

# Effects of temperature and mean cell residence time on biological nutrient removal processes

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**ABSTRACT:** The effects of temperature and mean cell residence time (MCRT) on biological nitrogen and phosphorus removal were investigated by operating two pilot-scale continuous-flow reactors in parallel over a range of temperatures and MCRTs. One system was operated as a high-rate Virginia Initiative Plant (VIP) biological nutrient removal (BNR) process, and the other was operated as a conventional, fully aerobic activated sludge process for comparison. Results showed that less aerobic volume was needed for complete nitrification in the BNR process than in the conventional process when conditions of temperature and MCRT were suitable for complete nitrification. However, the BNR system was more prone to nitrifier washout than the conventional system. Nitrification rates and the degree of nitrification achieved by the BNR system and the conventional system were equal when compared on the basis of aerobic MCRT. Enhanced biological phosphorus removal (EBPR) was adversely affected by colder temperatures, with lower MCRTs being most affected. EBPR was not possible at a 5 day system MCRT and 10°C. Nitrification, however, was more sensitive to MCRT and temperature effects than EBPR under all conditions studied. Operation of the BNR process at the lowest MCRT that provided complete nitrification provided the best combined nitrogen and phosphorus removal when EBPR was chemical oxygen demand (COD)-limited. Higher MCRTs were considered optimal when EBPR was limited by phosphorus because of lower sludge productions. *Water Environ. Res.*, 65, 110 (1993).

**KEYWORDS:** activated sludge, biological nutrient removal, mean cell residence time, nitrification, nitrifier washout.

The wastewater 5-day biochemical oxygen demand ( $BOD_5$ ); total Kjeldahl nitrogen (TKN) ratio strongly influences nitrification rates, with nitrification rates decreasing as the ratio increases (Nutrient Control, 1983). Therefore, it is generally conceded that the rate of nitrification in a separate stage activated sludge plant, that is, one that removes organic matter in the first stage and then accomplishes nitrification in the second stage, is faster than in a single-sludge system designed to accomplish both organic removal and nitrification in the same reactor. Various reasons are given for this, including: inhibition of nitrification in the single-sludge system by the heterotrophic competition for nutrients or the presence of organics, less competition for dissolved oxygen (DO) in the second stage reactor, the rate of nitrification is limited by the rate of deamination in the single-sludge reactor, and a greater concentration of nitrifiers in the second stage reactor compared to the single-sludge reactor. While the relative importance of these factors may be open to debate, the fact of higher rates of nitrification in the two-sludge system is widely accepted and used for design purposes.

A biological nutrient removal (BNR) system is an activated sludge process designed to remove nitrogen and phosphorus. BNR can be accomplished by incorporating anaerobic and an-

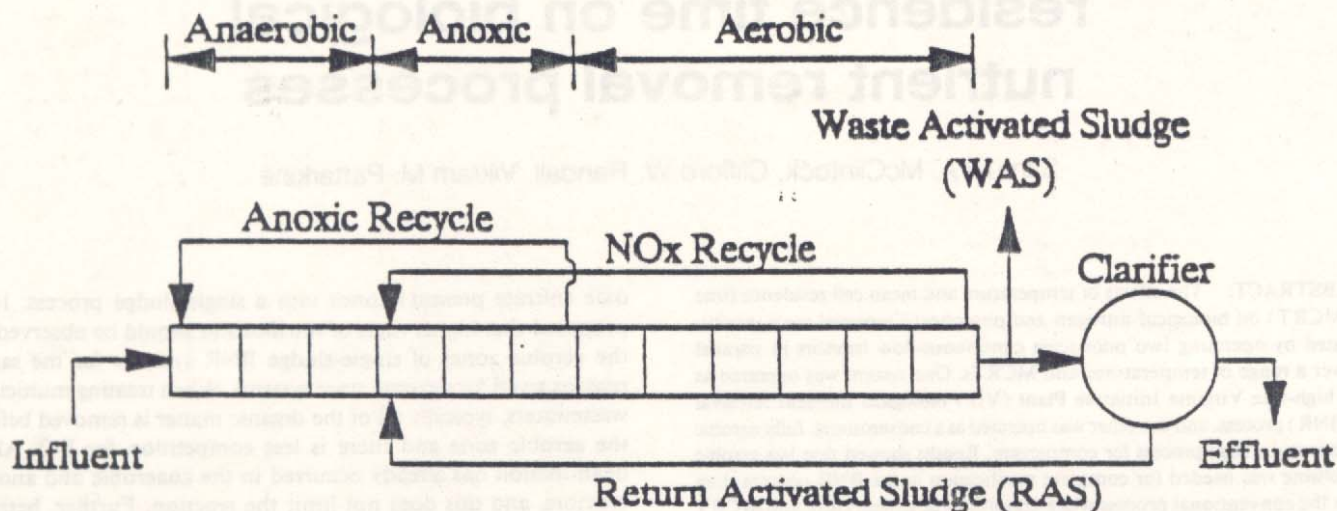
oxic (nitrate present) zones into a single-sludge process. It is proposed that higher rates of nitrification should be observed in the aerobic zones of single-sludge BNR systems for the same reasons given for separate stage systems. When treating municipal wastewaters, typically all of the organic matter is removed before the aerobic zone and there is less competition for DO. Also, deamination has already occurred in the anaerobic and anoxic reactors, and this does not limit the reaction. Further, heterotrophic activity is considerably less in the aerobic zone of a BNR system and competitive inhibition of nitrification should be minimal.

