THE IMPORTANCE OF OPERATIONAL CONTROLS FOR BIOLOGICAL NUTRIENT REMOVAL IN A TRICKLING FILTER-ACTIVATED SLUDGE PROCESS

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ABSTRACT

This paper deals with the development of a combination fixed (attached) and suspended growth system for biological removal of phosphorus and nitrogen from wastewaters. The process, called fixed growth-reactor-suspended growth reactor (FGR-SGR), is based on the addition of trickling filters as a principal component to conventional activated sludge technology for biological nutrient removal. The results of pilot-scale studies and full-scale operation supported the hypothesis that occasions of poor phosphorus removal in the FGR-SGR process were caused by endogenous phosphorus release under anaerobic conditions in the secondary clarifier sludge blanket. Two operational improvements were made to ensure that adequate nitrates were present in the process effluent to prevent the onset of anaerobic conditions in the clarifier sludge blanket. Initially, the trickling filter irrigation rate was increased during winter (cold temperature) operation; this resulted in enhanced nitrification, with a consequent reduction in plant effluent average orthophosphate concentration from 0.9 mg P/L to 0.2 mg P/L. An on-line dissolved oxygen control loop was subsequently added to the solids contact basin, to enhance nitrification and suppress denitrification; this resulted in a further reduction in plant effluent average orthophosphate concentration to less than 0.1 mg P/L. It was concluded that process phosphorus removal was enhanced by improved control of nitrification and denitrification.

KEY WORDS

Attached growth; nutrient removal; operating control; suspended growth; trickling filter

INTRODUCTION AND BACKGROUND

In 1986, the District of Salmon Arm in British Columbia, Canada undertook to upgrade and expand their wastewater treatment plant. At that time, the existing plant consisted of the activated sludge process for secondary treatment, using conventional aerobic digestion of waste primary and secondary solids. The expansion included the addition of two trickling filters and conversion of part of the aerobic digester to a solids contact basin, for retro-fitting of the secondary treatment train to the trickling filter solids contact (TF/SC) process. An autothermal thermophilic aerobic digester (ATAD) was added for stabilization and pasteurization of waste primary and secondary solids. Phosphorus removal at Salmon Arm was historically undertaken by the addition of chemicals. To investigate the feasibility of incorporating biological phosphorus removal into the trickling filter process, the remaining (unused) portion of the aerobic digester was converted to anaerobic and anoxic basins. The new process at Salmon Arm was named the fixed growth reactor-suspended growth reactor (FGR-SGR) process. The design for the process was developed from known principals for biological phosphorus removal in activated sludge systems, and from those developed for BOD removal and nitrification in trickling filter systems. The design of the plant was described previously (Kelly, 1987 and Kelly *et al.*, 1995).

Advantages of incorporating trickling filters as a principal component in biological nutrient removal systems (compared to strictly activated sludge-type systems) include the following (Kelly, 1987 and Gibb *et al.*, 1994):

1) existing trickling filter plants can be retro-fitted for biological nutrient removal while retaining the trickling filters as a principal process component;

2) cascade aeration of the process mixed liquor over the trickling filter media is a relatively low energy method of aeration compared to energy-intensive blower air with diffusers;

3) process stability is added by the fixed growth bacteria in the trickling filters;

4) partial or complete nitrification can be accomplished by the fixed growth in the trickling filters, and phosphorus uptake then becomes the governing factor for sizing the aeration or solids contact basin;

5) trickling filters have low space requirements; and

6) trickling filters followed by a short period of solids contact produce a biomass with good settling qualities.

This paper includes a brief summary of full-scale and pilot-scale studies undertaken since the inception of the FGR-SGR process, the application of the study results to control nitrification and denitrification in the full-scale plant, and the ensuing improvements in phosphorus removal.

