Practical Considerations for Design of a Step-Feed Biological Nutrient Removal System

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As the need to retrofit secondary treatment plants for biological nutrient removal (BNR) has become widespread, process variations such as step-feed BNR have been developed to adapt existing treatment facilities to meet effluent requirements. Since there are relatively few full-scale installations of step-feed BNR, the process and retrofit design concepts are still under development. Although step-feed BNR has a relatively small footprint for a suspended-growth process, it also is more complex than plug-flow or complete-mix regimes, and presents unique challenges to the designer. This article discusses major design components, including primary effluent flow splitting, chemical feed, dissolved oxygen carryover, nitrate recycle, and foam control. It also illustrates the impact of these design components on performance through process modeling examples and shows how they are being resolved in New York City and Cumberland, Maryland.

Key Words
Step-feed, biological nutrient removal, retrofit, anoxic, oxic, deoxygenation

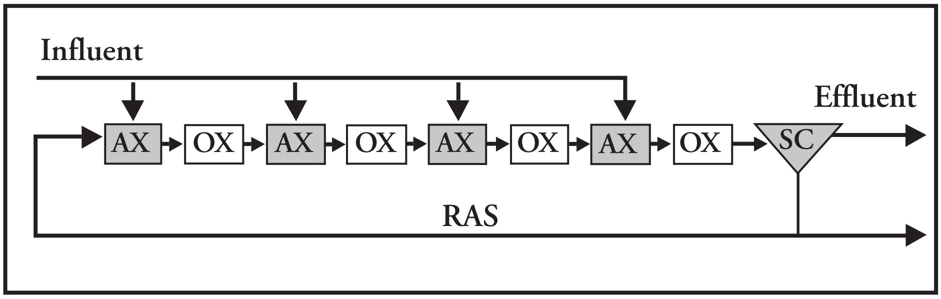
Introduction

Activated-sludge BNR systems can be designed in a number of configurations. Common features include anaerobic zones for the release of stored phosphorus, anoxic zones for denitrification, and oxic zones for oxidation of organic material, nitrification, and phosphorus uptake. A pumped recycle typically is included to return nitrified mixed liquor from the oxic zone to the anoxic zones for denitrification.

Historically, these systems have been configured in a plug-flow regime with the system influent and return activated-sludge (RAS) flows directed to the beginning of the tanks. More recently, adaptations of recognized plug-flow BNR regimes have been made to step-aeration systems. In New York City, the viability of implementing anoxic and oxic zones in each pass of a four-pass step aeration system (Figure 1) was demonstrated at the Tallman Island Water Pollution Control Plant (WPCP) (NYCDEP, 1991). The demonstration results and case studies from several plants were used to show that a tank-volume reduction is possible with step-feed systems because of the higher mixed-liquor concentrations in earlier passes (Carrio et al., 1993).

The Tallman Island work was further continued to examine system nitrification and denitrification rates. Significant simultaneous nitrification denitrification within the oxic zones of the demonstration system was also observed (Fillos et al, 1996). A comparison of plug-flow and step-feed full-scale configurations at the Moreno Valley California Regional Water Reclamation Facility further demonstrated the viability of step-feed systems for nitrification (Stephenson and Luker, 1994).

Figure 1. Step-Feed BNR Schematic for Four Pass Anoxic/Oxic System



Using an activated-sludge process simulator, an adaptation of the UCT process for a step-feed configuration, the Step BioP process, was developed for the Lethbridge, Alberta, plant (Nolasco et al., 1993). The process and model calibration were further developed during pilot testing and full-scale operation at the plant (Nolasco et al., 1995; Crawford et al., 1999).

Step-Feed BNR Design Considerations

This article focuses on step-feed nitrogen removal systems and the impact of design features on process optimization. Design considerations common to all step-feed BNR systems include primary effluent flow splitting, return activated-sludge flows, dissolved oxygen carryover from aerated to un-aerated zones, chemical feed locations, nitrate recycle, and foam control.

