Successful Implementation of Biological Nutrient Removal at the 500 ML/d Bonnybrook Wastewater Treatment Plant

Paul Do, Prasanna L. Amatya, and Wolf E. Keller

Calgary Wastewater, Utilities and Environmental Protection, The City of Calgary

pdo@calgary.ca, lamatya@calgary.ca, wkeller@calgary.ca

Abstract

This paper presents the 1989-1999 implementation of the biological phosphorus and nitrogen removal (BNR) technology carried out in 4 separate stages at Calgary's 500,000 m³/d Bonnybrook WWTP. The paper also summarizes Bonnybrook's successful BNR experiences in terms of 90 – 100% chemical cost savings, the production of an excellent effluent quality that is much better than the conventional activated sludge processes and consistently meeting Alberta Environment's stringent effluent standards, as well as the various advantages and disadvantages associated with the BNR processes.

1. Introduction

Calgary is the largest city in the Province of Alberta, Canada, with a 2005 population approaching 1,000,000. The City of Calgary owns and operates two wastewater treatment plants, Bonnybrook and Fish Creek, which together provide treatment to 100 percent of Calgary wastewater prior to its discharge to the Bow River. The Bow River is a world-class sport fishery, an important natural and recreation resource, as well as the water supply source for several downstream communities. It is one of the many tributaries of the Saskatchewan/Nelson river system that rise on the eastern slopes of the Rocky Mountains and flow eastward into the Hudson Bay.

Bonnybrook is a 500,000 m³/d biological nutrient removal (BNR) plant; while Fish Creek is a 72,000 m³/d oxygen activated sludge (UNOX) plant. Figure 1 presents the locations of the two Calgary wastewater treatment plants (WWTPs) and their respective sanitary sewer catchment areas.

This paper presents the 1989-1999 implementation of the various biological phosphorus and nitrogen removal (BNR) processes, which was carried out in 4 separate stages at Calgary's 500,000 m³/d Bonnybrook

advanced wastewater treatment plant. The paper also summarizes Bonnybrook's successful BNR experiences in terms of 90–100% chemical cost savings, the production of an excellent effluent quality consistently better than that produced by the conventional activated sludge process, and the various advantages and disadvantages associated with the BNR processes.

2. Alberta Environment's effluent limits

In the Licenses-to-Operate, Alberta Environment imposes various not-to-exceed effluent limits for the Bonnybrook and Fish Creek plants to protect the Bow River's water quality. Table 1 presents the current effluent limits for the Bonnybrook WWTP.

3. Implementation of BNR processes at the Bonnybrook WWTP

3.1. Bonnybrook WWTP

With an average design capacity of 500,000 m³/d, Bonnybrook is the largest BNR plant in Canada, as well as the largest cold-weather BNR plant in the world. It currently treats an average daily flow of 420,000 m³/d generated from a catchment area population of 800,000.

Calgary began treating its wastewater in 1932, when the Bonnybrook WWTP was built at its present site on the west bank of the Bow River, as a 72,700 m³/d primary treatment plant. Since then, Bonnybrook has undergone several major plant expansions and upgradings to provide adequate treatment to increasing wastewater flows, as well as to meet more and more stringent effluent standards imposed by the Provincial regulatory authority - Alberta Environment.

Figure 2 presents an aerial view of the plant showing the three secondary treatment sections A, B, and C, that had been converted to the BNR processes over the 10-year period of 1989 – 1999.

Figure 1. Calgary wastewater treatment plants' catchment areas

Table 1. Effluent limits for the Bonnybrook WWTP (Effective 1997)

Parameter	Units	Effluent Limit	Averaging Period (Monthly)
CBOD ₅	mg/L	20	Arithmetic Mean
TSS	mg/L	20	Arithmetic Mean
Ammonia nitrogen (July-Sept.)	mg/L	5	Arithmetic Mean
Ammonia nitrogen (Oct.-June)	mg/L	10	Arithmetic Mean
Total Phosphorus (TP)	mg/L	1.0	Arithmetic Mean
Fecal Coliforms (FC)	CFU/100 mL	200	Geometric Mean
Total Coliforms (TC)	CFU/100 mL	1000	Geometric Mean

Figure 2. Bonnybrook Wastewater Treatment Plant

Figure 3 illustrates a flowchart of the mainstream and side stream processing units. In all, there are:

- ◆ Six 19 mm mechanically-raked bar screens
- ◆ Four aerated grit chambers
- ◆ Fourteen primary clarifiers
- ◆ Ten reactors distributed among three distinct secondary treatment modules
- ◆ Thirty secondary clarifiers
- ◆ Three gravity thickeners for primary sludge thickening
- ◆ Five dissolved air flotation tanks for waste activated sludge thickening
- ◆ Twelve mesophilic anaerobic digesters
- ◆ A low-pressure mercury vapor lamp ultraviolet disinfection system.