METHODS

Full-Scale Feasibility Study

A study was carried out during 1988-1989 at the full-scale plant at Salmon Arm, to determine the feasibility of achieving effective biological phosphorus removal using the process described above. The flow schematic for the plant as constructed is shown on Figure 1. The second trickling filter (FGR 2) was bypassed for the duration of the feasibility study, to suppress nitrification and allow a focus on phosphorus removal. Aeration and mixing of the solids contact basin was initially undertaken by diffusers using one of the 56 kW (75 Hp) blowers installed with the original activated sludge plant. The operation of the process for the feasibility study was as follows:

1) anaerobic reactor (SGR) – mixing of settled wastewater with the return settled biosolids from the secondary clarifier, bacterial storage of soluble carbon by suspended bacteria with associated phosphorus release;

2) trickling filter (FGR 1) – cascade aeration of the mixed liquor leaving the anaerobic basin, phosphorus uptake and storage by suspended bacteria, BOD removal and nitrification by suspended and attached bacteria;

3) solids contact basin (SGR) – aeration and mixing of the mixed liquor leaving the trickling filter, phosphorus uptake and storage by suspended bacteria, BOD removal and nitrification by suspended bacteria, flocculation of the process biosolids;

4) secondary clarifier - gravity separation of the process biosolids, return of settled biosolids to the anaerobic reactor.

The feasibility study included weekly monitoring of the full-scale process at designated points, as well as bench-scale batch tests carried out on grab samples of the process mixed liquor. The study objectives were to determine whether the bacteria responsible for excess biological phosphorus removal could be cultured in the FGR-SGR process, and to evaluate the effects of various operating conditions (*e.g.*, process influent quality, diurnal flow fluctuations, seasonal changes, and mixed liquor suspended solids concentration) on process performance. Details of the study experimental procedures and laboratory analysis are available elsewhere (Gibb *et al.*, 1989 and Gibb, 1990). As noted above, the feasibility study did not include nitrogen removal, although the plant at Salmon Arm was designed for partial nitrification.

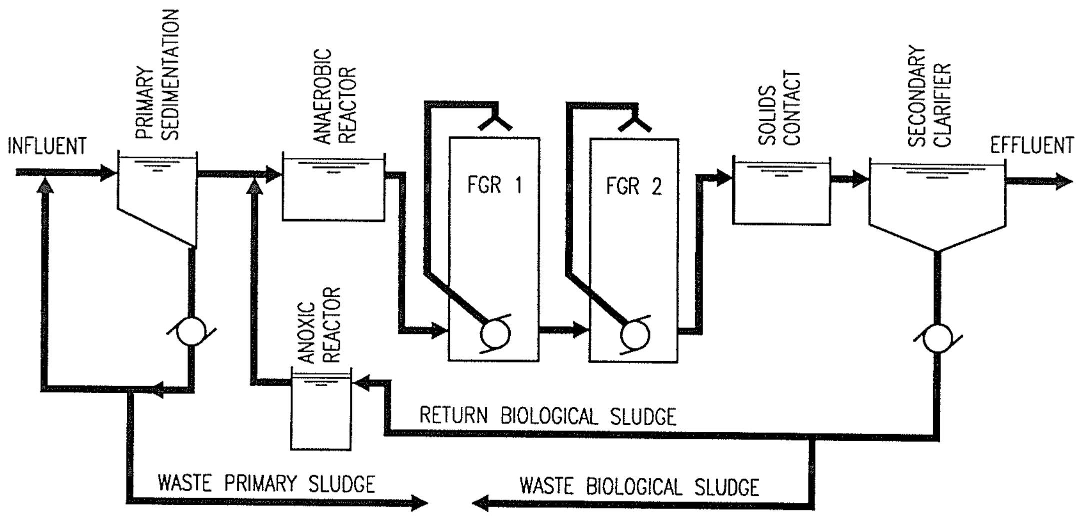

Figure 1: Full-Scale FGR-SGR Process Schematic

Pilot-Scale Optimization Studies

During 1990-1991, a pilot-scale project was designed to further the development of the FGR-SGR process. The pilot-scale study, which was completed in 1994, included biological phosphorus removal and nitrification-denitrification. For the pilot-scale work, two trickling filters in series were used promote fixed growth nitrification. An anaerobic-anoxic sequence similar to that used in the University of Cape Town (UCT) process was employed, to enhance denitrification and prevent nitrates in the return settled biosolids stream from reaching the anaerobic reactor. Two identical process trains were operated in parallel, to assess the effects of different design and operational parameters. Details of the study design and experimental procedures are available elsewhere (Gibb *et al.*, 1993 and 1994 and Gibb, 1995). The primary objectives of the pilot-scale study were to investigate the effects of hydraulic retention time in the suspended growth reactors, internal recycle flow rates, and mixed liquor suspended solids concentration.