The BiowinTM simulator was used to illustrate the impacts of each design feature on step-feed BNR system performance. A dummy step-feed BNR system with four influent feed locations (Passes A, B, C and D), six-hour hydraulic retention time, and secondary clarifiers was configured. Twenty-five percent of each pass was anoxic and the remainder was oxic. The example wastewater consisted of a 1-mgd primary effluent flow with chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and inert suspended solids (ISS) of 250, 25, 4 and 15 mg/L respectively. For simplicity, the BiowinTM default values were used for influent characterization fractions and kinetics, and simulations were performed with a 20oC wastewater temperature unless otherwise noted. For design, the specifics for each plant and the aims of the treatment process will impact how each issue is ultimately addressed.

Primary Effluent Flow Splitting

The percentage of influent flow that is directed to each step-feed pass impacts the

Table 1. Simulated Impacts of Primary Effluent Flow Splitting on Step-feed BNR Mixed Liquor Concentrations, SRT and Effluent Total Nitrogen

Pass	% PE FEED	MLSS, Mg/L	Average MLSS, Mg/L	SRT, days	Effluent TN, mg/L
A	25	4619	3324	12.0	9.1
B	25	3493			
C	25	2817			
D	25	2367			
A	50	3525	2960	10.6	10.0
B	0	3527			
C	50	2395			
D	0	2391			
A	100	2424	2425	8.6	10.8
B	0	2427			
C	0	2426			
D	0	2423			

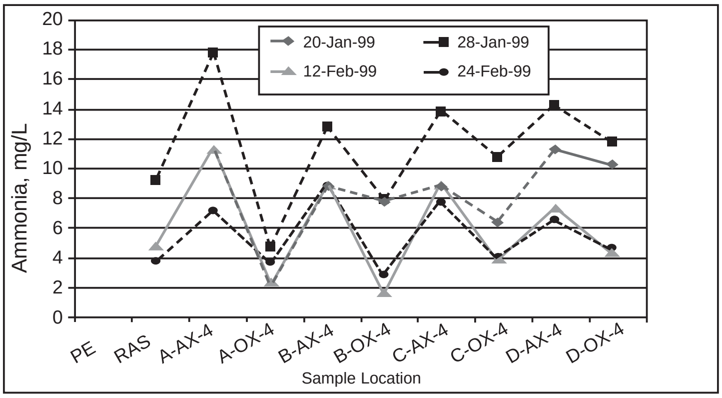
overall step-feed BNR system characteristics and performance. In general, by splitting the flow to several influent feed locations and directing RAS to the beginning of the first pass, a higher system solids retention time (SRT) is achieved than in a plug-flow system with the same basin volume. The increase in SRT can be obtained without increasing the aeration tank effluent mixed liquor suspended solids (MLSS), so the solids loading to the clarifiers is not increased. Since much of the system solids inventory is in the early passes of a step-feed system, the risk of solids washout can be reduced by directing higher percentages of the peak flow to later passes during storm events. Using the example 1-mgd step-feed BNR process model, a comparison of MLSS concentrations, SRT and effluent total nitrogen (TN) for several flow-split regimes was developed (Table 1).

Control of influent flow splitting can impact step-feed BNR system optimization in several ways, depending on which aspect of the BNR process is limiting. During winter operation, nitrification often is limiting. New York City Department of Environmental Protection (NYCDEP) has a BNR pilot facility at the 26th Ward Water Pollution Control Plant (WPCP). Several pilots are configured as four-pass step-feed BNR systems with anoxic and oxic zones in each pass, and are sized at the four-hour HRT that is representative of the existing NYC plants. In Pilot 1, a change in flow split in February 1999 from 10/30/30/30 to 10/40/30/20 appeared to reduce ammonia breakthrough in the fourth pass (Figure 2).