If nitrification rates are faster in the aerobic zones of a BNR process compared to a conventional process, less aerobic volume will be required for nitrification in the BNR process. If true, the lesser required aerobic volume should be incorporated into BNR design, and into zone volume determinations when retrofitting conventional plants for BNR. This could make retrofit of conventional plants to BNR more economical. The primary objective of this study was to compare nitrification rates and efficiencies for a BNR and a conventional process over a range of temperatures and mean cell residence times (MCRTs) to determine if this hypothesis is true. A secondary objective of the study was to monitor the enhanced biological phosphorus removal (EBPR) in the BNR process, and make recommendations for the operation of such processes to optimize nitrogen and phosphorus removal.

## Experimental Methods

The study was performed by operating two pilot-scale activated sludge systems side-by-side, treating the same wastewater. The two systems used are described and compared in Figure 1. The experimental system was a high-rate Virginia Initiative Plant (VIP) configuration (Daigger *et al.*, 1987, and Daigger *et al.*, 1988) BNR system with three anaerobic sections, three anoxic sections, and six aerobic sections, all of equal volume. The second system was a conventional, fully aerobic system, which also had a total of twelve sections of equal volume. Baffles were placed to separate the sections such that the flow was under the first one, over the second, and so on, to prevent short circuiting. The two systems were operated with the same nominal hydraulic retention time (HRT) of 8 hours, the same MCRTs, and the same temperatures throughout the research. The only differences in the two systems were the differences in reactor and recycle configuration.

Domestic wastewater was used as the substrate, and it was pumped from the main sanitary sewer of the Blacksburg, Virginia Polytechnic Institute collection system twice a day and stored



### BNR System

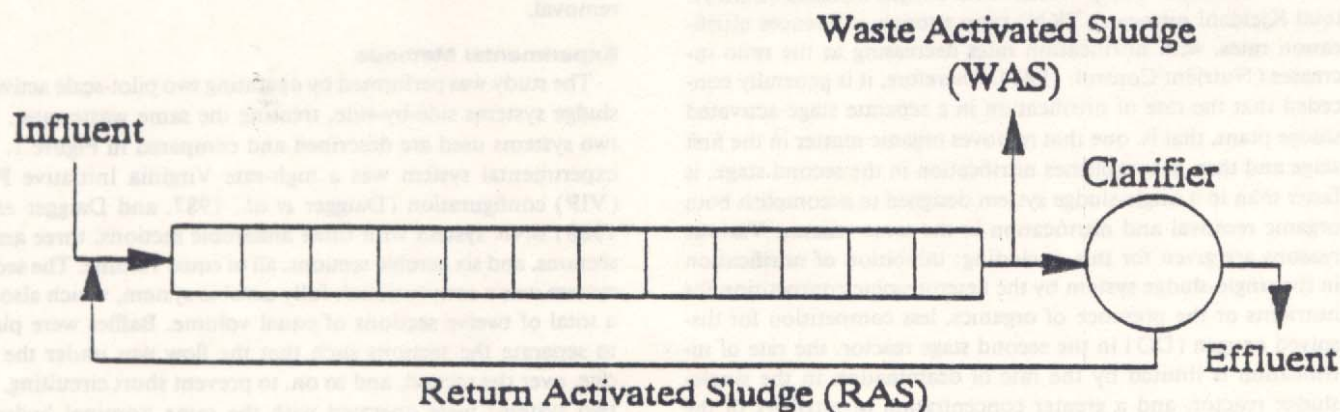
Influent Feed = Municipal Wastewater

Influent Flow Rate ( $Q$ ) = 151.2 L/d

All Recycles =  $1Q = 151.2$  L/d

Total Reactor Volume = 50.4 L

Total Nominal Hydraulic Retention Time (HRT) = 8 h



### Conventional System

Figure 1—Comparison of experimental BNR and conventional systems.

in two 265-L tanks. Potassium phosphate was added to the wastewater to increase the total phosphorus (TP) concentration by approximately 13 mg/L so that phosphorus would not be limiting relative to the biodegradable COD. Consequently, in

the BNR system, biodegradable COD removal was always virtually complete before the flow reached the aerobic zone. The sewage was held in the tanks for 12 hours before feeding to the two systems for three reasons: to equilibrate with room tem-

**Table 1—Parameters monitored (Standard Methods, 1985).**

Parameter	Method name (method number)
COD	Closed Reflux, Titrimetric Method (508 B)
MLSS	Total Suspended Solids Dried at 103–105°C (209 C)
MLVSS	Fixed and Volatile Solids Ignited at 550°C (209 D)
PO <sub>4</sub> -P	Ascorbic Acid Method (424 F)
Total P	Persulfate Digestion (424 C-III) followed by Ascorbic Acid Method (424 F)
TKN	Semi-micro-Kjeldahl Method (420 B) followed by Distillation (417 A) and Titration (417 D)
NH <sub>3</sub> -N	Preliminary Distillation Step (417 A) followed by Titrimetric Method (417 D)
NO <sub>3</sub> -N	Determination of Anions by Ion Chromatography with Conductivity Measurement (429)
Alkalinity	Alkalinity (269)
pH	Direct measurement with a pH meter assembly (Fisher Accumet pH meter, Model 610 A)
Dissolved oxygen	Direct measurement with a YSI Model 54 A membrane electrode oxygen meter (421 F)
Temperature	Direct measurement <i>in situ</i> using a mercury-filled Celsius thermometer (212)

perature, to eliminate any DO, and to promote fermentation. The entire system was housed in a building with the temperature kept constant within 1°C by thermostat-controlled air conditioning and heating equipment.

