EFFECT OF PROCESS CONFIGURATIONS AND ALUM ADDITION ON EBPR IN MEMBRANE BIOREACTORS

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ABSTRACT

Bench-scale studies were undertaken to explore the relative efficiency of three different process configurations for enhanced biological phosphorus (EBPR) removal; the University of Cape Town (UCT) process, the Sammamish Biological Nutrient Removal (SmBNR) process, and the University of Washington Membrane Biological Nutrient Removal (UW-MBNR) process. In this study, they all had the same anaerobic, anoxic, and aerobic volumes. The UCT process had the highest phosphorus (P) removal efficiency when the amount of P removed per unit of COD consumed was considered. It was found that addition of alum to the anaerobic zone of the process resulted in improved P removal. Critical to EBPR performance was the finding that phosphorus uptake rates are slower than anaerobic release rates and that the uptake rate is slower for lower reactor P concentrations. This encourages consideration of staged reactors to achieve lower effluent P concentrations. For all the systems, significant quantities of phosphorus accumulating organisms (PAO) and tetrad-forming glycogen accumulating organisms (GAO) were observed. Simulations using the commercial BioWin™ software overpredicted measured P removal. This may have been the result of GAO growth in the bench-scale reactors, which is not modeled in BioWin™. The BioWin™ models were calibrated by reducing the influent readily biodegradable COD in the model. Although the BioWin™ models confirmed that the UCT process had the highest P removal efficiency, it was found in simulations of a full-scale plant with lower relative nutrient concentrations than were used in the bench-scale tests that both the UCT and SmBNR process configurations resulted in near complete P removal.

KEYWORDS

Enhanced biological phosphorus removal, membrane bioreactors, phosphorus accumulating organisms, glycogen accumulating organisms, bench-scaled reactors, simulation model

INTRODUCTION

The combination of membrane bioreactor (MBR) technology and enhanced biological phosphorus removal (EBPR) for wastewater treatment offers the opportunity for nearly complete removal of effluent phosphorus (P) by combining removal of soluble phosphate by biological uptake with nearly complete elimination of particulates by membrane filtration. A potential disadvantage is that MBR systems have a relatively long solids retention time (SRT). This produces less excess biomass production, which affects EBPR efficiency as the phosphorus is removed via the wasted
excess biomass. EBPR-MBR systems will, in most cases, also result in nitrate production and removal and, depending on the process configuration, portions of the biodegradable COD (bCOD) that can be used to promote EBPR will be consumed by biological denitrification. There is a need to consider different process configurations that address both nitrate removal and EBPR efficiency in MBR systems. This was a key goal of the research reported here.

It is well established that ability to achieve a low effluent soluble phosphorus concentration from EBPR systems is related to the influent bCOD:P ratio. When this ratio is low enough to limit EBPR, chemical addition is often used to provide additional phosphorus removal. In EBPR-MBR systems, chemical addition may be in a primary treatment step or within the MBR process. An additional aspect of the study was to compare the performance of two UCT systems operated in parallel with and without alum addition to the anaerobic contact zone.

Following the laboratory work a biological process model was calibrated to the bench-scale data and then used to evaluate the performance of various configurations for a full-scale plant design.

In this study, three different process configurations for both nitrogen removal and EBPR were tested and compared in bench-scale MBR reactors using a synthetic wastewater. The processes are illustrated in Figure 1, which shows the commonly used University of Cape Town (UCT) process and two other process configurations unique to this study, termed the Sammamish biological nutrient removal (SmBNR) process and University of Washington membrane BNR (UW-MBNR) configuration. The reactor sequence is anaerobic-anoxic-aerobic for the UCT process, anoxic-anaerobic-aerobic for the SmBNR process, and anoxic-anaerobic-aerobic for the UW-MBNR process. The latter two processes eliminate a recycle line, and for the UW-MBNR process, the influent is fed to the anaerobic zone rather than the anoxic zone.

A disadvantage of the UCT process is the need for an additional recycle stream and that the concentration of the mixed liquor in the anaerobic zone is only about 80 percent of that for the other zones. A disadvantage of the SmBNR process is that a large portion of the influent bCOD will be used by denitrifying organisms, leaving less available for EBPR, and potentially a higher effluent soluble phosphorus concentration.