When the BNR system is fully nitrifying, denitrification may be limiting. Total nitrogen removal can be increased by adjusting the flow-splitting regime to minimize the quantity of unutilized carbon in the anoxic zones of certain passes. Using the 1-mgd example configuration described earlier, a comparison of several different flow-splitting regimes and the ammonia concentrations in each pass for a nitrification limited system at 15 oC was developed (Table 2, page 20).

Providing the means to accurately split and control the flow to each pass can be complex, depending on the number of tanks and passes, and the available head if the plant is existing. The NYC WPCPs typically have submerged slide gates at each aeration tank pass. With the existing facilities, it is difficult to regulate and measure flow to each pass, and at several of the WPCPs there may not be sufficient head available between the primary and final settling tanks to provide overflow gates at the aeration tank influent. To control the flow split, additional gates and automation of gates to each pass are being considered for full-scale step-feed BNR retrofits. Some of the plants do not have effluent weirs at the aeration tanks, and weirs with ultrasonic level sensors are being considered to further control distribution of flow between aeration tanks.

Figure 2. Grab Sample Ammonia Profiles from Step-Feed BNR Pilot Before and After Flow Splitting Adjustment on February 8, 1999.



The original configuration for Cumberland

Table 2. Simulated Impacts of Primary Effluent Flow Splitting on Nitrification, SRT and Effluent Total Nitrogen

Pass	% PE FEED	NH_3-N, mg/L	SRT, Days	Effluent TN, mg/L
A	10	0.6	13.3	8.2
B	30	2.8		
C	30	4.3		
D	30	5.4		
A	30	6.2	11.3	9.5
B	30	6.9		
C	20	6.7		
D	20	6.7		
A	25	3.3	11.9	7.6
B	25	3.6		
C	25	4.3		
D	25	4.9		

Table 3. Simulated Impacts of Return Activated Sludge Flow Rates on Step-feed BNR Mixed Liquor Concentrations, SRT and Effluent Total Nitrogen

% RAS, Flow	Pass	MLSS, mg/L	Average MLSS, mg/L	SRT, days	Effluent TN, mg/L at 20ºC	Effluent TN, mg/L at 14ºC
100	A	3062	2440	8.0	5.6	19.3
	B	2558				
	C	2202				
	D	1936				
75	A	3716	2834	9.5	5.4	7.5
	B	2979				
	C	2493				
	D	2149				
50	A	4812	3442	11.9	5.5	6.2
	B	3616				
	C	2905				
	D	2435				
25	A	7108	4580	16.0	6.0	6.4
	B	4749				
	C	3580				
	D	2883				

included inlet ports and slide gates at several locations along the aeration basin. Cumberland was recently upgraded from step-aeration to step-feed BNR to meet a seasonal average effluent TN of 10 mg/L. Due to a lack of available head, and the need to minimize entrainment of dissolved oxygen (DO) in the influent to the anoxic zones, a design with submerged inlet ports was preferred. The aeration tanks were retrofitted with piping and throttling valves to create a submerged discharge to each anoxic zone.

Return Activated Sludge Flows

The RAS flow also has an impact on the performance of step-feed systems. Typically RAS is discharged to the beginning of the first pass. If settling characteristics allow, increasing or reducing the RAS flow can impact TN removal. At lower RAS flows, the solids are more concentrated, which results in higher MLSS concentrations in the early passes and an increased SRT. At higher RAS flows, provided the system is fully nitrifying, increased denitrification of nitrate in the RAS in the Pass A anoxic zone can result in lower effluent TN concentrations. Simulations using the 1-mgd example configuration with a 25/25/25/25 influent flow split suggest that at 20° C a lower effluent TN is predicted with higher RAS flows (Table 3). Conversely, lower RAS flows resulted in a significantly lower effluent TN at 14° C due to more complete nitrification.