Both systems were seeded with sludge from full-scale plants operating in the same mode, that is, the BNR system was seeded from a full-scale BNR plant and the conventional system was seeded from a full-scale conventional plant. MCRT served as the primary control parameter and constant values were maintained by including the suspended solids lost in the effluent in the sludge wasting calculation. Wasting was performed at the end of each 24-hour interval for most MCRTs, but continuous wasting was practiced at MCRTs of less than 3 days.

The systems were assumed to be at an approximate steady state when operating and performance parameters remained

fairly constant over a period of several days. Steady-state data were never taken any sooner than three MCRTs after a change in operating MCRT was made. At least 30 days were allowed for steady state to be reached after the temperature was changed when operating at a 15-day MCRT, and at least three MCRTs were allowed to pass after a temperature change at a 5-day MCRT. Parameters such as observed yield, degree of nitrification, and percent phosphorus in the sludge were used to confirm steady-state conditions. True steady state with the wastewater was not achieved because there were daily variations in the wastewater characteristics. The day-to-day changes were not large, however, and were typical of changes at any full-scale plant. A complete listing of all experimental data is presented elsewhere (Pattarkine *et al.*, 1990).

Steady-state data consisted of analyses of samples from all 12 sections of each system, influents from the previous 24 hours, return activated sludge recycles, and effluents. Because of the extensive amount of sampling and analysis, steady-state sampling was performed for only one system per day, that is, the BNR system one day and the conventional system the next. The parameters monitored are listed in Table 1. As noted, DO, pH, and temperature measurements were made *in situ*.

The objectives of the research were accomplished by operating the pilot-plant systems continuously for approximately 15 months, with analysis as described above. The systems were operated at MCRTs of 1.5, 2.7, 5, and 15 days at a temperature of 20°C. They were also operated at temperatures of 10° and 15° at both 5- and 15-day MCRTs.

The initial objective was to establish BNR performance in the experimental BNR system. Because a BNR seed was used, acclimation was rapid and good performance was soon established. Following operation for the appropriate amount of time, steady-state data for the given condition of temperature and MCRT were collected.

## Results

Typical influent and effluent phosphorus (P), nitrogen (N), and chemical oxygen demand (COD) concentrations for the steady-state conditions are given for both systems in Table 2.

**Table 2—Summary of influent and effluent characteristics during steady-state periods.**

System	MCRT, days	Temperature, °C	Date	Influent (unfiltered, except for NO <sub>3</sub> -N)						Effluent (filtered)							
				TKN, mg/L	NH <sub>3</sub> -N, mg/L	NO <sub>3</sub> -N, mg/L	TN, mg/L	TP, mg/L	Avg. COD, mg/L	TKN, mg/L	NH <sub>3</sub> -N, mg/L	NO <sub>3</sub> -N, mg/L	TN, mg/L	TP, mg/L	OP,* mg/L	COD, mg/L	P/VSS, %
BNR	15	20	Jul 3, 1989	22.4	15.9	0.0	22.4	16.4	176	0.1	7.3	7.4	11.7	12	6.3		
	15	15	May 2, 1989	30.4	22.0	0.3	30.7	17.7	235	0.1	9.7	9.8	13.5	19	8.8		
	15	10	Aug. 8, 1989	24.5	17.8	0.0	24.5	14.3	166	0.2	9.6	9.8	12.6	17	6.1		
	5	20	March 28, 1990	30.0	27.5	0.1	30.1	20.3	244	0.0	0.0	11.4	11.4	13.4	12.6	29	12.4
	5	15	Nov. 21, 1989	34.3	27.2	0.1	34.4	19.0	201	6.2	5.9	8.8	15.0	18.6	18.5	27	8.7
	5	10	Dec. 7, 1989	38.0	28.4	0.0	38.0	17.6	283	21.1	19.4	1.6	22.7	15.8	15.9	24	3.2
	2.7	20	April 11, 1990	31.5	23.8	0.0	31.5	18.7	263	1.6	1.6	6.1	7.7	12.0	11.6	26 <sup>b</sup>	9.4
	1.5	20	April 19, 1990	36.6	29.8	0.0	36.6	19.5	247	16.2	15.4	2.3	18.5	15.3	14.9	33	5.6
	Conventional	15	20	July 4, 1989	25.6	17.4	0.0	25.6	15.3	281	0.6	13.8	14.4	13.6	13.0	35	1.5
		15	15	May 6, 1989	29.3	—	0.0	29.3	16.8	176	0.0	0.0	24.1	24.1	15.3	15	2.3
15		10	Aug. 10, 1989	25.4	17.6	0.1	25.5	15.8	173	0.0	0.0	18.8	18.8	13.3	14.1	23	2.4
5		20	March 29, 1990	35.0	28.9	0.3	35.3	20.3	344	0.0	0.0	21.5	21.5	19.2	18.2	24 <sup>b</sup>	1.9
5		15	Nov. 20, 1989	28.9	24.1	0.1	29.0	18.3	110	0.0	0.0	27.4	27.4	17.6	17.6	4	2.9
5		10	Dec. 8, 1989	31.6	23.2	0.0	31.8	18.6	266	9.9	8.1	12.6	22.5	17.4	17.2	36	2.6
2.7		20	April 10, 1990	34.3	26.0	0.2	34.5	19.1	257	0.0	0.0	21.7	21.7	17.4	16.6	27 <sup>b</sup>	3.1
1.5		20	April 17, 1990	36.6	30.0	0.0	36.6	19.2	263	6.4	5.6	15.5	21.9	17.6	17.2	31	3.9

\* OP = orthophosphate

<sup>b</sup> Section 12 COD concentration substituted for erroneous effluent value

Complete nitrification was achieved in both systems at all temperatures for the operating MCRT of 15 days. The conventional system also accomplished complete nitrification at all operating conditions except 1.5-day MCRT and 20°C, and 5-day MCRT and 10°C. Partial nitrification was achieved at both of those conditions. Nitrification was also complete in the BNR system at a 5-day MCRT and 20°C, but it was incomplete at a 5-day MCRT and 15°C, and was nearly nonexistent at a 5-day MCRT and 10°C. Nearly complete nitrification was accomplished in the BNR system with an MCRT of 2.7 days at 20°C, but was very incomplete when the MCRT was decreased to 1.5 days at the same temperature.

