15
Sequencing Batch Reactor Technology

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CONTENTS

Abstract Such Sequencing Batch Reactor (SBR) processes as Aqua SBR, Omniflo, Fluidyne, CASS, ICEAS and their applicability on a treatment plant are considered in this chapter. Advantages and disadvantages and such design criteria as process parameters, construction of reactor, and process safety altogether with process performance, operation, maintenance, and costs altogether with packaged SBR for onsite systems are described.

Key Words Sequencing batch reactor • SBR • reactor construction • packaged SBR • Aqua SBR • Omniflo • Fluidyne • CASS • ICEAS.

1. BACKGROUND AND PROCESS DESCRIPTION

The sequencing batch reactor (SBR) is a fill-and-draw activated sludge system for wastewater treatment (1). The prototype for the activated sludge concept was developed on a fill-and-draw basis (2). Shortly after that initial study, the emphasis switched to continuous flow “conventional” activated sludge. in an SBR system, wastewater is added to a single

From: *Handbook of Environmental Engineering, Volume 10: Environmental Biotechnology*
Edited by: L. K. Wang et al., DOI: 10.1007/978-1-60327-140-0_15

"batch" reactor, treated to remove undesirable components, and then discharged. Equalization, aeration, and clarification can all be achieved using a single batch reactor. To optimize the performance of the system, two or more batch reactors are used in a predetermined sequence of operations. SBR systems have been successfully used to treat both municipal and industrial wastewater. They are uniquely suited for wastewater treatment applications characterized by low or intermittent flow conditions.

Fill-and-draw batch processes similar to the SBR are not a recent development as commonly thought. Between 1914 and 1920, several full-scale fill-and-draw systems were in operation. Interest in SBRs was revived in the late 1950s and early 1960s, with the development of new equipment and technology. Innovations in aeration devices, control logic, level sensors, solenoids, and hydraulic energy dissipators have surmounted the earlier limitations and revitalized interest in SBR technology (3). The resurgence of interest in SBRs was initially limited to small treatment applications; however, the need for greater treatment efficiencies due to increasingly stringent effluent limits has resulted in the adoption of SBR technology in installations as large as 660 L/s (15 MGD) (4).

The first modern, full-scale plant for SBR treatment of municipal wastewater in the United States was the Culver, Indiana, wastewater treatment facility (5). Retrofitted for the SBR process, operation was initiated in May 1980 (6). Since that time, SBR technology has become widespread in the United States, with more than 150 plants in operation (7). SBRs can be modified to provide carbonaceous oxidation, nitrification, and biological nutrient removal (BNR). Approximately, 25% of all SBR systems were designed to achieve nutrient removal (8).

The unit processes of the SBR and conventional activated sludge systems are the same. A US EPA report summarized this by stating that the SBR is no more than an activated sludge system that operates in time rather than in space (1, 3). The difference between the two technologies is that the SBR performs equalization, biological treatment, and secondary clarification in a single tank using a timed control sequence. This type of reactor does, in some cases, also perform primary clarification. In a conventional activated sludge system, these unit processes would be accomplished by using separate tanks.

The SBR consists of a self-contained treatment system incorporating equalization, aeration, anoxic reaction, and clarification within one basin. Intermittently fed SBRs consist of the following basic steps (1, 3, 9):

1. *Fill* – The fill operation consists of adding the waste and substrate for microbial activity. The fill cycle can be controlled by float switches to a designated volume or by timers for multireactor systems. A simple and commonly applied mode to control the fill cycle is based on reactor volume, resulting in fill times inversely related to influent flow rates. The fill phase can include many phases of operation and is subject to various modes of control, termed static fill, mixed fill, and react fill. Static fill involves the introduction of waste influent with no mixing or aeration. This type of fill method is most common in plants requiring nutrient control. In such applications, the static fill will be accompanied by a mixed fill stage such that the microorganisms are exposed to sufficient substrate, while maintaining anoxic or anaerobic conditions. Both mixing and aeration are provided in the react fill stage. The system may alternate among static fill, mixed fill, and react fill throughout the fill cycle.

2. *React* – The purpose of the react stage is to complete reactions initiated during fill. The react stage may comprise mixing or aeration, or both. As was the case in the fill cycle, desired processes may require alternating cycles of aeration. The length of the react phase may be controlled by timers, by liquid level controls in a multitank system, or when the desired degree of treatment has been attained, verified by monitoring reactor contents. Depending upon the amount and timing of aeration during fill, there may or may not be a dedicated react phase.
3. *Settle* – Liquid–solid separation occurs during the settle phase, analogous to the operation of a conventional final clarifier. Settling in an SBR can demonstrate higher efficiencies than a continuous-flow settler, since total quiescence is achieved in an SBR.
4. *Draw* – Clarified effluent is decanted in the draw phase. Decanting can be achieved by various apparatus, the most common being floating or adjustable weirs. The decanting capability is one of the operational and equipment limitations of SBR technology. Adaptation or development of equipment compatible with a fluctuating liquid level is required.
5. *Idle* – The final phase is termed as the idle phase and is only used in multibasin applications. The time spent in the idle phase will depend on the time required for the preceding basin to complete its fill cycle. Biosolids wastage will typically be performed during the idle phase.

A typical SBR process sequence schematic is shown in Fig. 15.1.

Denitrification can occur during the fill or react stages by cycling the aerators and during the settle and draw period. An obvious advantage of an SBR system with low flows is that the reactor contents can be retained until the desired level of treatment is achieved, providing that sufficient tankage exists to equalize or accommodate the additional influent.

2. PROPRIETARY SBR PROCESSES

SBR manufacturers have adapted the sequence of batch treatment cycles in various ways. One classification of SBR systems distinguishes those which operate with continuous feed and intermittent discharge (CFID) from those which operate with intermittent feed and intermittent discharge (IFID). IFID reactors are characteristic of the conventional fill-and-draw SBR reactors in that the influent flow to the reactor is discontinued for some portion of each cycle. The CFID reactors receive wastewater during all phases of the treatment cycle. A key design consideration with such systems is minimization of short-circuiting between influent and effluent. This is accomplished by locating the feed and withdrawal points at opposite ends of the tank, using rectangular reactors with length-to-width ratios of at least 2–1 and providing baffling.

The steps and associated conditions and purpose of a complete, typical cycle for a single tank operated as part of an IFID SBR system designed to achieve nitrification are described in Table 15.1. Nitrification takes place during the react phase and during the portions of the fill period when aeration is practiced.

Several proprietary process and equipment innovations have been developed to enhance treatment, simplify operation, or control biosolids characteristics (9–15). All proprietary SBR manufacturers will guarantee TN effluent concentrations $< 5\,\mathrm{mg/L}$. To illustrate the variety of options available, the proprietary aspects of five SBR manufacturers are discussed in the following section.

