 50-55 percent, channel 2 about 30-35 percent, and channel 3 about 15-20 percent of the total bioreactor volume.

A typical design and operating strategy for the orbital process is to provide less oxygen to channel 1 than would be required to meet the full process oxygen demand.¹¹ The oxygen supply in channel 1 is typically 50-70 percent of the calculated demand. This is done to allow nitrification and denitrification to occur in the outer channel. Oxygen provided to the channel allows nitrification to

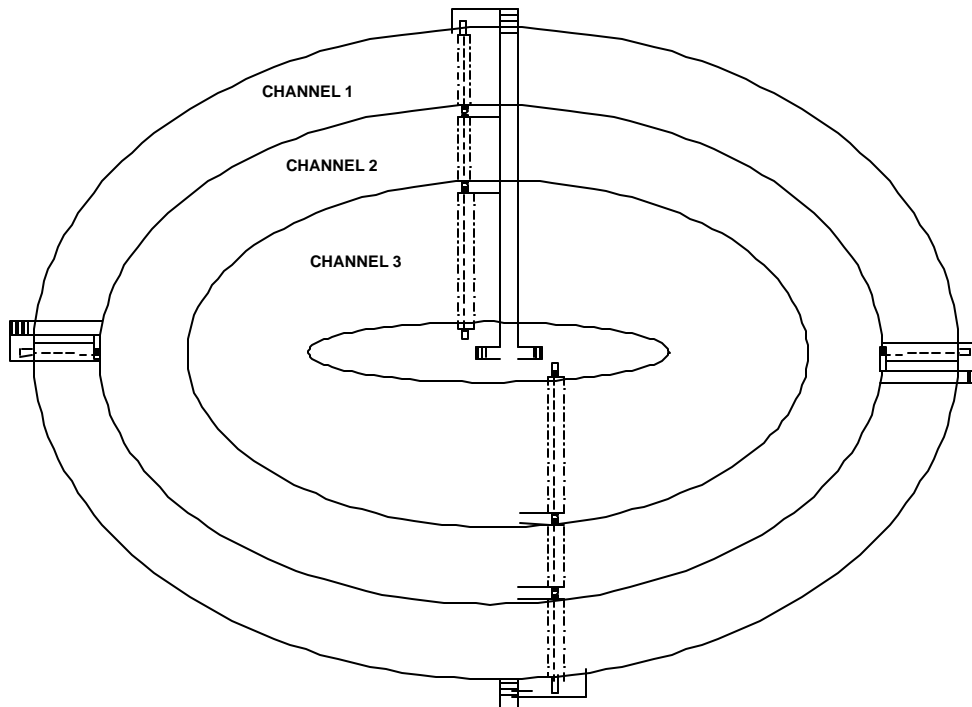


Figure 1. Orbal Process Schematic

occur but, because oxygen input is restricted, the nitrate-nitrogen produced through nitrification is consumed. It is presumed that heterotrophic microorganisms denitrify the nitrate-nitrogen produced by the nitrifiers. Use of oxygen control to control nitrification and denitrification is discussed elsewhere.^{1,9} Mixed liquor can also be recycled from channel 3 to channel 1 to transport nitrate-nitrogen formed in channels 2 and 3 back to channel 1 where it can be denitrified. Nitrogen removal efficiency in excess of 90 percent can be achieved using these strategies.^{11,12,13}

The orbal process can also be operated in the step feed mode by feeding all or a portion of the process influent to channels 2 and/or 3. This operating mode would generally be used during high wet weather flow conditions to avoid overloading the secondary clarifier and causing clarifier thickening failure. It is not expected that this operating mode will encourage SBNR.

Plants Studied

Table 2 summarizes the plants evaluated. They are located in the Eastern portion of the United States, and they serve principally municipal areas and receive domestic and commercial wastewater with only modest amounts of industrial wastewater. Their design capacities range from 6,600 to 45,400 m³/day. Most contained one or two process trains. The facilities were designed with hydraulic residence time (HRT) values ranging from 11 to 22.6 hours. Sludge processing at the facilities generally consists of aerated digestion followed by dewatering. These facilities all use the three channel orbal process, as illustrated in Figure 1.

Process Modeling Techniques

An analysis of the operating characteristics of the orbal process was conducted using the International Association on Water Quality (IAWQ) Activated Sludge Model number 1 (ASM 1).¹⁶ It was implemented using the Single Sludge Simulation Program (SSSP),¹⁷ using the wastewater characterization and plant simulation tool called PRO³D.¹⁸ ASM 1 was used to determine to what extent simultaneous nitrification and denitrification could be characterized in this process using generally accepted process models.