It was found that EBPR could be maintained at an MCRT of 15 days for any of the temperatures investigated, but decreased slightly as temperature decreased. The percent phosphorus in the sludge was the most consistent indicator of the propensity for EBPR. A maximum percent P/VSS of 20% was observed on one occasion at 20°C, and a minimum of 4% was observed at 10°C. Percent phosphorus was a strong function of the influent COD, which varied considerably depending upon whether the University was in or out of session. The best phosphorus removal was achieved at a 5-day MCRT and 20°C. EBPR was lost completely at an MCRT of 5 days and a temperature of 10°C, however, even with additional COD (as acetate) added. Analysis of the effects of temperature and MCRT on EBPR are presented elsewhere (McClintock *et al.*, 1991).

Total nitrogen removals achieved by the BNR system under various operating conditions are shown in Figure 2. High degrees of nitrogen removal (60–70%) were achieved at 20°C for all MCRTs of 2.7 days or more. Greater removals were achieved at a 15-day MCRT than at a 5-day MCRT for all temperatures studied. The data showed that nitrogen removal was greatest at an MCRT of 2.7 days and 20°C, as it varied from 62 to 76%. Operation under these conditions is not recommended, however, because nitrification was incomplete, and a small shock to the system could easily impair nitrification and nitrogen removal. It should be recognized that nitrogen removal was limited by the nitrate recycle rates used, which were always 1:1 compared to the influent flow,  $Q$ . The intent was to always obtain complete denitrification in the anoxic zone. Therefore, higher recycle rates were not used. Total nitrogen removal at the lower temperatures

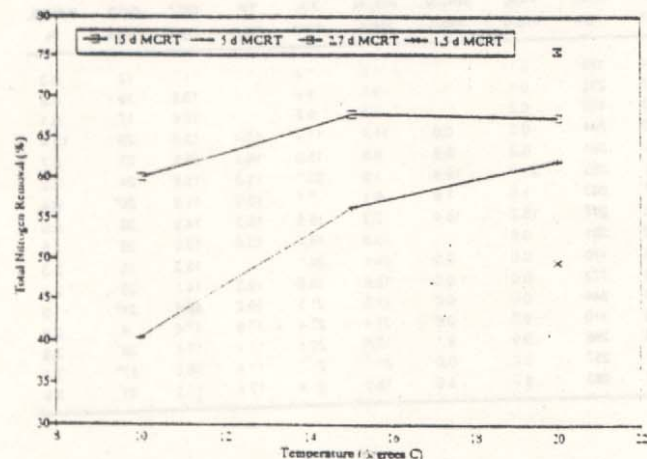


Figure 2—Total nitrogen removal in the BNR system.

was always limited by the degree of nitrification rather than denitrification.

The mixed liquor volatile suspended solids (MLVSS) in both systems had an average nitrogen content of 9.8% throughout the research. The COD per unit MLVSS was 1.34 for the BNR system and 1.30 for the conventional system.

### Nitrification Efficiency

Since the anaerobic and anoxic zones in the BNR system were not aerated, the solids retention time under aerobic conditions was always less than the system MCRT. The amount of time the solids were held in the aerobic sections of the reactor is referred to as the aerobic MCRT. For the conventional, fully aerobic activated sludge system, the aerobic MCRT is equal to the system MCRT. The aerobic MCRT in the BNR system is calculated by dividing the solids under aeration by the total solids contained in the system to obtain what is called the aerobic mass fraction, and multiplying the system MCRT by the aerobic mass fraction.

Data summarizing the nitrification efficiencies of the BNR and conventional systems are listed in Table 3. The aerobic MCRTs and temperatures for each phase are listed, along with total available ammonia-nitrogen ( $\text{NH}_3\text{-N}$ ), effluent  $\text{NH}_3\text{-N}$  concentrations, and the percent nitrification achieved. Total available  $\text{NH}_3\text{-N}$  concentrations were calculated from the influent TKN concentration minus nitrogen utilized for biomass synthesis and minus organic nitrogen in the effluent.

Trends were immediately obvious when effluent  $\text{NH}_3\text{-N}$  concentrations and percent nitrification from both the BNR and conventional systems were compared on the basis of aerobic MCRT. Figure 3 shows effluent  $\text{NH}_3\text{-N}$  concentrations for both systems together on the same graph versus aerobic MCRT. Each of the curves contains at least one data point from each system. Some of the points overlap. For example, at a 2.7-day aerobic MCRT and 20°C, both systems had complete nitrification, that is, 0 mg/L effluent  $\text{NH}_3\text{-N}$ . The curves follow a trend similar to what would be predicted from kinetic theory of *Nitrosomonas* growth using widely accepted kinetics and temperature correction coefficients (Nutrient Control, 1983).