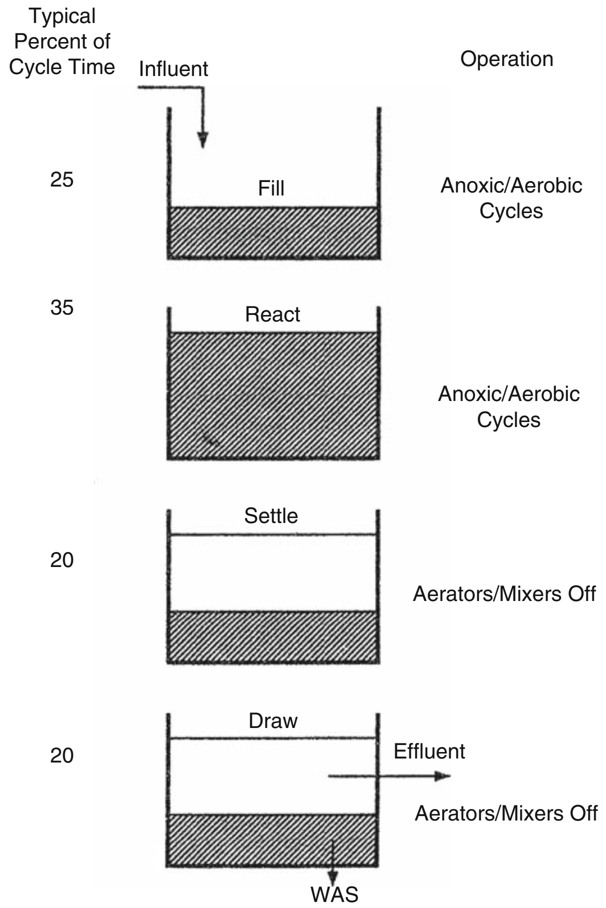

Fig. 15.1. Sequencing batch reactor (SBR) (Source: US EPA).

2.1. *Aqua SBR*

The Aqua SBR system provided by Aqua-Aerobic Systems, Inc. (11) is not a patented process, but the process does include a proprietary floating direct drive mixer, an effluent decanter, and a microprocessor control system. The floating decanter is designed to prohibit MLSS from entering the decanter during mixed or react phases, and it also withdraws supernate 30 cm (0.5 ft) below the water surface to mitigate scum losses to the effluent. If long settling times are provided, clear effluent can be obtained at high SVIs (Sludge Volume Index).

2.2. *Omniflo*

Jet Tech, Inc. (12) has developed SBR equipment and also has a patented logic control for their aeration system. The proprietary equipment includes dry pit pumps, headers, manifolds,

Table 15.1
Typical cycle for a single tank in a dual tank SBR system designed for nitrification (Source: US EPA)

Step	Conditions	Purpose
Fill	Influent flow into SBR Aeration occurs continually or intermittently Time = half of cycle time	Addition of raw wastewater to the SBR; COD removal and nitrification
React	No influent flow to SBR Aeration Time typically = 1–2 h (varies widely depending on nitrification kinetics, waste strength, and amount of aeration during fill)	Carbonaceous oxidation and nitrification
Settle	No influent flow to SBR No aeration Time = approximately1 h (depends on settling characteristics)	Allow SS to settle, yielding a clear supernatant
Draw	No influent flow to SBR No aeration Effluent is decanted Time = 1 h (variable)	Decant–remove clarified effluent from reactor; 15–25% of the reactor volume is typically decanted, depending on hydraulic considerations and SBR manufacturers design
Idle	No influent flow to SBR No aeration Sludge is wasted Time = variable (determined by flow rate)	Multi-tank system, which allows time for one reactor to complete the fill step before another starts a new cycle; waste sludge – remove excess solids from reactors

Note: A typical total cycle time is 4–6 h.

influent distribution hardware, jet aerators, and decanter apparatus. A proprietary aspect of the SBR process provided by Jet Tech is the Batch Proportional Aeration System. The function of this aeration system is to relate the volumetric change rate during the fill phase to the aeration capacity requirements by sensing the DO level in the reactor, optimizing nitrification and denitrification cycles.

2.3. *Fluidyne*

The Fluidyne Corp. (13, 14) offers a system with effluent decanters fixed in position to the reactor wall. The device excludes MLSS (missed liquor suspended solids) entry during aeration. These systems also commonly employ jet aeration with a combination of aeration and static conditions during fill.

2.4. *CASS*

The Cyclic Activated Sludge System (CASS) was developed and is marketed by Transenviro, Inc. CASS uses a similar sequence of operation as other batch technologies, but is configured with a proprietary captive selector reactor. The selector can also receive continuous flow. The selector is a baffled compartment that receives raw wastewater or primary effluent

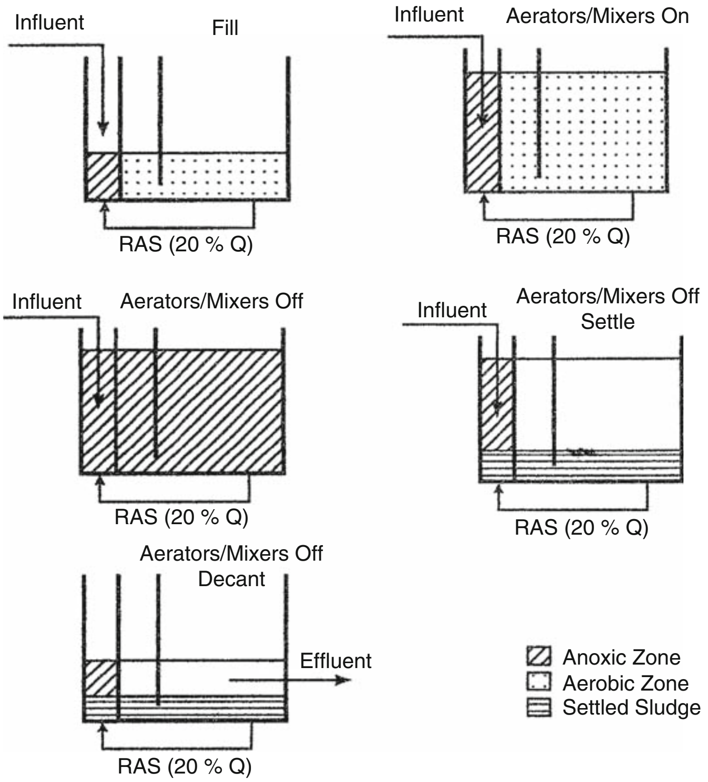

Fig. 15.2. Cyclical activated sludge system (CASS) (Source: US EPA).

where it is mixed with RAS or internally recycled MLSS. The selector then conveys flow to the reactor basin. By limiting or eliminating aeration to the selector, oxygen deficient conditions can be attained, while concurrent high substrate levels are maintained. This mode of operation is claimed to favor the propagation of floc formers and to inhibit growth of filamentous strains (15). A process schematic is presented in Fig. 15.2.

