

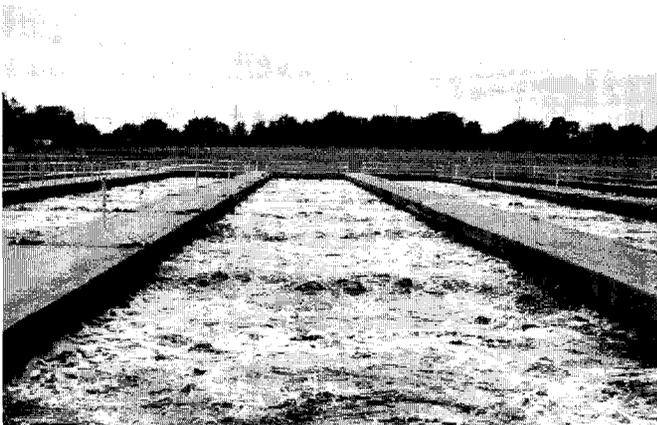
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Biological Phosphorus Removal Potential Test

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Abstract

Biological phosphorus removal (BPR) techniques offer a number of advantages over chemical addition, including enhanced treatment, reduced energy consumption, and reduced sludge production. A rapid, low-cost method for determining the feasibility of biological phosphorus removal should allow these techniques to be more widely used. A simple test is proposed to determine the amount of phosphorus that can be removed from a particular wastewater using a BPR process. The test involves measuring phosphorus release during a 2-hour anaerobic stage in a batch reactor containing phosphorus-removing organisms (PAOs) and estimating the effluent phosphorus concentration using a biochemical relationship. The BPR potential test developed in this study was used to evaluate BPR feasibility of five wastewaters. Comparing the test result with the effluent phosphorus concentration from a sequencing batch reactor validated the BPR potential test. An effluent phosphorus concentration predicted by the BPR potential test, compared favorably to the average effluent concentration obtained from the SBR. The initial sludge concentration affected the phosphorus release rate to a greater extent at the beginning of the anaerobic stage but to a lesser extent after 2 hours. It is recommended that the BPR potential test be conducted at a location where a PAO-containing sludge is available (either from an operating, full-scale BPR plant or from a lab-scale reactor) and that the wastewater samples be stored at 4°C for less than 24 hours.

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Introduction

Phosphorus removal from domestic and industrial wastewater is a key factor in preventing eutrophication of surface waters. Biological phosphorus removal (BPR) in activated sludge systems is one of the most economical and efficient methods for phosphorus removal. BPR is achieved by growing microorganisms that are capable of storing phosphorus intracellularly as polyphosphate. The growth of phosphorus-accumulating organisms (PAOs) is favored by subjecting the activated sludge to a cycle of anaerobic and aerobic conditions. Phosphorus is then removed by wasting excess sludge. The treatment efficiency of a BPR process depends not only on the size of anaerobic and aerobic basins but also on intrinsic wastewater characteristics. All wastewater may not be suitable for BPR. If the characteristics of the wastewater are not well defined, the BPR process may be improperly designed. Thus, it would be useful to develop a screening method to assess the feasibility of BPR for a wastewater of interest.

Parameters that have been used to evaluate the feasibility of BPR include ratios of biochemical oxygen demand (BOD_5) or chemical oxygen demand (COD) to phosphorus (P) and total Kjeldahl nitrogen (TKN) to COD. The BOD/P and COD/P ratios indicate that the strength of organic substrate is important for BPR. Having a large quantity of fermentation products, such as acetate and propionate, available in the anaerobic zone will increase the phosphorus removal efficiency.

Effluent phosphorus has been related to influent BOD/P and COD/P ratios. It has been known that total BOD/P ratio in the range of 20-30 would provide effluent, soluble phosphorus concentration < 1 mg/L for systems with relatively low sludge age (Sedlak 1991) and that an influent total COD/P ratio > 35 would result in an effluent total phosphorus concentration < 1 mg/L (Randall et al. 1992).

The TKN/COD ratio indicates the inhibitory effect of nitrate (NO_3^-) and nitrite (NO_2^-) in BPR. Nitrate is the by-product of nitrification. It can be introduced into the anaerobic zone by the returned sludge from

final clarifiers. Nitrate depletes the limited amount of the readily biodegradable substrate required for the growth of PAOs. Therefore, it is important to control nitrate in BPR systems.

For normal domestic wastewater, complete denitrification can only be achieved for TKN/COD ratios < 0.08 without the addition of an external energy source (Ekama et al. 1984). If $TKN/COD > 0.14$, it is unlikely that BPR will be achieved with any configuration because of the inability to achieve sufficient denitrification.

A major problem with using ratios of BOD or COD to phosphorus and TKN to COD for evaluating BPR is that only total BOD or COD is evaluated. The total BOD or COD ratios may exceed the criteria and yet not ensure that sufficient soluble biodegradable substrate will be available in the anaerobic zone. This may be the case where a treatment plant receives significant industrial wastewater discharges or where little fermentation occurs during transport in the sewer.

A second problem with using these ratios is that they do not reflect the effect of internal recycles on the BPR process. The degree of nitrification in a plant can result in fluctuating nitrate levels in the anaerobic zone. Nitrate is known to significantly inhibit BPR processes.

Thus, these ratios are not specific enough to show the feasibility of BPR under varying wastewater compositions. Other methods for evaluating BPR feasibility include long-term pilot testing or complete wastewater characterization along with computer modeling (Park et al. 1997).

The purpose of this study is to develop a simple procedure for determining whether BPR can be adapted for a wastewater of interest. A screening test developed by Kang et al. (1991) was evaluated, and an improved test, the BPR potential test, was developed and evaluated using wastewater samples from five wastewater treatment plants in Wisconsin.

The BPR potential test offers a rapid, low-cost alternative for assessing BPR feasibility and predicting the effluent soluble phosphorus concentration.

Screening Test

A screening test proposed by Kang et al. (1991) provided a simple procedure for testing the feasibility of BPR for a wastewater. The basic idea behind this screening test is the comparison of phosphorus release rates between wastewaters with and without acetate addition. By controlling parameters such as sludge composition and operational conditions, only the difference of substrate (with and without acetate addition) will determine the phosphorus release rate. If the phosphorus release rate with acetate addition is greater than that without acetate addition, it may indicate the lack of short-chain fatty acids (SCFAs) for PAOs in the wastewater. By comparing the differences between the phosphorus release rates, the feasibility of BPR for the wastewater of interest can be evaluated. This method can also be used to assess the effect of toxicants existing in wastewater on PAOs responsible for BPR.

In order to conduct the screening test developed by Kang et al., the following steps are required:

1. Obtain PAO-containing activated sludge.
2. Obtain the wastewater to be tested.
3. Conduct the screening batch test.

Phosphorus-Accumulating Organisms (PAOs)

A bench-scale sequencing batch reactor (SBR) was inoculated with activated sludge from the Nine Springs Wastewater Treatment Plant (WWTP) in Madison, Wisconsin. The SBR was used to develop PAOs for the screening test when PAO-containing sludge was not available. The SBR operation procedure used in this study is as follows:

1. Prepare an SBR with a total reactor volume of 6 L.
2. Feed with 4 L of primary effluent from Nine Springs WWTP, Madison, Wisconsin.
4. Operate the SBR with 2 hours/5 hours of the anaerobic/aerobic detention times and 1 hour of settling and decanting. Decant volume is 4 L.
5. One cycle lasts 8 hours. The hydraulic residence time (HRT) is 12 hours.

