Evaluation & Optimization of Design/Operation of Sequencing Batch Reactors for Wastewater Treatment

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Abstract

An evaluation of municipal sequencing batch reactor (SBR) installations in Ontario and the US Great Lakes Region was carried out in the first phase of a three-phase program for evaluation and optimization of SBRs. Plant physical characteristics, operating data, construction costs, and operator concerns were recorded from 75 facilities. Design and operational concerns encountered at these facilities and reported by plant staff were prioritized based on their impact on operating costs, plant capacity, and effluent quality, as well as on their frequency of occurrence. A list of recommendations to optimize this type of treatment plants was developed. Lack of proper operator training was found to have the largest impact on operating costs and effluent quality. The development of SBR operator training programs to complement traditional activated sludge operator training with SBR-specific theoretical and practical concepts was recommended. The preparation of a guideline manual for selection, design, evaluation, and operation of SBRs and the development of a methodology to evaluate the actual treatment capacity of existing SBRs were also recommended. Effluent data compiled from the plants evaluated showed that, in spite of design and operation concerns, the plants consistently met, and in many cases, exceeded their effluent criteria. Many of the concerns found during this evaluation were not SBR-specific and could apply to any type of activated sludge wastewater treatment plant. Using construction costs supplied by 17 of the plants evaluated, a preliminary cost comparison between SBRs and continuous flow activated sludge plants was made. The results indicated that, for similar effluent requirements, SBRs are more economic than continuous flow activated sludge plants.

Key words: sequencing batch reactor, optimization, design guidelines, construction costs

Introduction

The Sequencing Batch Reactor (SBR) is a mixed-culture, suspended growth activated sludge treatment system that is operated on a fill and draw basis (1). Since SBRs use a single tank for waste stabilization and solids separation, the need for a secondary clarifier is eliminated. The operation of an SBR, shown in Figure 1, consists of five distinct periods (fill, react, settle, decant, and idle) which comprise one complete reactor cycle (2).

Currently, SBR technology has been applied in over 500 communities and industries in the United States and Canada, and over 400 in Europe. Many of these facilities have been meeting stringent effluent requirements for several years. However, there is little well documented evidence on SBR performance, costs, reliability, and optimal design and operations associated with different system configurations. Currently, there are no guidelines for selection, design, evaluation, and operation published in North America.