Figure 4 shows the percentages of nitrification achieved by both systems as a function of temperature and aerobic MCRT. The numbers in the Figure represent the percentage of nitrification for the given condition. Numbers from the BNR system are followed by an asterisk, while the other numbers represent data from the conventional system. It can be seen that an aerobic MCRT of between 5 and 8 days was needed to maintain complete nitrification at 10°C, while a 2.7-day aerobic MCRT was sufficient at 20°C. It should be noted that aerobic MCRTs taken from this graph should be multiplied by a safety factor before using them for design. The safety factor is necessary to ensure high efficiency of treatment, process stability, and resistance to diurnal variations and toxic upsets. Typical recommended minimum safety factors for complete nitrification are 1.1 for plugflow systems and 1.5 for complete mix systems (U.S. EPA, 1975, and Nutrient Control, 1983).

### Nitrification Rates

Table 3 also shows the nominal aerobic HRT required to reduce the unoxidized nitrogen concentration to 1 mg/L in each of the systems, as determined from profiles of the available  $\text{NH}_3\text{-N}$

Table 3—Aerobic HRT needed for nitrification.

System	MCRT, days	Aerobic MCRT, days	Temperature, °C	Total NH <sub>3</sub> -N available, mg/L	Effluent NH <sub>3</sub> -N, mg/L	Nitrification, %	Influent COD, mg/L	Effluent pH	Aerobic <sup>a</sup> HRT to 1 mg/L NH <sub>3</sub> -N, hours	Grams N oxidized/h
BNR	15	8.33	20	18.8	0.0	100	176	7.2	1.7	10.5
	15	8.89	15	26.5	0.0	100	235	6.8	3.3	7.7
	15	8.31	10	20.5	0.0	100	166	7.1	2.2	8.9
	5	2.72	20	23.2	0.0	100	244	7.2	2.3	9.7
	5	2.80	15	28.3	5.9	79	201	7.4	—	—
	5	2.87	10	27.5	19.4	29	283	7.5	—	—
	2.7	1.55	20	23.2	1.6	94	263	7.4	5 <sup>b</sup>	4.4 <sup>b</sup>
	1.5	0.89	20	27.7	15.4	44	247	7.5	—	—
Conventional	15	15	20	21.2	0.0	100	281	7.2	3.2	6.3
	15	15	15	26.6	0.0	100	176	6.4	4.6	5.6
	15	15	10	22.5	0.0	100	173	6.9	3.2	6.7
	5	5	20	26.5	0.0	100	344	6.8	3.8	6.7
	5	5	15	21.9	0.0	100	110	7.0	6.0	3.5
	5	5	10	23.1	8.1	65	266	7.2	—	—
	2.7	2.7	20	27.1	0.0	100	257	7.1	6.0	4.4
	1.5	1.5	20	26.1	5.6	79	263	7.3	10 <sup>b</sup>	2.1 <sup>b</sup>

<sup>a</sup> This is the nominal HRT required to reduce the unoxidized nitrogen concentration to 1 mg/L in each of the systems.

<sup>b</sup> Estimated values.

N through the aerobic sections of each reactor. The nitrification performance of the two systems will be compared on the basis of these parameters.

The progressions of the ammonia concentrations through the aerobic sections of the conventional and BNR systems at a 15-day MCRT and 20°C are compared in Figure 5. The available ammonia-nitrogen concentration shown at an HRT of 0 hours is the actual concentration entering the first aerobic section after correction for nitrogen utilized for biomass synthesis and for organic nitrogen in the effluent. Concentrations entering the first aerobic zone of the BNR system are less than those entering the conventional system because of increased dilution due to the recycle configuration. The graph shows that considerably less aerobic volume was required in the BNR system to reduce NH<sub>3</sub>-N to less than 1 mg/L than was required in the fully aerobic

conventional system. The actual numbers, listed in Table 3, show that only 1.7 hours of aerobic HRT were required for nitrification to 1 mg/L NH<sub>3</sub>-N in the BNR system, and 3.2 hours were required in the conventional system. This can be translated directly into required basin volume and, therefore, construction costs. Similar results were obtained from all experiments where complete nitrification was obtained in the BNR system, that is, the aerobic basin volume required to accomplish complete nitrification in the BNR system was always significantly less than the volume required in the conventional system.

The implication of these results is that different design information should be used for determination of the required aerobic basin volume in a BNR system compared to what is used for conventional systems. Also, conversion of a fully aerobic plant to BNR operation requires less additional volume than previ-

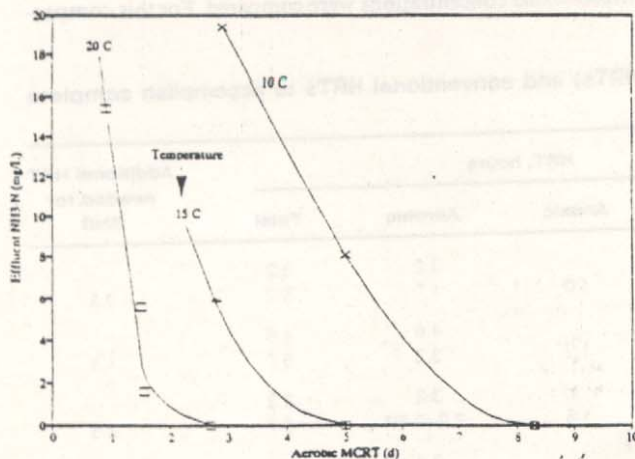


Figure 3—Effluent NH<sub>3</sub>-N concentration as a function of temperature and aerobic MCRT.