2.5. ICEAS

A modified batch system is available from Austgen-Biojet (ABJ). The ABJ system is termed as Intermittent Cycle Extended Aeration System (ICEAS) and is depicted schematically in Fig. 15.3. The distinguishing feature of ICEAS is that continuous inflow is incorporated in all phases, compared to other variable volume processes that do not receive continuous inflow. Noncontinuous inflow operation can be provided, if requested. Austgen-Biojet maintains that the continuous inflow mode is preferable to noncontinuous flow operation, as the distribution box used by ABJ will ensure that variations in load and flow are distributed evenly between the reactors and prevent diurnal variations or shock loads from continually overloading one reactor. The manufacturer asserts an additional advantage of the ICEAS flow regime is that continuous flow via the distribution box reduces the valving and

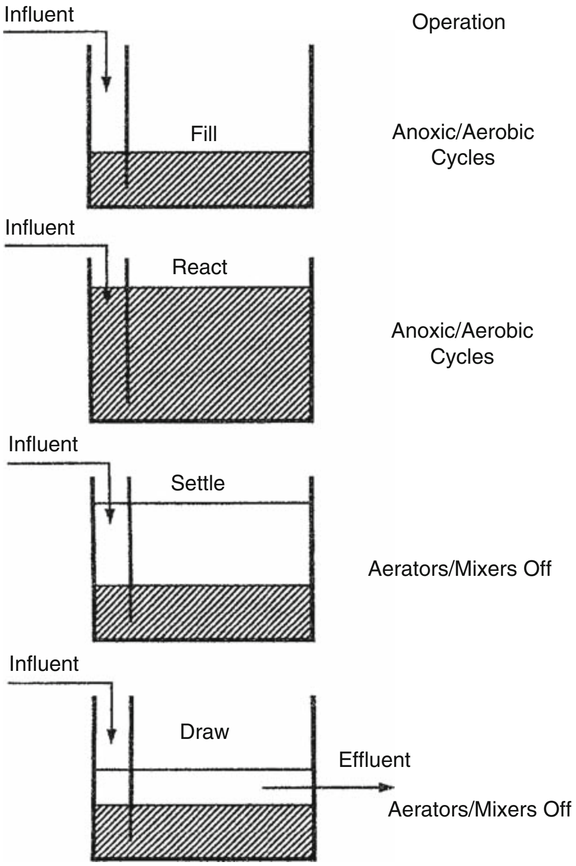

Fig. 15.3. Intermittent cycle extended aeration system (Source: US EPA).

head-works engineering compared to requirements for a noncontinuous flow SBR. A complete ICEAS treatment cycle consists of three phases: Aeration, Settle, and Draw. Since influent is received during all phases, ICEAS does not offer total quiescence during the settle phase, a characteristic of an intermittently fed SBR. Although ICEAS is proprietary, no royalty or license fees are imposed. ICEAS uses a patented anoxic selector to provide denitrification and to promote growth of zoogleal microorganism, and to inhibit filamentous strains. The ABJ selector has characteristics similar to the patented CASS selector, but ABJ claims to be the developer of the original selector concept.

3. DESCRIPTION OF A TREATMENT PLANT USING SBR

A typical process flow schematic for a municipal wastewater treatment plant using an SBR is shown in Fig. 15.4 (1, 3). Influent wastewater generally passes through screens and grit removal prior to the SBR. The wastewater then enters a partially filled reactor, containing biomass, which is acclimated to the wastewater constituents during preceding cycles. Once the

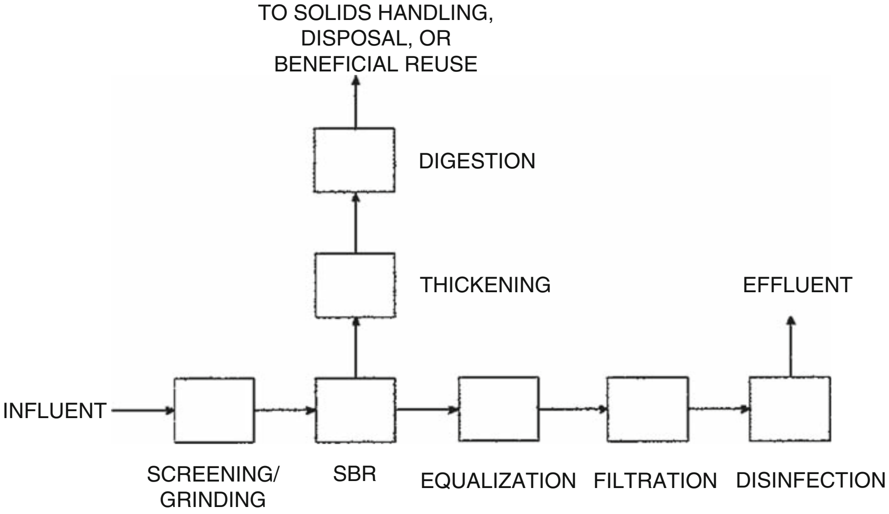

Fig. 15.4. SBR process flow diagram (Source: US EPA).

reactor is full, it behaves like a conventional activated sludge system, but without a continuous influent or effluent flow. The aeration and mixing is discontinued after the biological reactions are complete, the biomass settles, and the treated supernatant is removed. Excess biomass is wasted at any time during the cycle. Frequent wasting results in holding the mass ratio of influent substrate to biomass nearly constant from cycle to cycle. Continuous flow systems hold the mass ratio of influent substrate to biomass constant by adjusting return activated sludge (RAS) flowrates continually as influent flowrates, characteristics, and settling tank underflow concentrations vary. After the SBR, the "batch" of wastewater may flow to an equalization basin where the wastewater flow to an additional processing unit can be controlled at a determined rate. In some cases, the wastewater is filtered to remove additional solids and then disinfected.

As illustrated in Fig. 15.4, the solids handling system may consist of a thickener and an aerobic digester. With SBRs there is no need for RAS pumps and primary sludge (PS) pumps like those associated with conventional activated sludge systems. With the SBR, there is only one sludge biomass (biosolids) to handle. The need for gravity thickeners prior to digestion is determined on a case by case basis depending on the characteristics of the biosolids.

An SBR serves as an equalization basin when the vessel is filling with wastewater, enabling the system to tolerate peak flows or peak loads in the influent and to equalize them in the batch reactor. In many conventional activated sludge systems, separate equalization is needed to protect the biological system from peak flows, which may wash out the biomass, or peak loads, which may upset the treatment process.

It should also be noted that primary clarifiers are typically not required for municipal wastewater applications prior to an SBR. In most conventional activated sludge wastewater treatment plants, primary clarifiers are used prior to the biological system. However, primary clarifiers may be recommended by the SBR manufacturer if the total suspended solids (TSS) or biochemical oxygen demand (BOD) are greater than 400–500 mg/L. Historic data should be evaluated and the SBR manufacturer consulted to determine whether primary clarifiers or equalization are recommended prior to an SBR for municipal and industrial applications.

Equalization may be required after the SBR, depending on the downstream process. If equalization is not used prior to filtration, the filters need to be sized in order to receive the batch of wastewater from the SBR, resulting in a large surface area required for filtration, Sizing filters to accept these "batch" flows is usually not feasible, which is why equalization is used between an SBR and downstream filtration. Separate equalization following the biological system is generally not required for most conventional activated sludge systems, because the flow is on a continuous and more constant basis.

4. APPLICABILITY

SBRs are typically used at flowrates of 219 L/s (5 MGD) or less (1, 3). The more sophisticated operation required at larger SBR plants tends to discourage the use of these plants for large flowrates. The SBR technology is particularly attractive for treating smaller wastewater flows. The majority of plants were designed at wastewater flow rates of less than 22 L/s (0.5 MGD) (7). The cost-effectiveness of SBRs may limit their utilization to flows less than 440 L/s (10 MGD) (6). Depending on the number of SBR reactors in a plant and the duration of the discharge cycle, the downstream units often must be sized for two or more times the influent flow rate. Plants with four or more separate reactors may have the reactor process cycles offset such that the discharge is nearly continuous.

As these systems have a relatively small footprint, they are useful for areas where the available land is limited. In addition, cycles within the system can be easily modified for nutrient removal in the future, if it becomes necessary. This makes SBRs extremely flexible to adapt to regulatory changes for effluent parameters like nutrient removal. SBRs are also very cost effective if treatment beyond biological treatment is required, such as filtration.