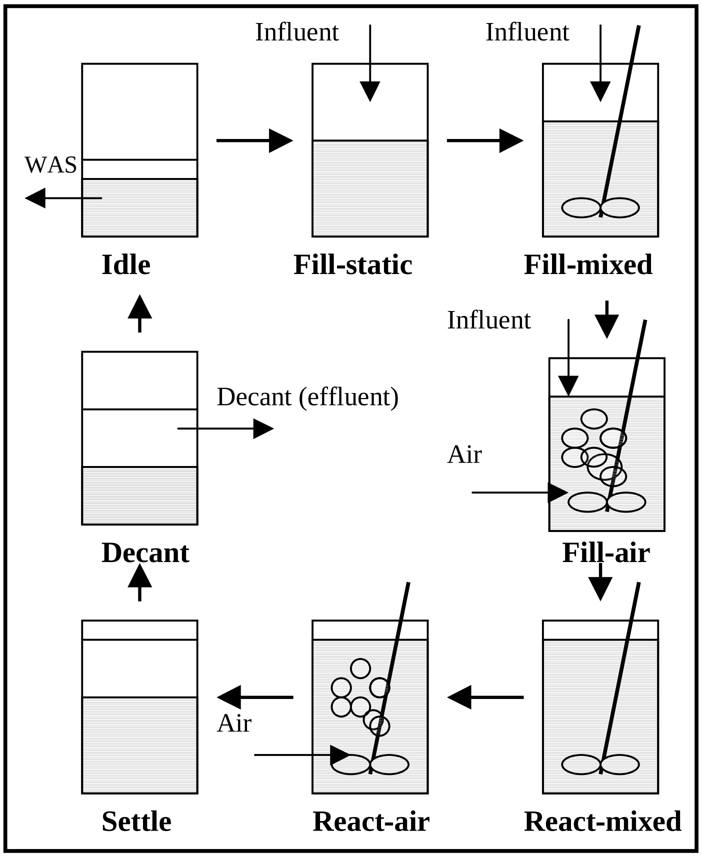


Figure 1: Typical SBR cycle

Project background and objectives

The Water Environment Association of Ontario (WEAO), Environment Canada's Great Lakes 2000 Cleanup Fund (GL2000CUF), and the Ontario Ministry of the Environment (MOE) recognize that SBRs can be a cost-effective technology for treating municipal and industrial wastewaters. However, in spite of the growing number of SBR plants in Canada, there is limited information to ensure that SBRs are correctly selected, designed, evaluated, and operated in Ontario. To meet this need, these organizations sponsored a program for the evaluation and optimization of design/operation of SBRs for municipal wastewater treatment. The program is divided into three main phases with the following major objectives:

- Phase 1: Document the application and performance of municipal SBR treatment facilities in Canada and in the US Great Lakes states.

- Phase 2: Optimize the design and operation of representative SBR plants.

- Phase 3: Produce a guidance manual for SBR selection, design, evaluation, and operation.

This paper summarizes the findings from Phase 1 of this program.

Methodology

Phase 1 of this program started in October 1997 and was completed in February 1998.

In Phase 1, the application and performance of 75 municipal SBR plants in Ontario and in the U.S. Great Lakes Region were compiled and documented. These geographic areas were selected for their similar weather conditions and effluent quality requirements.

The information was obtained from plant operators, equipment suppliers and through visits to selected facilities. A three-page questionnaire was sent to leading suppliers of SBR equipment and to approximately 60 SBR facilities.

The information requested in the questionnaire was classified in five sections:

- General information (e.g., location, design engineer, SBR supplier)
- Design parameters (flow rate, influent characteristics, effluent objectives)
- Actual influent and effluent characteristics
- Installation characteristics (e.g., pre-treatment equipment, type of decanter, SBR operating cycle, control strategies applied)
- Capital and O&M costs
- Common operating concerns

Discussion

In Phase 1, information from 75 municipal SBR facilities was compiled using the responses submitted by plant operators and suppliers, and from plant visits. The distribution of the responses was:

- Information from 12 facilities was compiled during site visits.
- Information from 29 facilities was sent directly by SBR suppliers (using the questionnaire and/or plant operating data sheets).
- Information from 34 facilities was supplied by plant staff (using the questionnaire and/or through phone and e-mail communications)

The visits to the US facilities augmented Ontario's experience with SBRs and provided data from SBR suppliers that are currently not present in the Ontario market.

Achievable effluent quality

One of the objectives of the project was to evaluate the capacity of SBR facilities to achieve different sets of effluent requirements. To achieve this goal, the facilities assessed were classified by achievable effluent quality in three groups, based on three sets of effluent limits defined with the Technical Steering Committee:

Limit 1: Conventional limit
$CBOD_5$ = 25 mg/L TSS = 25 mg/L ***Annual***
TP = 1 mg/L ***Monthly***

Limit 2: Conventional w/nitrification requirements – *All Monthly*
$CBOD_5$ = 10 mg/L TSS = 10 mg/L
TP = 0.5 mg/L
NH_3-N = 3 mg/L (summer) 5 mg/L (winter)

Limit 3: BNR/RAP-type limit – *All Monthly*
$CBOD_5$ = 5 mg/L, TSS = 5 mg/L,
TP = 0.2 mg/L, and
TN = 5 mg/L (summer) 10 mg/L (winter)
NH_3-N = 2 mg/L (summer) 4 mg/L (winter)

Many of the plants evaluated do not have to meet the effluent phosphorus criteria shown in these limits. For this reason, many plants reaching good levels of nitrification, BOD, SS, and nitrogen removal, but not achieving the effluent P levels specified, were classified within less stringent limits. For example, plants meeting Limit 3 criteria for $CBOD_5$, TSS, NH_3-N and TN, were classified within Limit 2 because their effluent P concentrations were within the value stated for Limit 2.

The results of this classification were:

- Fourteen of the plants assessed met the effluent requirements for Limit 1. Most of these plants had considerably lower $CBOD_5$ and TSS concentrations than those stated in this limit, and were classified within this group due to their effluent phosphorus concentrations. Some of the plants fitting within Limit 1 had good levels of nitrification and in some cases, low effluent concentrations of total nitrogen.