The schematic of the SBR is shown in Figure 1. The SBR is mixed with a magnetic stirrer equipped with three blades. Dissolved oxygen (DO) and pH are recorded. An air pump, a magnetic stirrer, and influent and effluent pumps are connected to the timer. Dissolved oxygen is typically maintained at < 0.02 mg/L for the anaerobic stage and 2-6 mg/L for the aerobic stage.

After 2 months of operation, 600 ml of activated sludge was wasted every day at the end of the reaction cycle to achieve a sludge age of about 10 days. SBR performance data are summarized in Table 1. When the effluent phosphorus concentration was < 1 mg P/L, the PAOs were considered fully developed in the SBR.

The behavior of phosphorus release/uptake and the readily biodegradable COD uptake by PAOs after 30 days of operation is shown in Figure 2. The biodegradable soluble COD was consumed from 155 to 95 mg/L, and phosphorus was released from 9 to 43 mg/L during the anaerobic stage. The ratio of phosphorus release to readily biodegradable COD uptake was 0.57 mg P/mg COD. Nitrate from recycled sludge, about 5 mg N/L, was totally denitrified in 10 minutes during the anaerobic stage (not shown in Figure 2). Phosphorus was taken up from 43 to 0 mg/L in 3 hours during the aerobic stage. PAOs appeared to be fully established in the SBR.

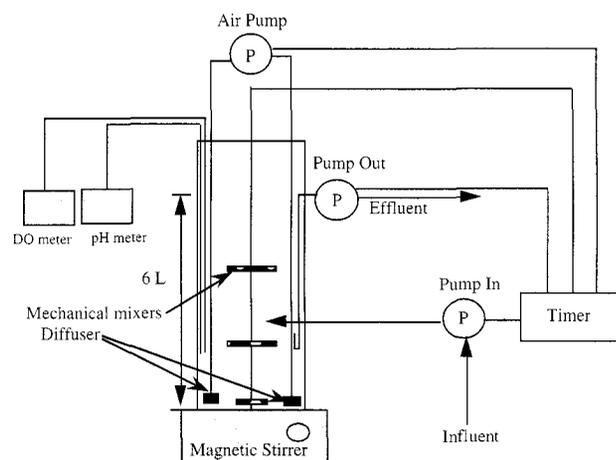


Figure 1. Schematic of SBR.

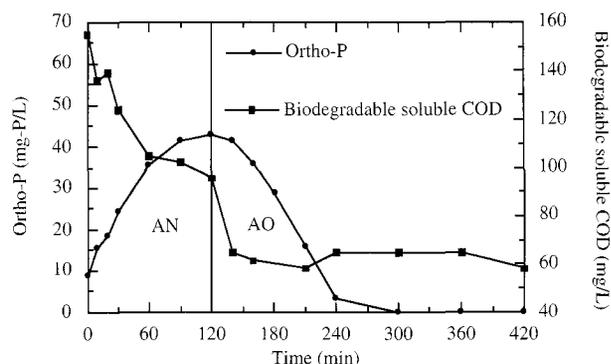


Figure 2. Change of phosphorus and biodegradable soluble COD in SBR.

Table 1. SBR monitoring data.

Date	Influent			Effluent		
	P (mg/L)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	Ortho-P (mg/L)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)
Jan. 2	6.0			3.4		
Jan. 4	9.0			< 1	0.6	16.7
Jan. 5	8.0			~ 0	0	15.5
Jan. 10	—			~ 0		
Jan. 16	—			~ 0		
Jan. 17	—			~ 0		
Jan. 24	7.3	21.2	0.5	0	0	14.4
Jan. 29	8.5			0		

Wastewater Tested Using Screening Test

Wastewater samples from the Oakfield, Nine Springs, and Badger Army Ammunition Plant WWTPs were evaluated using the screening test developed by Kang et al. (1991). The Madison Metropolitan Sewerage District's Nine Springs wastewater treatment plant has an average design capacity of 57 million gallons/day (MGD). Currently, flows average about 40 MGD of residential, commercial, and industrial wastewater. The plant was recently modified for BPR using a variation of the University of Cape Town (UCT) process. Sludge is digested anaerobically. Oakfield treats primarily domestic wastewater in a conventional activated sludge plant with a design flow of about 0.3 MGD. Sludge is aerobically digested. The Badger Army Ammunition Plant WWTP has a nominal design flow of 0.5 MGD and currently treats about 0.046 MGD of domestic wastewater. The plant consists of an Imhoff tank, trickling filter, and final clarifier.

Screening Test Procedure

The screening test procedure developed by Kang et al. is as follows:

1. Prepare two batch reactors, each containing 2 L of the wastewater to be tested.
2. Add 25 mg COD/L of sodium acetate to one reactor only.
3. Add 2 L of PAO-containing activated sludge to each reactor and mix anaerobically.
4. Obtain filtered samples in 1-hour anaerobic and 3-hour aerobic stages.
5. Examine the phosphorus release rate.
6. Evaluate the feasibility of BPR for the wastewater of interest.

Screening Test Results

Figure 3 shows the phosphorus profile during the screening test for the Oakfield WWTP sample. The phosphorus release rates with and without acetate addition were totally different. According to the method of Kang et al., the Oakfield wastewater is unfavorable for BPR. Figure 3 shows good phosphorus uptake but no phosphorus release. The PAO-containing activated sludge developed in the SBR may have contained enough energy (poly-β-hydroxybutyrate) for PAOs to take up phosphorus even if it did not release phosphorus.

Figure 4 shows the phosphorus profile during the screening test for the Nine Springs WWTP. The phosphorus release rates with and without acetate addition are almost the same. This indicates the wastewater can be treated by a BPR process. The screening test results are validated by the fact that the Nine Springs WWTP is currently removing phosphorus below 1 mg TP/L using a BPR process.

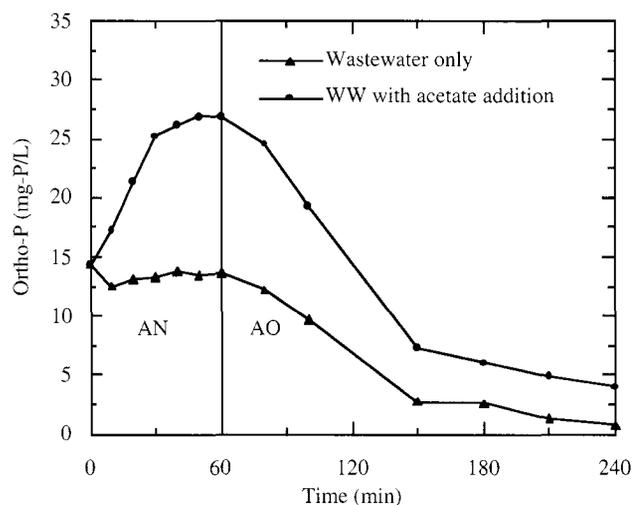


Figure 3. Phosphorus profile for Oakfield Wastewater Treatment Plant.