Full-Scale Operation and Monitoring

After completion of the feasibility study at the full-scale plant in August of 1989, the second trickling filter (FGR 2) was activated to promote nitrification, and the return settled biosolids from the secondary clarifier were routed through a mixed anoxic basin for endogenous denitrification. Chemical additions were resumed for phosphorus removal. The plant operators subsequently determined that the provision of blower air to the solids contact basin was not required. Adequate mixing of the basin was provided by the turbulent flow entering from the trickling filters, and a detectable concentration of dissolved oxygen (DO) was usually observed at the basin outlet without blower air. Use of the blower was permanently discontinued in the late fall of 1990.

Subsequent process improvements included the addition of a mechanical thickener for waste process biosolids, and configuration of the primary sedimentation tanks to operate as "activated primary tanks" (Frese *et al.*, 1993). Chemical additions for phosphorus removal were permanently discontinued in October of 1992, and the process has operated using biological phosphorus removal alone since that time. The current process flow schematic is shown on Figure 1. The average daily flow to the plant is currently about 3,600 m^3/d.

Based on the work described in this paper, two significant changes to plant operation were made between October of 1992 and May of 1997. The first change, undertaken in January of 1995, involved a seasonal operating strategy for the trickling filters as follows:

1) for winter (cold temperature) operation, the irrigation rate to the second (nitrifying) trickling filter in the process train was increased by the activation of a second recycle pump; and

2) for summer (warm temperature) operation, the second recycle pump was de-activated.

The second operational change was undertaken in late July of 1996, when a 3.75 kW (5 Hp) surface aspirating aerator-mixer (Turborator) was installed in the solids contact basin. The aerator speed was controlled by a closed feedback loop from an on-line dissolved oxygen (DO) monitor installed in the basin. As described later in this paper, the above operating improvements were undertaken to enhance process phosphorus removal by improving control of nitrification and denitrification.

Plant performance was monitored by weekly grab samples taken from the primary clarifier overflow, return settled biosolids stream, anaerobic basin outlet, and solids contact basin outlet; plant effluent quality (secondary clarifier overflow) was monitored by weekly grab samples until November of 1996, and by 24 hour composite samples thereafter. Laboratory analysis for orthophosphate (PO_4) was carried out by the stannous chloride method according to APHA (1992). Analysis for nitrate+nitrite (NO_x) was undertaken using a HACH colorometric analysis kit, according to manufacturer's instructions. On-line analysis recently installed in the existing plant at Salmon Arm includes continuous monitoring of effluent PO_4 concentration and solids contact basin mixed liquor suspended solids concentration.

RESULTS AND DISCUSSION

Full-Scale Feasibility Study

The results of the full-scale study showed that the FGR-SGR process had the capacity for effective biological phosphorus removal, and that the process produced a biomass with good settling qualities. Over an 8-month period, bacterial phosphorus uptake rates across the aerated section of the process (trickling filter plus solids contact basin) were competitive with those in strictly activated sludge biological nutrient removal systems (average 8.5 mg P/L/hr), and phosphorus removal from the process influent averaged 7 mg P/L without chemical additions. The process total suspended solids consistently contained 4-5% phosphorus by dry weight, and the average sludge volume index (SVI) was 68 mL/g (Gibb *et al.*, 1989 and Gibb, 1990).

Pilot-Scale Optimization Study

For the purposes of this discussion, the significant findings of the pilot-scale study were as follows (from Gibb *et al.*, 1994 and Gibb, 1995):

1) in the anoxic phase of batch tests, uptake of PO_4 from solution was observed until NO_x disappeared from solution, indicating that at least some of the bacteria responsible for biological phosphorus removal in the FGR-SGR process were capable of denitrification (others have also documented phosphorus uptake in the anoxic zone of biological nutrient removal processes - *e.g.*, Bortone *et al.*, 1994);

2) after the disappearance of NO_x from solution, PO_4 release was observed (endogenous phosphorus release under anaerobic conditions in biological nutrient removal systems has also been observed by others - termed "secondary release" by Barnard, 1983); and

3) a trickling filter irrigation rate of 1.1 $L/s/m^2$ resulted in a significantly greater degree of nitrification than an irrigation rate of 0.6 $L/s/m^2$.

