J. ENVIRONMENTAL SYSTEMS, Vol. 28(1) 25-42, 2000-2001

SEQUENTIAL BATCH REACTORS—TECHNOLOGY AND PERFORMANCE EVALUATION

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ABSTRACT

Data were collected from nineteen municipal and private Sequential Batch Reactor (SBR) wastewater treatment plants in the United States. The average design flow for these plants ranged from 0.028 to 3.0 mgd. The average effluent BOD_5 concentration ranged from 3.0 to 14.0 mg/l with removals ranging from 88.9 to 98.1 percent. The average effluent TSS ranged from 3.7 to 20.2 mg/l (excluding one plant) and removals for TSS were between 84.7 to 97.2 percent. Effluent NH3-N concentrations ranged from 0.29 to 1.68 mg/l and ammonia removals were between 90.8 to 96.8 percent. The average effluent phosphorus concentrations were between 0.53 to 4.27 mg/l. The SBR performance data shows that typical SBR designs can meet effluent BOD_5 and TSS concentrations of less than 10 mg/l. With some additional design modifications, SBRs can successfully nitrify to limits of 1 to 2 mg/l NH3-N. The limited data available suggests that SBRs achieve denitrification when properly designed and achieve phosphorus removal without chemical addition to less than 1.0 mg/l. The SBR market is competitive, which will encourage cost-effectiveness when compared to competing technologies. Current designs are based on several factors, including fundamental process knowledge, manufacturer's supplied information, actual plant performance experience, and permit requirements.

INTRODUCTION

A sequencing batch reactor (SBR) is an activated sludge biological treatment process that is applicable to treatment of municipal and industrial wastewater for small to medium flowrates (0-5 mgd). There are approximately 170 wastewater treatment facilities in the United States which employ the SBR technology [1]. Approximately forty of these SBR systems are designed or operated for Biological Nutrient Removal (BNR).

SBRs can be modified to provide secondary, advanced secondary treatment, nitrification, denitrification, and biological nutrient removal (BNR). SBR manufacturers have adapted various configurations and sequence of batch treatment cycles. Some systems use a continuous inflow and provide a baffle to minimize short-circuiting. SBRs were originally configured in pairs so that one reactor was filling during half of each cycle (while the wastewater in the other reactor was reacting, settling and being decanted). The modified configurations available include one SBR with an influent surge/holding tank; a three SBR system in which the fill time is one-third of the total cycle time; and a continuous inflow SBR. An SBR treatment cycle consists of a timed sequence which typically includes the following steps: FILL, REACT, SETTLE, DECANT, IDLE. When biological nutrient removal (BNR) is desired, the steps in the cycle are adjusted to provide anoxic or anaerobic periods within the standard cycles.

This study was conducted to evaluate the technology and performance of Sequencing Batch Reactors (SBRs) for BOD_5, suspended solids, nitrification, and nutrient removal. In evaluating the performance of SBRs, information was collected from well-established plants that had nutrient data available. There are few plants with total nitrogen or phosphorous permit limits, so the data for these nutrients are limited. For technology evaluation, information was compiled from the literature, equipment manufacturers, and wastewater treatment personnel.

BACKGROUND

SBR technology is not new. In fact, it preceded the use of continuous-flow activated sludge technology. There are many examples of batch processes in the history of municipal wastewater treatment. Many difficulties were associated with operating these fill-and-draw systems, most resulting from the valving required to switch flow from one tank to the other and initiating different periods required in these batch systems. As a result, batch systems never became popular in large-scale municipal plants. By 1920, when larger facilities were being constructed, batch systems were no longer considered viable. The birth and widespread use of continuous-flow systems resulted primarily from operational considerations and not from any process-related weaknesses of the batch systems.

New hardware devices, such as motorized valves, pneumatically actuated valves, level sensors, flowmeters, automatic timers, and microprocessors or process controllers have been developed and have prompted reevaluation of what is now known as sequencing Batch Reactors (SBRs).

Although limited use of SBRs began in the 1960s, it was not until the early 1980s that the technology became more widely accepted and used. After early acceptance and use, U.S. Environmental Protection Agency (USEPA) expressed increased interest in this technology especially in the comparative costs and performance [2].

The USEPA funded a development project in 1980, conducted by the University of Notre Dame, to evaluate batch treatment of municipal wastewater. The project involved the conversion of an existing 0.4 MGD continuous flow activated sludge facility at Culver, Indiana, into a two-tank SBR [3]. Results of this twenty-month project led to the use of SBR technology at several other municipal facilities.

Recently, concern over nutrient discharges to natural water systems and more stringent regulations has led to modifications in SBR systems to achieve nitrification, denitrification, and biological phosphorous removal.