- Nine plants met the effluent requirements for Limit 2. As in the case of plants meeting Limit 1 criteria, many of these plants classified within Limit 2 met more stringent effluent limits for ammonia and total nitrogen than those specified for this limit, but were classified within this group due to the effluent phosphorus concentrations.

- No facilities met the effluent requirements for Limit 3. Even though five facilities met the ammonia and nitrogen limits of Limit 3, none of these plants met the TP requirements stated in this limit.

- The remaining facilities did not fit within Limits 1, 2, or 3.

- The specific effluent requirements (as stated in their C. of A. or NPDES) were met in all but one of the 75 facilities assessed in Phase 1.

- The average effluent $CBOD_5$ and SS concentrations for all the plants evaluated were below 10 mg/L.

- 53 facilities reported yearly average effluent NH_3-N concentrations. The average of all the NH_3-N concentrations reported was 1.5 mg/L.

- 32 facilities reported yearly average effluent TP concentrations. The average of all the TP concentrations reported was 1.4 mg/L.

- 9 facilities reported yearly average effluent TN concentrations. The average of all the TN concentrations reported was 4.3 mg/L.

Examples of plants meeting stringent effluent criteria in Canada and the US Great Lakes States are shown in Table 1.

Many of the facilities shown in Table 1 are operating at flows that are well below their design capacity. However, to compensate for the low flows and reduce energy expenditures and equipment maintenance costs, some of these facilities are being operated with part of the SBRs out of service.

Table 1
Examples of plants meeting stringent effluent criteria in Great Lakes Region

Plant/ Supplier	Actual/ Design Flow [m^3/d]		CBOD$_5$ [mg/L]	TSS [mg/L]	NH$_3$-N [mg/L]	NO$_3$-N [mg/L]	TP [mg/L]	Filtr.	Chem. Add'n
New Freedom, PA Aqua Aerobics	4100/ 8520	Inf	73	81	N/A	N/A	N/A	No	No
		Eff	< 5	5	0.8	N/A	0.9		
Garden Spot, PA Aqua Aerobics	90/ 1060	Inf	276	380	33	N/A	10	Yes	Yes
		Eff	< 5	< 5	0.4	N/A	1.0		
Flushing, MA Jet Tech	6880/ 7570	Inf	120	122	13	N/A	2.8	No	No
		Eff	< 5	< 5	0.5	0.2	0.5		
Soaring Eagle, MI Jet Tech	760/ 2200	Inf	285	190	65	N/A	7.0	Yes	Yes
		Eff	< 5	< 5	0.5	N/A	0.2		
Catawba Is., OH CASS	1730/ 5070	Inf	236	394	21	N/A	7.5	No	Yes
		Eff	10	12	3.6	0.9	0.5		
Casinorama, ON ABJ	700/ 2100	Inf	289	375	18.3	N/A	9.5	Yes	No
		Eff	<4	<5	0.6	0.7	0.3		
Frackville, PA ABJ	3030/ 5300	Inf	207	188	N/A	N/A	5.95	Yes	Yes
		Eff	<5	<5	1.0	5.0	0.5		

Design and operating concerns and recommendations for optimization

The information compiled during this evaluation was used to identify opportunities and methods to optimize the design and operation of SBRs.

The concerns recorded during site visits and those reported by plant staff in the questionnaires were ranked based on their frequency of occurrence, prevalence of occurrence, and their impact on operating costs, plant capacity and effluent limit compliance. A total of 20 concerns were compiled. A summary of the top ten concerns is shown in Table 2.

The information gathered was used to identify probable causes, recommend remedial actions, and identify opportunities and means to optimize the design and operation of SBRs. For each concern, there was a recommendation made. The goal of the recommendations listed in Table 2 is to reduce capital and O&M costs, and whenever feasible, improve effluent quality.

Several observations can be made from the list of concerns compiled:

- Lack of proper operator training has the largest impact on operating costs and effluent quality.
- Many of the concerns found during this evaluation are not SBR-specific and could apply to any type of activated sludge wastewater treatment plant.
- The average effluent data from the reporting plants show that in spite of experiencing some degree of concern with design/operation issues, the plants met, and in many cases, exceeded their effluent criteria.