Dissolved Oxygen Carryover

Minimizing carryover of DO from the last oxic zone of one pass to the anoxic zone of the next pass optimizes anoxic zone performance and reduces the readily biodegradable carbon consumed during reduction of residual DO. This must be considered for plug-flow BNR systems, but is even more critical for step-feed systems because of the need to minimize the DO entering the anoxic zones of each pass. At New York City's 26th Ward pilot facility, the effluent total nitrogen in step-feed BNR Pilot 3 was reduced from 11 to 6 mg/L (without supplemental carbon feed) by reducing backmixing and turning off the air to the last oxic zone of each pass to reduce DO carryover to the anoxic zones (Figure 3, page 33).

The impact of DO carryover on denitrification was modeled with the 1-mgd example step-feed BNR configuration and a 25/25/25/25 primary effluent flow split (Table 4, page 33).

At Cumberland, a deoxygenation (deox) zone is provided after the last oxic zone of passes A, B, and C to allow the mixed-liquor DO to decrease before entering the next anoxic zone. Each deox zone is sized at approximately 1.5% of the total system volume. Cumberland has primary effluent BOD concentrations of 60 to 70 mg/L, and it was deter-

Continued on page 33

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mined during design that the deox zones were required to avoid supplemental carbon addition.

Figure 3. Step-feed BNR Pilot 3 Effluent Nitrate, Nitrite and Ammonia Nitrogen Before and After Reduction of DO Carryover to Anoxic Zones

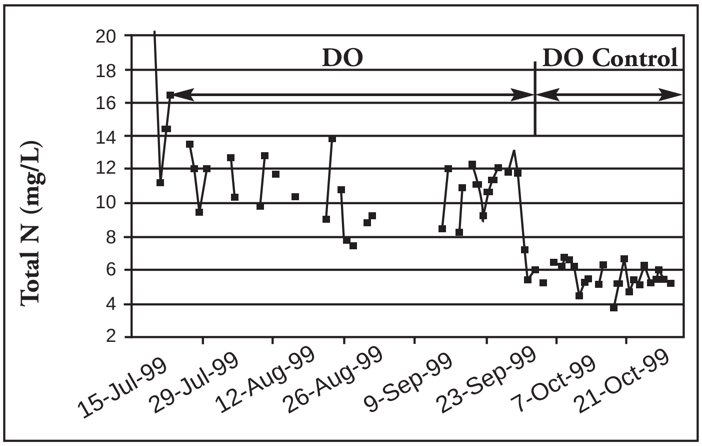

Table 4. Simulated Impacts of Dissolved Oxygen Carry-over to Anoxic Zones on Step-feed BNR Effluent Nitrate Concentrations

Mixed Liquor DO Entering Anoxic Zones, mg/L	Effluent Nitrate, mg/L	Effluent TN, mg/L
4	4.6	6.4
3	4.0	6.0
2	3.5	5.5
1	2.9	5.1
0	2.9	4.9

Since Cumberland will be required to meet a seasonal total nitrogen limit, the deox zones also are equipped with diffusers to allow operation in an oxic mode when denitrification is not required.

Since step-feed BNR mixed-liquor concentrations differ from pass to pass, required deoxygenation volumes also differ based on specific oxygen uptake rates (SOURs). At the New York City 26th Ward pilots and at Tallman Island, Bowery Bay, Red Hook, and Wards Island full-scale plants, oxygen depletion rates were measured and divided by the appropriate mixed-liquor concentration. SOURs of 8 to 30 mg O2/g TSS/hr were observed, and average values of 8, 19, and 19 mg O2/g TSS/hr were developed for Passes A, B, and C, respectively for a system with a 10/30/30/30 influent flow split (NYCDEP, 1999). Using the SOURs, a sizing of deoxygenation zones can be estimated based on the anticipated DO at the end of the oxic zone, the total system flow, and the mixed liquor solids concentrations in each pass at the design SRT. A process simulator also can be used to develop oxygen uptake rates specific to the wastewater and proposed BNR configuration. The zone sizing requirements may differ from plant to plant, depending on the system configurations, effluent requirements, and operating conditions.