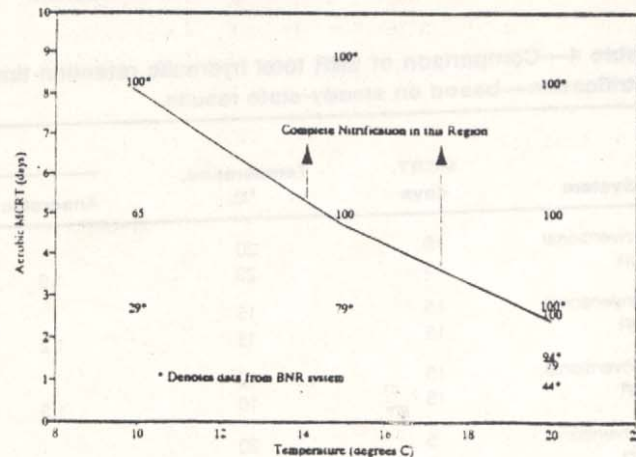


Figure 4—Percent nitrification as a function of temperature and aerobic MCRT.

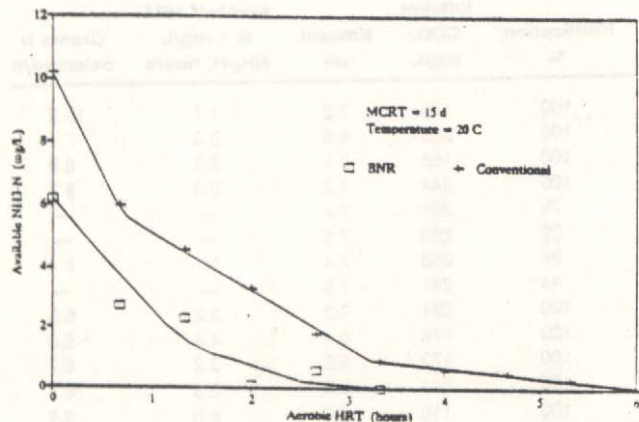


Figure 5—Aerobic hydraulic retention time (HRT) needed for nitrification.

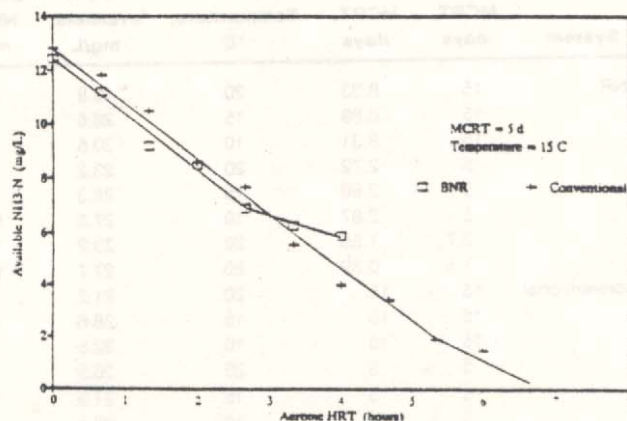


Figure 6—Aerobic hydraulic retention time (HRT) needed for nitrification.

ously thought. The additional volumes required for the different operating conditions of these experiments were found to be a function of both operating MCRT and temperature. These results are summarized in Table 4. Shown with the aerobic HRTs are the estimated HRTs needed for anaerobic and anoxic zones under the various operating conditions. The total estimated HRT needed for BNR can then be compared to the HRT needed for nitrification to 1 mg/L  $\text{NH}_3\text{-N}$  in the conventional system. The amount of additional HRT needed is relatively small (0.5–2.5 hours).

While it was determined that the BNR system required less aerobic volume than the conventional system to accomplish complete nitrification when operated at conditions where complete nitrification was achievable, it was also found that nitrification in the BNR system was more sensitive to low temperatures compared to the same size fully aerobic system. The BNR system was more prone to washout of nitrifying bacteria at a given system MCRT because the aerobic MCRT was less than that in the conventional system. This is not surprising when the differences in the aerobic MCRTs are considered, but it is an important

consideration when comparing the relative costs of the two designs.

The temperature sensitivity is illustrated in Figure 6, which shows available  $\text{NH}_3\text{-N}$  profiles at a 5-day MCRT and 15°C. Nitrification was progressing at the same rate in the two systems, but the conventional system had sufficient aerobic volume to complete nitrification whereas the BNR system did not. At a 5-day MCRT and 10°C, nitrification was lost in the BNR system, and the conventional system's nitrification was incomplete.

Observed specific nitrification rates were calculated for all experiments, and are shown in Table 5. These values are based on total  $\text{NH}_3\text{-N}$  oxidized in the system divided by the total volatile solids under aeration. The nitrification rate was always higher in the BNR system than in the conventional system for all MCRTs except 15 days, where they were approximately equal, based on the total MCRTs of the systems. However, when plotted versus aerobic MCRT, the rates from the two systems fit the same curve, as shown in Figure 7. Similar results were obtained when observed ammonia oxidation rates based on calculated *Nitrosomonas* concentrations were compared. For this compar-

Table 4—Comparison of BNR total hydraulic retention times (HRTs) and conventional HRTs to accomplish complete nitrification—based on steady-state results.

System	MCRT, days	Temperature, °C	HRT, hours				Additional HRT needed for BNR
			Anaerobic	Anoxic	Aerobic	Total	
Conventional	15	20			3.2	3.2	
BNR	15	20	1.0	1.0	1.7	3.7	0.5
Conventional	15	15			4.6	4.6	
BNR	15	15	1.2	1.2	3.3	5.7	1.1
Conventional	15	10			3.2	3.2	
BNR	15	10	1.5	1.5	2.2 (2.7) <sup>a</sup>	5.7	2.5
Conventional	5	20			3.8	3.8	
BNR	5	20	1.0	1.5	2.3	4.8	1.0
Conventional	2.7	20			6.0	6.0	
BNR	2.7	20	1.0	1.5	5.0 <sup>b</sup>	7.5	1.5

<sup>a</sup> Recommend increasing aerobic HRT to 2.7 hours (5.7 hours total HRT) to maintain an aerobic mass fraction of 0.50

<sup>b</sup> Estimated.