DESCRIPTION OF SBR PROCESS

The SBR is a modification of conventional continuous-flow activated sludge treatment system. The SBR is a fill-and-draw system that operates in a batch rather than in a continuous mode. A conventional activated sludge (CAS) system carries out aeration and sedimentation/clarification simultaneously in separate tanks. The SBR process performs these operations sequentially in the same tank. An SBR system is comprised of either a storage tank and an SBR tank, or a minimum of two SBR tanks to handle continuous influent. A modification of the SBR process, the Intermittent Cycle Extended Aeration System (ICEASR), manufactured by Austgen Biojet, operates with a continuous feed and intermittent withdrawal. A baffle wall installed in the ICEASR treatment tank buffers this continuous inflow [4].

The SBR process is usually preceded by some type of preliminary treatment such as screening, communition or grit removal. Because the SBR process operates in a series of timed steps, reaction and settling can occur in the same tank, eliminating the need for a final clarifier. The SBR technology has the advantage of being very flexible in terms of matching reaction and settling times to the strength and treatability characteristics of a particular waste stream.

Complete SBR package systems are available in the United States from several manufacturers including Aqua-Aerobic Systems, Austgen Biojet, Fluidyne, Jettech, Purestream, and Transenviro [1, 5-8].

Cycle Operation

A typical SBR cycle for BOD_5 and TSS (Total Suspended Solids) removal is divided into the following five steps:

1. Fill—Raw wastewater flows into the tank and mixes with mixed liquor held in the tank. Aeration is on and biological degradation begins to take place.
2. React—The mixed liquor is aerated for a specified time until the design effluent BOD_5 is reached.
3. Settle—Aeration is stopped and the solids settle to the bottom of the tank.
4. Draw—Treated effluent is decanted from the top of the tank and discharged.
5. Idle Time between cycles—Idle is used in multiple tank configurations to adjust cycle times between SBR reactors. Sludge wasting can occur during idle, draw or settle. Differences in fill time may exist due to diurnal fluctuation. Other minor variations in individual SBR tank cycles are regulated with the idle step.

Figure 1 illustrates this sequence of events [9]. The ICEASR modification does not have a separate idle or fill phase since it uses continuous fill. The baffled pre-reaction compartment in an ICEASR tank permits wastewater to enter continuously without causing a significant disturbance during settle and draw.

DESCRIPTION OF EQUIPMENT

The SBR system consists of one or more tanks equipped with a reactor inlet, aeration equipment, a sludge draw-off mechanism, a decant mechanism for removing clarified supernatant, and a control mechanism to time and cycle the processes. Tanks may be constructed of steel or concrete. The shape is not critical and SBRs can be retrofitted into existing rectangular or circular tanks.

SBR manufacturers offer a variety of features designed to meet different performance needs. Decant mechanisms and air diffuser designs may differ markedly between manufacturers. Decant mechanisms include a submerged outlet pipe with automated valves, weir troughs connected to flexible couplings, floating weirs, movable baffles, tilting weirs and floating submersible pumps [2].

Aeration systems include jet aeration, fine bubble, and coarse bubble diffused aeration, and mechanical aeration. Jet aeration can provide either aeration or mixing without aeration in one unit by operating the pumping system with the air supply on or off. Some manufacturers supply separate mixing mechanisms for this purpose. One variation to the typical aeration system is retrievable aerators, which allow aerators to be cleaned or replaced without emptying the SBR [10]. Other systems include backflush mechanisms to clean the aerators.