Full-Scale Operation

Mass balances based on grab samples taken at the plant during the period prior to July of 1996 showed that occasions of higher effluent PO_4 concentration were often associated with an increase in orthophosphate concentration across the secondary clarifier (the recorded increases in PO_4 concentration ranged from 0.1 mg P/L to 0.7 mg P/L). Further, no increase in orthophosphate concentration was observed across the secondary clarifier when effluent NO_x concentration was greater than 2 mg N/L. Based on these observations and the pilot-scale results discussed above, it was hypothesized that the occasions of higher plant effluent PO_4 concentration were caused by endogenous PO_4 release in the clarifier sludge blanket, induced by the following sequence:

1) endogenous denitrification in the sludge blanket consumed all available NO_x in solution;

2) following the disappearance of NO_x from solution, endogenous PO_4 release occurred in the sludge blanket; and

3) released PO_4 diffused upward out of the sludge blanket and caused plant effluent phosphorus concentration to increase.

It was reasoned that the above sequence could be blocked by ensuring that adequate NO_x was available in the process liquid leaving the solids contact basin to prevent the onset of anaerobic conditions in the secondary clarifier sludge blanket. Two process operating parameters known to impact process effluent NO_x concentration were the degree of nitrification in the trickling filters (affected by the irrigation rate) and suspended growth nitrification/denitrification in the solids contact basin (affected by the input of dissolved oxygen). Based on the above, plant operators undertook the two operational changes described earlier (*i.e.*, activation of the second trickling filter recycle pump during winter operation and installation of the DO control loop in the solids contact basin). The objective of the changes was to prevent anaerobic conditions from developing in the secondary clarifier sludge blanket by controlling process effluent NO_x concentration.

The concentration of NO_x in the plant effluent from October of 1992 to May of 1997 is summarized on Figure 2. The effluent average NO_x concentration during winter operation (December 1 to March 31) in 1992/93 and 1993/94 was 0.4 mg N/L and 0.2 mg N/L, respectively. After the second recycle pump was activated in January of 1995, plant effluent average NO_x concentration increased to 1.0 mg N/L for the remainder of that winter, and to 2.5 mg N/L during the winter of 1995/96. Further, there were fewer occasions when the effluent NO_x concentration was less than 1 mg N/L after the second recycle pump was activated.

The plant effluent PO_4 concentration from October of 1992 to May of 1997 is summarized on Figure 3. Note that there was a significant reduction in plant effluent PO_4 concentration following the activation of the second trickling filter recycle pump for winter operation. Before activation of the pump (October 1992 to December 1994), the effluent average PO_4 concentration was 0.9 mg P/L, and the maximum observed value was 3.6 mg/L. After activation of the pump and before the addition of the DO control loop (January 1995 to late July 1996), the effluent average PO_4 concentration was 0.2 mg P/L, and the maximum observed value was 0.9 mg/L. It is apparent that the seasonal increase in trickling filter irrigation rate resulted in a significant improvement in process phosphorus removal (the second recycle pump was de-activated during summer operation, to reduce energy consumption and to prevent excess nitrification, with subsequent overloading of the anoxic basin and recycling of NO_x to the anaerobic basin).

