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Center for Environmental
Research Information
Cincinnati OH 45268

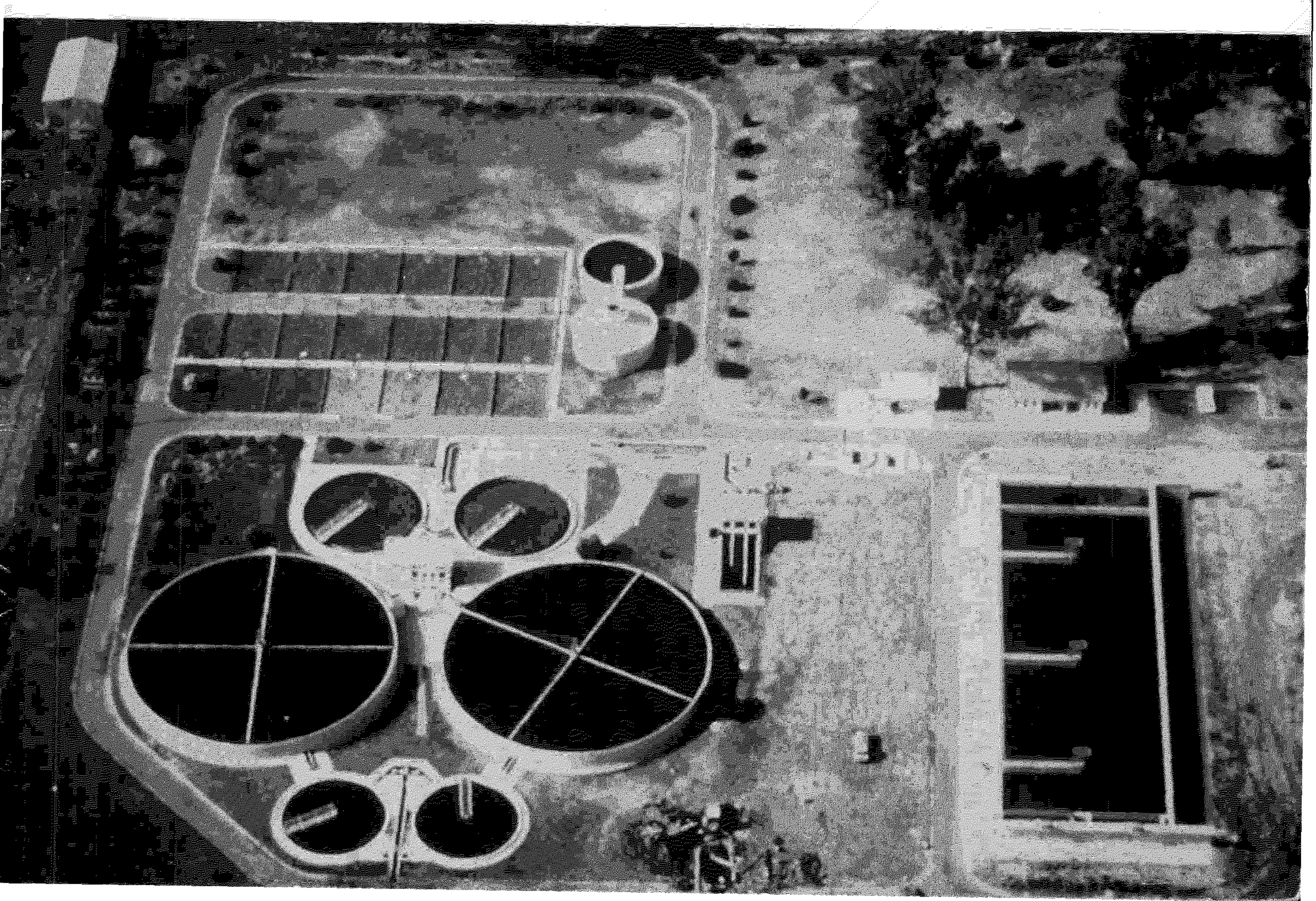
Technology Transfer

EPA/625/8-86/011

EPA

Summary Report

Sequencing Batch Reactors



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Summary Report

Sequencing Batch Reactors

October 1986

This report was developed by the
Center for Environmental Research
Information, Cincinnati, OH 45268

Foreword

The United States Environmental Protection Agency (EPA) has a responsibility to identify and develop potential innovative technologies for reducing and/or mitigating adverse effects on the ecosystem of the U.S. In order to be most effective, these efforts must be documented in a manner that facilitates the transfer of the developed technologies to the public for consideration and use.