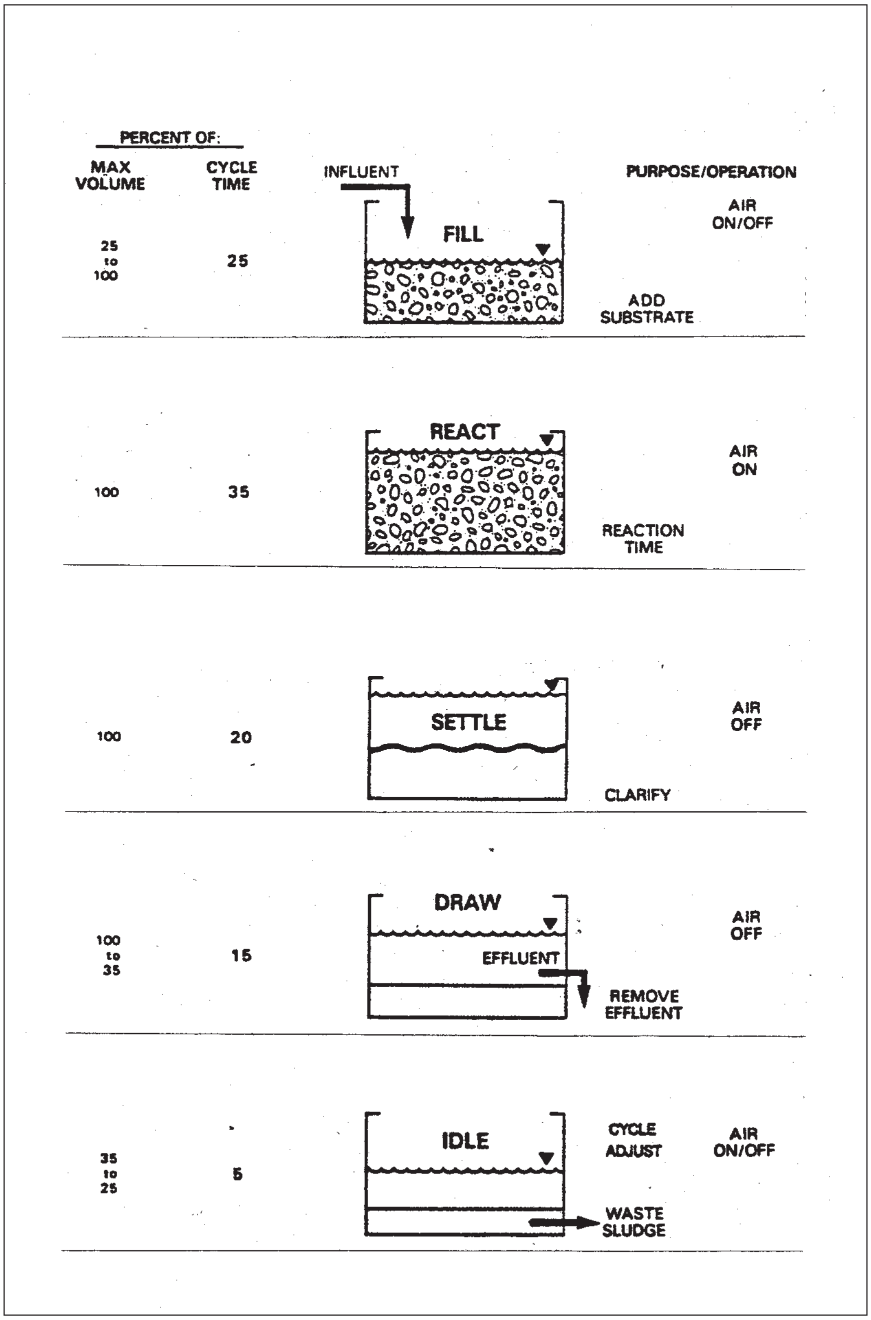

Figure 1. Typical SBR Operation for One Cycle

ADVANTAGES AND DISADVANTAGES OF SBR SYSTEM

Advantages

The SBR system has advantages compared to a conventional activated sludge (CAS) system and offers much flexibility. Some of the advantages are:

- Early in plant lifetime, when plant flow may be significantly below design flow, level sensors that control cycle times can be set at a lower level. Cycle times would be the same as design, but power would not be wasted in over-aeration [10].
- A greater dissolved oxygen driving gradient exists during the first part of the react cycle due to the low/zero dissolved oxygen (DO) concentration during anoxic fill. This results in somewhat higher oxygen transfer efficiencies for a given size of aeration equipment [3].
- An SBR tank operates as an equalization tank during fill and can therefore tolerate peak flows and shock loads of BOD without degradation of effluent quality.
- A return activated sludge (RAS) pumping system is not needed since aeration and settling occur in the same tank. Sludge volume and sludge age are controlled by sludge wasting.
- Periodic discharge of flow may enable effluent to be held until permit limitations are met.
- Growth of filamentous organisms which cause sludge bulking can be controlled by adjustments in the food-to-Giomass ratio (F/M) and aeration time during the fill cycle.
- SBR systems may require less physical space than a CAS system when considering the entire plant. SBR systems can be retrofitted into a wide range of existing tank structures.

Disadvantages

The following are potential disadvantages of the SBR system. These are usually overcome through proper design, process adjustments, or equipment modifications:

- Problems with sludge settling will result in solids in the effluent and a loss of the process performance.
- Floating decant mechanisms may be subject to mechanical problems. Fixed systems require that the sludge blanket be below the intake before decanting. Both systems may draw in trapped solids when first starting the decant phase.
- Surface freezing of controls and decant mechanisms may occur in cold climates.
- The relatively high flow rate during decant may require flow equalization or over design when followed by disinfection or filtration facilities [6].

- With long SRTs, denitrification may occur during settling and sludge may begin to rise due to the formation of nitrogen gas. This is usually aggravated at elevated temperatures [11].
- Aeration equipment must be larger, since process air must be supplied over a shorter period.
- Effluent pipes must be oversized where decant flows are much higher than normal inflow.