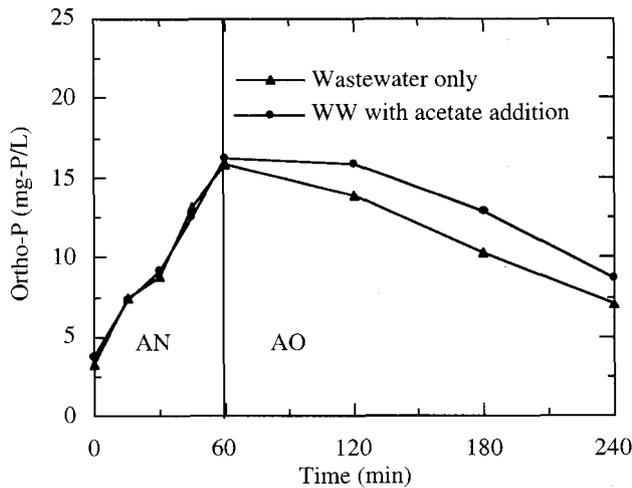


Figure 4. Phosphorus profile for Nine Springs Wastewater Treatment Plant.

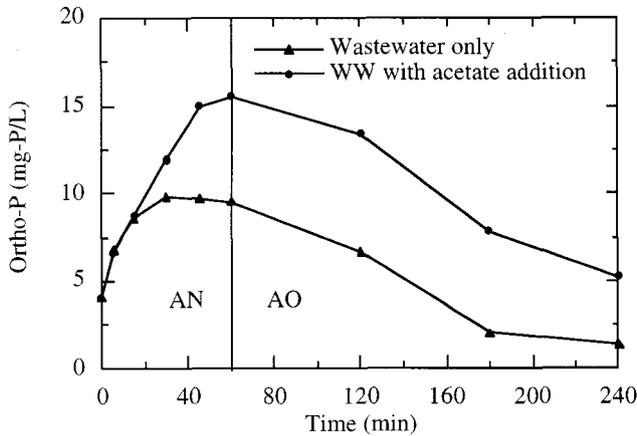


Figure 5. Phosphorus profile for Badger Army Ammunition Wastewater Treatment Plant.

Figure 5 shows the phosphorus profile during the screening test for the Badger Army Ammunition Plant WWTP. The phosphorus release with and without acetate addition was the same in the first 15 minutes, but decreased afterwards for raw wastewater. Using the method of Kang et al., no conclusive answer can be given for this situation.

A major problem with the screening test is that there are no absolute criteria to compare the difference between phosphorus release rates with and without acetate addition; therefore, no definitive answer is given by the screening test when phosphorus release rates are neither identical nor completely different. A better method must be developed to properly evaluate the feasibility of BPR properly.

BPR Potential Test

Experimental observations by Wentzel et al. (1985) and Abu-ghararah and Randall (1991) indicated the magnitude of biological excess phosphorus uptake was strongly linked to the magnitude of phosphorus release in the anaerobic reactor. The ratio of phosphorus uptake to release has been found to be relatively constant. Using this ratio together with the phosphorus release obtained from a batch test will herein be called the BPR potential test.

Phosphorus Uptake/Release Ratio

A series of pilot-scale experiments was conducted by Wentzel et al. (1985) with the modified UCT process at sludge ages of 8, 10, 15, and 20 days with a raw municipal wastewater having an influent COD of approximately 500 mg COD/L. As shown in Figure 6, there was a close linear relationship between phosphorus release and uptake, with the slopes having nearly the same magnitude irrespective of sludge age (θ_c). The ratio of phosphorus uptake to phosphorus release ranged from 1.15 to 1.2.

Abu-ghararah and Randall (1991) conducted pilot-scale tests using the UCT process. Seven different SCFAs (formic acid, acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, and isovaleric acid) were separately added to the influent wastewater, and their effects on the performance of the system were observed. The actual anaerobic hydraulic retention time was 2.1 hours, and the mixed liquor volatile suspended solids (MLVSS) concentration in the anaerobic zone was 1,300 mg/L. The recycling ratio from the anoxic zone to the anaerobic zone was unity. The average

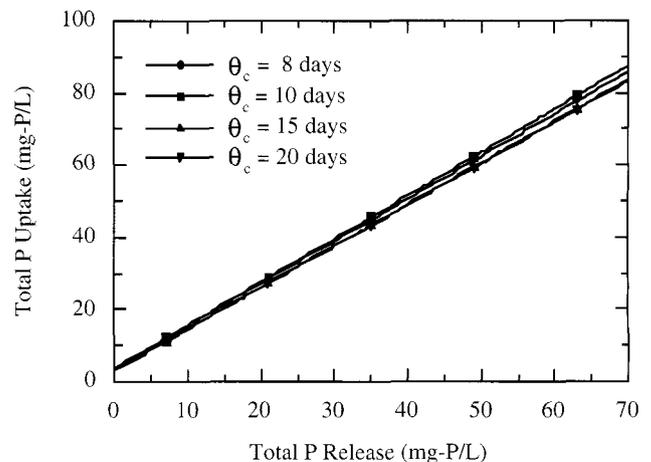


Figure 6. Relationship between phosphorus release and uptake under different sludge ages.

contents of phosphorus in MLVSS were 4.3, 9.8, 8.2, 7.4, 7.0, 6.9, and 6.1% for the seven different SCFAs, respectively. A linear relationship with a correlation coefficient of 0.99 and a slope of 1.2 was found between phosphorus uptake and phosphorus release. The results indicated the ratio of phosphorus uptake to phosphorus release was a constant of 1.2.

Rubens (1994) and Karlovich (1994) operated A2O and modified UCT processes, respectively, to treat a municipal wastewater. Both studies showed a good linear relationship between phosphorus release and uptake with the correlation coefficient of 0.99. Table 2 summarizes the linear relationship between phosphorus release and uptake from the literature. The slightly lower values of the ratio in the studies of Rubens (1994) and Karlovich (1994) were thought to be more the result of a low influent phosphorus concentration rather than the actual phosphorus uptake potential. It is believed that the ratio of phosphorus uptake to release ranges from 1.15 to 1.2. As a conservative estimate of phosphorus uptake, 1.15 is thought to be a reasonable value.

Relationship Between Phosphorus Uptake and Release

By accepting the observed linear relationship and postulating that the phosphorus value of the intercept on the uptake axis is equal to the basic metabolic phosphorus requirements of the total organism mass, Wentzel et al. (1985) proposed the following relationship for phosphorus release and phosphorus uptake:

$$P(\text{uptake}) = \alpha P(\text{release}) + P(\text{metabolic}) \quad (1)$$

where

$P(\text{uptake})$ = total phosphorus uptake, mg TP/L;

α = a constant ranging from 1.15 to 1.2;

$P(\text{release})$ = released phosphorus during anaerobic conditions, mg P/L; and

$P(\text{metabolic})$ = phosphorus requirement for removing BOD, mg P/L.