This report summarizes one of these potential innovative technologies, Sequencing Batch Reactors (SBR) for municipal and industrial wastewater treatment. Contained in the report are process descriptions, performance evaluations, and economic comparisons with conventional technologies. The report is not an engineering manual. Rather, it is a generalized report written for the public and including references for those interested in pursuing details of engineering.

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References

1. Arora, Madan L. and Umphres, Peggy B., "Technical Evaluation of Sequencing Batch Reactors" for U.S. Environmental Protection Agency, Cincinnati, OH, September 1984.

2. Irvine, Robert L. "Technology Assessment of Sequencing Batch Reactors," U.S. EPA, Cincinnati, OH, November 1983.

Cover Photo:

Provided by Austgen Biojet
The 0.5 ICEAS plant in the right foreground has the same capacity as the older technology plant in the background, but produces a 10 BOD_5 and 10 SS denitrified effluent.

1.0 Introduction

1.1 A Sequencing Batch Reactor (SBR) is a fill-and-draw activated sludge treatment system. As such, SBRs are capable of handling all wastewaters commonly treated by conventional activated sludge plants. Municipal and industrial wastewaters have both been successfully treated in SBR systems.

The unit processes involved in the SBR and conventional activated sludge systems are identical. Aeration and sedimentation/clarification are carried out in both systems. However, there is one important difference. In conventional plants, the processes are carried out simultaneously in separate tanks, whereas in SBR operation the processes are carried out sequentially in the same tank.

The Intermittent Cycle Extended Aeration System (ICEAS) represents a modified version of SBR. Whereas the inflow and outflow are intermittent in SBR (at the beginning and end of the treatment cycle), the inflow is continuous in ICEAS. An SBR system must comprise either a storage tank and an SBR tank or a minimum of two SBR tanks to accommodate continuous inflow. A baffle wall may be installed in the ICEAS treatment tank, to buffer this continuous inflow. Otherwise the design configurations of the SBR and ICEAS systems are very similar.

1.2 The use of fill-and-draw (batch) processes for treating wastewater is not a recent development. Fill-and-draw systems similar to SBRs have been in development and use since the turn of the century. Most sewage treatment studies between 1884 and 1912 used either chemical precipitation, coarse media filters, or a combination of the two in fill-and-draw tanks. Aeration was only infrequently employed. In 1914 the value of aeration was demonstrated, and between then and 1920 several full-scale fill-and-draw systems were operated. After 1920, however, the emphasis moved to continuous flow "conventional" systems, and most of the fill-and-draw systems then in operation were converted to the conventional configuration. Reasons for moving away from the batch process included the high energy that must be dissipated during discharge of the treated effluent, greater demand for operator attention, and clogging of air diffusers because of the periodic settlement of sludge. In the late 1950s and early 1960s interest was revived in the fill-and-draw systems with the development of the new technology and equipment. Improvements in aeration devices and control systems have allowed the development of fill-and-draw systems to their present level of efficiency, which now enables SBR technology to successfully compete with the conventional systems.

1.3 As currently in use, all SBR systems have five steps in common, which are carried out in sequence as follows:

- FILL
- REACT (Aeration)
- SETTLE (Sedimentation/Clarification)
- DRAW (Decant)
- IDLE (sludge wasting)

IDLE is necessary in a multiple tank configuration where one tank is not yet full (during periods of low flow) and another has completed its cycle and is waiting to receive raw wastewater.

1.4 In comparison with conventional continuous flow systems, the outstanding feature of SBR technology is its flexibility. Table 1 compares various features of conventional and SBR systems. The advantages of the SBR over the conventional system can be summarized as follows:

- An SBR tank serves as an equalizing basin during FILL, and therefore can tolerate greater peak flows and/or shock loads of Biochemical Oxygen Demand (BOD) without degradation of effluent quality.

- Since the discharge of effluent is periodic, it is possible, within limits, to hold effluent until it meets specified requirements.

- During early design life, when flow is significantly smaller than design capacity, liquid level sensors can be set at a lower level, thus using a fraction of the SBR tank capacity. In this way, the length of treatment cycles can be kept constant without unnecessarily wasting power by overoperation.