A good measure of the efficiency of the EBPR processes is the amount of phosphorus removed relative to the amount of bCOD applied to the system. This could be defined as a bCOD-applied:P-removed ratio (bC/P ratio). EBPR systems that operate with higher bC/P need more influent degradable COD to achieve the same effluent P concentration versus a system that can operate with a lower bC/P ratio, and are thus less efficient. Factors that result in higher bC/P ratios include longer SRT and consumption of degradable COD by denitrifying organisms or glycogen accumulating organisms (GAO) instead of phosphorus accumulating organisms (PAO). Thus, this study also included monitoring and evaluating nitrate removal and bCOD utilization in the anaerobic and anoxic reactors, as well as microscopic surveillance of tetrad forming organisms (TFO).
Figure 1 MBR Process Configurations Studied for Nitrogen Removal and EBPR

UCT Process

SmBNR Process

UW-MBNR Process
MATERIALS AND METHODS

Experimental plan

The experimental plan for the bench-scale studies included 4 different phases:

- Phase 0 – A sequencing batch reactor (SBR) was operated to develop and evaluate the synthetic feed composition and verify its readily biodegradable fraction. The focus of this phase was to establish a more complex synthetic feed than most often used in laboratory-scale investigations for EBPR systems, where traditionally only acetate (or glucose) is used as the carbon source.

- Phase 1 – Two continuous flow membrane reactors with different configurations (UCT and SmBNR) were operated in parallel to compare differences in EBPR performance. The primary interest was phosphorus removal, but other biological process parameters, such as COD-utilization and nitrogen removal were also investigated. The microbial community was monitored by microscopic investigations and batch kinetics testing was performed to verify EBPR performance.

- Phase 2 – The SmBNR configuration was modified to the UW-MBNR configuration by feeding the influent to the anaerobic zone leaving the initial anoxic reactor only for nitrate removal from the return solids via endogenous respiration. This was operated in parallel with the UCT process.

- Phase 3 – Two UCT membrane bioreactors (MBR) were operated in parallel with one receiving metal salt (alum) in the anaerobic contact zone at a feed concentration to achieve 2.0 mg/L phosphorus removal by precipitation, based on a stoichiometric reaction. The focus of this phase was to see how the metal salt addition affected the overall EBPR removal efficiency of the processes, and to determine if the metal salt affected the biological phosphorus removal mechanism.

The synthetic wastewater consisted of acetate, glucose, peptone, starch, and oleic acids and a nutrient/trace mineral media with 40 percent of the COD as rbCOD and 60 percent as slowly biodegradable. For the operating phase to assess the effect of alum addition, acetate represented 90 percent of the influent rbCOD. The total COD, NH4-N and P concentrations were 750, 58, and 15 to 28 mg/L, respectively. Excess P was provided to assess process efficiency.

Sequencing Batch Reactor

One SBR was operated for almost two months, with the sole purpose of investigating and developing a synthetic wastewater to be used for subsequent experimental trials. For further discussion of SBR operation, see Johannessen (2005).

Continuous Flow Reactors

Two identical continuous flow MBR reactors were constructed of acrylic plastic on individual base frames and consisted of two smaller reactors used for anaerobic and anoxic stages and a larger aerobic reactor, which contained the membrane for liquid-solids separation. A flat plate type membrane provided by Enviroquip Inc. and manufactured by Kubota (Japan) was used in this study. The membrane was an ultrasonically welded polyethylene sheet on an ABS plastic
housing with a nominal 0.4-millimeter (mm) pore size. Figure 2 below shows the SmBNR MBR system during clean water trials. Final reactor dimensions are shown in Table 1.

**Table 1 Continuous Flow MBR Reactor Dimensions**

<table>
<thead>
<tr>
<th>Component</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Liquid Depth (mm)</th>
<th>Liquid Volume (L)</th>
<th>Free-Board (mm)</th>
<th>Tank depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anoxic (Ax)</td>
<td>80.38</td>
<td>80.38</td>
<td>198</td>
<td>1.28</td>
<td>20</td>
<td>218.0</td>
</tr>
<tr>
<td>Anaerobic (An)</td>
<td>80.38</td>
<td>80.38</td>
<td>198</td>
<td>1.28</td>
<td>30</td>
<td>228.0</td>
</tr>
<tr>
<td>Aerob (Ae)</td>
<td>96.41</td>
<td>225.00</td>
<td>400</td>
<td>8.33</td>
<td>40</td>
<td>455.0</td>
</tr>
</tbody>
</table>

The volumes of the anaerobic, anoxic, and aerobic reactors were 0.97 L, 0.97 L and 7.81 L, respectively. The aerobic reactor contained a flat plate membrane manufactured by Kubota. Peristaltic pumps fed concentrated separate solutions of organic and inorganic feed and tap water for a total feed rate of 28.5 L/day. The recycle streams were provided with peristaltic pumps at the ratios indicated in Figure 1 for each process. The reactors were operated in a walk-in chamber controlled to a temperature of 20°C. The MBR reactors were seeded with EBPR sludge from full-scale EBPR plants and operated at a target SRT of 12 days.