5. ADVANTAGES AND DISADVANTAGES

Some advantages and disadvantages of SBRs are listed in the following section (1, 3, 8).

5.1. Advantages

1. Equalization and the ability to tolerate peak flows and shock loads of BOD_5
2. Primary clarification (in most cases), biological treatment, and secondary clarification can be achieved in a single reactor vessel
3. Operating flexibility and control of effluent discharge
4. Minimal footprint
5. Potential capital cost savings by eliminating clarifiers and other equipment

5.2. Disadvantages

1. A higher level of sophistication is required (compared to conventional systems), especially for larger systems of timing units and controls
2. Higher level of maintenance (compared to conventional systems) associated with more sophisticated controls, automated switches, and automated valves

Table 15.2
SBR design parameters for conventional load (Source: US EPA)

	Municipal	Industrial
Food to mass (F:M)	0.15–0.4/day	0.15–0.6/day
Treatment cycle duration	4.0 h	4.0–24 h
Typically low water level mixed liquor suspended solids	2,000–2,500 mg/L	2,000–4,000 mg/L
Hydraulic retention time	6–14 h	Varies

3. Potential of discharging floating or settled biosolids during the draw or decant phase with some SBR configurations
4. Potential plugging of aeration devices during selected operating cycles, depending on the aeration system used by the manufacturer
5. Potential requirement for equalization after the SBR, depending on the downstream processes

6. DESIGN CRITERIA

For any wastewater treatment plant design, the first step is to determine the anticipated influent characteristics of the wastewater and the effluent requirements for the proposed system. These influent parameters typically include design flow, maximum daily flow BOD_5, TSS, pH, alkalinity, wastewater temperature, total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_3-N), and total phosphorus (TP). For industrial and domestic wastewater, other site specific parameters may also be required.

The state regulatory agency should be contacted to determine the effluent requirements of the proposed plant. These effluent discharge parameters will be dictated by the state in the National Pollutant Discharge Elimination System (NPDES) permit. The parameters typically permitted for municipal systems are flowrate, BOD_5, TSS, and Fecal Coliform (FC). In addition, many states are moving toward requiring nutrient removal. Therefore, total nitrogen (TN), TKN, NH_3-N, or TP may also be required. It is imperative to establish effluent requirements because they will impact the operating sequence of the SBR. For example, if there is a nutrient requirement and NH_3-N or TKN is required, then nitrification will be necessary. If there is a TN limit, then nitrification and denitrification will be necessary.

6.1. *Design Parameters*

Once the influent and effluent characteristics of the system are determined, the engineer will typically consult SBR manufacturers for a recommended design. Based on these parameters, and other site specific parameters such as temperature, key design parameters are selected for the system. An example of these parameters for a wastewater system loading is listed in Table 15.2.

A unified approach to SBR technology has yet to be developed (16); however, the principles used to design nitrification–denitrification facilities in single anoxic or dual anoxic zone systems, such as flow and loadings, may be applied with some modifications. One factor to consider specifically for the design of an SBR is the flow volume which will determine

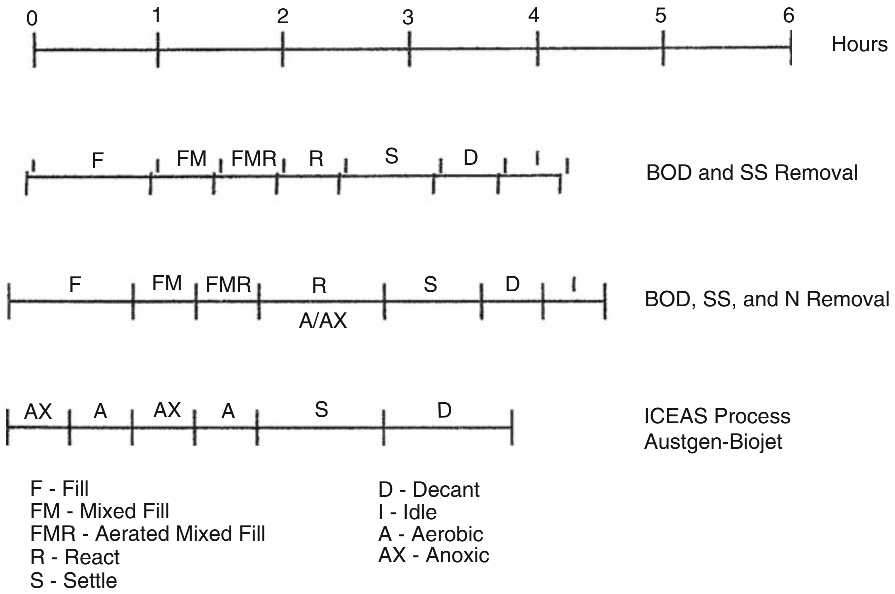

Fig. 15.5. Operating strategies for SBR systems (Source: US EPA).

whether one reactor will suffice (generally for flows $< 2\,\mathrm{L/s}$ or 0.05 MGD) or whether a two-vessel system is required. Additional vessels should be considered for sites that experience a wide transient variation in either organic or hydraulic loading. Conditions, including wet weather with ingress of surface or ground waters, may be accommodated by effecting more frequent decant cycles, without causing washout of the reactor biomass. The SBR process can accommodate peak hourly flows 3–10 times as large as the design flow without adverse effects, if excess capacity is available. The F/M ratio must be determined by the desired effluent quality which in turn dictates reactor sizing.

The critical operational feature is the cycle time for fill, react, settle, and draw, and the amount of oxygen that is supplied. A typical cycle for an intermittent-feed, intermittent-discharge SBR based on average flow conditions is 4-h duration; 2 h allocated to fill/aeration/anoxic react, 1 h to settling, and 1 h to decant and idle. The total time for a batch cycle consists of the time allowed for each component phase. Design cycle times in full-scale plants have varied from 2 to 24 h (17). A suggested strategy is presented in Fig. 15.5. Some typical design criteria are presented in Table 15.3.

SBR systems are typically designed and operated at long solids residence times (>15 day) and low F/M (less than 0.1 kg $\mathrm{BOD_5/kg\,MLSS/day}$). Consequently, partial or complete nitrification is nearly always observed (7, 8). In an evaluation of 19 SBR treatment plants (8) (all originally designed for nitrification), influent and effluent ammonia-nitrogen data were reported for eight of the plants (Table 15.4). The average effluent ammonium-nitrogen concentration for the eight plants was less than 2.0 mg/L, implying that a high degree of nitrification

Table 15.3
Typical design criteria for SBRs (Source: US EPA)

Parameter	SBR	ICEAS
BOD load, g/day/m^3	80–240	
Cycle time, h		
Fill (aeration)	1–3	
Settle	0.7–1	
Draw	0.5–1.5	
MLSS, mg/L	2,300–5,000	
MLVSS, mg/L	1,500–3,500	
HRT, h	15–40	36–50
θ_c, day	20–40	—
F/M, g BOD/g MLVSS/day	0.05–0.20	0.04–0.06

Table 15.4
Nitrification performance information for SBR operating plants[a] (Source: US EPA)

Plant location	Period of evaluation	Wastewater flow		Percent of design flow	BOD_5, mg/L		Ammonia-N, mg/L	
		m^3/day	MGD		Influent	Effluent	Influent	Effluent
Buckingham, PA	04/89–04/91	439	0.116	49	324	8	25.3	1.1
Clarkston, MI (Chateau estates)	11/89–04/91	208	0.055	50	192	12	39.1	1.7
Grundy center, IA	12/89–11/90	2,176	0.575	72	195	4	15.8	1.2
Marlette, MI	07/90–06/91	1,578	0.417	60	103	4	10.1	0.5
Mifflinburg, PA	10/88–03/91	2,763	0.73	81	105	12	7.8	0.4
Monticello, IN (white oaks resort)	10/89–05/91	15	0.004	8	131	5	3.1	0.3
Muskegon heights, MI (clover estates)	01/88–10/90	132	0.035	78	185	9	21.2	0.7
Windgap, PA	02/90–10/90	2,116	0.559	56	160	7	12.9	0.6

[a] Average monthly values based on all data available.

was achieved in all cases. These efficiencies reflect the long design solids residence times that are employed and operations that are generally well below the design flow.