Table 5—Summary of specific nitrification rates and ammonia oxidation rates.

System	MCRT, days	Aerobic MCRT, days	Temp., °C	Total NH <sub>3</sub> -N oxidized, mg/L	Aerobic MLVSS, mg/L	Specific nitrification rate, mg N/g MLVSS · h	<i>Nitrosomonas</i> <sup>a</sup> VSS, mg/L	Ammonia oxidation rate, <sup>a</sup> mg N/mg <i>Nitrosomonas</i> · days
BNR	15	8.3	20	18.8	2 636	1.783	122	0.834
	15	8.9	15	26.5	3 457	1.916	191	0.703
	15	8.3	10	20.5	2 538	2.019	161	0.687
	5	2.7	20	23.2	1 014	5.720	74	1.729
	5	2.8	15	22.4	1 207	4.640	75	1.593
	5	2.9	10	8.1	1 352	1.498	28	1.494
	2.7	1.5	20	21.6	749	7.210	42	2.695
	1.5	0.9	20	12.3	446	6.895	14	4.382
	Conventional	15	15	20	21.2	1 348	1.966	101
15		15	15	26.6	2 177	1.527	143	0.560
15		15	10	22.5	2 092	1.344	133	0.506
5		5	20	26.5	1 284	2.580	72	1.107
5		5	15	21.9	1 050	3.095	75	1.036
5		5	10	15.0	1 373	1.366	46	0.982
2.7		2.7	20	27.1	658	5.148	47	1.716
1.5		1.5	20	20.5	424	6.044	22	2.774

<sup>a</sup> Based on calculated values.

ison, *Nitrosomonas* concentrations were calculated on the basis of aerobic MCRT using kinetic values found in the literature (U.S. EPA, 1975; Benefield and Randall, 1980; and Nutrient Control, 1983). The result was a remarkably good fit of the combined data, as can be seen in Figure 8.

#### Denitrification Rates

Figure 9 shows the observed specific denitrification rates in the BNR system as a function of temperature and MCRT. These rates were determined from nitrogen balances around the first anoxic section. Denitrification rates at the 5-day MCRT were strongly affected by temperature, while temperature had little effect at a 15-day MCRT. At 20°C, specific denitrification rates generally increased as MCRT decreased, and ranged from 6 to 19.6 mg NO<sub>3</sub>-N removed/g MLVSS · h at the 15-day and 2.7-day MCRTs, respectively. It should be noted that at a 1.5-day MCRT, the NO<sub>3</sub>-N concentration in the anoxic zone was 0

mg/L, and the denitrification rate was limited. The NO<sub>3</sub>-N concentrations for the other conditions ranged from 0.1 to 2.9 mg/L. It was not possible to develop a temperature correction coefficient for denitrification rates because some points were limited by nitrate concentrations while others were not, and the 5-day MCRT rate was more affected by temperature than the 15-day MCRT.

#### Discussion

The data were analyzed further to determine why the BNR system required less aerobic volume than the fully aerobic system to accomplish nitrification, considering that the nitrification rates were the same when compared on the basis of aerobic MCRT. It was noted that the BNR system always had a higher MLVSS concentration in the aerobic zone than did the fully aerobic system, as shown in Table 5. It was also determined that the yield coefficients for the two systems were the same, 0.41 mg

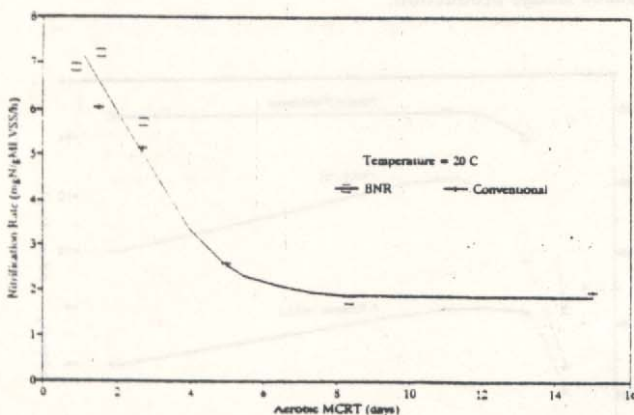


Figure 7—Comparison of observed specific nitrification rates versus aerobic MCRT.

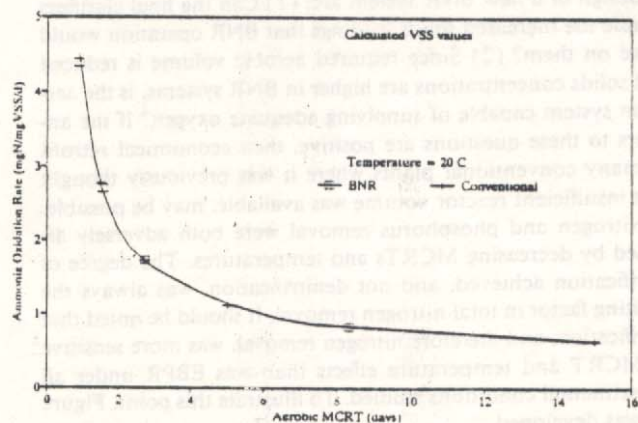


Figure 8—Ammonia oxidation rates by *Nitrosomonas* versus aerobic MCRT.