RESULTS AND DISCUSSION

Overall Plant Performance

Table 3 summarizes process loading and operating characteristics for the six plants evaluated. The actual hydraulic loading on the plants ranged from 36 to 89 percent of their design values, while actual organic loading rates varied from 47 to 115 percent of their design values. The plants were generally operated in an extended aeration mode, as indicated by solids residence time (SRT) values of 20 days or more. The Sweetwater Creek WWTP was the only exception to this. The MLSS concentrations ranged from 2,200 to 4,000 mg/L.

Table 2. Summary of Plants Studied.

Plant	Location	Design Capacity (m ³ /day)	Number of Trains	Design HRT (hr)	Number Disk Aerators	Sludge Processing
Elmwood WWTP ¹	Evesham, NJ, USA	11,400	2	22.6	356	Aerobic Digestion, Belt Filter Press Dewatering
Hartford WWTP	Mount Laurel, NJ, USA	22,700	1	14.5	270	Aerobic Digestion, Belt Filter Press Dewatering
Hammonton WWTP ¹	Hammonton, NJ, USA	9,500	1	19.0	308	Aerobic Digestion, Belt Filter Press Dewatering
Chalfont WWTP	New Britain, PA, USA	15,100	1	14.0	336	Anaerobic Digestion, Belt Filter Press Dewatering
Sweetwater Creek WWTP ¹	Gwinnett County, GA, USA	45,400	4	11.0	980	Aerobic Digestion
Lake Geneva WWTP	Lake Geneva, WI, USA	6,600	1	15.3	132	Thickening, Aerobic Digestion

¹ Effluent Filtration.

Table 3. Summary of Plant Operating Parameters

Plant	Average Flow		Organic Load		SRT (Days)	MLSS (mg/L)	Operating Period
	(m ³ /day)	% Design	(Kg/m ³ /day)	% Design			
Elmwood WWTP	7,100	63	0.15	55	33	3,175	1-9/98
Hartford WWTP	15,000	66	0.16	47	30	3,500	1-9/98
Hammonton WWTP	3,400	36	0.18	51	20	2,200	7/94-6/95
Chalfont WWTP	11,400	75	0.20	91	24	4,000	1-12/94
Sweetwater Creek WWTP	40,500	89	0.46	85	7-10	3,411	1-12/94
Lake Geneva WWTP	5,700	87	0.28	115	22	4,000	1-12/94

Table 4 summarizes performance data. As expected for extended aeration activated sludge, they provide excellent removal of five-day biochemical oxygen demand (BOD₅) and total suspended solids (TSS) with effluent values generally less than 5 mg/L each. Effluent filtration is provided at some of the plants. For these plants, biological process effluent BOD₅ and TSS concentrations are not much different than plant effluent values. Nitrification was also essentially complete, with effluent ammonia-nitrogen (NH₃-N) values generally less than 1 mg/L as N. In spite of the extensive nitrification occurring, effluent nitrate-nitrogen (NO₃-N) values were generally less than about 5 mg/L as N, and often well less than that. Total nitrogen removal for the Elmwood and Hartford Wastewater Treatment Plants (WWTPs), where influent total nitrogen data were available, was in the 85 to 90 % range. The effluent total nitrogen concentration for the Lake Geneva WWTP was less than 4 mg/L as N. This generally indicates that significant total nitrogen removal was occurring at each of these facilities.

Effluent total phosphate (TPO₄-P) data were available for four of the facilities and generally indicate removal to effluent concentrations of about 1 mg/L as P or lower. Phosphorus removal at the Elmwood WWTP was 0.22 mg P/mg BOD₅, while it was 0.24 mg P/mg BOD₅ at the Hammonton WWTP. This generally exceeds the phosphorus removal expected for biomass synthesis alone for a

long SRT process and suggests that some other mechanism is contributing to phosphorus removal. Metal salts are not added to these two plants, suggesting that enhanced biological phosphorus removal may be occurring at these two plants. Taken together, these data suggest that biological nutrient removal may be occurring at some of these plants.