DESIGN

Standard SBR systems have been consistently able to achieve removals of greater than 90 percent of BOD_5 and TSS. An SBR system can be designed to achieve nitrification, denitrification, and biological phosphorus removal, in which case adjustments to the standard operating strategies and/or design modifications are required. These modifications may include additional plant capacity and equipment and are included in the design of a system.

Cycle times are an essential aspect of an SBR system design. The basic steps in an SBR cycle vary both by manufacturer and design conditions. Total cycle times may be constant or vary with flow. The percent of the reactor volume that is decanted during each cycle (percent decant) is a design parameter important to batch systems. The size of the reactor volume is determined by design flow requirements, the design volume occupied by settled MLSS, and a design decant depth.

In a multi-tank system, air piping may be arranged so that one blower can aerate more than one reactor. Table 1 shows the sequence of events in a three-tank system which offsets the REACT phase in each basin [2].

Other important SBR design criteria are similar to those used in the design of a conventional activated sludge treatment facility. These include hydraulic retention time (HRT), solids retention time (SRT), MLSS concentration, nutrients availability, influent wastewater characteristics, and effluent requirements

Design Criteria

The following design criteria generally was used to design SBR systems depending on the effluent requirements:

BOD_5 Loading:	30 to 60 lbs BOD_5/100 ft3/day
SRT:	5 to 30 days
Detention time:	6 to 12 hours
F/M:	0.05 to 0.5 lbs BOD_5/lb MLSS
Cycle time (conventional):	4 to 6 hours
Cycle time (BNR):	6 to 8 hours

Secondary sludge quantities depend on the system operating conditions (SRT and organic load).

Table 1. Sequence of Events in a Three Tank System

Tank Number		
1	2	3
		Settle
Fill	React	
		Draw
		Idle
	Settle	
React		Fill
	Draw	
	Idle	
Settle		
	Fill	React
Draw		
Idle		
		Settle
Fill	React	
		Draw
		Idle
	Settle	
React		Fill
	Draw	
	Idle	
Settle		
	Fill	React
Draw		
Idle		

SBR Designs with Nitrification

A standard SBR system is designed to reduce the BOD_5 and TSS concentrations of a wastewater. Some standard systems are designed for nitrification as well. Table 2 lists typical steps for a standard SBR cycle with nitrification. This table also describes the purpose of each step and the conditions that should be present to achieve that purpose. Nitrification can only occur under conditions of adequate dissolved oxygen (minimum 1 to 2 mg/l) and sufficiently long SRT (5 to 20 days or more depending upon temperature) to ensure growth of nitrifying bacteria. In an SBR system, nitrification takes place during the REACT phase and periods of aerated fill [9, 11]. The cycles designed by the majority of the SBR manufacturers studied deviate from the standard cycle of Table 2 in one or more ways. Other differences occur in tank configuration and design parameters.

Table 2. Typical Cycle for a Standard SBR with Nitrification

Step	Conditions	Purpose
FILL	Influent flow into SBR Aeration Time — half of cycle time	Addition of raw wastewater to the SBR, BOD removal and nitrification
REACT	No influent flow to SBR Aeration Time typically — 1 to 2 hours (varies widely depending on BOD removal kinetics and waste strength	Biological BOD removal and nitrification
SETTLE	No influent flow to SBR No aeration Time — approx. 1 hour (depends on settling characteristics	Allow suspended solids to settle, yielding a clear supernatant
DRAW	No influent flow to SBR No aeration Effluent is decanted Time — 1 hour (varies)	Decant — remove effluent from reactor; 10 to 50 percent of the reactor volume is typically decanted, depending on hydraulic considerations and SBR manufacturer's design
IDLE	No influent flow to SBR No aeration Sludge is wasted Time — variable, determined by flow rate	Multi-tank system, allows time for one reactor to complete the fill step before another starts a new cycle. Waste sludge — remove excess solids from reactors

A typical total cycle time is 4 to 6 hours.

SBR Designs for Biological Nutrient Removal

When a wastewater treatment facility must meet phosphorus or total nitrogen limits, SBR designs become somewhat more complex. Operating strategies for nitrification and denitrification are similar for most systems. Figure 2 illustrates a typical denitrification cycle for an SBR [2]. For denitrification to occur, an anoxic period in the SBR is necessary following BOD_5 removal and nitrification. The dissolved oxygen (DO) is reduced to less than 0.5 mg/l during SETTLE, DRAW, and IDLE periods.