Chemical Feed Locations

The feed locations for supplemental alkalinity and readily biodegradable carbon can significantly impact required dosages. For example, if carbon is fed to the primary effluent and the influent flow split is 10/40/30/20, the carbon will not be efficiently utilized because the highest dosage is to the second pass, which will receive the least nitrate. To illustrate the difference in required carbon quantities, the 1-mgd example configuration with a 25/25/25/25 flow split was simulated with several carbon addition locations. Since the simulated system showed good denitrification with the addition of deoxygenation zones as discussed in the previous section, the influent TKN was increased from 25 to 30 mg/L to create a carbon-limited system. With this increase in the influent TKN, the effluent nitrate from the simulated system was over 5 mg/L. In each simulation, the supplemental carbon dose was increased until an effluent nitrate of approximately 3 mg/L was obtained (Table 5).

Table 5. Simulated Impacts of Supplemental Carbon Feed Location on Total Dosage Required

Carbon Dose Location	Carbon Dose, lbs/day as COD	Effluent Nitrate, mg/L	Effluent TN, mg/L
None	0	5.3	7.2
Primary Effluent	417	3.2	5.0
Pass D Only	259	3.2	5.0
Pass C and D	250	3.2	5.0

A direct carbon feed to the anoxic zones of each pass would be optimal but is complex for a plant with multiple aeration tanks. To test a simpler and optimized configuration, one of the New York City 26th Ward step-feed BNR pilots is currently operated with carbon addition to the anoxic zones in the last pass only.

Alkalinity addition is less difficult because excess alkalinity is conserved from pass to pass in the step-feed system. For a typical domestic wastewater, alkalinity feed to the primary effluent may be simplest, but the specifics of each application must be considered. For example, in New York City several of the WPCPs proposed for BNR upgrades have central dewatering facilities. These WPCPs dewater anaerobically digested sludge generated on site as well as sludge from other plants. The proposed addition point for the dewatering centrate is Pass A of the step-feed BNR system. Since the centrate is low in alkalinity compared to the nitrogen load, significant supplemental chemical is required for the centrate to completely nitrify in Pass A. One possible location for alkalinity addition is the RAS wetwells, where it would be pumped with the RAS to the first pass of each aeration tank. An alternate location would be to dose directly to Pass A. The chemical selected for alkalinity supplementation, the dosage, and its overall impact on pH at the addition point also should be considered.

Nitrate Recycle

Although one of the benefits of the step-feed BNR configuration is the ability to introduce nitrified mixed liquor to the anoxic zones without pumping, nitrate recycle can be used as a process enhancement. Interpass recycle involves pumping nitrified mixed liquor from one pass to the anoxic zones of an earlier pass. Intrapass recycle involves pumping nitrified mixed liquor from the last oxic zone to the anoxic zone of the same pass. The benefit is similar to the use of nitrate recycle in a plug-flow system.

The interpass recycle mode was tested by the City College of New York (CCNY) and the NYCDEP at Tallman Island WPCP in 1998. A nitrate recycle of 30% of the step-feed BNR basin flow was pumped from the end of the Pass D oxic zone to the Pass A anoxic zone. The interpass recycle resulted in an increase in the DO in Pass A and a decrease in the mixed-liquor concentrations in each pass. Under the summer operating conditions, no conclusive difference in system performance with the interpass recycle was observed (CCNY, 1998). To illustrate the impacts of interpass recycle on system SRT, a BiowinTM simulation was conducted using the 1-mgd example configuration. An interpass recycle of 100%Q from Pass D to Pass A lowered the system SRT from 12.6 to 10.6 days and resulted in an increase in the predicted effluent TN from 7.2 to 7.5 mg/L.