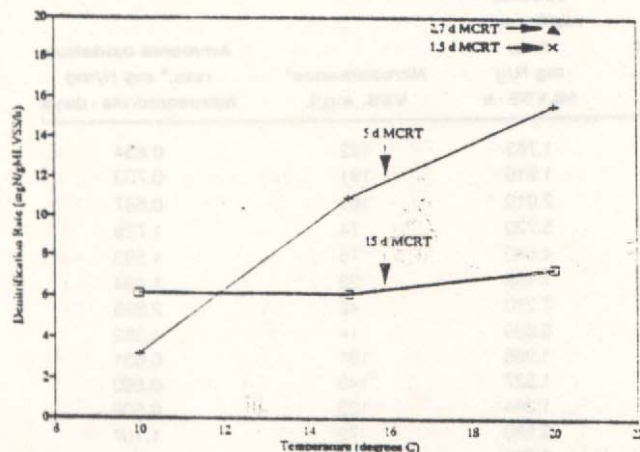


Figure 9—Observed specific denitrification rates.

VSS/mg COD, but there was a large difference in the endogenous decay rate coefficients (McClintock *et al.*, 1992). The fully aerobic system had a decay rate of 0.110/d while the decay rate in the BNR system was only 0.063/d.

Thus, the BNR system had greater MLVSS concentrations in the aerobic sections than did the fully aerobic system for two reasons. First, the BNR system was operated in the VIP mode, where the recycles are configured such that MLVSS concentrations in the anoxic and aerobic sections are approximately double that in the anaerobic sections. Therefore, even though aerobic volume in the experimental BNR system was 50% of the total volume, the aerobic mass fraction was always greater than 50%. Consequently, a higher MLVSS concentration would exist in the aerobic sections of the BNR system compared to the conventional system, all other factors being equal. Second, the endogenous decay rate in the BNR system was considerably less than in the fully aerobic system which would result in a greater observed yield in the BNR system when operated under the same conditions, that is, the same substrate, MCRT, and HRT.

With the exception of reactor volume requirements, probably the two most critical factors that must be considered in the retrofit or design of a new BNR system are: (1) Can the final clarifiers handle the increased solids loadings that BNR operation would place on them? (2) Since required aerobic volume is reduced and solids concentrations are higher in BNR systems, is the aeration system capable of supplying adequate oxygen? If the answers to these questions are positive, then economical retrofit of many conventional plants where it was previously thought that insufficient reactor volume was available, may be possible.

Nitrogen and phosphorus removal were both adversely affected by decreasing MCRTs and temperatures. The degree of nitrification achieved, and not denitrification, was always the limiting factor in total nitrogen removal. It should be noted that nitrification, and therefore nitrogen removal, was more sensitive to MCRT and temperature effects than was EBPR under all experimental conditions studied. To illustrate this point, Figure 10 was developed.

Figure 10 shows steady-state data from the BNR system at 20°C over the range of MCRTs studied. Included are the percent nitrification, the percent P/VSS, and the phosphorus removal in mg/L. The graph shows that phosphorus removal was greatest at an MCRT of 5 days—the lowest MCRT that provided com-

plete nitrification. Nitrification was more severely affected by lower MCRTs than was phosphorus removal. Similar results were obtained for analysis of data at temperatures of 15° and 10°C. The practical application of these results is that operation at the lowest MCRT that provides complete nitrification (with a safety factor built in) provides the best combined nitrogen and phosphorus removal when EBPR is limited by influent COD rather than phosphorus, which was the case for these data. Operation at higher MCRTs would be optimal as long as low effluent phosphorus concentrations are maintained, that is, when EBPR is limited by phosphorus rather than COD, because of reduced sludge production at higher MCRTs.

## Conclusions

This investigation shows that single-sludge BNR systems require less aerobic volume to accomplish complete nitrification than do conventional, fully aerobic activated sludge systems. This advantage is probably enhanced when the VIP or UCT configuration is used.

Complete nitrification occurred in less volume in the BNR system under favorable conditions because of greater biomass concentrations in the aerobic sections of the BNR system compared to the conventional system. The greater biomass is maintained because of the recycle configuration and because the endogenous decay rate in the BNR system is much less than the decay rate in the fully aerobic system. The smaller required aerobic volume should be incorporated into BNR design and into zone volume determinations when retrofitting conventional plants for BNR.

Nitrification rates (VSS basis) and the degree of nitrification achieved by the BNR system and the conventional systems were equal when compared on the basis of aerobic MCRT. Design for nitrification in BNR systems should be on the basis of aerobic MCRT.

Operation at the lowest MCRT that provides complete nitrification (with a safety factor built in) provides the best combined nitrogen and phosphorus removal when EBPR is COD-limited. Operation at higher MCRTs would be optimal as long as low effluent phosphorus concentrations are maintained because of reduced sludge production.

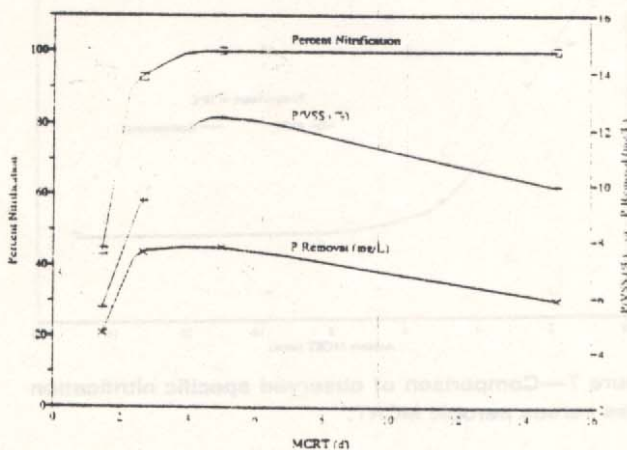


Figure 10—Effect of MCRT on percent nitrification and phosphorus removal: temperature equals 20°C.

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