Practical Application

The magnitude of released phosphorus is strongly dependent on the characteristics of the wastewater of interest. Using the measured amount of phosphorus release under the anaerobic condition, a conservative P uptake/P release ratio of 1.15, and a ratio for metabolic phosphorus requirement of BOD/P, which is a function of sludge age (Benefield and Randall 1980), the feasibility of BPR can be evaluated. Therefore, the soluble effluent phosphorus concentration can be predicted as follows:

$$P_{\text{eff}} (\text{mg/L}) = P_{\text{inf}} (\text{mg/L}) - [P(\text{release}) (\text{mg/L}) \times 0.15] - \{[5 \times (\text{sludge age}) (\text{days}) + 90]^{-1} \times \text{BOD} (\text{mg/L})\} \quad (2)$$

For example, if the BOD and phosphorus values of the wastewater of interest are 230 and 6 mg/L, respectively, and the amount of phosphorus release measured with the BPR potential test is 20 mg/L, then the predicted excess uptake phosphorus will be 23 mg/L ($20 \times 1.15 = 23$), and the metabolic phosphorus requirement will be 2 mg/L at the sludge age of 5 days. Finally, the removed phosphorus will be 5 mg/L ($23 + 2 - 20 = 5$), and consequently, the effluent phosphorus concentration will be 1 mg/L ($6 - 5 = 1$).

Proposed BPR Potential Test

The following procedure is used to measure the magnitude of released phosphorus, which is influenced by the characteristics of the wastewater of interest:

1. Prepare two batch reactors, each containing 2 L of the wastewater.
2. Add 25 mg COD/L of sodium acetate to one reactor only.
3. Add 2 L of PAO-containing activated sludge taken at the end of the aerobic phase to each reactor and have the MLVSS concentration at about 1,400 mg/L (or at the level that an actual WWTP will target) and pH at about 7.

Table 2. Linear relationship between phosphorus release and phosphorus uptake.

Source	BPR System	Substrate	Influent P Concentration (mg/L)	Effluent P Concentration (mg/L)	Ratio	Correlation
Wentzel et al. (1985)	Modified UCT	Municipal WW	15-20	>0	1.15-1.2	0.99
Abu-ghararah and Randall (1991)	UCT	Municipal WW with SCFAs addition	11 ± 2.5	>1	1.2	0.99
Wentzel et al. (1989)	Modified Bardenpho	Acetate	>40	>4	1.16-1.2	—
Rubens (1994)	A2O	Municipal WW	6-8	<1	1.1	0.99
Karlovich (1994)	Modified UCT	Municipal WW	6-8	<1	1.12	0.98

4. Obtain filtered samples every 15 minutes during the 2 hours in the anaerobic stage.
5. Examine the phosphorus release rate.
6. Evaluate the phosphorus release rate obtained from the one with acetate addition for potential inhibition of PAOs by an unknown compound(s) in wastewater. (If there is no indication of industrial wastewater input, this step can be skipped; instead, a duplicate test can be conducted.)
7. Evaluate whether BPR is feasible by determining the potential phosphorus uptake and effluent phosphorus concentration.

Figure 7 shows the BPR potential test procedure. If recycle streams contain a high level of phosphorus, this should also be taken into account by increasing the initial phosphorus concentration.

BPR Potential Test Results

Five wastewater samples from the Oakfield, Green Lake, Ashland, Campbellsport, and Green Bay WWTPs were used for this test. The Green Bay WWTP is an advanced secondary plant with a total design flow of about 35 MGD. The plant receives significant industrial wastewater containing high soluble BOD and low phosphorus. Treatment includes primary sedimentation, anoxic selector basins, nitrifying activated sludge, and final clarification. Primary sludge and secondary sludge are mixed, dewatered, and incinerated. The Campbellsport WWTP treats primarily domestic wastewater. The design flow is 0.47 MGD, and the plant currently treats about 0.25 MGD. The plant is an oxidation ditch with sand filtration and aerobic sludge digestion. The Ashland WWTP treats mostly domestic wastewater in an oxidation ditch with aerobic sludge digestion. The design flow is 1.92 MGD. The Green Lake WWTP has a design flow of about 0.282 MGD and currently treats about 0.2 MGD of primarily domestic wastewater. The plant is a complete-mix activated sludge plant with aerobic digestion. The grab samples were taken from raw wastewater except for the Green Bay sample, which was taken at

the primary sedimentation tank effluent channel. The characteristics of each grab wastewater sample are summarized in Table 3. According to the commonly used criteria—the values of BOD/P and COD/P—all five wastewater samples are considered adequate to achieve an effluent phosphorus concentration < 1 mg TP/L when a BPR process is employed.

BPR potential test results are shown in Figures 8 to 12. Oakfield, Green Lake, and Ashland wastewater samples showed poor phosphorus release, while the acetate-added wastewater samples had relatively high phosphorus release. This indicates there was insufficient readily biodegradable soluble COD in these wastewater samples. The BOD/COD ratios of the Oakfield, Green Lake, and Ashland wastewater samples were 0.24, 0.4, and 0.42, and the readily biodegradable COD fractions were 0.26, 0.44, and 0.18, respectively. In a previous study of Ashland's wastewater, four 24-hour composite samples were characterized over a 1-year period. The readily biodegradable soluble COD fraction ranged from 0.19 in the winter to 0.3 in the summer (Park et al. 1997). Although the grab sample used for the BPR potential test showed poor phosphorus release, it may still be possible to adapt BPR processes, considering the readily biodegradable soluble COD fractions measured using composite samples taken for the earlier study by Park et al. (1997). We highly recommend that the BPR potential test be conducted with several composite samples taken during various seasons to represent the wastewater characteristics over a period of a year and that consideration be given to recycle streams.

The Campbellsport wastewater samples with and without acetate had similar phosphorus release for the first 15 minutes; however, after 15 minutes the phosphorus release for the sample without acetate was much lower than that with acetate. This indicates that there was insufficient readily biodegradable soluble COD despite the high readily biodegradable soluble COD fraction of 0.48. In the case of the Green Bay wastewater samples, the sample without acetate had phosphorus release similar to that with

Table 3. Characteristics of each grab wastewater sample tested.

	Oakfield	Green Lake	Ashland	Campbellsport	Green Bay
BOD ₅ , mg/L	93	121	190	205	157
COD, mg/L	388	300	462	450	427
Readily biodegradable soluble COD, mg/L	100	131	81	214	244
Total P, mg P/L	3.9	3.8	6.5	8.2	4.2
Ortho-P, mg P/L	1.6	2.4	3	4.4	2.3
BOD/P	24	32	29	25	37
COD/P	100	79	71	55	101