- Mixed liquor solids cannot be washed out by hydraulic surges, since they can be held in the tank as long as necessary.

- No return activated sludge (RAS) pumping is required, since the mixed liquor is always in the reactor.

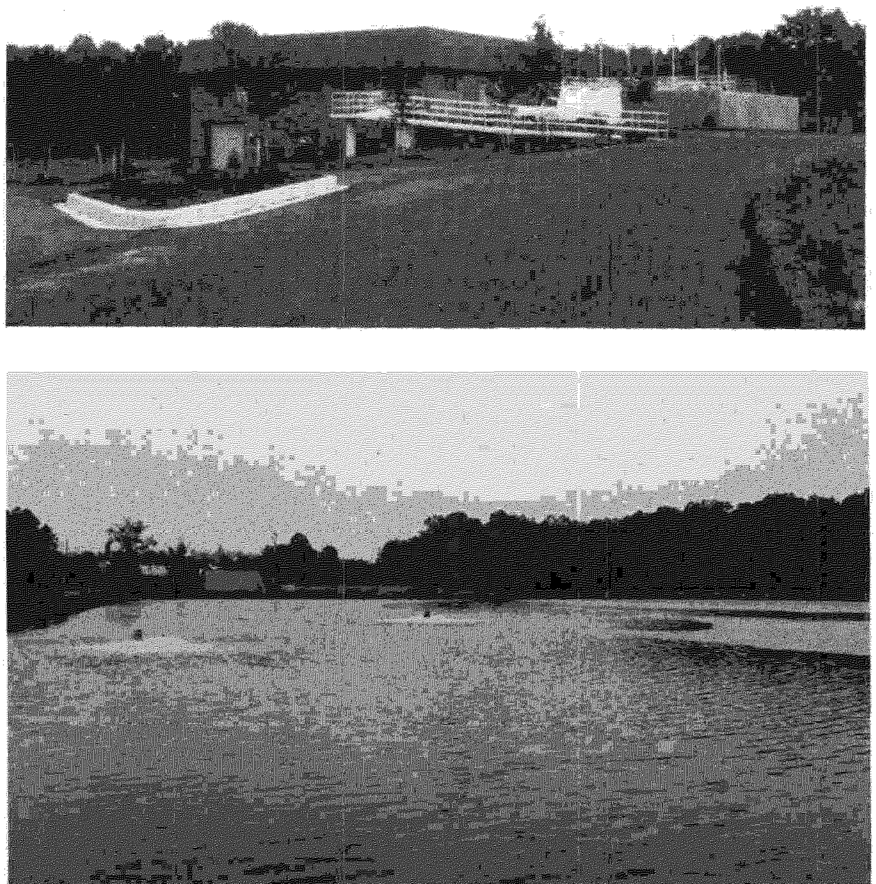
- Solid-liquid separation occurs under nearly ideal quiescent conditions. Short circuiting is non-existent during SETTLE. Further, larger reactor size achieves small surface settling rates, resulting in settling of even small floc particles that may be washed out in continuous flow systems.

- Filamentous growth can be easily controlled by varying the operating strategies during FILL.

- An SBR can be operated to achieve nitrification, denitrification, or phosphorus removal without chemical addition.

- It has been reported that the RNA content of the microorganisms in the SBR is three to four times greater than would be expected from a conventional continuous flow system. Since the growth rate of microorganisms is known to depend on the RNA content of the cells, the presence of more of this intracellular machinery allows the SBR culture to process a greater quantity of substrate at a rate greater than that possible in a conventional continuous flow system.

Disadvantages of the SBR include the increasing sophistication, as systems get larger, of the timing units and level sensors used to control the process sequences, and the difficulties involved in controlling the DRAW or decant phase so as to minimize the discharge of floating or settled sludge. Also, concerns remain about plugging of aeration devices during settle, draw, and idle periods.



New SBR plant replaces old treatment lagoon with greater capacity, better treatment and smaller area requirements.