Digested sludge is pumped to the Shepard Sludge Lagoons, located approximately 12 km southeast of the plant. At Shepard, the sludge is allowed to settle by gravity and thickened to about 8.0 percent solids content. From May to October, lagoon sludge is transported to agricultural lands for sub-surface injection, in accordance with Alberta Environment's guidelines and application rates. Supernatant from Shepard is decanted and returned continuously to the headworks of the

Bonnybrook Plant.

3.2. Chemical costs for phosphorus removal

Since 1982, under Alberta Environment's direction, The City of Calgary has been required to remove phosphorus from both treatment plants to a monthly average limit of 1.0 mg/L to prevent eutrophication in the Bow River. Initially, liquid alum solution, at an average dosage of 65 mg/L as $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$, was metered into the mixed liquor leaving the reactors to precipitate phosphorus. By the late 1980s, the annual chemical expenditures at Bonnybrook alone were approaching CDN \$2.6 million. Therefore, rapid population growth requiring additional treatment capacity, together with new and more stringent effluent limits, forced the City to undertake a detailed review of new and promising technologies for nutrient removal having the potential of being more economical and effective than the conventional activated sludge processes using costly phosphorus-precipitating chemicals such as iron or aluminum salts.

Figure 3. Bonnybrook Wastewater Treatment Plant - Process flow diagram

3.3. Implementation of Biological Nutrient Removal (BNR)

A full-scale trial of biological phosphorus removal (BPR) was initiated in November 1989 by the retrofitting of half of the oldest secondary treatment portion of the plant (Secondary Plant A) to a simple anaerobic/aerobic process configuration. This represented about 20 % of the plant's design capacity at that time. The trial was successful to the extent that the CDN \$0.92-million retrofit cost was recovered in about four months by the cost savings in liquid alum. The plant management then decided to retrofit the entire Secondary Plant A to BNR technology, this time using a Modified Bardenpho process configuration to provide nitrate-oxygen recovery, some degree of total nitrogen removal, and to minimize the adverse effect caused by nitrates in the return activated sludge (RAS) on BPR performance.

To provide additional capacity for increasing wastewater flows, a major plant expansion was completed in 1994 at the total cost of about CDN \$40 million, which, among other innovative technologies such as primary sludge fermentation and UV disinfection, included a greenfield, 100,000 m³/d

Secondary Plant C module with full BNR capabilities.

A retrofit BNR design for Secondary Plant B, which was initially commissioned as a complete-mix activated sludge plant in 1984, had also been completed and entered the construction stage in the summer of 1997. The total cost of this BNR retrofit is CDN \$4 million. In June 1998, all four aeration tanks of Secondary B were commissioned as BNR reactors.

In early 1998, design was also underway to provide fine-bubble aeration to Secondary Plant A to improve the oxygen transfer efficiency, as well as to provide additional design features such as foam and scum removal, short-circuiting prevention, automatic DO control, new WAS pumps, etc. This latest BNR improvement and aeration upgrading costed approximately CDN \$5.5 million.

Figure 4 illustrates the layout of a typical BNR reactor in Secondary Plants A, B, and C, respectively. All the layouts follow the BNR principle of providing three different process zones (anaerobic, anoxic, and oxic) required for the growth and reproduction of various species of naturally-occurring microorganisms, that simultaneously carry out biological phosphorus and nitrogen removal, as well as organic matter removal. The anaerobic zone is designed for the selection of biological

phosphorus removal bacteria, which are also called bioP bacteria or polyP bacteria. The anoxic zone is reserved for the growth and activity of denitrifying bacteria. The

oxic zone is designed for the growth and activity of various species of bacteria including bioP bacteria, nitrifying bacteria, as well as heterotrophic bacteria.