**Figure 2 SmBNR Reactor During Start Up Trials with Clean Water**
The influent was pumped continuously at 20 milliliter per minute (mL/min) with 1 pump for tap-water (15 mL/min), 1 pump for Feed No.1 (2 mL/min), 1 pump for Feed # 2 (1 mL/min) and 1 pump for Feed No.3 (2 mL/min). Effluent pumping rate from the membrane was set to equal the volume fed, but at a higher rate to account for the membrane operational requirement of a resting period of 1 minute every 10th minute. Peristaltic pumps (Masterflex®) where also used with a timer controller (Chrontrol®). The mixed liquor flowed from chamber to chamber by gravity through overflow weirs.

The system UCT and SmBNR configurations are shown in Figures 3 and 4. The internal recycle (IR) ratio for the flow from the anoxic reactor to the anaerobic reactor for the UCT configuration was set at 200 percent of influent flow rate, and the return activated sludge (RAS) flow rate from the aerobic reactor to the anoxic reactor was 500 percent of the influent flow rate. For the SmBNR configuration, the RAS flow rate was also 500 percent of the influent and directed to an anoxic reactor located before the anaerobic reactor. With this configuration the second IR stream is eliminated.

**Figure 3 UCT Configuration for Continuous Flow Laboratory MBR**
For all phases NO3-N, soluble P, and soluble COD were measured routinely in the effluent and in each reactor to observe P release and uptake and nitrate removal. In the bench-scale studies, EBPR was evaluated by observations on the P release in the anoxic and anaerobic zones and of the amount of P uptake in the aerobic zones. Microscopic examinations of the mixed liquor were conducted using a phase contrast microscope at magnifications from 100x to 1000x and a Neisser staining method was used to observe PAO. For all phases the mixed liquor suspended solids (MLSS) was in the range of 7000-8000 mg/L.

Process model simulations were conducted using the commercial simulation program BioWin™. Influent wastewater characterizations for calibration to the bench-scale studies were initially determined based on the synthetic feed composition.

**RESULTS AND DISCUSSION**

**P Removal Efficiency**

During Phases 1, the UCT process provided a higher P removal efficiency. The average effluent soluble P concentration in the SmBNR system was higher by 4.8 mg/L. Profiles showed that P release was occurring in the first stage anoxic zone of the SmBNR system along with nitrate reduction. Release continued in the second stage anaerobic zone. The high available degradable COD could support both nitrate removal and COD uptake by the PAO. The total amount of P release (normalized to influent flow) in the anoxic/anaerobic stages of the SmBNR and the anaerobic stage of the UCT systems was 92.5 and 93.2 mg/L, respectively, but the amount of P uptake in the UCT system was greater.
Two factors that may explain this are the possibility of secondary P release in the SmBNR process and the longer time for P uptake in the UCT process. Average performance data for Phase 1 are presented in Table 2. The mixed liquor concentrations varied over the operation period with highest levels around day 20 to 25 at approximately 7,700 mgVSS/L. The MLVSS concentration declined steadily in both systems ending up at approximately 5,500-6,000 mg/L in the last weeks of operation.

**Table 2 Average Performance Data during Phase 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (mg/L)</th>
<th>UCT Effluent (mg/L)</th>
<th>SmBNR Effluent (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>747</td>
<td>11.6</td>
<td>11.0</td>
</tr>
<tr>
<td>NH4-N</td>
<td>57.9</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>NO3-N</td>
<td>0</td>
<td>16.1</td>
<td>10.1</td>
</tr>
<tr>
<td>PO4-P</td>
<td>20.0</td>
<td>6.6</td>
<td>11.4</td>
</tr>
<tr>
<td>bCOD/P Ratio</td>
<td>-</td>
<td>35</td>
<td>46</td>
</tr>
</tbody>
</table>

Table 3 presents the average performance data for Phase 2, the phase in which the UW-MBNR configuration was tested in lieu of the SmBNR configuration. The UW-MBNR system had a lower P removal efficiency than the UCT system. This was likely due to excess nitrate leaving the first stage anoxic zone. The same anaerobic and anoxic volumes were used for all systems, and thus there was insufficient volume for nitrate reduction via endogenous respiration in the UW-MBNR system. In addition, there was less time for P uptake after anaerobic P release in the UW-MBNR compared to the UCT system.