Biological phosphorus removal requires an anaerobic period. This step can be included in an SBR system. Table 3 lists typical steps for a SBR cycle that includes

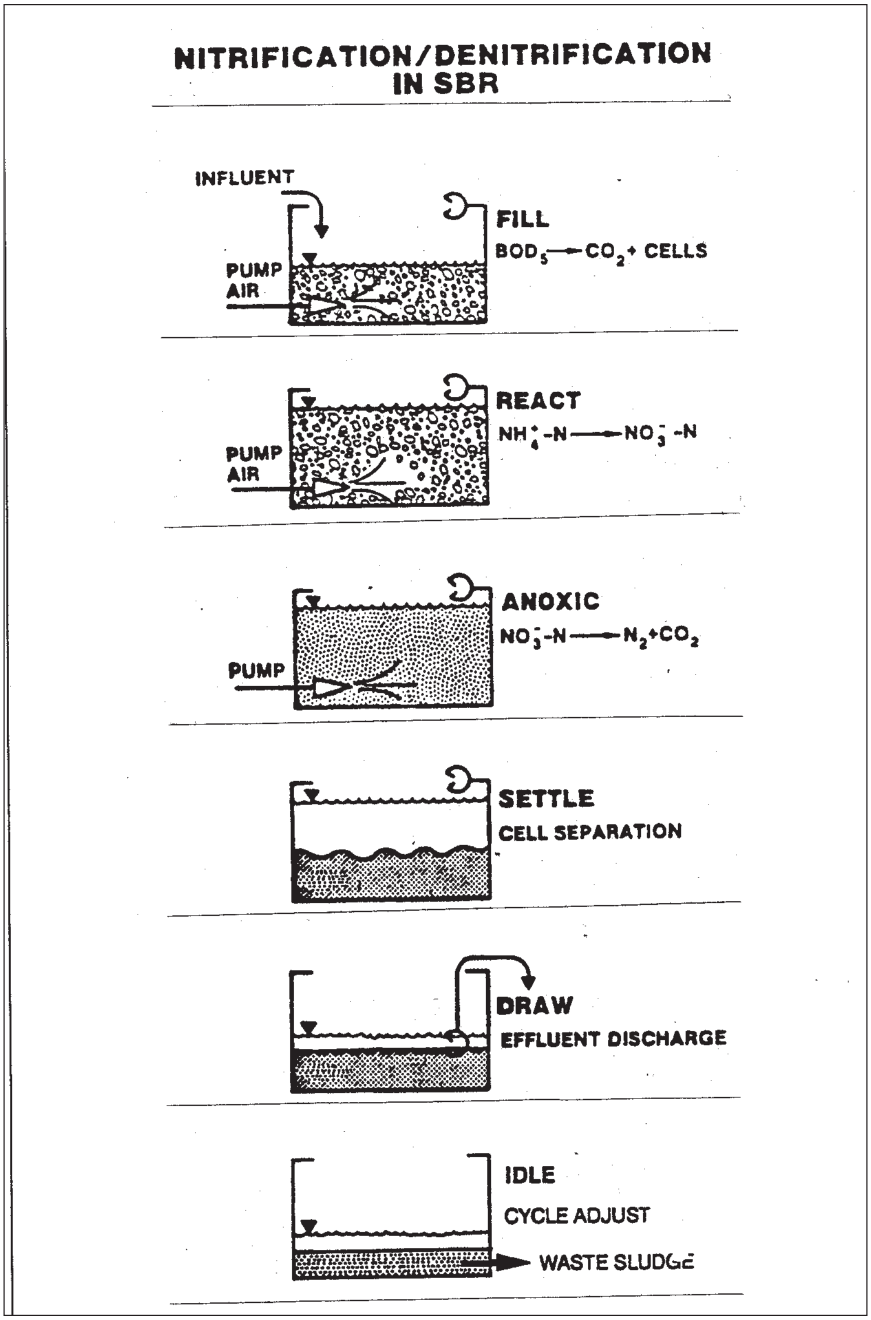

Figure 2. Denitrification cycle for SBR.

biological nutrient removal. This table also describes the purpose of each step and the conditions that should be present to best achieve that purpose. To incorporate the phosphorus removal strategy, the anaerobic period will be longer than the anoxic period required for denitrification. Two additional steps can be added to maximize phosphorus removal. The first step is a separate anaerobic period following decant which releases some phosphorus to the liquid above the sludge. This step is followed by a second decant step where supernatant with phosphorus is drawn off for separate chemical treatment, and phosphorus starved sludge is returned in the fill period. Sludge wasting occurs following the aerobic step.

In addition to the information presented in Table 3, it is essential to biological phosphorus removal that sludge be wasted under aerobic conditions. The maximum amount of phosphorus is incorporated into the sludge under aerobic conditions. For similar reasons, an aerobic digester that maintains an aerobic environment for sludge is used with the SBR plants since digester supernatant is normally recycled.