Costs

Evaluations performed in the 1980's indicated that SBRs are a cost-effective wastewater treatment technology (5). Other literature sources indicate that SBR systems are likely to be extremely cost-effective over a wide range of flows (7). Unfortunately, limited historical data have been compiled comparing the cost of SBRs with other types of activated sludge treatment systems. Clearly, the lack of need for an external secondary clarifier and return sludge pumping system offers potential savings in construction costs. In addition, primary clarification is not normally employed (none of the 75 plants evaluated had primary clarifiers).

Determining the cost-effectiveness of this technology was not an objective of Phase 1 of this project. However, construction cost data submitted by 17 of the facilities evaluated was compared to cost estimates provided in the literature (5,6,7,8,9). The results of this cost comparison are shown in Figure 2.

Only two sources of construction costs for municipal SBR facilities were found in the literature (5,6). These data are shown in Figure 2 as EPA Municipal SBRs 83 and EPA Municipal SBRs 92, for 1983 and 1992 construction cost data, respectively.

Costing data for SBR systems treating high strength industrial wastewater and leachate were also used in this comparison (8,9,10). To compare on an equal basis these construction costs to those of municipal plants, the flow rate capacities of the high strength wastewater facilities were increased using the ratio of their influent wastewater oxygen demand to that of a typical municipal WWTP. Two sets of data are shown in Figure 2: construction costs from actual industrial SBRs (EPA Industrial SBR plants) and construction costs derived from a proposed equation (EPA industrial SBR eq'n).

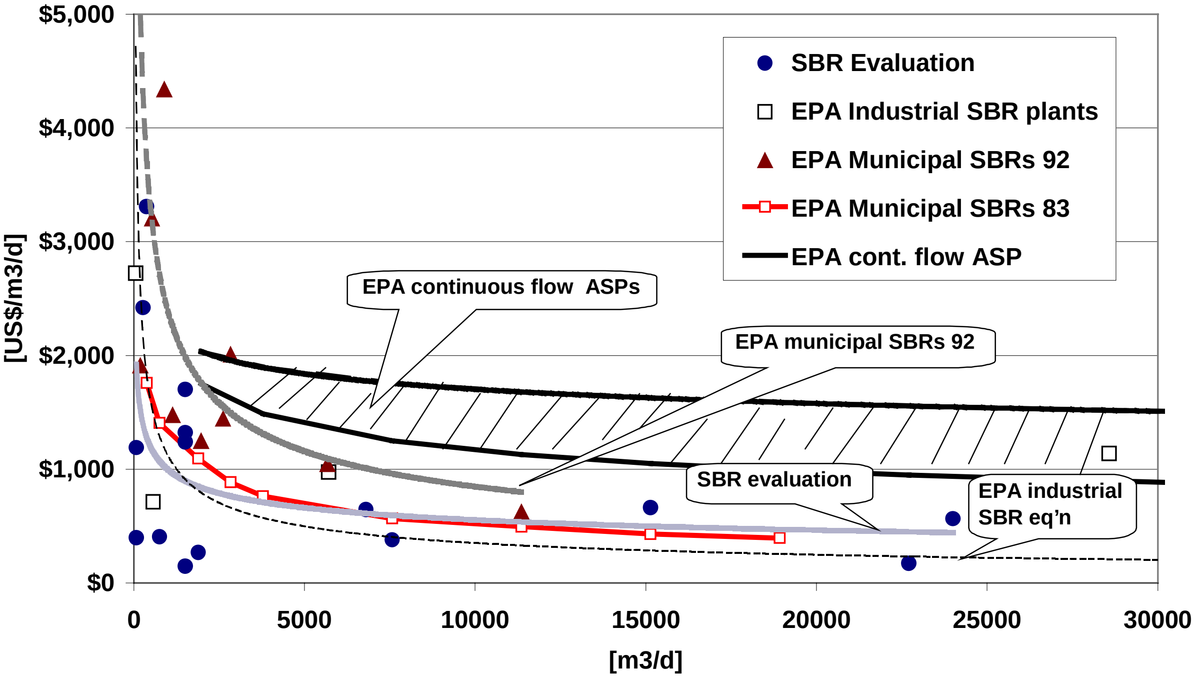
Table 2
List of concerns and related recommendations