Table 1

Comparison of Batch and Continuous Processes

Parameter	SBR System	Continuous Flow Activated Sludge System (CFS) (a)	Remarks
Concept	Time sequence in the same tank	Spacial sequence in different tanks	Time sequence can be varied in SBR; no such flexibility in CFS.
Inflow	Periodic—normal SBR Continuous ICEAS	Continuous	
Discharge	Periodic	Continuous	Decant period can be easily changed in SBR. Further, somewhat possible to hold effluent until it meets specific requirements. CFS-inflexible.
Organic Load	Cyclic—normal SBR Continuous—ICEAS	Continuous	Several variations of organic loading are possible by changing durations of cycle periods. CFS-inflexible.
Aeration	Intermittent	Continuous	Increased flexibility in SBR. Both the aeration rate and the aeration duration can be varied. CFS—only aeration rate can be changed.
Mixed Liquor	Always in reactor; no recycle	Recycle through reactor and clarifier	No need for final clarifiers and RAS pumps in SBR. CFS requires above facilities.
Clarification	Ideal—normal SBR Not as ideal—ICEAS	Not ideal. Short circuiting and density currents are common.	Several CFS systems are known to perform unsatisfactorily because of less than ideal settling conditions present in the clarifiers. SBR free from these problems.
Flow Pattern	Perfect Plug	Complete mix or approaching plug	A perfect plug flow condition in SBR achieves rapid biodegradation of pollutants (shorter reaction time). CFS requires longer reaction time.
Equalization	Inherent	None	SBR is an ideal reactor in situations with excessive diurnal variations in flow and BOD. CFS can fail under above conditions.
Flexibility	Considerable	Limited	Operator can routinely change cycle durations, aeration/mixing strategies. CFS is somewhat limited in these areas.
Reactor Size	Could be larger than CFS because it has to provide space for accommodating sludge blanket.	Generally smaller than SBR	Inspite of larger reactor size, SBR can be more compact and require less overall space because no separate clarifiers and RAS pumps are needed.
Operation (Process)	Relatively easy to operate—achieved by microprocessor technology	Same as SBR	SBR ideal for small plants. CFS may not be practical in small plants with excessive diurnal flow variations.
(Equipment)	Fewer mechanical equipment result in easier operation	Significantly more mechanical equipment result in somewhat difficult operation.	
Effluent Quality	Excellent in most cases.	Excellent in most cases.	
Flexibility to meet changing effluent requirements (C,N,P removals)	Tremendous flexibility in SBR; achieved by changing operational strategy (cycle durations, cycle sequence, and aeration/mixing strategy). Somewhat less in ICEAS.	Limited as compared to SBR.	

(a) Includes aeration tank(s), clarifier(s), and RAS pumping.

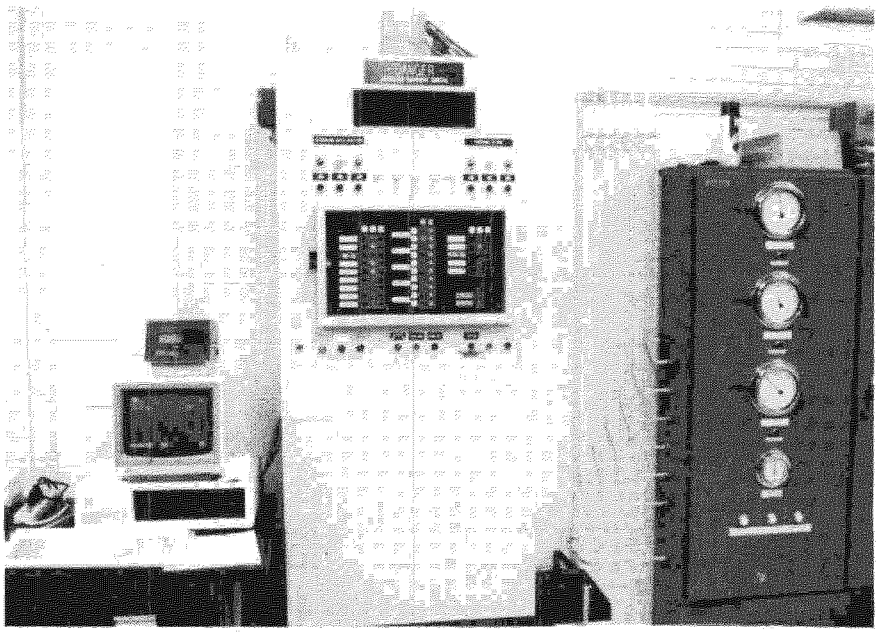
Table from Arora, *Technical Evaluation of Sequencing Batch Reactors,* p. 2–6.