Chemical addition for phosphorus removal is sometimes used, especially when effluent permit limitations are 2.0 mg/l or less. When properly operating, an SBR can achieve high rates of biological phosphorus removal, though removal rates may decrease during periods of storm flow. Larger reactors, with longer cycle times, would be required if biological phosphorus removal were utilized. The additional cost of the larger reactors, however, may be favorable compared to the cost of continuous chemical addition. This trade-off needs to be evaluated on a case-by-case basis during the design phase. SBR manufacturers typically offer systems that incorporate nutrient removal and deviate in one or more ways from the cycle described in Table 3.

PERFORMANCE DATA

Performance data were collected from nineteen municipal and private SBR wastewater treatment plants in the United States. The average design flow for these plants ranged from 0.028 to 3.0 mgd. The average mixed liquor suspended solids (MLSS) concentration for eight of the plants ranged from 2000 to 3600 mg/l. The food to Giomass ratio (F/M), available for six plants, ranged from 0.01 to 0.09 lb BOD/lb MLSS-day. The solids retention time (SRT) was available for two plants, which were designed for nitrification, denitrification, and biological phosphorus removal. The SRT for these two plants ranged from seventeen to thirty days. Influent and effluent composite samples at these plants were analyzed weekly according to Standard Methods [12] for BOD_5 TSS, ammonia nitrogen, nitrate and nitrite nitrogen, TKN, total phosphorus, pH, and temperature.

Tables 4 and 5 indicate process reliability—the percent of time when the summer and winter monthly average effluent concentration of the given pollutants met the criteria shown in the first column. These tables were developed from the data discussed in this section, although some start-up data were eliminated.

Table 3. Typical SBR Cycle for Biological Nutrient Removal

Step	Conditions	Purpose
UNAERATED FILL	Influent flow into SBR No aeration Time — approx. 1.5 hours Mixed	Addition of wastewater to the SBR, continuation of anoxic or anaerobic conditions to allow denitrification and to encourage the growth of phosphorus-removing bacteria
AERATED FILL	Influent flow into SBR Aeration (DO > 2 mg/l) Time — half of the total cycle time minus the unaerated fill time	Addition of wastewater to the SBR, BOD removal and nitrification, phosphorus uptake
REACT	No influent flow to SBR Aeration (DO > 2 mg/l) Sludge may be wasted Time — typically 1 to 2 hours (varies widely)	Biological BOD removal and nitrification, phosphorus uptake
SETTLE	No influent flow to SBR No aeration Sludge is wasted Time — approx. 1 hour	Allow suspended solids to settle, to yield a clear supernatant, decrease the DO concentration to encourage denitrification; waste sludge under aerobic conditions with maximum phosphorus content
DRAW	No influent flow to SBR No aeration Effluent is decanted Time — 1 to 2 hours	Remove effluent from reactor, decrease the DO concentration further to encourage denitrification and the growth of phosphorus-removing bacteria
IDLE	No influent flow to SBR No aeration. Time — 1 to 15 minutes (typically occurs during the end of the DECANT step)	Allow coordination of cycles in multi-tank system, maintain a low DO concentration to encourage denitrification and the growth of phosphorus-removing bacteria

A typical total cycle time is 6 to 8 hours

The performance data for nineteen plants are summarized in Table 6. Twelve of the nineteen plants have effluent ammonia limits, while three are required to monitor for ammonia. The effluent limits ranged from 1.5 to 10.0 mg/l during the summer months. Two plants have nitrate plus nitrite limits and two have total inorganic nitrogen limits. Effluent limits on total nitrogen are required for two plants. Five plants have effluent phosphorus limits that ranged from 0.5 to 2.0 mg/l.

BOD$_5$ and TSS removal ranged from 85 to 98 percent and consistently met effluent requirements. These removal rates were similar to those achieved by conventional activated sludge systems. The average performance data is summarized below:

BOD$_5$ removal	89-98%
TSS removal	85-97%
Nitrification	91-97%
Total nitrogen removal	> 75%
Biological phosphorus removal	57-83%

Table 4. SBR Unit Reliability (Summer)
Monthly Average Data (%)

	BOD$_5$ mg/l	TSS mg/l	TKN mg/l	NH$_3$-N mg/l	NO$_3$+NO$_2$–N mg/l	P mg/l	TN mg/l
< .5 mg/l	0.0	0.0	16.7	42.6	6.7	24.4	0.0
< 1 mg/l	0.0	0.0	16.7	61.7	53.3	53.7	0.0
< 2 mg/l	1.4	2.1	16.7	77.4	68.9	78.0	0.0
< 3 mg/l	14.4	7.6	16.7	87.8	75.6	82.9	0.0
< 4 mg/l	26.7	16.7	16.7	91.3	91.1	85.4	0.0
< 5 mg/l	34.9	25.0	83.3	92.2	93.3	95.1	0.0
<10 mg/l	69.9	61.8	83.3	98.3	97.8	100.0	25.0
<20 mg/l	96.6	88.2	83.3	100.0	97.8	100.0	75.0
<30 mg/l	98.6	93.8	100.0	100.0	97.8	100.0	91.7