Figure 4. BNR reactors in secondary treatment sections A, B, C

3.4. Success of BNR processes at Bonnybrook

Additional Primary Sludge Fermenters for Bonnybrook

Short-chain Volatile Fatty Acids (SCVFAs or VFAs), such as acetic acid, propionic acid, and butyric acid, have been identified as the carbon compounds required for triggering the biochemical pathways involved in phosphorus release and uptake mechanisms in the anaerobic and aerobic zones of the BPR

bioreactors. Where VFAs are present in sufficient concentrations (approximately 15 – 25 mg/L) in the raw wastewater, biological phosphorus removal to very low levels (about 0.1 – 0.2 mg/L soluble P) can readily be achieved in a variety of BPR process configurations.

Insufficient VFAs quantity in the influent wastewater is not only pertinent to Calgary wastewater, but is very common with Canadian wastewaters because of the very low wastewater temperatures in the winter. Bonnybrook's influent wastewater has very low naturally-occurring VFAs, with an average of 10 – 12

mg/L in the summer months, and an average of 4 – 6 mg/L in the winter months. Earth Tech Canada Inc. has confirmed that an additional VFAs concentration of about 10 mg/L is needed, on a continuous basis, to stabilize and improve the performance of the BPR processes utilized at the Bonnybrook WWTP.

The two existing primary sludge fermenters at Bonnybrook were constructed in 1994 to supply the additional VFAs required by the BPR processes in Secondary C, consisting of Reactors 9 and 10. Figure 5 presents these two primary sludge fermentation systems. When Secondaries A and B were retrofitted to BNR processes, no primary sludge fermenters were built for the 8 bioreactors (Reactors 1 – 8) of Secondaries A and B. By contrast, other Canadian municipalities, such as Kelowna, Penticton, and Edmonton, constructed brand-new fermenter systems in conjunction with the construction of their BNR treatment plants. Additional primary sludge fermenters for Bonnybrook, costing about CDN\$ 6 million, are scheduled to be constructed in 2005/2006 to continuously supply the supplemental VFAs required to optimize the stability and efficiency of the BPR processes in Reactors 1 – 8. After the commissioning of the additional fermenters, it is anticipated that no or very little alum will be used at Bonnybrook.

Figure 5. Secondary C's primary sludge fermenters at Bonnybrook

Substantial Chemical Cost Savings

Figure 6 illustrates the dramatic chemical cost savings achieved for the Bonnybrook Plant even though there is the permanent lack of sufficient VFAs required for the BPR processes. From the first implementation of BNR technology at the plant in November 1989, the population in the Bonnybrook catchment area has steadily increased. In spite of population increases, annual chemical costs have sharply and continually decreased. In 2002, the annual chemical cost decreased

to CDN \$ 546,136 from CDN \$2.6 million in 1985. If there were no BNR process at Bonnybrook, the activated sludge process with chemical precipitation of phosphorus would have required an average alum dosage of 65 mg/L, thus resulting in a 2002 chemical expenditure of CDN\$ 3.2 million. The 2002 alum cost savings due to the BNR process were therefore over CDN\$ 2.8 million.

Alternatively, Figure 7 presents the per capita annual chemical costs versus the percentage of BNR flows. It can be seen that these costs decreased rapidly as the volumes of wastewater receiving BNR treatment increased. From a 1985 unit cost of \$ 5.57, the per capita chemical costs have continually and steadily decreased over a 12-year period to \$ 0.83 in 2002. It is anticipated the per capita chemical costs will decrease to \$0.00 in 2005/2006, after the commissioning of the additional primary sludge fermenters for Bonnybrook.

Consistently Better Effluent Quality

Table 2 compares the quality of the treated effluents from the three secondary plants with the quality of raw wastewater and primary effluent. Secondary Plant B is the complete-mix activated sludge process using chemical phosphorus removal. It is noted the two BNR plants consistently produced effluents having much better quality than the chemical-feed activated sludge plant while requiring little or no chemical.

Figures 8, 9, 10 and 11 illustrate the CBOD₅, TSS, Total P, and NH₃-N performance of Secondary Plant C since its commissioning in early 1995. It can be seen Secondary C's treated effluent not only consistently met but often surpassed Alberta Environment's stringent effluent limits. In reality, this degree of excellent and stable performance can be achieved with any well-designed and well-operated BPR or BNR plant, even in cold climate such as that of Calgary.