The design mixed liquor volume can be calculated from the selected MLSS concentration, which decreases throughout the fill cycle. The MLSS concentration at the end of the draw phase is that of settled mixed liquor and is similar to that in a conventional clarifier underflow (18). Once the tank volumes have been calculated, the cycle times can be determined. If the cycle times are unsatisfactory, the tank volumes can be adjusted accordingly. The number of cycles per day, number of basins, decants volume, reactor size, and detention times can then be calculated.

Other site specific information is needed to size the aeration equipment, such as site elevation above mean sea level, wastewater temperature, and total dissolved solids concentration. The sizing of aeration equipment is done according to criteria for complete nitrification and BOD removal, except that the required oxygen transfer must be accomplished in a shorter period. The actual amount of aeration time per cycle must be considered when sizing the aeration equipment.

The operation of an SBR is based on the fill-and-draw principle, which, as discussed in a previous section, consists of five basic steps: Idle, Fill, React, Settle, and Draw. More than one operating strategy is possible during most of these steps. For industrial wastewater applications, treatability studies are typically required to determine the optimum operating sequence. For most municipal wastewater treatment plants, treatability studies are not required to determine the operating sequence because municipal wastewater flowrates and characteristic variations are usually predictable and most municipal designers will follow conservative design approaches.

The Idle step occurs between the Draw and the Fill steps, during which treated effluent is removed and influent wastewater is added. The length of the Idle step varies depending on the influent flowrate and the operating strategy. Equalization is achieved during this step if variable idle times are used. Mixing to condition the biomass and biosolids wasting can also be performed during the Idle step, depending on the operating strategy.

Influent wastewater is added to the reactor during the Fill step. The following three variations are used for the Fill step and any or all of them may be used depending on the operating strategy: static fill, mixed fill, and aerated fill. During static fill, influent wastewater is added to the biomass already present in the SBR. Static fill is characterized by no mixing or aeration, meaning that there will be a high substrate (food) concentration when mixing begins. A high food to microorganisms (F:M) ratio creates an environment favorable to floc forming organisms versus filamentous organisms, which provides good settling characteristics for the biosolids. Additionally, static fill conditions favor organisms that produce internal storage products during high substrate conditions, a requirement for biological phosphorus removal. Static fill may be compared to using "selector" compartments in a conventional activated sludge system to control the F:M ratio.

Mixed fill is classified by mixing influent organics with the biomass, which initiates biological reactions. During mixed fill, bacteria biologically degrade the organics and use residual oxygen or alternative electron acceptors, such as nitrate-nitrogen. In this environment, denitrification may occur under these anoxic conditions. Denitrification is the biological conversion of nitrate-nitrogen to nitrogen gas. An anoxic condition is defined as an environment in which oxygen is not present and nitrate-nitrogen is used by the microorganisms as the electron acceptor. In a conventional BNR activated sludge system, mixed fill is comparable to the anoxic zone which is used for denitrification. Anaerobic conditions can also be achieved during the mixed fill phase. After the microorganisms use the nitrate-nitrogen, sulfate becomes the electron acceptor. Anaerobic conditions are characterized by the lack of oxygen and sulfate as the electron acceptor.

Aerated Fill is classified by aerating the contents of the reactor to begin the aerobic reactions completed in the React step. Aerated Fill can reduce the aeration time required in the React step.

The biological reactions are completed in the React step, in which mixed react and aerated react modes are available. During aerated react, the aerobic reactions initialized during aerated fill are completed and nitrification can be achieved. Nitrification is the conversion of ammonia-nitrogen to nitrite-nitrogen and ultimately to nitrate-nitrogen. If the mixed react mode is selected, anoxic conditions can be attained to achieve denitrification. Anaerobic conditions can also be achieved in the mixed react mode for phosphorus removal.

Settle is typically provided under quiescent conditions in the SBR. In some cases, gentle mixing during the initial stages of settling may result in a clearer effluent and a more concentrated settled biosolids. In an SBR, there are no influent or effluent currents to interfere with the settling process as in a conventional activated sludge system.

The Draw step uses a decanter to remove the treated effluent, which is the primary distinguishing factor between different SBR manufacturers. In general, there are floating decanters and fixed decanters. Floating decanters offer several advantages over fixed decanters as described in the Tank and Equipment Description Section.

SBR technology requires unique and innovative strategies to accomplish each phase of the process cycle. Large facilities that require dual vessels can accommodate continuous flow by alternating fill cycles between reactors; single-vessel facilities except for ICEAS systems will require flow equalization or a selector. Compartments or baffles may be included within a selector to control the hydraulic regime and biosolids characteristics. Several criteria have been proposed that can be used to design an appropriate selector (19, 20). The CASS process by Transenviro is a proprietary SBR that includes an integral selector as a part of the process. For more details on SBR design, the readers are referred to Wilderer et al (21) and Toby (22).

6.2. *Construction*

Construction of SBR systems can typically require a smaller footprint than conventional activated sludge systems because the SBR often eliminates the need for primary clarifiers. The SBR never requires secondary clarifiers. The size of the SBR tanks themselves will be site specific; however, the SBR system is advantageous if space is limited at the proposed site. A few case studies are presented in Table 15.5 to provide general sizing estimates at different flowrates. Sizing of these systems is site specific and these case studies do not reflect every system at that size.

SBR reactors have been constructed with a variety of shapes including rectangular, oval, circular, and with sloped sidewalls. Design bottom water levels after decant are typically 3–4 m (10–13 ft) and design top water levels are typically 4.3–5.5 m (14–18 ft). A freeboard of 1 m (3 ft) is common.

The actual construction of the SBR tank and equipment may be comparable or simpler than a conventional activated sludge system. For BNR plants, an SBR eliminates the need for RAS pumps and pipes. It may also eliminate the need for internal Mixed Liquor Suspended Solid

Table 15.5
Case studies for several SBRs facilities (Source: US EPA)

Flow	Reactors			Blowers	
(MGD)	No.	Size (feet)	Volume (MG)	No.	Size (HP)
0.012	1	18 × 12	0.021	1	15
0.10	2	24 × 24	0.069	3	7.5
1.2	2	80 × 80	0.908	3	125
1.0	2	58 × 58	0.479	3	40
1.4	2	69 × 69	0.678	3	60
1.46	2	78 × 78	0.910	4	40
2.0	2	82 × 82	0.958	3	75
4.25	4	104 × 80	1.556	5	200
5.2	4	87 × 87	1.359	5	125

Conversion factors: 1 MGD = 43.8L/s; 1 feet = 0.3048 m; 1 MG = 3.785 ML; 1 HP = 0.7457 kW

(MLSS) recirculation, if this is being used in a conventional BNR system to return nitrate-nitrogen.