Table 5. SBR Unit Reliability (Winter)
Monthly Average Data (%)

	BOD$_5$ mg/l	TSS mg/l	TKN mg/l	NH$_3$-N mg/l	NO$_3$+NO$_2$–N mg/l	P mg/l	TN mg/l
< .5 mg/l	0.0	0.0	0.0	45.5	25.5	24.6	0.0
< 1 mg/l	0.0	0.0	0.0	65.2	51.7	50.8	0.0
< 2 mg/l	0.7	2.0	0.0	76.8	68.1	80.3	0.0
< 3 mg/l	12.2	7.4	0.0	82.1	78.7	86.9	0.0
< 4 mg/l	23.7	16.8	0.0	83.0	89.4	93.4	0.0
< 5 mg/l	35.3	20.8	0.0	86.6	89.6	96.7	0.0
<10 mg/l	65.5	55.0	0.0	92.6	95.7	100.0	38.5
<20 mg/l	89.2	82.6	100.0	100.0	100.0	100.0	100.0
<30 mg/l	95.7	90.6	100.0	100.0	100.0	100.0	100.0

Table 6. Summary of Performance Data

Plant	Flow mgd	% of Design Flow	BOD$_5$ (mg/l)			TSS (mg/l)		
			INF	EFF	% REM	INF	EFF	% REM
Plant 1	0.293	98					11.4	
Plant 2	0.116	49	324	8.4	97.4	208	7.2	96.5
Plant 3	0.294	57	229	7.6	96.7	287	15.3	94.7
Plant 4	0.055	50	192	12.4	93.5	260	7.4	97.2
Plant 5	0.26	87	256	8.0	96.7	183	9.6	94.8
Plant 6	2.6	87	158	5.0	96.8	136	7.0	94.9
Plant 7	0.7	93	108	3.2	97.0	56	3.7	93.4
Plant 8	0.195	56		12.0			12.5	
Plant 9	0.5	67	130	4.2	96.8			
Plant 10	0.575	72	195	3.8	98.1	169	7.6	95.5
Plant 11	0.39	75		3.0			52.0	
Plant 12	0.417	60	103	3.5	96.6			
Plant 13	1.8	90	218	6.2	97.2	188	10.6	94.4
Plant 14	0.73	81	105	11.7	88.9		9.8	
Plant 15	0.004	8	131	4.8	96.3	77	4.8	93.8
Plant 16	0.035	78	185	9.1	95.1	132	20.2	84.7
Plant 17	0.026	93	148	5.6	96.2	135	6.5	95.2
Plant 18	0.006	24		14.0			16.1	
Plant 19	0.559	56	160	6.6	95.6	131	5.2	96.0

M = monthly maxima
S = summer average
W = winter average
CH = chemical added
TN = total nitrogen

NH_3–N (mg/l)			TKN (mg/l)			NO_3–N+NO_2–N (mg/l)		Total P (mg/l)		
INF	EFF	% REM	INF	EFF	% REM	INF	EFF	INF	EFF	% REM
									0.88	
25.3	1.07	95.8	67.8	11.65	82.9		2.11	12.0	4.3	64
						TN = 13.5				
39.1	1.68	95.7					3.11			
	0.92					TN = 6.2			1.01	
	0.45									
	1.74									
	0.45									
	0.94S 4.92W						5.6		1.40	
15.8	1.24	92.2								
	6.6M								1.12	
10.1	0.51	95.0						3.3	0.78	76CH
	0.17									
7.8	0.42	94.6								
3.1	0.285	90.8						2.6	0.45	83CH
21.2	0.67	96.8					3.55	4.3	1.85	57
			17.5	4.4	74.9	0.8	3.69			
							2.75			
12.0	0.59	95.4								

The nineteen plants evaluated in the study were all originally designed for nitrification and are believed to be presently operating under conditions favoring nitrification. Influent and effluent ammonia nitrogen data were available for seven plants. Removal ranged from 90.8 to 96.8 percent. The average effluent ammonia nitrogen concentration for each of the seven plants was less than 2.0 mg/l. The low effluent concentrations indicated that nitrification was occurring.

Effluent ammonia data concentrations for six plants ranged from 0.17 to 1.74 mg/l. These low concentrations indicate that nitrification was occurring, at least during the summer months. The twelve plants with effluent ammonia limits were consistently able to meet their requirements.

Limited information was available to evaluate denitrification in SBRs. Few of the plants surveyed have effluent limitations on nitrate or total nitrogen, and therefore do not measure for these constituents. Two of the nineteen plants evaluated measured effluent total nitrogen, and six plants measured effluent nitrate and nitrite nitrogen. Effluent nitrate and nitrite nitrogen data ranged from 2.11 to 5.6 mg/l for the six plants.