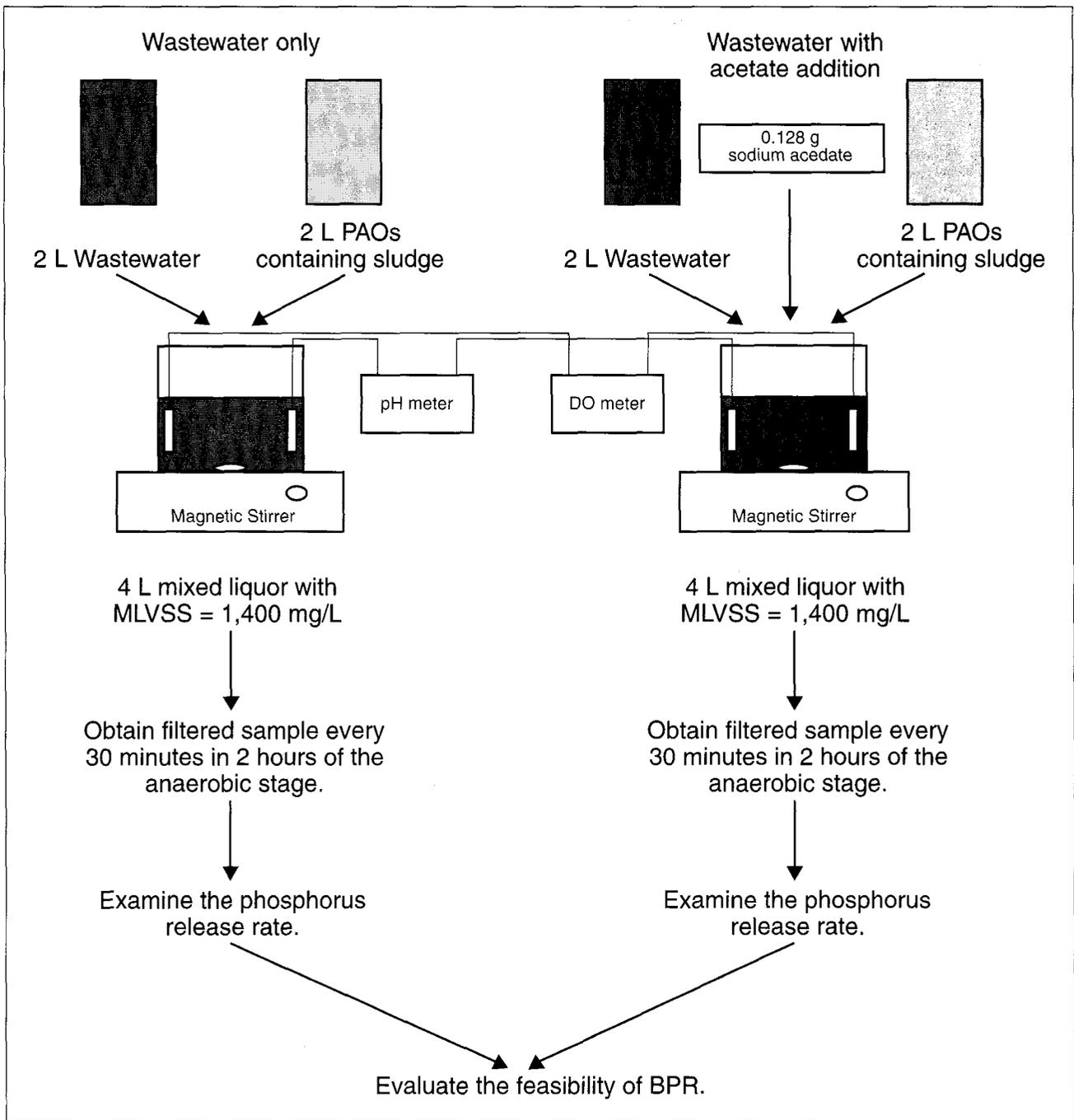


Figure 7. BPR potential test procedure.

acetate for the first 30 minutes and then had slightly lower release than that with acetate. Due to the high readily biodegradable soluble COD fraction of 0.57, there appeared to be sufficient readily biodegradable soluble COD required for the growth of PAOs in the anaerobic zone.

The total phosphorus removal for each wastewater sample can be calculated using Equation 2. The results are summarized in Table 4.

Randall et al. (1992) showed that if BOD/P is >

20~30 or COD/P is > 35, BPR is, in general, feasible. However, from Table 4, only the Green Bay wastewater would meet the phosphorus effluent permit. The Green Bay WWTP is currently removing phosphorus to below 0.5 mg TP/L by employing an anaerobic selector, originally installed for bulking control, ahead of the aeration basin. In the five wastewaters we studied, the BOD/P and the readily biodegradable COD fraction for Green Bay were the highest because the Green Bay WWTP receives wastewater

from industries that contribute large amounts of soluble BOD with low phosphorus. The BPR test result of the Campbellsport wastewater showed that 5.2 mg/L of phosphorus could be removed. However, it may not meet the effluent phosphorus limit as the total phosphorus concentration in influent was 8.2 mg TP/L. The BPR potential test result for Ashland wastewater showed that 2.7 mg TP/L could be removed, but it could not meet the discharge limit because of the high influent total phosphorus concentration of 6.5 mg TP/L. A previous study found the phosphorus concentration in Ashland wastewater ranged from 2.9 to 5.7 mg TP/L (Park et al. 1997). The BPR potential test results of the Green Lake and Oakfield wastewater samples showed that almost no excess phosphorus could be removed due to low phosphorus release. This is assumed to be because fermentation of raw wastewater does not occur in a collection system with a short travel time.

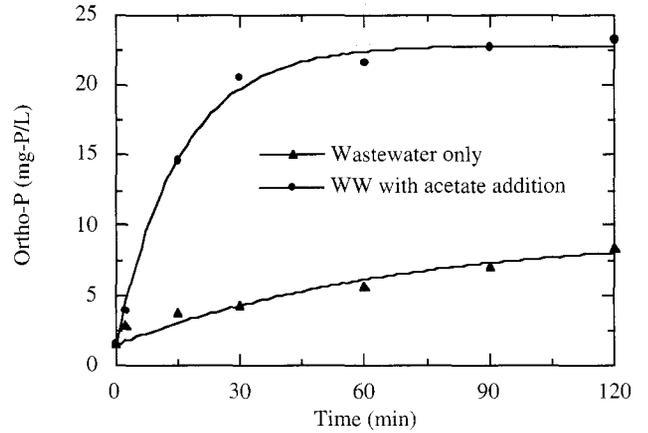


Figure 10. Phosphorus release profile for Ashland Wastewater Treatment Plant.

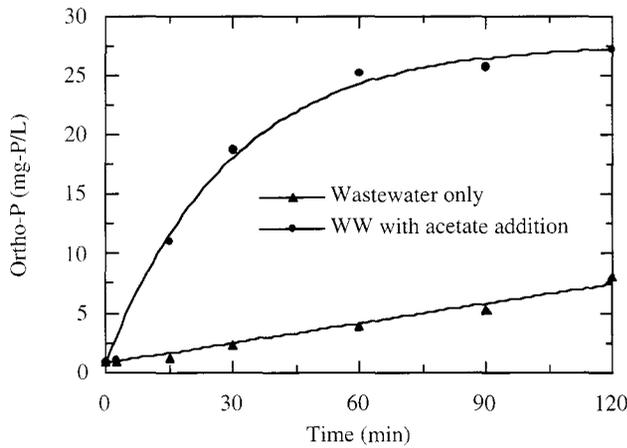


Figure 8. Phosphorus release profile for Oakfield Wastewater Treatment Plant.