**Table 3 Average Performance Data during Phase 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (mg/L)</th>
<th>UCT Effluent (mg/L)</th>
<th>UW-MBNR Effluent (mg/L)</th>
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</thead>
<tbody>
<tr>
<td>COD</td>
<td>747</td>
<td>13.6</td>
<td>12.6</td>
</tr>
<tr>
<td>NH4-N</td>
<td>57.9</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>NO3-N</td>
<td>0</td>
<td>17.2</td>
<td>10.3</td>
</tr>
<tr>
<td>PO4-P</td>
<td>20.0</td>
<td>7.4</td>
<td>10.5</td>
</tr>
<tr>
<td>bCOD/P Ratio</td>
<td>-</td>
<td>59</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 4 shows results of the effect of alum addition and changes in the influent P concentration during Phase 3 testing with two UCT systems in parallel. After a baseline-operating period of 19 days, one reactor received 21.5 mg/L alum in the anaerobic zone. This alum dose corresponds to a P removal of 2.0 mg/L. The primary goal of this study was to evaluate whether the alum addition in the anaerobic zone had any effect on the EBPR performance. The results showed that the implementation of chemical addition was beneficial for the overall P-removal performance, and suggested no adverse effect on the EBPR mechanisms. The systems were operated for a period equal to approximately 2.6 SRT, and for a period equal to approximately 1.5 SRT the systems’ responses were as expected, showing a 2.1 mg/L better P removal in the UCT reactor that received alum. After this period, the influent P concentration was lowered in three steps from the original 20 mg/L to 17-, 13-, and 10 mg/L. The results indicate that an
unknown reactor disturbance had affected the system concurrently with the start of the influent P concentration decrease, and the UCT system with alum had a lower EBPR efficiency than the UCT Control system without alum. The alum fed UCT system also had a higher level of nitrate in the recycle flow to the anaerobic zone, which would be expected to cause reduced EBPR performance. However, the difference in effluent P concentration appeared to be related to the change in influent P concentration and subsequent decline in P concentration just before the aerobic P uptake zone. With a lower influent P concentration the reactor effluent P concentration was lower. The reactor with the lower initial P concentration due to alum addition in the anaerobic zone had lower P uptake kinetics, which may be related to it having a lower reactor P concentration.

Table 4 Average P-Removal Performance for the Control and Alum Systems for UCT Systems in Parallel Operation

<table>
<thead>
<tr>
<th>Day</th>
<th>Influent P (mg/L)</th>
<th>Effluent P (mg/L)</th>
<th>P-removal (mg/L)</th>
<th>Estimated bio-P removal in Alum reactor (mg/L)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Alum</td>
<td>Control</td>
<td>Alum</td>
</tr>
<tr>
<td>19 to 36</td>
<td>20</td>
<td>5.9</td>
<td>3.9</td>
<td>14.1</td>
</tr>
<tr>
<td>37 to 40</td>
<td>17</td>
<td>5.3</td>
<td>4.6</td>
<td>11.7</td>
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<tr>
<td>40 to 43</td>
<td>13</td>
<td>3.9</td>
<td>3.1</td>
<td>9.2</td>
</tr>
<tr>
<td>44 to 50</td>
<td>10</td>
<td>2.5</td>
<td>1.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>

¹Corrected for P-removal by precipitation of 2.0 mg/L P

Results of the laboratory investigations show the effect of three important factors on EBPR systems: the effect of NO\textsubscript{3}-N removing substrate needed by the PAO, secondary phosphorus release, and the importance of phosphorus uptake kinetics. They suggest that to achieve low effluent P concentrations, staged anoxic/aerobic reactors would be more efficient.
Microbiological Observations

Neisser staining was used to investigate both PAO and tetrad-forming GAO under the microscope. PAO stain positive in either the entire cell or intracellular granules, whereas GAO stain positive in the cell walls but not in the cell interior. In addition, the typical tetrad shapes of GAO become more apparent because of the Neisser staining. The Neisser staining procedure was taken from Jenkins et al (2004). Figure 5 shows typical microphotograph of mixed liquor containing both GAO and PAO. Other GAO organisms that do not form tetrad-shaped clumps are possible and cannot be measured by these microscopic methods.