The benefit of intrapass recycle is that the nitrate load can be increased to an anoxic zone in which excess readily biodegradable carbon is available. During testing of a three-pass pilot system in Japan, theoretical relationships were developed showing the impacts of the number of stages and the recirculation ratio on nitrogen removal efficiency. Intrapass recycle of 50%Q in the final pass was tested (Sakai and Koike, 1998).

For the example configuration with a 25/25/25/25 flow split, an intrapass recycle in Pass B alone is of minimal benefit because the readily biodegradable carbon is already being utilized (Table 6). However, for the same configuration, an intrapass recycle in Pass A provides a benefit because the nitrate in the RAS does not deplete all the carbon in the Pass A anoxic zones. With a recycle in Pass A, the nitrate load to Pass B is reduced and the subsequent addition of an intrapass recycle in Pass B also shows a benefit. In the example configuration, additional intrapass recycles in passes C and D did not show a benefit because the available carbon in the Pass C and D anoxic zones was already being utilized.

Table 6. Simulated Impacts of Intrapass Recycle Location on Step-feed BNR Effluent Total Nitrogen and System SRT

Recycle Location	Recycle Flow	SRT, days	Effluent TN, mg/L
None	0	12.6	7.2
Intrapass, Pass B oxic zone to Pass B anoxic zone	10%Q	12.6	7.2
Intrapass, Pass A oxic zone to Pass A anoxic zone	50%Q	12.6	6.9
Intrapass, Pass A oxic to Pass A anoxic and Pass B oxic to Pass B anoxic	50%Q each recycle	12.6	6.5
Intrapass, Pass A oxic to Pass A anoxic, Pass B oxic to Pass B anoxic and Pass C oxic to Pass C anoxic	50%Q each recycle	12.6	6.6

Foam Control

Foam control considerations for step-feed systems are similar to those associated with plug-flow systems except that foaming can be more problematic with the high MLSS concentrations in the early passes. The additional passes and zones in a step-feed system complicate control of foaming because there are more locations for the foam to become trapped in the aeration tanks.

In New York City, foam control “hoods” have been developed by the DEP. The “hoods” consist of fiberglass baffles with a cover that allow mixed liquor to pass, but foam is trapped behind the baffle. A chlorinated spray solution is applied to the trapped foam. New York City also plans to test RAS chlorination and continuous mixed-liquor surface wasting. The continuous mixed-liquor surface wasting differs from selective wasting regimes in that all wasting would be from the mixed liquor. New York City currently has the capability of mixed-liquor wasting, but the continuous mixed-liquor wasting proposed for foam control includes collection of foam and wasting from the surface of the first pass, rather than from the aeration basin effluent channel.

At Cumberland, foam collection boxes with weir gates were built at the end of the final aeration tank pass for selective wasting. Foam will be sprayed with chlorine solution and pumped to solids handling. RAS chlorination equipment and aeration tank spray headers also are being provided.

Summary

Step-feed BNR configurations can remove high levels of nutrients in a reduced tank volume as compared to plug-flow configurations. Typically, however, an increase in complexity of appurtenant equipment is needed to optimize the process. The ability to control and select primary effluent flow splitting combinations allows optimization of both summer and winter operation, as well as operation during peak wet weather flows. Similarly, control of RAS flows can optimize process performance with pump capacities comparable to those normally provided for plug-flow BNR configurations.

Carryover of dissolved oxygen from oxic zones can be of great concern in a step-feed system due to the increased number of passes. Control of DO carryover can be accomplished with deoxygenation zones and control of DO at the end of each oxic zone. Targeting supplemental chemical feed to individual step-feed BNR system passes rather than to the primary effluent can reduce chemical quantities. If there is unused readily biodegradable carbon in the anoxic zones of a given pass, an intrapass nitrate recycle can be used to improve performance without impacting the system SRT. Foaming can be complicated by the higher MLSS content of the early passes and additional locations for foam to become trapped. Foam-control considerations are similar to those in other activated-sludge BNR systems, but additional equipment may be required.

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