Concern	Recommendation
1. Operators do not have formal training on SBR operation/process control: When compared to conventional continuous flow systems, SBRs are a relatively new activated sludge process. Conventional training does not prepare new SBR staff to operate these facilities effectively.	**Develop SBR operator training programs:** These programs should complement traditional activated sludge operator training with SBR-specific theoretical and practical concepts.
2. Mechanical equipment located outdoors may freeze: In some facilities, air valves, solenoid valves, decanter arms, and level monitoring floats freeze or malfunction when exposed to low temperatures.	**Specify proper heating, insulation, and O&M procedures to protect exposed equipment from the elements:** Using heat tracing, cold-weather grease for lubrication decanter arms, and designing the system to have sensitive equipment located inside buildings are some of the low-cost options available for preventing SBR malfunctioning during cold weather conditions.
3. Decanters not adequate for specific treatment requirements: In some plants, the decanters used were unable to adequately control the discharge of floatables present in the reactor. This impacted downstream processes (e.g., grease clogging in sand filters and floatables covering UV lamps).	**Select decanters that meet the plant treatment objectives:** There are many types of decanters on the market, each has different performance characteristics and cost. Some of the factors to take into account when selecting a decanter are the effluent quality required, type of downstream processes, and the budget available.
4. Discontinuous SBR effluent flow impacted downstream treatment processes: Two examples of the impact of the discontinuous discharge from SBRs on post-treatment processes are: 1. Initial high flow rate discharges from fixed level decanters resulted in reduced degree of UV disinfection; and 2. Operation of continuous backwashing filters was affected by discontinuous decant discharges.	**Design adequately SBR post-treatment processes:** For example, the discontinuity between the SBR intermittent discharge and the post-treatment unit process can be eliminated by providing adequate flow equalization downstream of the SBR. If flow equalization is not desirable, the post-treatment systems selected should be able to work properly under discontinuous flow conditions.
5. Lack of online DO monitoring instrumentation and control: In many of the plants evaluated, there was no specific aeration control strategy in place. These plants still met and in some cases, exceeded their effluent criteria. However, potential energy savings related to DO control were not achieved.	**Development and implementation of aeration control strategies:** Energy savings could be achieved by using DO monitors to control blower operation. In small facilities (under 3000 m^3/d), hand-held probes and on/off aeration control are recommended. In larger facilities, online DO monitors and automatic aeration control systems may prove more economic and also achieve considerable energy savings.

Table 2 (cont.)
List of concerns and related recommendations

Concern	Recommendation
6. **SBRs are supplied without a specific SRT control strategy:** In several plants, SRT control is achieved by maintaining an optimum MLSS concentration in the reactors. However, the optimum MLSS is rarely provided to plant staff and operators, who have to determine the target MLSS based on their experience or using a trial-and-error approach.	**Provide target MLSS:** If SRT control is MLSS-based, the target MLSS should be initially provided by the supplier or consultant. The target MLSS could be modified later based on operating experience or when changes in influent characteristics or effluent limits require an adjustment of the SBR operation.
7. **Inadequate design of pre-treatment systems:** In a large number of facilities, inadequately designed bar screens, comminutors, and other pre-treatment systems caused accumulation of floating and coarse material in the SBRs, flow metering inaccuracies, and frequent O&M problems.	**Design pre-treatment systems taking into account operating conditions:** For example, if the plant is going to be part-time staffed, self-cleaning pre-treatment units should be selected and back-up pre-treatment capacity should be considered.
8. **Lack of automation for selection of wasting time:** In most facilities evaluated, the operators manually select the wasting time. The WAS time is changed to increase or decrease the MLSS, thereby controlling the SRT of the system.	**Develop a system for automatic WAS control:** Sludge wasting can take place during React, Settle, Draw, or Idle (i.e., when the sludge is completely mixed or settled). An automatic SRT-control system can be developed to control WAS time. The system can be based on online measurements of MLSS concentration during the MIX period and if necessary in the WAS line. Using the WAS pump capacity and these SS measurements, the time for wasting can be automatically set to meet the target SRT.
9. **Potential secondary phosphorus release in aerobic digesters:** A large percentage of the facilities evaluated used aerobic digesters for sludge treatment. When biological phosphorus removal is used, a considerable portion of the phosphorus is accumulated in the biomass and removed in the WAS. If the WAS is aerobically digested prior to disposal, inefficient operation of the digesters may result in phosphorus being recycled back to the plant headworks.	**Assess the impact of sludge recycle streams and evaluate aerobic digestion strategies:** sampling from the sludge recycle streams at SBR facilities is unusual. Therefore, at this stage, the impact of aerobic digestion on P removal is not easily quantifiable. It is recommended to assess this impact and if found necessary, investigate optimum operating strategies for the SBR – aerobic digestion treatment system in bio-P removal plants.
10. **Partial failure of the SBR control program during peak flows**: Automatic control systems at some facilities worked properly under average diurnal flow variations, but failed to adjust to peak flow conditions (e.g., high flows caused by I/I during rainfall events). This led to high effluent concentrations during the storm event.	**Improve control system programming:** The time-oriented nature of the SBR allows the system to have flexibility to achieve a wide range of treatment objectives including BOD, suspended solids, nitrogen, and phosphorus removal under various flow regimes. The facilities where this concern was reported had the control equipment in place. In these cases, appropriate settings should be entered in the control program to allow the SBR cycles to adjust to peak flow conditions.