Table 4. Summary of Plant Performance Data

Plant	BOD ₅ (mg/L)		TSS (mg/L)		TPO ₄ -P (mg/L P)		TKN (mg/L N)		NH ₃ -N (mg/L N)		NO ₃ -N (mg/L N) Out
	In	Out	In	Out	In	Out	In	Out	In	Out	
Elmwood WWTP ¹	221	2.3	184	1.1	5.4	0.53	32.5	2.0	25.0	1.1	1.13
Hartford WWTP	210	3.6	292	4.8	-	-	-	-	-	0.12	-
Hammonton WWTP ¹	353	2.1	390	4.2	-	1.70	37.0	2.1	-	0.24	2.93
Chalfont WWTP	160	3.2	152	4	3.2	0.90	-	-	15.8	1.03	5.50
Sweetwater Creek WWTP ¹	237	1.8	359	1.5	6.0	0.22	-	-	13.0	0.14	4.50
Lake Geneva WWTP ¹	203	4.2	196	6.2	-	-	-	1.3	-	-	2.62

¹ With Internal Mixed Liquor Recycle.

² Following Effluent Filtration.

Data Suggesting Simultaneous Removal of Nitrogen

Data from the Elmwood WWTP were evaluated to characterize the environment within each bioreactor channel. Table 5 summarizes typical dissolved oxygen (DO) concentration profile data. DO concentrations were measured before and after the disk aerators in each channel in each of the two process trains at this facility. The recorded DO concentrations are actually the average of four values taken at uniformly spaced depths and representing the average concentration at each location. As can be seen, the DO concentration immediately upstream and downstream of the disk aerators is essentially the same. These results are typical for the Elmwood WWTP, and for several other of the facilities evaluated. They are also the same as those obtained by Applegate, *et al.* in their study of the Huntsville, TX orbal system.⁵ These data indicate that distinct aerobic and anoxic zones, as indicated by high and low DO concentrations, do not necessarily develop within the orbal bioreactor.

Table 5. Example Elmwood WWTP Aerator DO Data for 02/23/96.

Location	Train Number 1			Train Number 2	
	Channel 1	Channel 2	Channel 3	Channel 2	Channel 3
Before Aerator	0.2	0.2	0.25	0.25	0.7
After Aerator	0.2	0.2	0.25	0.4	0.7 ¹

¹ 3.2 mg/L at Surface

Nutrient concentration profile data were also collected through the Elmwood WWTP, and some typical data are presented in Table 6. The results indicate that, even when significant nitrification occurs in channel 1, as indicated by low soluble TKN and ammonia-nitrogen concentrations, the nitrite- and nitrate-nitrogen concentrations do not increase appreciably. This suggests that nitrification and denitrification are occurring in channel 1.

The IAWQ ASM 1 was used to characterize nitrogen removal in the Elmwood WWTP. A simplified model was set up in which channel 1 was simulated as six equal sized completely mixed cells in series and channels 2 and 3 were simulated as individual completely mixed cells. Two aeration zones were assumed for channel 1 to represent locations for the disc aerators. Channels 2 and 3 were also assumed to be aerated. Oxygen mass transfer coefficients (K_L values) were input to the simulation, and the simulation calculated the resulting dissolved oxygen concentration. A recirculation flow rate of 580,000 m³/day was used in channel 1 to simulate the mixed liquor recirculation created by the pumping action of the disc aerators. The sizes of the cells are summarized in Table 7. A mixed liquor recirculation pumping capacity from channel 3 to channel 1 of 22,800 m³/day is also provided. Average process influent wastewater flow rates and wastewater characteristics, as summarized in

Tables 3 and 4, were used in the simulations. A temperature of 20 °C was used. The calculated mixed liquor suspended solids (MLSS) concentration was 3,117 mg/L as TSS, which corresponds well with the reported value (see Table 4).

Table 6. Example Elmwood WWTP Nutrient Profile Data.

Location	TKN ¹ (mg/L N)	TPO ₄ -P ¹ (mg/L P)	NH ₃ -N (mg/L N)	NO ₃ -N (mg/L N)	NO ₂ -N (mg/L N)	DO (mg/L)
2/23/96						
Orbal 1						
Channel 1	-	-	7.0	<0.02	<0.02	0.35
Channel 2	-	-	6.5	<0.02	0.3	0.18
Orbal 2						
Channel 1	-	-	7.6	<0.02	0.25	0.15
Channel 2	-	-	6.8	<0.02	<0.02	0.10
4/17/96						
Calculated Influent	12.0	0.91	8.8	-	-	-
Orbal 1						
Channel 1	3.1	0.55	2.2	<0.4	0.02	-
Channel 2	1.1	0.34	1.3	1.3	0.10	-
Orbal 2						
Channel 1	3.6	1.03	2.7	0.8	<0.02	-
Channel 2	<1.0	0.53	1.6	0.9	0.02	-

¹ Measured after filtration through glass fiber filter.