Figure 5 PAO and GAO Stained with the Neisser Stain Method

Batch tests with the UCT and SmBNR mixed liquor were done with acetate addition to an anaerobic mix period followed by an aerobic period. Phosphorus release and uptake were monitored in these respective periods. The purpose of these tests was to assess the phosphorus characteristics of the EBPR system’s mixed liquor. Changes in the phosphorus release and uptake amount and rates could indicate a change in the mixed liquor. In addition, the P-release to acetate uptake ratio was expected to be indicative of the relative PAO/GAO population. Systems with a high level of PAO relative to GAO population are expected to show an anaerobic P release to acetate COD added ratio of about 0.50 grams per gram (g/g) (Pramanik et al. 1999, Yagci et al. 2003, Neethling et al. 2005).
In addition to the relative GAO and PAO population concentrations, the pH condition can also affect the P-release to acetate uptake ratio. The Phase 1 anaerobic/aerobic batch test results showed a decline in the P released to COD used ratio from day 10 to day 80 from about 0.3 to 0.2 g/g. These values are much lower than the expected value of 0.50 g/g for a PAO dominated system.

The microscopic observations did not indicate an initial high ratio of GAO based on tetrad formations and only later in Phase 1 did the microscopic observations support the suggestion of a high GAO dominance in Phase 1. Thus, either the model by Yagci overestimates the fraction of GAO or some of the GAO were not tetrad morphological.

Tsai and Liu (2002) identified GAO as tetrad forming organisms (TFO) and these formations were monitored in the mixed liquor as a means to indicate the presence of GAO. The GAO population became increasingly abundant with time during Phase 1. The increase in the GAO population may have been related to a change made in the influent P concentration. In an effort to achieve lower effluent P concentration it was decided to lower the influent P concentration, which increased the COD/P ratio, and vice versa decreased the P/COD ratio. Low P/COD ratios have been associated with more GAO dominance and Sudiana et al. (1998) reported that at P/COD ratios of 0.02 GAO are the dominant bacteria over PAO. When the influent P concentration was decreased to 15 mg/L, the P/COD ratio became approximately 0.02. When the low P/COD ratio was realized, the influent P concentration was immediately raised to 20 mg/L. The low P/COD ratio seemed to have a greater effect on the UCT system, for which a greater abundance of GAO was seen in microscopic observations compared to that for the SmBNR system.

As discussed above, both the batch test results and the microscopic examinations indicated that the GAO population (as determined by observations) was increasing. An interesting finding was that the initial batch P-release and uptake tests indicated a substantial GAO population, but it was not possible to detect a significant amount of TFO in the same period. This suggests that TFO were not the dominating GAO at an initial stage and that they increased over the course of Phase 1. Figure 6 presents a microphotograph taken from the UCT reactor at the end of Phase 1.
During Phase 1 filamentous growth developed (probably induced by low DO incidents which occurred during the phase) and by the end of the period became the predominant group of organisms in the mixed liquor. From what could be estimated from microscopic examinations the extent of filamentous growth was similar in the two systems. Filamentous growth has previously been suggested to have a positive impact on the transmembrane pressure (Keefe-Nelson 2005). This was confirmed in this study. When stopping the polymer addition no noticeable effect on the membrane fouling could be detected. Thus, it was decided to abort the polymer addition as long as substantial filamentous growth was occurring. Figure 7 shows filament-dominated growth in the SmBNR reactor.
Membrane Performance

Membrane performance was monitored for operational purposes, including daily observations of the trans-membrane pressure drop, and filterability analysis about every two weeks, and to evaluate the membrane performance as a result of operational changes and changes in the mixed liquor characteristics.

The trans-membrane pressure (TMP) was measured daily. TMP is an important operational parameter. When this increases rapidly or reaches very high levels, the membranes need to be cleaned or replaced. When the TMP rose to above 4.2 ft (50 inches on the manometer) water pressure in this study, the membranes were cleaned or replaced.