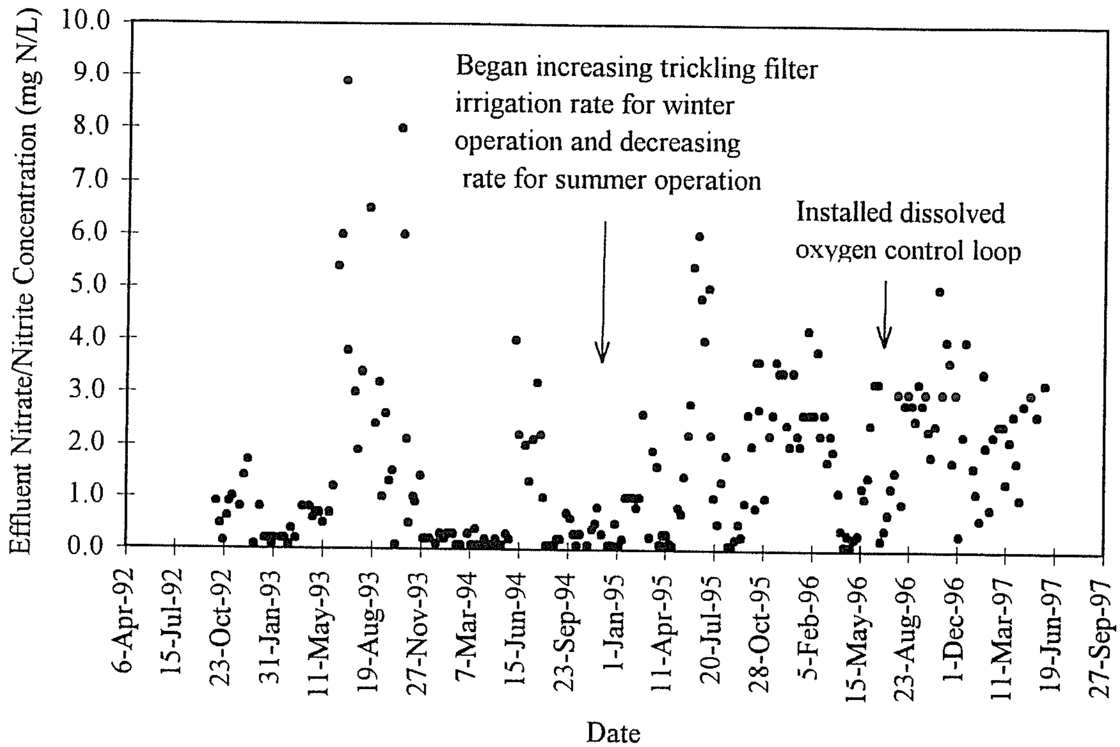

Figure 2: Full-Scale Plant Effluent Nitrate+Nitrite Concentration

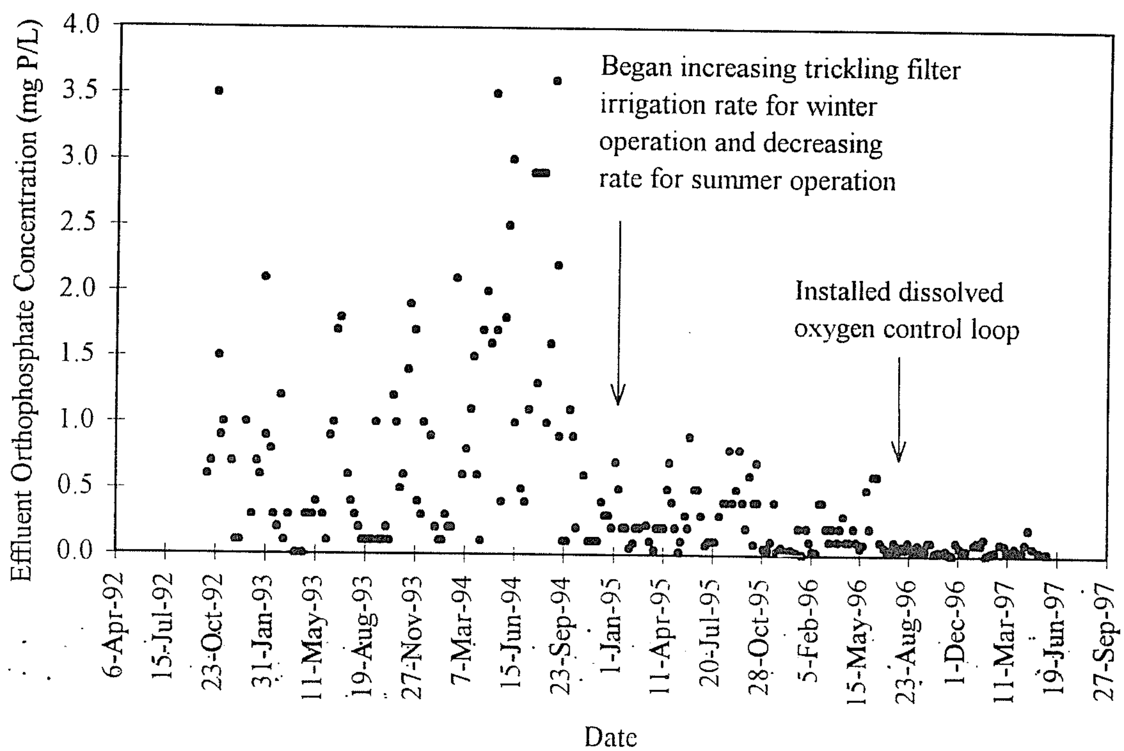

Figure 3: Full-Scale Plant Effluent Orthophosphate Concentration

As described earlier, no blower air was provided to the solids contact basin between October of 1992 and late July of 1996. The DO concentration at the basin outlet during this period (based on spot measurements with a portable meter) ranged from non-detectable to 6 mg/L (average 2 mg /L). The DO control loop was added in late July of 1996, to maintain a constant supply of oxygen to the process bacteria in the solids contact basin. The objective was to suppress denitrification and promote nitrification, and consequently increase the NO_x concentration in the process liquid entering the secondary clarifier. As shown on Figure 2, plant effluent NO_x concentration was less than 1 mg N/L on only 3 occasions after the addition of the DO control loop. The plant effluent average PO_4 concentration during that period was less than 0.1 mg P/L, with a maximum observed value of 0.2 mg P/L (Figure 3). It is apparent that the addition of the DO control loop resulted in a significant improvement in process phosphorus removal.

Future Operating Controls

The FGR-SGR plant at Salmon Arm is now being upgraded and expanded. Information from the full-scale and pilot-scale studies and operational experience over the past 10 years was used in the process design for the expansion. The recently installed on-line effluent PO_4 monitor will be used to monitor plant performance, evaluate the effects of diurnal loading fluctuations, and assess the effects of changes to operating parameters. The on-line suspended solids monitor will be used for automated control of the biosolids wasting rate as described by Kelly and Gibb (1995). Other on-line instrumentation to be installed after the plant expansion includes automated control of trickling filter irrigation rates, and monitoring of the oxidation reduction (ORP) potential in the anaerobic and anoxic basins. Future studies are to include an investigation of using the ORP signal to control NO_x loading to the anoxic basin; the objectives are to minimize endogenous PO_4 release in the anoxic basin, and to prevent NO_x from entering the anaerobic basin.