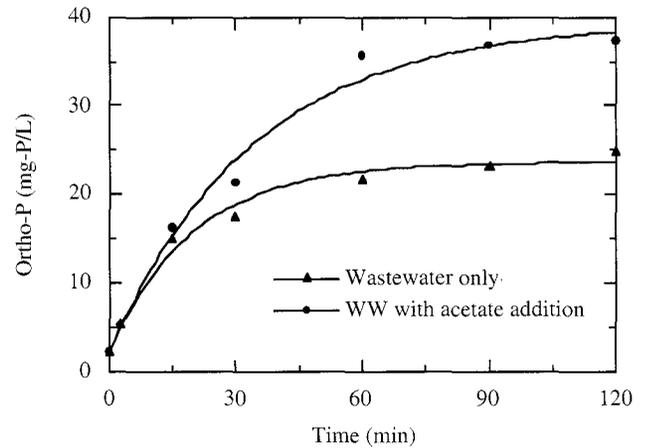


Figure 11. Phosphorus release profile for Campbellsport Wastewater Treatment Plant.

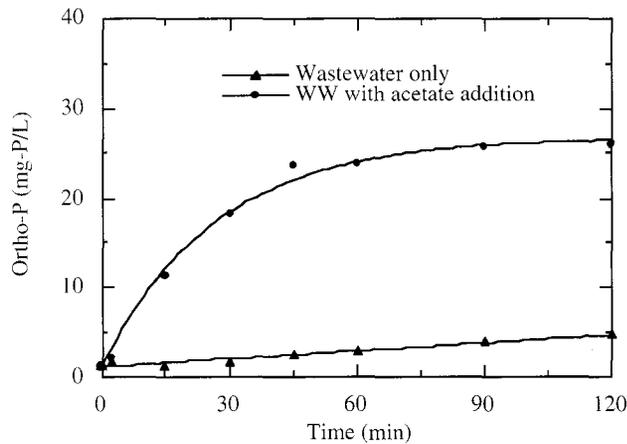


Figure 9. Phosphorus release profile for Green Lake Wastewater Treatment Plant.

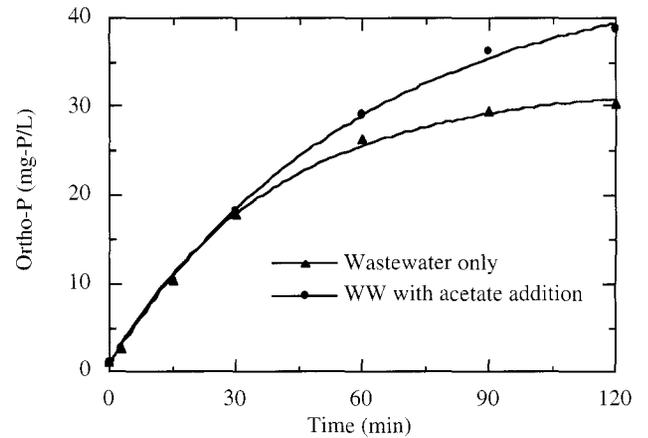


Figure 12. Phosphorus release profile for Green Bay Wastewater Treatment Plant.

Table 4. Estimated results for BPR potential test.

	Oakfield	Green Lake	Ashland	Campbellsport	Green Bay
P (release)	7.3	3.6	6.9	22.7	29
α P (release) ($\alpha = 1.15$)	8.4	4.14	7.94	26.1	33.4
Excess phosphorus uptake	1.1	0.54	1.04	3.4	4.4
P (metabolic) ^a	0.8	1.1	1.7	1.8	1.4
Total phosphorus removal (mg P/L)	1.9	2.2	2.7	5.2	5.8
Estimated phosphorus effluent (mg P/L)	2	2.2	3.8	3	0
Calculated effluent limit (mg P/L) ^b	1.3	1.3	1.6	1.7	1.3

^a The sludge age of 5 days was used; thus, BOD:P = 115:1.

^b NR 217 of the Wisconsin Administrative Code requires that all existing wastewater treatment plants that discharge in excess of 150 pounds of total phosphorus per month to surface water must meet an effluent total phosphorus limit of 1 mg/L. If an enhanced biological phosphorus removal process is used, 90% of the total phosphorus required to meet 1 mg/L of total phosphorus in the effluent must be removed.

Evaluation of the BPR Potential Test

Using an SBR to Validate the BPR Potential Test

The BPR potential test was validated by operating a bench-scale SBR and comparing the effluent phosphorus concentrations measured from the SBR to that predicted by the BPR potential test. Wastewater obtained from the Oakfield WWTP was used as influent. The initial PAO-containing activated sludge with 7.5% of phosphorus content in volatile suspended solids (VSS) was obtained from the Nine Springs WWTP. The wastewater sample taken on June 5, 1997, was used as influent feed for the first 9 days, and the wastewater sample taken on June 12, 1997, was used for the remainder of this experiment. The SBR was run for 18 days. The results of SBR performance are shown in Figure 13.

The phosphorus concentration was higher in the effluent than in the influent until the 9th day due to release of phosphorus from the PAO-containing activated sludge with P/VSS content of 7.5%. Only a small fraction of phosphorus was removed in the last 9 days of the experiment. During the experiment, the P/VSS content decreased from 7.5% to 4.5%. PAOs did not seem to prosper in the SBR fed with Oakfield wastewater. The phosphorus release/uptake profile obtained using the sludge taken on the 18th day is shown in Figure 14. It can be seen that phosphorus was not removed in the aerobic zone below the initial concentration, although there was slight release of phosphorus (~2.4 mg P/L) in the anaerobic stage.

Based on our BPR potential model (Equation 2), the predicted effluent phosphorus concentration was $3.9 - [7.3 \times 0.15] - \{[(5 \times 5) + 90] - 1 \times 93\} = 2$ mg TP/L (see Tables 3 and 4). The average effluent soluble phosphorus concentration in the SBR after 9 days of acclimation period was 1.7 mg P/L, which is similar to the predicted value from the BPR potential test.

The BPR potential test was validated by comparing the test result with the performance of the SBR test using the Oakfield wastewater sample. Both tests demonstrated that BPR alone would not meet the effluent phosphorus discharge permit for the Oakfield WWTP.

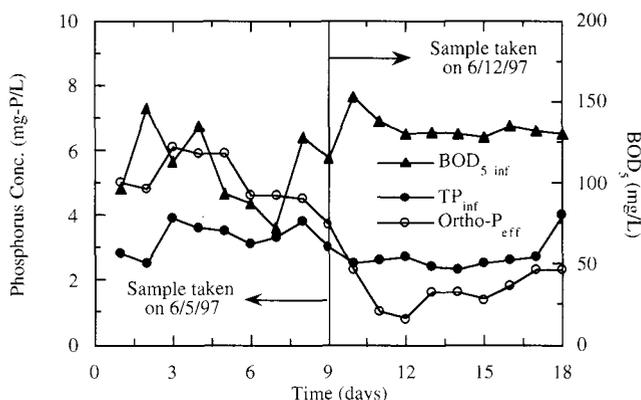


Figure 13. BOD₅ and Phosphorus concentration in SBR with Oakfield wastewater.