The TMP in Phase 1 was unexpectedly high, and by day 8, severe membrane fouling was experienced and was thought to be due to slowly degradable substrate (starch) coating the membrane. There was a persistent slime layer on the membrane. Different slowly degradable substrates were tested to find ways to reduce this operational problem. Because only the slowly degradable substrate was tested, it was considered not to affect the bio-P removal mechanisms.

A change in scour aeration from 5 L/min to 10 L/min showed minor improvement, but still the membrane fouling rate was unreasonably high. The changes in feed composition did not affect the overall membrane performance. However, it was confirmed that the expected slowly degradable organic compounds (starch and cellulose) were affecting the membrane fouling.
adversely. In a period where these compounds (starch and cellulose) were taken out of the influent feed in the SmBNR to see the effect on membrane fouling, filter runs were increased and the membrane fouling rate was lowered as shown in Figure 8. “Filter run” is defined as the interval between membrane replacement or cleaning, and “membrane fouling rate” is defined as the rate of increase in TMP per unit time.

**Figure 8 Transmembrane Pressure (TMP) Versus Time in the SmBNR**

Vertical lines on the same day in the graph means that the membranes were either replaced with new ones or that the membranes were cleaned with pressurized water. The lower level is therefore the new reading with clean membrane. The positive effect from removing starch and cellulose was not satisfactory, however, as it was desired to have a complex feed including slowly degradable COD compounds.

At the end of phase 1, polymer (Nalco PermaCare MPE50™) was added to decrease membrane fouling, with an initial dose of 450 mg/L (based on total reactor volume) and a daily maintenance dose of 46.5 mg/L. The polymer addition had a positive effect as the time between membrane-replacements increased. These effects are illustrated in Figures 9 and 10.
Figure 9 Transmembrane Pressure During Test with Polymer in UCT System

Figure 10 Transmembrane Pressure During Test With Polymer In SmBNR System

Model Simulations

Table 5 presents results from computer modeling using the commercial simulation program BioWin™. The model was configured for the feed concentrations measured during Phase 1 of the bench-scale studies. The three different configurations tested in the bench-scale studies were configured as shown in Figure 11. The table shows the effluent concentrations predicted by the models for each configuration. Effluent P concentrations were approximately 30 percent less
than average measured concentrations in the bench-scale for the UCT configuration, approximately 20 percent greater for SmBNR and 15 percent greater for UW-MBNR. These results were obtained with an influent rbCOD percentage of 20 percent for the model compared to 40 percent for the bench-scale feed. With the default kinetic and stoichiometric coefficients for BioWin™ Version 2.2, a 40 percent rbCOD feed resulted in nearly complete P removal for all configurations. This over prediction of P removal may have been caused by inadequate simulation of cellular storage mechanisms in the model. Another possible explanation is the substantial growth of GAO that was seen in the lab scale reactors, which would compete for rbCOD with PAO. GOA growth is not modeled in the BioWin™ model.

**Table 5 Model Prediction: Calibration To Bench-Scale Studies**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (mg/L)</th>
<th>UCT Effluent (mg/L)</th>
<th>SmBNR Effluent (mg/L)</th>
<th>UW-MBNR Effluent (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>747</td>
<td>12.88</td>
<td>11.12</td>
<td>10.43</td>
</tr>
<tr>
<td>NH4-N</td>
<td>57.87</td>
<td>0.37</td>
<td>0.38</td>
<td>0.39</td>
</tr>
<tr>
<td>NO3-N</td>
<td>0</td>
<td>15.9</td>
<td>7.8</td>
<td>7.84</td>
</tr>
<tr>
<td>TKN</td>
<td>64.3</td>
<td>1.48</td>
<td>1.43</td>
<td>1.44</td>
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<tr>
<td>TN</td>
<td>64.3</td>
<td>1.48</td>
<td>9.23</td>
<td>9.27</td>
</tr>
<tr>
<td>PO4-P</td>
<td>20.16</td>
<td>4.84</td>
<td>9.64</td>
<td>11.93</td>
</tr>
<tr>
<td>Total P</td>
<td>21</td>
<td>4.84</td>
<td>9.64</td>
<td>11.93</td>
</tr>
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</table>
Figure 11 Schematic Diagrams For Bench-Scale Simulations