Under denitrifying conditions, nitrate would be converted to nitrogen gas and removed from the wastewater. Significantly low effluent ammonia and nitrate nitrogen concentrations (much less than the influent ammonia nitrogen concentration) would indicate that both nitrification and denitrification were occurring. Data from plants 2, 4, and 16 indicate that denitrification occurred at these plants. Relatively low effluent concentrations of nitrate plus nitrite nitrogen and total nitrogen at plants 3, 5, 9, and 18 indicate that denitrification was probably occurring, to some degree, at these plants. Three plants—plants 1, 7, and 13—were designed for denitrification. Information on nitrate or total nitrogen, however, was not available and denitrification could not be verified.

Phosphorus removal has become an important concern in many areas, most notably in states surrounding the Great Lakes and Chesapeake Bay. Six of the sixteen plants evaluated have effluent phosphorus limitations. In addition, plant 5 is required to monitor quarterly for phosphorus.

Influent phosphorus data was very limited. Four plants that measured influent phosphorus concentrations had concentrations from 2.6 to 12.0 mg/l. Eight of the plants measured effluent phosphorus levels. Two of these plants—plants 12 and 15—add ferric or ferrous chloride for phosphorus removal, though plant 12 only adds the chemical during storm events. Effluent phosphorus concentrations for the eight plants ranged from 0.45 to 4.30 mg/l. The seven plants that did not add ferric or ferrous chloride, and plant 12 during normal flows, rely solely on biological phosphorus removal. The relatively low concentration of phosphorus in the effluent indicate that at least some phosphorus is being removed biologically, beyond that normally expected from sludge wasting. Plants 1, 7, 11, and 12 usually met their effluent phosphorus requirements, with an occasional excursion beyond limits. Plant 2's limit of 2.0 mg/l in the summer was rarely met, although the plant averaged 64 percent removal of influent phosphorus.

FINDINGS AND CONCLUSIONS

1. Sequencing Batch Reactors are designed for biochemical oxygen demand (BOD) and total suspended solids (TSS) removal from typical domestic wastewater for small (< 5 MGD) municipal and private installations. Modifications to the basic design can be made to allow nitrification, denitrification, and biological phosphorus removal to occur. Cycle time, design parameters, and equipment vary among manufacturers. Influent wastewater characteristics, effluent requirements, and site specific conditions influence design development.

2. The average effluent BOD_5 concentration ranged from 3.0 to 14.0 mg/l with removals ranging from 89 to 98 percent. The average effluent TSS ranged from 3.7 to 20.2 mg/l, excluding one plant with an average effluent TSS of 52 mg/l. No influent TSS data was available for this plant. Removals for TSS ranged from 85 to 97 percent.

3. Eight plants measured both influent and effluent ammonia-nitrogen (NH3-N) concentrations. Effluent NH3-N concentrations for these eight plants ranged from 0.285 to 1.68 mg/l. Ammonia removal ranged from 91 to 97 percent.

4. Denitrification data were limited. One plant monitored both influent and effluent total nitrogen concentrations. Total nitrogen removal for this plant averaged 56 percent. Denitrification was occurring at three additional plants that measured both effluent nitrate-nitrite nitrogen (NO3 + NO2-N) and influent NH3-N.

5. Eight plants measured effluent phosphorus concentrations. The average effluent phosphorus concentrations ranged from 0.45 to 4.30 mg/l. Four plants measured both influent and effluent phosphorus concentrations. The average percent phosphorus removal ranged from 57 to 83 percent. Two plants added chemicals for phosphorus removal.

6. The SBR performance data shows that typical SBR designs can meet effluent BOD_5 and TSS concentrations of less than 10 mg/l. With some additional design modifications, SBRs can successfully nitrify to limits of 1 to 2 mg/l NH3-N. They also appear to achieve denitrification when properly designed and achieve phosphorus removal without chemicals to less than 1.0 mg/l, although data on both processes are limited.

7. SBRs flexibility to meet changing influent conditions due to ability to adjust cycles can be especially important for biological nutrient removal design and process optimization. Current SBR designs are typically very conservative with long HRTs, low F/Ms, and high MLSS.

8. SBR aeration design is different from a conventional activated sludge system, since all the process air must be supplied during the FILL and REACT cycles. Downstream processes following SBRs must be sized for higher flow rates due to high decant ratios unless flow equalization is used.

9. Current designs are based on several factors, including fundamental process knowledge, manufacturer's information, actual plant performance experience, and

permit requirements. State standards have not yet been developed for SBRs similar to those that many states have for conventional systems.

ACKNOWLEDGMENTS

The views/opinions expressed in this article are those of the authors and should not be construed as the opinions of the U.S. Environmental Protection Agency.

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