In addition, a Fuzzy Cognitive Map computer program has been selected to evaluate the relative importance of interrelated process operating parameters. The Fuzzy Cognitive Map is used to model the interrelationships between parameters of interest (conceptual states) and causal events (FSE, 1995). In this case, the conceptual states are the process operating parameters known to affect process performance, as well as the process effluent PO_4 concentration. The causal events are the relative impacts that the conceptual states have on one another. Initiation is as follows: 1) the conceptual states are selected and related values are entered; 2) causal weighting factors are initiated for the interrelated states from expert knowledge to be later refined; and 3) the map is run to establish preliminary causal connections. This forms the cognitive map, which can then be trained using real data sets for known values of the conceptual states. Once the cognitive map is established for the historical data, all states can be assigned values except process effluent PO_4 concentration, and the model run to determine the effect that the assigned values have on process performance. It is intended to experiment with the Cognitive Map model as an operational tool to predict the impacts of changes to operating parameters.

CONCLUSIONS

The following conclusions are based on the work described in this paper.

1) The FGR-SGR process is an effective biological nutrient removal system, capable of producing an effluent containing orthophosphate concentrations consistently less than 0.1 mg P/L without chemical additions.

2) The performance of the full-scale FGR-SGR facility at Salmon Arm has steadily improved since 1992, due to iterative process improvements as more knowledge and operating experience were gained.

3) Control of nitrification-denitrification can be used to enhance process phosphorus removal, by preventing the onset of anaerobic conditions (no available NO_x in solution) in the secondary clarifier sludge blanket.

4) On-line operational controls can be used to significantly improve process performance.

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