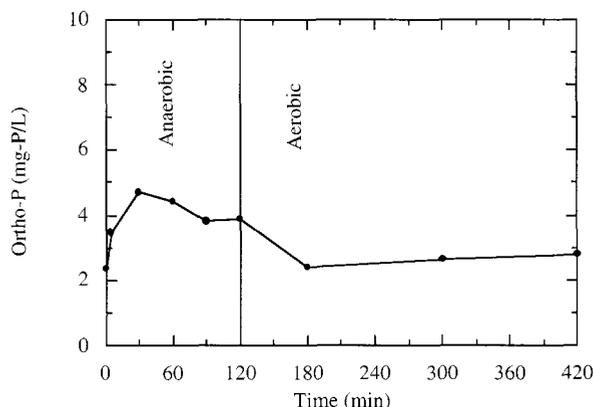


Figure 14. Phosphorus release/uptake profile in SBR with Oakfield wastewater.

Effect of Sludge Characteristics on the BPR Potential Test

From the behavioral pattern of phosphorus release under anaerobic conditions in a BPR system, Wentzel et al. (1985, 1990) proposed the following hypotheses:

1. Only readily biodegradable soluble COD (S_{bs}) can be converted to SCFAs, which are then taken up by PAOs under the anaerobic conditions.
2. The conversion is mediated by non-PAOs in the anaerobic zone.
3. All S_{bs} converted is immediately taken up by PAOs, i.e., the rate of phosphorus release is controlled by the rate of conversion.
4. The rate of conversion is considered first-order with respect to non-PAO biomass concentration (X_{ahn}) and the readily biodegradable COD concentration (S_{bs}):

$$dS_{bs}/dt = -K X_{ahn} S_{bs},$$

where K = first-order rate constant.

5. The rate of phosphorus release is assumed to be stoichiometrically related to the mass of the converted S_{bs} uptake:

$$dP/dt = -C_{sp} (dS_{bs}/dt) = C_{sp} K X_{ahn} S_{bs}$$

where C_{sp} = stoichiometric ratio between phosphorus release and converted S_{bs} uptake.

Based on kinetic studies of biological phosphorus release (Wentzel et al. 1985, 1990), the phosphorus release rate is determined indirectly by both the characteristics of wastewater and the active biomass. In addition, Mino et al. (1987) indicated that the ability of sludge to take up acetate anaerobically is limited by the amount of polyphosphorus stored in the cell when the phosphorus content of sludge is < 35 mg P/g VSS.

In the BPR potential test, a basic assumption is that the characteristics of PAO-containing sludge will not affect the outcome. Therefore, the effect of sludge characteristics on the BPR potential test results must be evaluated. PAO-containing sludge from different types of BPR systems (modified UCT and SBR), different wastewater treatment plants (Nine Springs and Beloit), and different sludge concentrations (MLVSS = 1,190 and 2,250 mg/L, both PAO-containing sludges obtained from the Nine Springs WWTP) were tested with wastewater from the Nine Springs WWTP.

Figure 15 shows the phosphorus release for sludge in the modified UCT and SBR BPR systems

fed with the Nine Springs wastewater. Both sludges were acclimated with the Nine Springs wastewater, and both BPR systems could remove phosphorus to below 0.5 mg TP/L. The phosphorus contents in sludge of the modified UCT process and SBR were 6.2% and 5.5%, respectively. Figure 15 shows that there was no difference in phosphorus release response in the first 60 minutes. After 2 hours the difference in phosphorus release was approximately 5 mg P/L. This difference may be due to the different sludge concentration (1,340 mg VSS/L for the modified UCT-process sludge and 1,150 mg VSS/L for the SBR sludge).

Figure 16 shows the phosphorus response of PAO-containing sludges obtained from different WWTPs mixed with wastewater from the Nine Springs WWTP. The Beloit treatment plant has an

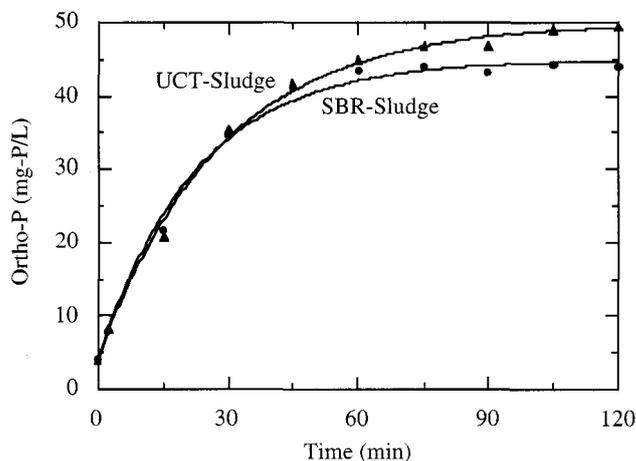


Figure 15. Phosphorus release profile for PAO-containing sludge from UCT and SBR systems.

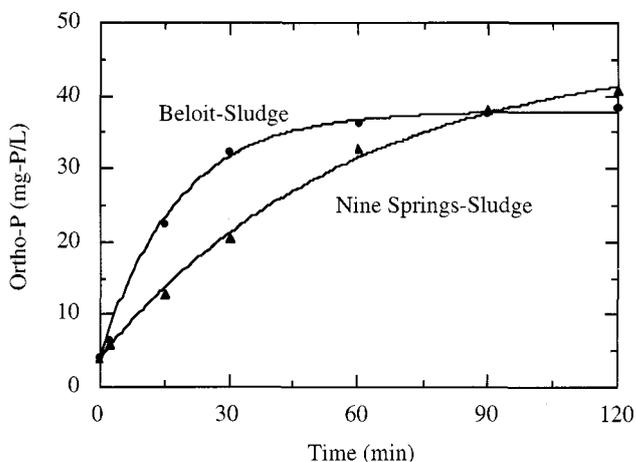


Figure 16. Phosphorus release profile for PAO-containing sludge from the Nine Springs and Beloit Wastewater Treatment Plants.

average design flow of about 7 MGD. The plant receives significant industrial loadings, primarily from the food processing and organic chemical industries. The Beloit WWTP is currently removing phosphorus from 17 to 3 mg TP/L by using an anaerobic/anoxic selector followed by aeration basins. The Nine Springs WWTP is currently removing phosphorus to below 0.5 mg TP/L using a variation of the UCT process. From Figure 16, the sludges obtained from the Beloit WWTP released phosphorus faster than those from the Nine Springs WWTP in the first 90 minutes of operation, but slower after that. The faster phosphorus release of the Beloit sludge in the first 90 minutes might be due to its higher sludge concentration. The sludge concentrations for the Nine Springs sludge and Beloit sludge during this test were 1,150 and 2,580 mg/L, respectively. The lower total amount of released phosphorus of the Beloit sludge may be due to its lower phosphorus content. The phosphorus contents in the Nine Springs sludge and the Beloit sludge were 7.3% and 4.3%, respectively.

In order to evaluate the effect of sludge concentration on the BPR potential test, two batch reactors containing the same wastewater and PAO-containing sludge obtained from the Nine Springs WWTP at different sludge concentrations were conducted. Figure 17 shows the phosphorus release profiles of these two batch tests. Phosphorus was found to be released faster at a higher sludge concentration than at a lower sludge concentration. The total amount of phosphorus released was slightly greater at a higher sludge concentration at the end of test, as well. However, the total phosphorus release is anticipated to be the same when the test is conducted longer than 2 hours.