At the Bonnybrook WWTP, the quality of the treated effluents from each of the 10 BNR reactors is continuously monitored by 5 on-line ChemScan analyzers. Each analyzer is a multiple-wavelength ultraviolet absorbance spectrometer capable of measuring 4 parameters (TSS, PO₄-P, NH₃-N, NO₃-N), every 30 minutes, from 2 effluent streams. The analyzer system consists of a manifold with automatic zeroing and cleaning, a sample pump, a sample conditioning unit, and the UV-400 analyzer.

In view of the accuracy and reliability of the ChemScan analyzers, decision was made, in June 1998, to discontinue the Laboratory's analyses of TSS, PO₄-P, NH₃-N, and NO₃-N for all effluent streams, except for Bonnybrook's combined final effluent discharged to the Bow River. The concentrations of these four pollutants in all bioreactors' effluent streams were subsequently monitored using the ChemScan analyzers' readings.

Table 2. Comparison of raw wastewater, primary effluent, and treated effluents from Bonnybrook's BNR and activated sludge processes

Item	CBOD ₅ (mg/L)		TSS (mg/L)		Total P (mg/L)		Alum Dosage (mg/L)	
	Average	Range	Average	Range	Average	Range	Average	Range
Raw Wastewater	162	137-182	162	151-179	5.4	4.6-6.6	-	-
Primary Effluent	118	72-144	81	62-92	5.0	4.2-6.2	-	-
Secondary Plant A (BNR)	5	4-6	10	6-14	0.7	0.4-1.0	10	0-20
Secondary Plant B (Act. Sl.)	6	4-8	12	8-16	0.7	0.4-1.0	65	60-70
Secondary Plant C (BNR)	4	2-6	7	4-10	0.4	0.2-0.6	0 - 5	0-10

Figure 6. Bonnybrook - Annual cost savings versus population

Figure 7. Bonnybrook – Per capita chemical costs versus % of BNR flows

Figure 8. 1995 – 1998 Secondary C removal of CBOD₅

Figure 9. 1995 – 1998 Secondary C removal of TSS

Although BPR and BNR processes are normally reliable and effective, there is always the possibility of process upsets and/or performance deterioration caused by uncontrollable factors, such as inhibitory or toxic substances contained in the influent wastewater, insufficient or unsuitable SCVFAs, insufficient biodegradable organic matter, insufficient nutrients, power outages, equipment or instrument failures, computer system problems, etc. As a result, it is a necessity for BPR and BNR plants to have a standby chemical facility that can provide either low chemical dosages for polishing purposes, or even maximum chemical dosages in disastrous cases, to ensure the compliance with the regulatory authority's Permit limits

at all times.

4. Advantages and disadvantages of BNR processes

4.1. Advantages of BNR processes

- ◆ BNR processes are considered as the “green” solution to the removal of phosphorus and nitrogen from wastewater because they utilize naturally-occurring microorganisms instead of expensive chemicals that eventually appear in digested sludges and plant effluents.

Figure 10. 1995 – 1998 Secondary C removal of TP

Figure 11. 1995 – 1998 Secondary C removal of $\text{NH}_3\text{-N}$

- ◆ Generating less excess sludge that requires processing and disposal. In addition, this excess sludge has a much lower metal content. If the sludge is applied to agricultural land, the phosphorus nutrient in the sludge is more available for crops' utilization.
- ◆ Reducing aeration requirements and energy required for aeration because most of the substrate removal already takes place in the anaerobic and anoxic zones preceding the aerobic zone.
- ◆ Denitrification in the anoxic zone can recover up to 50% of the oxygen utilized in the nitrification process. This may save up to 15 to 20% of aeration energy.
- ◆ Denitrification in the anoxic zone can recover approximately 50% of wastewater alkalinity consumed in the nitrification reaction, resulting in a more stable mixed liquor pH and better process efficiency.
- ◆ The selector effects, created by having an anaerobic zone and an anoxic zone, can improve sludge settling characteristics, thereby resulting in better performance of the secondary clarifiers.
- ◆ Less inert matter is in the mixed liquor, resulting in higher reactor treatment capacity and lower solids loading rates on the secondary clarifiers.