2.0 Process

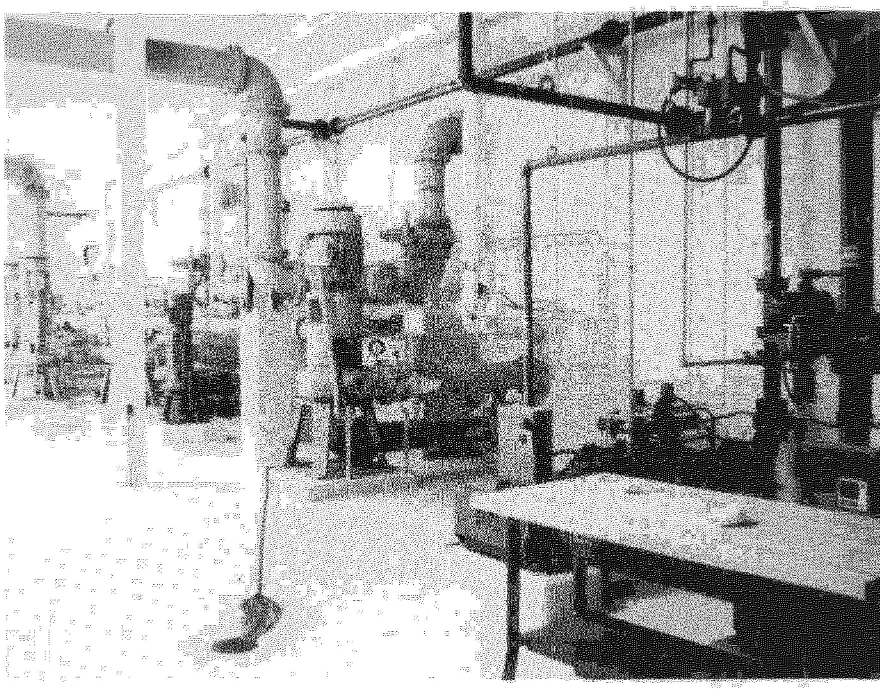
2.1 A treatment plant utilizing the SBR concept has only one type of process unit, the batch reactor tank. It is possible, and even preferable in many cases, to link several identical reactor vessels in a multiple tank configuration, to limit the size of individual units and increase flexibility. There are no units dedicated to a single process, such as equalizing basins, aeration chambers, and clarifiers, as in continuous flow systems.

In its simplest form, a batch reactor consists of a single tank equipped with an inlet for raw wastewater; air diffusers, with associated compressors and piping for aeration; a sludge draw-off mechanism at the bottom to waste sludge; a decant mechanism to remove the supernatant after settling; and a control mechanism to time and sequence the processes. Various suppliers of SBR systems include different modifications to the basic system, such as the installation of a baffle near the inlet to provide a prereact chamber separated from the aerated portion of the basin. Many decant structures are marketed with features designed to limit the discharge of floating solids and settled sludge. Air diffuser design and construction also varies among suppliers, but many SBRs use jet aerators or mechanical aeration to accomplish aeration and/or mixing with a single device.

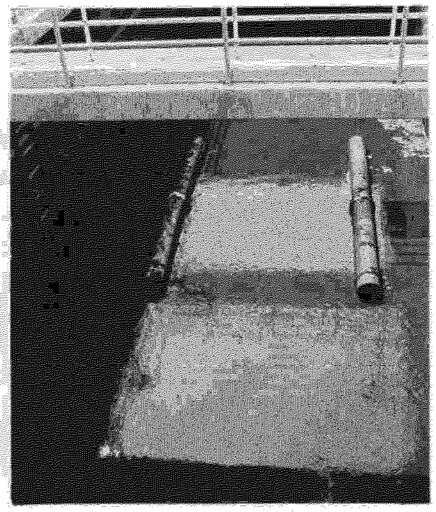
The heart of the SBR system is the control unit and the automatic switches and valves that sequence and time the different operations. The advent of reliable microprocessors at reasonable cost, used in conjunction with modern limit/level switches and automatic valves, has been a major factor in the recent development of SBR technology. The ability to control the processes in time rather than space is crucial to the SBR concept.