UCT Configuration

Sm-BNR Configuration

UW-MBNR Configuration
The calibrated models were used to simulate conditions anticipated for the full-scale Carnation Wastewater Treatment Plant, designed by Carollo Engineers for King County in Washington State. Full-scale plant configurations are shown in Figure 12. Tank volumes are given in Table 6. Simulation results are shown in Table 7. For the full-scale plant, anticipated influent COD is approximately the same concentration as was used in the bench-scale studies, but nutrient concentrations are less. With these lower expected nutrient concentrations, the modeling predicts nearly complete removal of soluble phosphorus and substantial nitrogen removal. Influent P concentrations in the bench-scale studies were elevated to ensure that P removal was not P-limited. In the full-scale plant this is not the case and the differences between the different process configurations are not reflected in different effluent P concentrations, except in the case of the UW-MBNR configuration, which the model indicated would have a somewhat higher effluent P. Since the SmBNR configuration eliminates the recycle system required for the UCT configuration and gives good nitrogen and phosphorus removal for this application, this configuration was used for full-scale plant design.

### Table 6 Full-Scale Tank Volumes

<table>
<thead>
<tr>
<th>Description</th>
<th>Volume (mgal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anoxic Tank</td>
<td>0.036</td>
</tr>
<tr>
<td>Anaerobic Tank</td>
<td>0.036</td>
</tr>
<tr>
<td>Aerobic Zone One</td>
<td>0.062</td>
</tr>
<tr>
<td>Aerobic Zone Two</td>
<td>0.086</td>
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<tr>
<td>Membrane Tank</td>
<td>0.029</td>
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### Table 7 Simulation Results for Full-Scale Tank Configurations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (mg/L)</th>
<th>UCT Effluent (mg/L)</th>
<th>SmBNR Effluent (mg/L)</th>
<th>UW-MBNR Effluent (mg/L)</th>
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Figure 12 Schematic Diagrams for Full-Scale Simulations

UCT Configuration

Sm-BNR Configuration

UW-MBNR Configuration
SUMMARY

The principal goal of this research was to evaluate the performance of three different enhanced biological phosphorus removal (EBPR) processes in membrane bioreactors (MBR), and to determine the effect of alum addition to the EBPR process anaerobic contact zone on effluent P concentration. The EBPR-MBR processes were the University of Cape Town (UCT) EBPR process, the Sammamish BNR process (SmBNR) derived by Carollo Engineers P.C., and a modification to the SmBNR process, termed the UW-MBNR process. Process configurations and the effect of alum additions were evaluated and compared in two parallel continuous flow laboratory-scale reactors in a 20°C temperature control chamber fed a synthetic wastewater. The reactors were seeded with sludge from an EBPR plant in Las Vegas, Nevada and operated in all cases with a 12-day SRT.

In Phases 1 the two process configurations operated in parallel were the UCT process having an anaerobic, anoxic, and aerobic sequence with 2 recycle streams, and the SmBNR having an anoxic, anaerobic and aerobic sequence with only one recycle stream. The results showed that the UCT system had better EBPR performance than the SmBNR system. Three factors were identified that could explain the difference:

1) A longer non-aerobic hydraulic retention time (HRT) that may have allowed secondary phosphorus release in the SmBNR system
2) A longer aerobic HRT in the UCT system that may have allowed more phosphorus uptake
3) A relatively high amount of nitrate removal in the first contact zone of the SmBNR system that removed COD that could have been used instead by the phosphorus accumulating organisms (PAO).

In Phase 2, influent wastewater was bypassed to the second reactor (anaerobic) in the SmBNR system and the recycle mixed liquor was held in an anoxic zone prior to feeding the anaerobic zone. This led to a new process configuration termed the UW-MBNR (University of Washington membrane biological nutrient removal) process. In this process only one recycle line is used, but more influent COD is available to the PAO compared to the SmBNR process. The nitrate removal in the recycle stream is promoted by endogenous respiration. The UW-MBNR system performance was compared to the performance of the UCT system that was operated in parallel over a short study-period of 1 week. The results suggest that the UW-MBNR system was not as effective for phosphorus removal as the UCT system, but it was an improvement over the SmBNR process configuration. A larger anoxic zone in the UW-MBNR system would be expected to give phosphorus removal performance more similar to that of the UCT system.

In Phase 3 two UCT systems were operated in parallel with alum addition to the anaerobic contact zone of one for a stoichiometric removal of 2.0 mg/L. As the influent P concentration was decreased the phosphorus uptake kinetics decreased and the
difference in effluent P concentration between the reactor with alum addition and without became closer. This may have been due to phosphorus uptake kinetics, which are affected by the reactor P concentration.