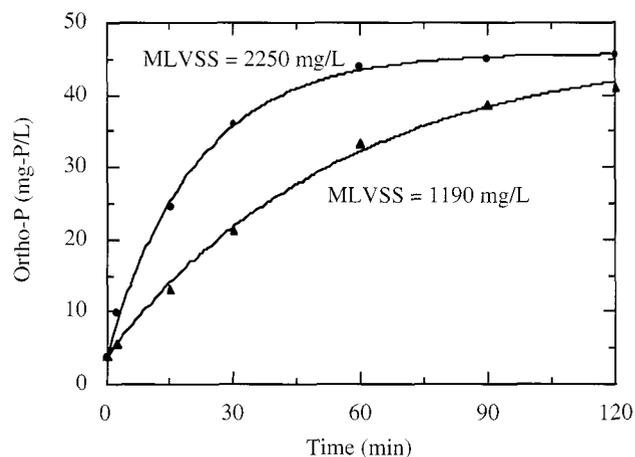


Figure 17. Phosphorus release profile for different PAO-containing sludge concentrations (both sludges from the Nine Springs Wastewater Treatment Plant).

The P release vs. time plot can be modeled empirically as follows (Wentzel et al. 1985):

$$P_t = P_{\max} \left[1 - \left(\frac{P_{\max} - P_0}{P_{\max}} \right) e^{-kt} \right] \quad (3)$$

where

- P_t = phosphorus concentration at time t, mg P/L;
- P_{\max} = maximum potential phosphorus concentration, mg P/L;
- P_0 = initial phosphorus concentration, mg/L;
- $P_{\max} - P_0$ = maximum potential release of phosphorus, mg P/L; and
- k = first order rate constant.

A nonlinear regression program written with Fortran language (Chen 1996) was used to estimate empirical model parameters, P_{\max} and k . This program basically followed the Gauss-Newton method (Bates and Watts 1988) using a linear approximation to the expectation function to iteratively improve an initial guess θ^0 for θ (parameters) until there is no change. This program can also plot the approximate 95% inference regions for parameters automatically (Bates and Watts 1988). The accuracy of estimated results from this program was comparable with the results estimated from XLISP-STAT (Tierney 1990) and SYSTAT® (SPSS, Inc. 1996) commercially available statistical programs.¹

Table 5 summarizes the estimated P_{\max} and k values by using Chen's program to fit Equation 3 with experimental results of these six batch tests.

The fitted values, P_t , can be obtained from estimated parameters (Table 5) and Equation 3. An approximate 95% confidence interval of fitted values can also be obtained (Bates and Watts 1988, Seber and Wild 1989). The confidence intervals of fitted values at 2 hours for each experiment can be constructed, and the fitted values of

Table 5. P_{\max} and k values of six batch tests.

	Estimated P_{\max}	Estimated k
Modified UCT sludge	50.0	0.0356
SBR sludge	45.0	0.0442
Nine Springs sludge	46.7	0.0173
Beloit sludge	37.9	0.0564
Low MLVSS sludge	46.9	0.0180
High MLVSS sludge	45.8	0.0477

¹ Mention of specific products does not constitute government endorsement.

each test can be compared. Table 6 summarizes the calculation results of fitted values and the approximate 95% confidence intervals. From the comparison of the P_t values at 2 hours, no significant difference between the different sludges was found in all three tests. This implied that the effect of sludge characteristics on the BPR potential test will be insignificant if the total phosphorus release were measured at 2 hours. However, from Figure 17, the effect of sludge concentration on biological phosphorus release will be considered to be significant if the total phosphorus release were measured at 1.5 or 1 hour. Therefore, the BPR potential test must be conducted at the real MLVSS concentration used at the wastewater treatment plant of interest.

Effect of Wastewater Storage on the BPR Potential Test

Since properties of a wastewater may change during transportation and storage before the BPR potential test is conducted in a laboratory, an experiment was conducted to evaluate the effect of storage time at 4°C on the BPR potential test. Profiles of the phosphorus release in the BPR potential test with three different storage times are shown in Figure 18.

It can be seen that the phosphorus release was not significantly affected when the wastewater was tested within 24 hours. Therefore, a wastewater sample of interest can be tested without significantly affecting the BPR potential test within 24 hours if it is preserved at 4°C.

Table 6. Calculation results of fitted values and approximate 95% confidence intervals (C.I.).

	Fitted value P_t at time = 2 hrs	Approximate C.I.
Test 1		
Modified UCT sludge	49.3	49.3 ± 2.9
SBR sludge	44.8	44.8 ± 3.1
Test 2		
Nine Springs sludge	41.3	41.3 ± 2.9
Beloit sludge	37.9	37.9 ± 2.7
Test 3		
Low MLVSS sludge	41.9	41.9 ± 3.1
High MLVSS sludge	45.7	45.7 ± 2.3

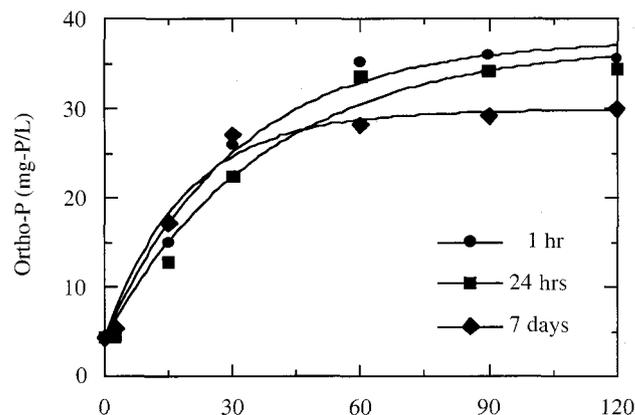


Figure 18. Effect of wastewater storage duration on BPR potential test.

Conclusions

The feasibility test proposed by Kang et al. (1991) seems to be a good procedure to evaluate the feasibility of BPR if the phosphorus release rates of the wastewater of interest with and without acetate addition are very similar or very different. However, it does not provide a clear answer on the feasibility of BPR if the phosphorus release rates of the wastewater with and without acetate addition are neither identical nor completely different.

The BPR potential test, using a constant ratio between phosphorus uptake and phosphorus release, appears to properly determine the feasibility of BPR for a specific wastewater. The test was validated by comparing the result with the effluent phosphorus concentration obtained from a SBR operation. The BPR potential test was not affected if the wastewater sample was stored at 4°C for less than 24 hours.

Although BOD/P and COD/P values indicated that Oakfield, Green Lake, Ashland, Campbellsport, and Green Bay wastewaters were feasible for BPR, the BPR potential test demonstrated that only Green Bay wastewater could meet the phosphorus discharge limit set by the Wisconsin Department of Nature Resources.

The effect of sludge mixed liquor concentration on the BPR potential test was significant; therefore, the sludge concentration should be controlled at a target level. Since the effects of phosphorus content in sludge and differently acclimated sludges on the BPR potential were noticeable, further studies are needed.

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