The control system of an SBR operation is more complex than a conventional activated sludge system and includes automatic switches, automatic valves, and instrumentation. These controls are very sophisticated in larger systems. The SBR manufacturers indicate that most SBR installations in the United States are used for smaller wastewater systems of less than 2 MGD (87.6 L/s) and some references recommend SBRs only for small communities where land is limited. This is not always the case, however, as the largest SBR in the world is currently a 10 MGD (438 L/s) system in the United Arab Emirates (23).

6.3. *Tank and Equipment Description*

The SBR system consists of a tank, aeration and mixing equipment, a decanter, and a control system. The central features of the SBR system include the control unit and the automatic switches and valves that sequence and time the different operations. SBR manufacturers should be consulted for recommendations on tanks and equipment. It is typical to use a complete SBR system recommended and supplied by a single SBR manufacturer. It is possible, however, for an engineer to design an SBR system, as all required tanks, equipment, and controls are available through different manufacturers. This is not typical of SBR installation because of the level of sophistication of the instrumentation and controls associated with these systems.

The SBR tank is typically constructed with steel or concrete. For industrial applications, steel tanks coated for corrosion control are most common while concrete tanks are the most common for municipal treatment of domestic wastewater. For mixing and aeration, jet aeration systems are typical as they allow mixing either with or without aeration, but other aeration and mixing systems are also used. Positive displacement blowers are typically used for SBR design to handle wastewater level variations in the reactor. The varying liquid volume restricts the feasibility of fixed mechanical surface aerators. The most common aeration system in SBRs are diffused bubblers; but both the floating aerator as manufactured by Aqua SBR and diffused bubble aeration systems will benefit from submerged mixers used to ensure proper agitation of the reactor contents under anoxic conditions.

As previously mentioned, the decanter is the primary piece of equipment that distinguishes different SBR manufacturers. Types of decanters include floating and fixed. Floating decanters offer the advantage of maintaining the inlet orifice slightly below the water surface to minimize the removal of solids in the effluent removed during the DRAW step. Floating decanters also offer the operating flexibility to vary fill-and-draw volumes. Fixed decanters are built into the side of the basin and can be used if the Settle step is extended. Extending the Settle step minimizes the chance that solids in the wastewater will float over the fixed decanter. In some cases, fixed decanters are less expensive and can be designed to allow the operator to lower or raise the level of the decanter. Fixed decanters do not offer the operating flexibility of the floating decanters.

6.4. Health and Safety

Safety should be the primary concern in every design and system operation. A properly designed and operated system will minimize potential health and safety concerns. Manuals such as the Manual of Practice (MOP) No. 8, Design of Municipal Wastewater Treatment Plants (24), and MOP No. 11, Operation of Municipal Wastewater Treatment Plants (25) should be consulted to minimize these risks. Other appropriate industrial wastewater treatment manuals, federal regulations, and state regulations should also be consulted for the design and operation of wastewater treatment systems.

7. PROCESS PERFORMANCE

The performance of SBRs is typically comparable to conventional activated sludge systems and depends on system design and site specific criteria. Depending on their mode of operation, SBRs can achieve good BOD and nutrient removal. For SBRs, the BOD removal efficiency is generally 85–95% and nitrogen removal can be considerably higher than in conventional activated sludge systems (26–32). Performance results from full-scale facilities are provided in Table 15.6.

SBR manufacturers will typically provide a process guarantee to produce an effluent of less than (1, 3):

1. 10 mg/L BOD
2. 10 mg/L TSS
3. 5–8 mg/L TN
4. 1–2 mg/L TP

One of the primary features of SBR technology is the flexibility to exercise control as a function of time rather than space (as in conventional flow-through systems). Several key aspects include (1, 3):

Table 15.6
Summary of SBR plant operating data (Source: US EPA)

Plant	Flow m^3/day, (MGD)	Influent BOD_5, mg/L	Influent TKN (Total N), mg/L	Effluent TKN (Total N), mg/L	Influent NH_4^+-N, mg/L	Effluent NH_4^+-N, mg/L	Effluent NO_x-N, mg/L	Effluent Total N, mg/L	% N Removal
Nonproprietary Culver, IN	N/A	170	N/A	N/A	20.0	1.0	N/A	1.0[a]	88
Cass Deep River, CT	189 (0.05)	100	54.5	3.6	40.4	1.3	1.0	4.6	92
Cass Dundee, Ml	N/A	123	28.9	2.2	16.9	0.5	4.9	2.7	75
Nonproprietary Grundy Center, IA	1,249 (0.33)	210	N/A	N/A	17.3	0.8	2.8	3.6[a]	90
Aqua SBR Grundy Center, IA	3,028 (0.8)	140	28.0	4.4	19.0	1.6	0.5	4.9	83
Aqua SBR Rock Falls, IN	530 (0.14)	109	39.8	1.8	35.9	0.6	1.0	2.8	93
Aqua SBR Oak Hill, MI	416 (0.11)	220	N/A	N/A	25.0	0.6	3.5	4.1[a]	84
Jet Tech Oak Pt., Ml	227 (0.06)	142	N/A	N/A	19.0	0.6	2.8	3.4[a]	82
Jet Tech Cow Creek, OK	9,841 (2.6)	119	24.0	2.7	17.0	1.8	1.9	4.6	81
Jet Tech Del City, OK	13,248 (3.5)	115	(28.3)	(5.4)	17.6	0.9	3.5	5.4	81
ICEAS Buckingham, PA	492 (0.13)	349	N/A	N/A	29.2	0.6	0.9	1.5[a]	95
ICEAS Burkeville, PA	530 (01.4)	296	35.7	3.6	19.3	0.3	1.0	4.6	87
ICEAS Shiga Kogen	757 (0.2)	484	(36.9)	(5.4)	N/A	N/A	N/A	5.4	85

N/A – Data not available.
[a] Based on effluent NH_4^+-N + NO_x-N.

1. The SBR system can tolerate shock loads and peak flows because of the equalizing basin characteristics of the fill phase.
2. Periodic effluent discharge may permit retention of reactor contents until desired clarity or treatment quality is achieved.
3. A fraction of the total volume may be used during low flow periods, resulting in lower aeration requirements. If aerators or blowers have turn-down capability, O&M costs may be reduced.
4. No RAS or internal recycles are required; however, some systems (e.g., CASS) include recycle to an antecedent basin or selector chamber.

5. With intermittently fed SBRs, clarification occurs under total quiescence, thereby eliminating short-circuiting. Consequently, small flocs will settle in an SBR that would be washed out in a continuous-flow regime.
6. Filamentous growth can be controlled by operational strategies along with adjustments during the fill phase.

Readers interested in the performance of SBR systems in industrial wastewater treatment are referred to Refs. (33–35).

8. OPERATION AND MAINTENANCE

The SBR typically eliminates the need for separate primary and secondary clarifiers in most municipal systems, which reduces operations and maintenance (O&M) requirements. In addition, RAS pumps are not required. In conventional BNR systems, anoxic basins, anoxic zone mixers, toxic basins, toxic basin aeration equipment, and internal MLSS nitrate-nitrogen recirculation pumps may be necessary. With the SBR, this can be accomplished in one reactor using aeration/mixing equipment, which will minimize operation and maintenance requirements otherwise be needed for clarifiers and pumps.