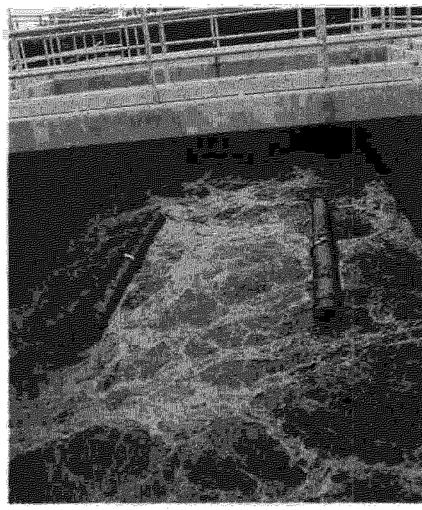
Flows and processes are controlled and monitored via computer (center of picture). Microcomputer (to left) tracks processes and allows operator input and review.



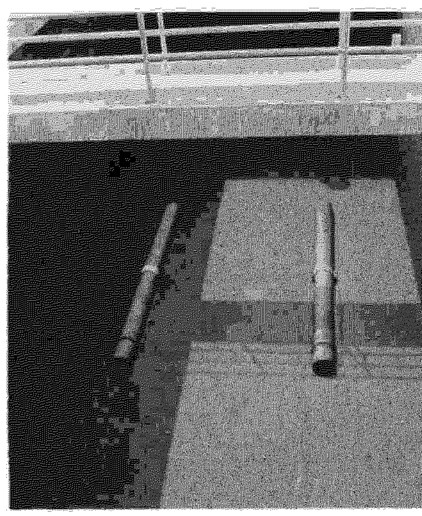
Hydraulics works which control flows and processes are automatically operated by computer.



Fill stage



Aeration during react stage



Idle stage

2.2 In SBR operations, the cycle processes FILL, REACT, SETTLE, DRAW, and IDLE are controlled by time to achieve the objectives of the operation. Each process is associated with particular reactor conditions (turbulent/quiescent, aerobic/anaerobic) that promote selected changes in the chemical and physical nature of the wastewater. These changes lead ultimately to a fully treated effluent. Figure 1 is a schematic of one cycle of a typical SBR operation, showing typical percentages of the total time (in this case approximately 6 hours) spent in each process.

FILL. The purpose of the FILL operation is to add substrate (raw wastewater or primary effluent) to the reactor. The addition of substrate can be controlled either by limit switches to a set volume or by timer to a set time period. If controlled by volume, the FILL process typically allows the liquid level in the reactor to rise from 25 percent of capacity (at the end of IDLE) to 100 percent. If controlled by time, the FILL process normally lasts approximately 25 percent of the full cycle time.

These percentages are representative proportions. As with each of the five processes, the time and volume limits of the FILL process are determined by actual operational constraints and performance requirements. In reality, the initial volume (that volume of activated sludge remaining in the reactor at the end of the IDLE phase, to which the raw wastewater is added during FILL) is determined based on a number of factors, including desired loading and sludge retention time (sludge age), and could be as much as 70 percent of the reactor capacity.

During FILL, performance standards often require alternating conditions of low and high Dissolved Oxygen (DO) concentrations. Periods of aeration and/or mixing during FILL are critical to the development of organisms with good settling characteristics and to biological nutrient removal (Nitrogen (N), Phosphorous (P)). An advantage of the SBR system of time control is its ability to modify the reactor conditions during the phases to achieve the treatment goals.

Figure 1.