As indicated in Table 7, three operating scenarios were evaluated. One involved providing sufficient oxygen input into channels 1, 2, and 3 to maintain dissolved oxygen concentration values of 2 mg/L or greater throughout the bioreactor. As indicated in Table 7, nitrification was predicted to be reasonably complete in channel 1, with little nitrification and nitrate production in channels 2 and 3. This is a result of the temperature (20° C) and the relatively long operating SRT (33 days) used at the Elmwood WWTP. For this simulation, nearly 75 percent of the total process oxygen demand occurred in channel 1, about 20 percent in channel 2, and the remainder in channel 3. The process oxygen requirement was 2,250 kg/day.

Table 7. Summary of Process Analysis of Elmwood WWTP Using IAWQ ASM 1.

Location	Volume (m ³)	Concentration (mg/L)								
		Excess Oxygen			Oxygen Limited			Oxygen Limited ¹		
		DO	NH ₃ -N	NO ₃ -N	DO	NH ₃ -N	NO ₃ -N	DO	NH ₃ -N	NO ₃ -N
Channel 1 ²	5,375									
Cell 1 ³	895	2.9	0.5	19.7	0.6	1.4	2.1	0.6	1.0	4.0
Cell 2	896	2.3	0.4	19.7	0.3	1.3	2.0	0.4	1.0	3.9
Cell 3	896	1.9	0.4	19.7	0.1	1.3	2.0	0.2	0.9	3.8
Cell 4 ³	896	2.9	0.3	19.7	0.6	1.2	2.0	0.7	0.9	3.8
Cell 5	896	2.5	0.3	19.8	0.3	1.2	2.0	0.4	0.8	3.8
Cell 6	896	2.1	0.2	19.8	0.2	1.2	1.9	0.2	0.8	3.8
Channel 2 ³	3,560	2.4	0.1	19.5	2.2	0.1	1.8	1.6	0.1	3.6
Channel 3 ³	1,815	2.7	0.1	19.6	2.8	0.1	1.8	2.3	0.1	3.4

¹ Mixed Liquor Recirculation From Channel 3 to Channel 1 of 22,500 m³/day.

² Internal Recirculation Rate to Achieve 0.3 m/sec Channel Velocity = 580,000 m³/day.

³ Cells with Aerators.

In the second simulation the oxygen input to channel 1 was restricted to allow nitrification and denitrification to occur there and to maximize nitrogen removal. The lowest effluent total nitrogen concentration was observed when about 50 percent of the oxygen was added to channel 1, about 35

percent to channel 2, and the remainder to channel 3. The total process oxygen requirement was reduced to 1,710 kg/day, a 24 percent reduction. The predicted DO and nitrogen concentrations (Table 7) were similar to those observed in the full-scale plant (see Tables 5 and 6). Sufficient oxygen was supplied in channel 1 so that most of the ammonia-nitrogen was nitrified there, but restriction of the oxygen input also allowed significant denitrification to occur.

Mixed liquor was recycled from channel 3 to channel 1 in the third simulation. Surprisingly, effluent nitrate-nitrogen concentrations increased slightly. This occurred because recirculation of low organic matter containing channel 3 mixed liquor reduced the availability of organic matter for denitrification in channel 1. This is not a general result, but rather it illustrates the interactive nature of these systems.

These results suggest that nitrogen removal can be characterized in these processes using existing process models. It is interesting to note that distinct aerobic and anoxic zones are not predicted by the simulation results presented in Table 7. Thus, the second simultaneous nitrogen removal mechanisms discussed above (the floc micro-environment) may be the most significant one for these systems. Note, IAWQ ASM 1 is based on: (1) independent functioning of autotrophic nitrifiers and heterotrophic denitrifiers and (2) no denitrification by the autotrophs. Thus, it appears that novel microorganisms are not necessary to explain SBNR in these systems. However, they may still be present and contribute to SBNR. Nevertheless, these analysis results provide a conceptual basis to begin analyzing the nitrogen removal capability of these systems.