4.2. Disadvantages of BNR processes

- ◆ For any BPR or BNR plant, it is necessary to have a standby chemical facility, as previously discussed, to ensure the compliance with Permit limits. However, the facility's capital cost is small and insignificant when compared to the large and continual savings in annual chemical costs.
- ◆ Because of the large unaerated zones (anaerobic and anoxic), BNR processes are susceptible to biological foaming and sludge bulking. These problems tend to occur or become more severe during the cold winter months. Low dosages of RAS chlorination can successfully eliminate sludge bulking problems. Spraying the foam with fine mist of chlorine solution can successfully eliminate foaming problems. Experiences at Bonnybrook also indicate the application of low chlorine dosages over longer application periods will successfully eradicate bulking and foaming problems, without overly affecting the beneficial microorganisms in the mixed liquor.
- ◆ BNR processes require higher levels of operators' skills and attention, more extensive laboratory work, and a higher degree of process monitoring and adjustment.
- ◆ Particular care must be taken in the management of waste activated sludge to prevent excessive recycling of soluble phosphorus back to the BNR processes.

5. Conclusions

Beginning in November 1989, with the objective of reducing the increasingly expensive chemical costs, The City of Calgary took a proactive step forward by experimenting with a new but innovative technology - biological phosphorus removal. The success of this initial experimentation has understandably lead to successive modifications of the other secondary treatment sections to an even more efficient and promising technology - biological phosphorus and nitrogen removal.

By the fall of 1999, Bonnybrook became a 100% BNR plant. It is presently the largest BNR plant in Canada, and the largest cold-weather BNR plant in the world. Bonnybrook's treated effluent has consistently met or surpassed Alberta Environment's stringent effluent limits, with the achievement of 90 – 100% cost savings in phosphorus-precipitating chemicals. With the completion of additional primary sludge fermenters in 2005 – 2006 to supply sufficient SCVFAs for the bioP

bacteria associated with the BPR processes, it is anticipated no phosphorus-precipitating chemicals will be used, except for occasional, small polishing dosages due to the natural fluctuations of biological processes' efficiency and stability.

Because of the Bonnybrook Plant, The City of Calgary is the only city, out of 22 major Canadian cities, to be awarded a grading of A+ by the Sierra Club, in 2004, for its proactive efforts in the protection of the Bow River's water quality. In May 1995, Chatelaine Magazine gave Calgary the No. 1 rating for wastewater treatment. In May 1997, the Bonnybrook Plant was chosen by Environment Canada as one of five Canadian sustainable development success stories presented at the Asia Pacific Economic Cooperation conference. The Consulting Engineers of Alberta, in January 1998, gave the Bonnybrook Plant Expansion project the Award of Excellence for its innovative technology and environmentally-beneficial impact. The prime consultant, Reid Crowther and Partners Ltd., and The City of Calgary were praised "... for pioneering and implementing new technology on a large scale and for creating a win-win situation for client and the environment".

6. References

- [1] *Operation of Municipal Wastewater Treatment Plants. Manual of Practice - MOP 11- Volume 1*, Water Environment Federation, Alexandria, VA 22314 - 1994, USA, 1996.
- [2] B. Rabinowitz, P. Do, M.K. Fries, R.N. Dawson, and W.E. Keller, "Biological Nutrient Removal at the Calgary Bonnybrook WWTP Replacing Costly Chemical Phosphorus Removal" in *Proc. 70th Annual Conference and Exposition of the Water Environment Federation*, Chicago, Illinois, USA, October 18-22, 1997.
- [3] C.W. Randall, "Why use Fermentation?" in *Proc. 67th Annual Conference and Exposition of the Water Environment Federation*, Chicago, Illinois, USA, Oct.15-19, 1994.
- [4] J.L. Barnard, "Alternative Prefermentation Systems" in *Proc. 67th Annual Conference and Exposition of the Water Environment Federation*, Chicago, Illinois, USA, October 15-19, 1994.
- [5] A.W. Wilson and P. Do, "Case History: Retrofitting of the Bonnybrook Wastewater Treatment Plant with Biological Nutrient Removal" in *Proc. 23rd Annual Conference of the Water Environment Association of Ontario*, Windsor, Ontario, Canada, April 14-19, 1994.
- [6] P. Do, W.E. Keller, and A.W. Wilson, "Implementation of the Biological Nutrient Removal Program at Calgary's Bonnybrook Wastewater Treatment Plant" in *Proc. 19th Biennial Conference of the International Association on Water Quality*, Vancouver, British Columbia, Canada, June 21-26, 1998.