Typical SBR Operation for One Cycle

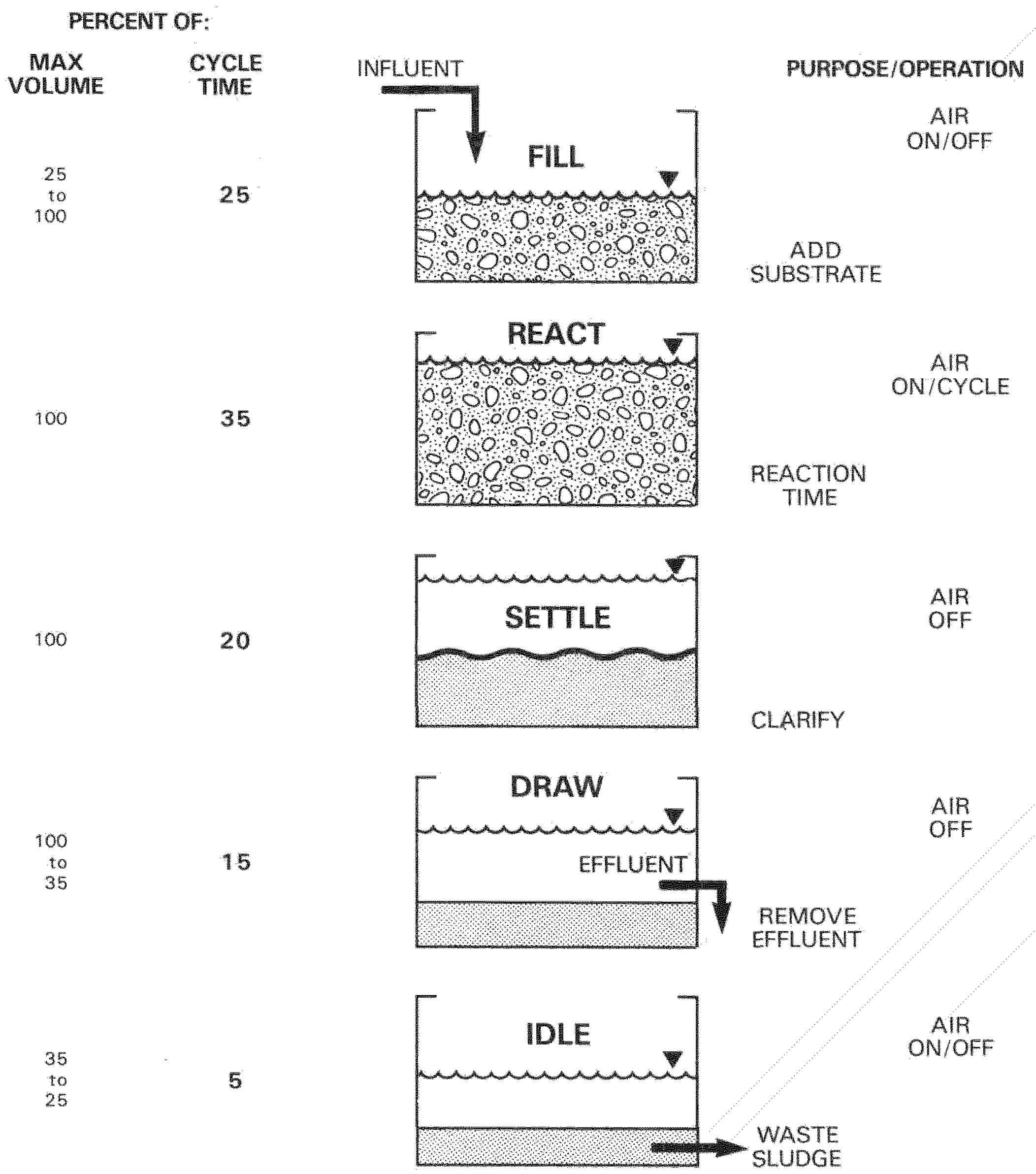


Figure from Irvine, *Technology Assessment of Sequencing Batch Reactors,* p. 3.

A modification of the pure SBR system with only one reactor allows the continuous feed of raw wastewater to the SBR throughout the cycle. Baffles are used to minimize short-circuiting and turbulence during critical phases of the cycle such as SETTLE and DRAW.

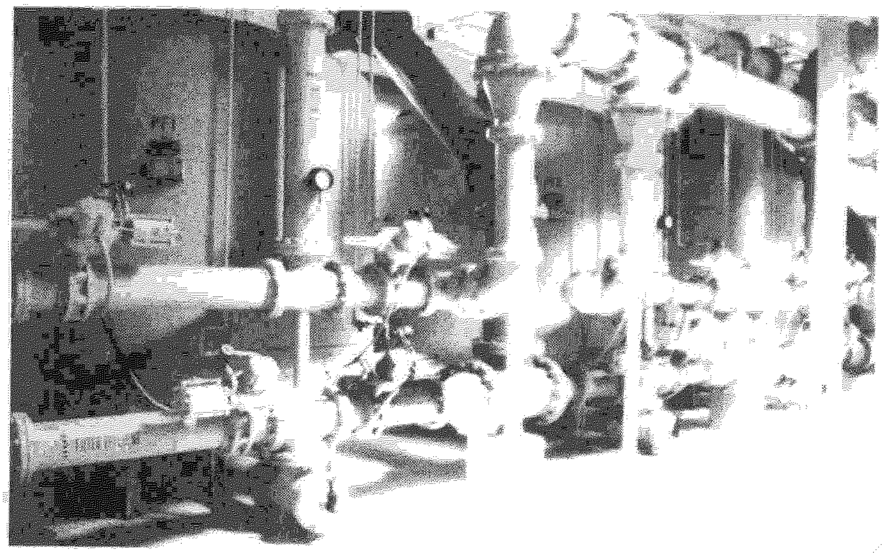
REACT. The purpose of REACT is to complete the reactions that were initiated during FILL. As in FILL, performance considerations might require alternating periods of high and low DO concentrations. The length of the REACT phase can be controlled by a preset time limit or, in a multipletank system, by liquid level controls.