In all phases in this study glycogen accumulating organisms (GAO) were observed at fairly high concentrations, as determined by the microscopic observation of tetrad forming organisms (TFO). A greater TFO level was observed at lower overall P removal towards the end of Phase 1. Operating periods with a lower feed P/COD ratio were also suspected to have encouraged more GAO growth. The fact that only a few GAO were observed in the start of Phase 1, combined with the overall low EBPR performance and low P/COD ratios from batch tests, suggest that non-tetrad shaped GAO could have been present. This suggests that not all GAO are tetrad shaped morphologically, and that microscopic examinations of TFO for determination of GAO might be a substantial source of error when examining such systems.

The membrane separation performance was not as good as expected in this study. The membrane-fouling rate was very high in all phases as compared to what is observed in full-scale plants and may have been related to the laboratory reactor air scour design. This resulted in operational problems with very frequent membrane cleanings. Filamentous growth, polymer dosing and alum addition had a positive impact on the membrane operation and prolonged the periods between cleaning. The adverse membrane fouling rates in Phase 1 suggested a negative effect of starch in the influent synthetic wastewater. The filterability parameter was not significantly affected by filamentous growth and polymer dosing, but a positive trend was observed with alum addition.

Simulation of the three process configurations using equal-sized anaerobic, anoxic, and aerobic reactors generally confirmed the lab testing observations, that the UCT process arrangement has the greatest potential for P removal. However for the lower nutrient concentrations anticipated for full-scale plants and with sufficient influent bCOD, either the UCT or the SmBNR configuration could be expected to achieve near complete P removal. A larger pre-anoxic zone could also result in similar performance with the UW-MBNR process. Caution should be used in interpreting these results, however, because the modeling did not account for GAO populations, which the bench-scale results showed could reduce P removal.

CONCLUSIONS

The experimental results obtained and observations made during the four phases of continuous flow systems operation produced the following conclusions:

- For a given influent rbCOD content and same SRT, the UCT process has a greater phosphorus removal capacity than the SmBNR process configuration.
- The longer non-aerated HRT of the SmBNR system can encourage secondary P-release, which will lower the EBPR performance.
• The UW-MBNR process configuration improved the EBPR performance as compared to the SmBNR configuration in the bench-scale studies under non-P-limit conditions.

• The improved phosphorus removal performance of the UW-MBNR process compared to the SmBNR is due to having less nitrate available in the initial contact zone, providing more rbCOD for the PAO.

• The UCT process had a higher P removal efficiency over the UW-MBNR process with both having equal anoxic, anaerobic, and aerobic volume and SRT. A higher anoxic zone volume would be needed for the UW-MBNR process to achieve an EBPR performance comparable to the UCT process.

• Partial chemical precipitation with alum was shown to improve the overall P removal efficiency in an EBPR system.

• Alum addition in the anaerobic reactor did not significantly affect the biologically induced P removal performance in the system, as the ratio of COD removal in the anaerobic zone to the P removed remained in the same range as for the UCT process with and without alum.

• Aerobic zone phosphorus uptake kinetics are slower than the anaerobic zone phosphorus release kinetics in an EBPR system.

• Aerobic zone phosphorus uptake rates are related to the P concentration and decrease at lower P concentrations.

• Decreasing the influent phosphorus concentration did not result in an equal reduction in the effluent P concentration. A lower phosphorus uptake rate at lower P concentrations is a factor that affects the effluent P concentration for lower influent P concentration.

• GAO had a negative impact on the EBPR performance. In all the operating phases GAO were present, leading to an unexpectedly low P removal efficiency.

• The GAO were present in the seed sludge and during the study operating time it was not possible to improve the PAO/GAO distribution ratio.

• The ability to assess a GAO population level by microscopic observation of TFO is limited and may not include all GAO.

• The laboratory membrane performance was not as good as reported for full-scale plants due to difference in the coarse aeration fouling control system and the use of a synthetic feed (effect of starch).

• Both polymer dosing, alum addition and filamentous growth had a positive impact on membrane performance, resulting in lower fouling rates.

• Even though the bench-scale results showed that the UCT process has a greater potential for P removal than either the SmBNR or the UW-MBNR process arrangements, simulations conducted with lower influent P concentrations anticipated for a full-scale plant showed that either the UCT process or the SmBNR process could be expected to result in near complete P removal.
REFERENCES