Since the heart of the SBR system is the controls, automatic valves, and automatic switches, these systems may require more maintenance than a conventional activated sludge system. An increased level of sophistication usually equates to more items that can fail or require maintenance. The level of sophistication may be very advanced in larger SBR wastewater treatment plants requiring a higher level of maintenance on the automatic valves and switches (1, 3). The recent advances and cost reductions of microprocessors have been some of the causes of the revival of interest in SBR technology, permitting automated control of the timing and sequence of process phases and operation. The use of timers and DO monitors can be used to reduce costs attributable to over aeration, thereby reducing the lag period of DO depletion and allowing the maximum time for denitrification to occur.

Significant operating flexibility is associated with SBR systems. An SBR can be set up to simulate any conventional activated sludge process, including BNR systems. For example, holding times in the aerated react mode of an SBR can be varied to achieve simulation of a contact stabilization system with a typical hydraulic retention time (HRT) of 3.5–7 h or, on the other end of the spectrum, an extended aeration treatment system with a typical HRT of 18–36 h. For a BNR plant, the aerated react mode (oxic conditions) and the mixed react modes (anoxic conditions) can be alternated to achieve nitrification and denitrification. The mixed fill mode and mixed react mode can be used to achieve denitrification using anoxic conditions. In addition, these modes can ultimately be used to achieve an anaerobic condition at which phosphorus removal can occur. Conventional activated sludge systems typically require additional tank volume to achieve such flexibility. SBRs operate in time rather than in space and the number of cycles per day can be varied to control desired effluent limits, offering additional flexibility with an SBR.

9. COST

This section includes some general guidelines as well as some general cost estimates for planning purposes. It should be remembered that capital and construction cost estimates are site-specific.

Budget level cost estimates presented in Table 15.7 are based on projects that occurred from 1995 to 1998 (1). Budget level costs include such as the blowers, diffusers, electrically operated valves, mixers, biosolids pumps, decanters, and the control panel. All costs in this chapter have been updated to year 2009 costs, using the Cost Index for Utilities shown in Appendix (36). The 1998 costs were multiplied by a factor = 570.38/459.40 = 1.24 i.e., costs were increased by 24% to obtain their values in terms of 2005 US Dollars.

In Table 15.8, a range of equipment costs for different design flowrates is provided (1).

Again the equipment cost items provided do not include the cost for the tanks, sitework, excavation/backfill, installation, contractor's overhead and profit, or legal, administrative, contingency, and engineering services. These items must be included to calculate the overall construction costs of an SBR system. Costs for other treatment processes, such as screening, equalization, filtration, disinfection, or aerobic digestion, may be included if required.

The ranges of construction costs for a complete, installed SBR wastewater treatment system are presented in Table 15.9 (1). The variances in the estimates are due to the type of biosolids handling facilities and the differences in newly constructed plants versus systems that use

Table 15.7
SBR equipment costs based on different existing facilities (Source: US EPA)

Design flowrate (MGD)	Budget level equipment costs ($)
0.012	117,000
0.015	169,000
1.0	419,000
1.4	502,000
1.46	502,000
2.0	699,000
4.25	1,448,000

Costs are adjusted to current 2009 US dollars. 1 MGD = 43.8 L/s.

Table 15.8
Equipment costs based on flowrates (Source: US EPA)

Design flowrate (MGD)	Budget level equipment costs($)
1	187,000–433,000
5	568,000–903,000
10	1,348,000–1,695,000
15	2,722,000
20	2,600,000–3,712,000

Costs are adjusted to current 200918 US dollars. 1 MGD = 43.8 L/s.

Table 15.9
Installed costs per gallon treated (Source: US EPA)

Design flowrate (MGD)	Budget level equipment costs ($/gal)
0.5–1.0	2.40–6.19
1.1–1.5	2.27–3.33
1.5–2.0	2.05–4.07

Costs are adjusted to current 2009 US dollars. 1 MGD = 43.8 L/s; 1 gal = 3.785 L.

existing plant facilities. As such, in some cases these estimates include other processes required in an SBR wastewater treatment plant.

There is typically an economy of scale associated with construction costs for wastewater treatment, meaning that larger treatment plants can usually be constructed at a lower cost per gallon than smaller systems. The use of common wall construction for larger treatment systems, which can be used for square or rectangular SBR reactors, results in this economy of scale.

Operations and Maintenance costs associated with an SBR system may be similar to a conventional activated sludge system. Typical cost items associated with wastewater treatment systems include labor, overhead, supplies, maintenance, operating administration, utilities, chemicals, safety and training, laboratory testing, and solids handling. Labor and maintenance requirements may be reduced in SBRs because clarifiers, clarification equipment, and RAS pumps may not be necessary. On the other hand, the maintenance requirements for the automatic valves and switches that control the sequencing may be more intensive than for a conventional activated sludge system. Operations and Maintenance costs are site specific and may range, in terms of 2009 US Dollars, from $1,000 to $2,500/MG (1).

10. PACKAGED SBR FOR ONSITE SYSTEMS

As discussed earlier, SBRs can be designed and operated to enhance removal of nitrogen, phosphorus, and ammonia, in addition to removing TSS and BOD. The intermittent flow (IF) SBR accepts influent only at specified intervals and, in general, follows the five-step sequence (Fig. 15.6). There are usually two IF units in parallel. Because this system is closed to influent flow during the treatment cycle, two units may be operated in parallel, with one unit open for intake while the other runs through the remainder of the cycles. In the continuous inflow SBR, influent flows continuously during all phases of the treatment cycle. To reduce short-circuiting, a partition is normally added to the tank to separate the turbulent aeration zone from the quiescent area (37).

The SBR system is typically found in packaged configurations for onsite and small community or cluster applications. The major components of the package include the batch tank, aerator, mixer, decanter device, process control system (including timers), pumps, piping, and appurtenances (37). Aeration may be provided by diffused air or mechanical devices. SBRs are often sized to provide mixing as well and are operated by the process control timers. Mechanical aerators have the added value of potential operation as mixers or aerators. The

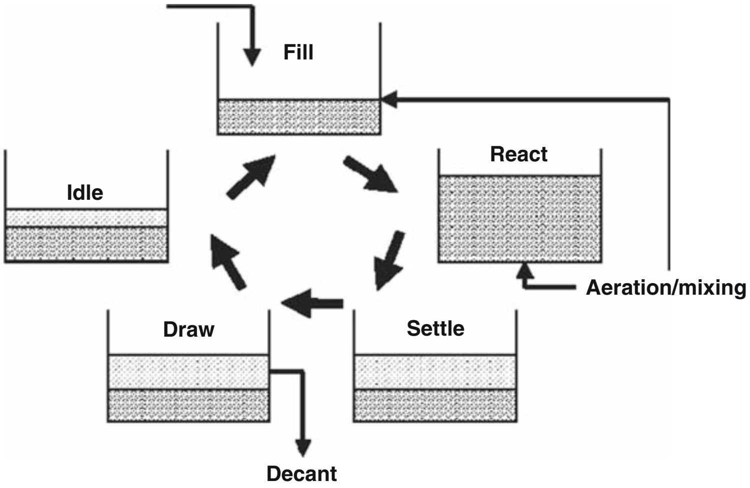

Fig. 15.6. SBR design principle for onsite systems (Source: US EPA).

decanter is a critical element in the process. Several decanter configurations are available, including fixed and floating units. At least one commercial package employs a thermal processing step for the excess biosolids produced and wasted during the "idle" step. The key to the SBR process is the control system, which consists of a combination of level sensors, timers, and microprocessors. Programmable logic controllers can be configured to suit the owner's needs. This provides a precise and versatile means of control.