Figure 2
Unit construction cost as a funcion of plant capacity
Comparison between SBR evaluation and EPA figures



Typical costs for continuous flow municipal activated sludge plants (ASPs) were obtained from the literature and used in this comparison (11). Two levels of treatment were considered:

- advanced wastewater treatment with nutrient removal (BOD/SS/TP/TN = 10/10/3/5), and
- advanced secondary treatment with nutrient removal (BOD/SS/TP/TN = 25/25/3/5).

These construction costs are valid for plants with flow rate capacities of over 1800 m^3/d and are shown in Figure 2 as a range (EPA continuous flow ASPs). The upper and lower limits of this range represent the unit costs for the most and less stringent of these two effluent requirements, respectively. It should be pointed out that most SBR plants evaluated in Phase 1 met the most stringent of these two limits.

The values reported from all sources were actualized to 1998 values using published construction cost indexes (12).

This comparison indicates that the construction costs recorded during Phase 1 of this program fit between the values derived from the EPA equation for industrial SBRs (corrected according to equivalent oxygen demand) and those from actual SBR facilities reported by EPA (EPA municipal SBRs 92). Also, the construction costs recorded during Phase 1 matched very closely those proposed for municipal SBR facilities in 1983 (EPA Municipal SBRs 83).

The construction cost differences between SBRs and continuous flow ASPs are drastic. However, this comparison should only be used as an indication of the relative construction costs of SBRs and continuous flow ASPs. Additional cost analyses involving a larger number of facilities and more detailed construction cost information will be required. More up to date information from continuous flow ASPs achieving N and P removal should also be used (the EPA equations used for this comparison are from 1980). Also, life cycle cost analyses using operation and maintenance data should be performed.

Conclusions

The number of SBR plants in Canada is growing at a fast pace. Unlike continuous flow activated sludge systems, there was little well documented evidence on SBR performance, costs, reliability, and optimal design and operations.

During Phase 1 of this program, the authors found that SBRs are cost-effective treatment systems that tend to meet and exceed their effluent criteria.

However, in spite of excellent removal rates and effluent limit compliance achieved by the SBR facilities evaluated, there is still room for optimization.

The development of a guideline manual with standards for selection, design, evaluation, and operation of SBRs should be a priority as the number of SBR plants in Ontario and North America in general is continuously increasing. Phase 3 of this program will tackle this task.

From the list of concerns compiled, lack of proper operator training has the largest impact on operating costs and effluent quality. The development of SBR operator training programs to complement traditional activated sludge operator training with SBR-specific theoretical and practical concepts should be addressed.

A methodology to evaluate the actual treatment capacity of existing SBR plants should be developed. Operation strategies for process optimization should be investigated. These two tasks will be addressed in Phase 2 of this program for Evaluation & Optimization of Design/Operation of SBRs for Wastewater Treatment.

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