Data Suggesting Simultaneous Removal of Phosphorus

As discussed above, effluent total phosphate data from at least two of the plants studied suggested that enhanced biological phosphorus removal may be occurring. These two plants (Elmwood WWTP and Sweetwater Creek WWTP) both have influent wastewater BOD₅/TPO₄-P ratios of about 40 mg BOD₅/mg TPO₄-P, values that are favorable for achieving excellent biological phosphorus removal.¹ Table 8 provides data from two of the plants evaluated above, and from two additional plants. None of these plants practice chemical addition, indicating that excellent phosphorus removal can be achievable with the orbal process without the addition of chemicals.

Table 8. Phosphorus Removal for Orbal Plants Without Chemical Addition.

Plant	Flow (m³/day)	TP In (mg/L P)	TP Out (mg/L P)
Hartland, MI	227	10.7	3.26
Hammonton, NJ	3,400	-	1.70
Elmwood WWTP	7,100	5.4	0.53
McMinnville, Or	15,100	4.5	0.17

One of these plants listed in Tables 4 and 8 is the Elmwood WWTP. As indicated by the example profile data for this plant presented in Table 6, dissolved total phosphate concentrations in channels 1 and 2 are generally low. One might expect to see elevated phosphate concentrations in one of the channels, suggesting phosphate release associated with enhanced biological phosphorus removal.¹ However, this was not the case. The phosphorus content of the mixed liquor at the Elmwood WWTP was measured at about 2.5 % (P/VSS), indicating an accumulation of phosphorus in the mixed liquor in excess of that associated with biomass synthesis and consistent with the occurrence of enhanced biological phosphorus removal. Cinar, *et al.*, observed biological phosphorus removal in a closed loop bioreactor using disk aerators of the same type used in the orbal process, but they were unable to characterize it mathematically using IAWQ ASM 2.⁷ Additional research is needed to more fully understand the mechanism responsible for phosphorus removal in these processes. As for biological nitrogen removal, it does not appear that distinct anaerobic zones develop within the bioreactor, characteristic of the biological phosphorus removal process. However, as for biological nitrogen removal, it is possible that the necessary anaerobic conditions develop within the biological flocs.

SUMMARY AND CONCLUSIONS

In summary, the performance of six full-scale staged, closed loop bioreactor activated sludge plants was studied to characterize their overall nutrient removal performance. This evaluation was conducted in the context of an overall evaluation of simultaneous biological nutrient removal (SBNR). Based on the results of this preliminary evaluation, the following conclusions were reached:

1. Low effluent ammonia-nitrogen, TKN, and nitrate-nitrogen concentrations were generally observed at each of the plants evaluated. The removal efficiency for total nitrogen was in the range of 85 to 90 percent for two of the facilities, with total nitrogen concentrations in the 3 to 5 mg/L as N range for three facilities. The data generally indicate the potential for excellent total nitrogen removal with this process configuration. The plants are all operated at SRT values that allow reliable nitrification, and low DO concentrations are maintained, especially in channel 1. Plants with mixed liquor recycle from the last to the first channel generally produced effluents with lower effluent nitrate-nitrogen concentrations.
2. Dissolved oxygen profile data around the orbital process channels do not generally indicate the development of separate and distinct anoxic and aerobic zones. Dissolved oxygen concentrations are uniformly low in channel 1.
3. Profile data indicate uniformly low nitrogen concentrations in facilities achieving good overall nitrogen removal. Again, this is consistent with the general absence of distinct anoxic and aerobic zones.
4. Nitrogen removal in these facilities can be characterized using the IAWQ ASM 1. ASM 1 is based on a conventional understanding of the nature and function of the microorganisms responsible for nitrogen removal. This suggests that it is not necessary for novel microorganisms to be present for nitrogen removal to occur in these systems. This does not mean, however, that novel microorganisms are not present.
5. Process modeling using ASM 1 also suggests that separate and distinct anoxic and aerobic zones do not necessarily develop in these systems. This further suggests that denitrification occurring within biological flocs might be a relatively important nitrogen removal mechanism in these systems.
6. Phosphorus data were available for some of the plants studied. In each case, either the effluent total phosphate concentration was relatively low or phosphorus removal appeared to exceed that required simply for biomass synthesis. Since chemicals are not added to these plants for phosphorus removal, this suggests that excess biological phosphorus removal may be occurring.
7. The available data do not indicate the existence of distinct anaerobic zones where phosphorus release is occurring from phosphorus accumulating organisms (PAOs). It is possible, however, that phosphorus release is occurring inside of the biological flocs. The low bulk fluid DO concentrations maintained in the process would facilitate the development of these conditions in the floc.
8. The likely occurrence of SBNR in these systems makes them good candidates for further study of this phenomenon.

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