10.1. Typical Applications

SBR package plants have found application as onsite systems in some states and counties where they are allowed by code. They are normally used to achieve a higher degree of treatment than a continuous-flow, suspended-growth aerobic system (CFSGAS) unit by eliminating impacts caused by influent flow fluctuations. For discharge to surface waters, they must meet effluent permit limits on BOD, TSS, and possibly ammonia. Additional disinfection is required to meet effluent FC requirements. For subsurface discharge, they can be used in situations where infiltrative surface organic loadings must be reduced. There are data showing that a higher quality effluent may reduce soil absorption field area requirements. The process may be used to achieve nitrification as well as nitrogen and phosphorus removal prior to surface and subsurface discharge (37).

10.2. Design Assumptions

Typical IF system design information is provided in Table 15.10 (37). With CF-type (continuous flow) SBRs, a typical cycle time is 3–4 h, with 50% of that cycle devoted to aeration (step 2), 25% to settling (step 3), and 25% to decant (step 4). With both types, downstream or subsequent unit processes (e.g., disinfection) must be designed for greater capacity (because the effluent flow is several times the influent flow during the decant period) or an equalization tank must be used to permit a consistent flow to those processes.

Table 15.10
Design parameters for IF-Type SBR systems (Source: US EPA)

Parameter[b]	SBR systems
Pretreatment	Septic tank or equivalent
MLSS (mg/L)	2,000–6,500
F/M load (lb BOD/day/lb MLVSS)	0.04–0.20
Hydraulic retention time (h)	9–30
Total cycle times (h)[a]	4–12
Solids retention time (day)	20–40
Decanter overflow rate (gpm/ft^2)	<100
Biosolids wasting	As needed to maintain performance

[a] Cycle times should be tuned to effluent quality requirements, wastewater flow, and other site constraints.

[b] Conversion factors: 1 gpm/ft^2 = 40.7 Lpm/m^2; 1 1b BOD/day/1b MLVSS = 1 kg BOD/day/kg MLVSS

Onsite package units should be constructed of non corrosive materials, such as coated concrete, plastic, fiberglass, or coated steel. Some units are installed aboveground on a concrete slab with proper housing to protect against local climatic concerns. The units can also be buried underground as long as easy access is provided to all mechanical parts, electrical control systems, and water surfaces. All electric components should meet NEC code and should be waterproofed and/or sheltered from the elements. If airlift pumps are used, large-diameter pipes should be provided to avoid clogging. Blowers, pumps, and other mechanical devices should be designed for continuous heavy-duty use. Easy access to all moving parts must be provided for routine maintenance. An effective alarm system should be installed to alert home owners or management entities of malfunctions (38).

10.3. Performance

With appropriate design and operation, SBR plants have been reported to produce high quality BOD and TSS effluents. Typical ranges of $CBOD_5$ (carbonaceous 5-day BOD) are from 5 to 15 mg/L. TSS ranges from 10 to 30 mg/L in well-operated systems. Fecal Coliform removal of 1–2 logs can be expected. Normally, nitrification can be attained most of the time unless cold temperatures persist. The SBR systems produce a more reliable effluent quality than CFSGAS owing to the random nature of the wastewater generated from an individual home. The CF/SBR is also capable of meeting secondary effluent standards (30 mg/L of CBOD and TSS), but more subject to upset by randomly generated wastewaters than the IF/SBR (39) if short-circuiting cannot be minimized.

10.4. Management Needs

Long-term management (including operation and maintenance) of SBRs through homeowner service contracts or local management programs is an important component of the operation and maintenance program. Homeowners do not typically possess the skills needed or the desire to learn to perform proper operation and maintenance. In addition, homeowner neglect, ignorance, or interference (e.g., disabling alarm systems) has contributed to operational malfunctions. No wasting of biomass should be practiced until a satisfactory concentration has developed. Intensive surveillance by qualified personnel is desirable during the first months of startup.

Most operating parameters in SBR package systems can be controlled by the operator. Time clock controls may be used to regulate cycle times for each cycle, adjusted for and depending on observed performance. Alarm systems that warn of aerator system failure and/or pump failure are essential.

Inspections are recommended three to four times per year; septage pumping (biosolids wasting) is dependent upon inspection results. Operation and maintenance requires semi-skilled personnel. Based on field experience, 5–12 person-hours per year, plus analytical services, are required. The process produces 0.6–0.9 lb TSS/lb BOD (0.6–0.9 kg TSS/kg BOD) removed and requires between 3.0 and 10 kwh/day for operation (37). Operating personnel prefer these systems to CFSGAS for their simplicity of O/M tasks. The key operational components are the programmer and the decanter, and these must be maintained in proper working order.

10.5. Risk Management Issues

With proper management, a package SBR system is reliable and should pose no unacceptable risks to the homeowner or the environment (37). If neglected, however, the process can result in environmental damage through production of poor-quality effluent that may pose public health risks and can result in the premature failure of subsurface systems. Odor and noise may also create some level of nuisance. SBRs are less susceptible to flow and quality loading changes than other aerobic biological systems, but they are still not suitable for seasonal applications. They are similarly susceptible to extreme cold and should be buried and/or insulated in areas subjected to these extremes. Local authorities can provide guidance on climatic effects on equipment and how to prevent them. The controller should be located in a heated environment. Long power outages can result in odors and effluent degradation, as is the case with other aerobic biological systems.

10.6. Costs

For residential applications, typical system equipment costs, in term of 2009 US Dollars, are \$9,000–\$11,000. Installation costs vary depending on site conditions; installation costs between \$1,770 and \$3,740 are typical for uncomplicated sites with good access (37). It should be noted that additional system components (e.g., subsurface infiltration system) will result in additional costs.

Annual operation and maintenance costs include electricity use (<\$370/year), sludge removal (>\$120/year), and equipment servicing. Some companies are providing annual service contracts for these units for \$300–\$500 (37). Actual costs will vary depending on the location of the unit and local conditions.

Various biological and physicochemical SBRs were developed by Dr. Lawrence K. Wang, Dr. Lubomyr Kurylko, and Dr. Mu-Hao S. Wang (40–42). Today the biological SBR becomes a main stream biological process, but the physicochemical SBR remains to be an innovative process which should be further researched promoted. The case history of a major physico-chemical SBR plant in Europe can be found from the literature (42).

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APPENDIX

US Army Corps of Engineers Civil Works Construction Yearly Average Cost Index for Utilities (36)

Year	Index	Year	Index
1967	100	1989	383.14
1968	104.83	1990	386.75
1969	112.17	1991	392.35
1970	119.75	1992	399.07
1971	131.73	1993	410.63
1972	141.94	1994	424.91
1973	149.36	1995	439.72
1974	170.45	1996	445.58
1975	190.49	1997	454.99
1976	202.61	1998	459.40
1977	215.84	1999	460.16
1978	235.78	2000	468.05
1979	257.20	2001	472.18
1980	277.60	2002	484.41
1981	302.25	2003	495.72
1982	320.13	2004	506.13
1983	330.82	2005	516.75
1984	341.06	2006	528.12
1985	346.12	2007	539.74
1986	347.33	2008	552.16
1987	353.35	2009	570.38
1988	369.45		