In the second case, the REACT phase is ended when the liquid level in the tank undergoing FILL reaches a predetermined level. Typically, REACT takes up 35 percent of the total cycle time, but performance demands might require substantial deviation from this average.

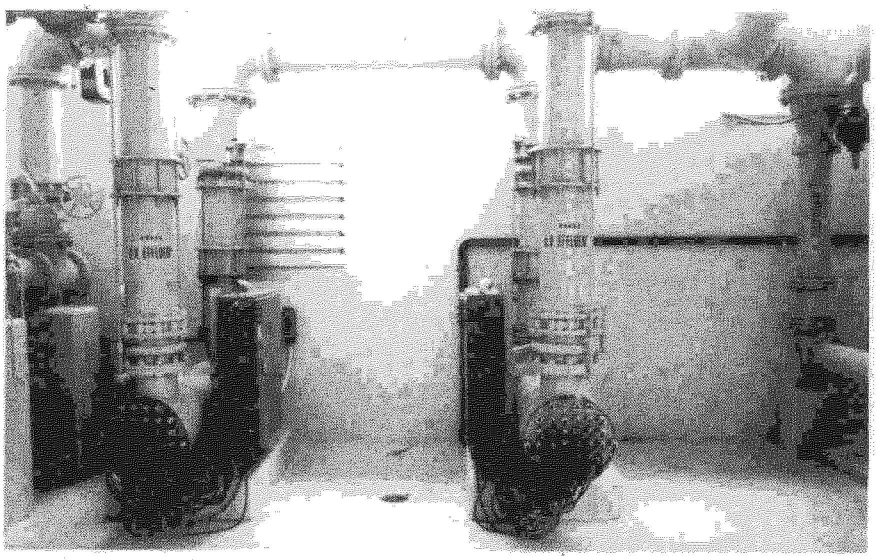
SETTLE. The purpose of SETTLE is to allow solids separation to occur, providing a clarified supernatant to be discharged as effluent. In an SBR, this process is normally much more efficient than in a continous flow system, because in the SETTLE mode the reactor contents are completely quiescent. The SETTLE process is controlled by time and is usually fixed between 1/2 and 1 hour so that the sludge blanket remains below the withdrawal mechanism during the next phase, DRAW, and does not rise (because of gas formation) before DRAW is completed.

DRAW. The purpose of DRAW is to remove clarified, treated water from the reactor. Many types of decant mechanisms are in current use, with the most popular being floating or adjustable weirs. The decanting rate can be controlled by automatic valves in a gravity system or by pumping. The time dedicated to DRAW can range from 5 percent to 30 percent of the total cycle time (15 minutes to 2 hours), 45 minutes being a typical DRAW period.

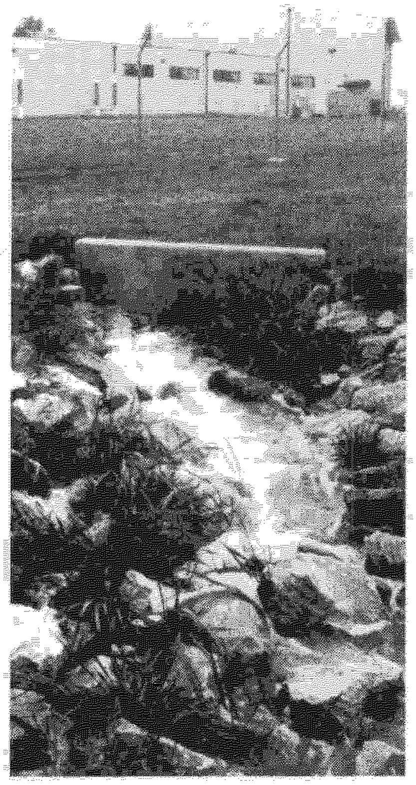
IDLE. The purpose of IDLE in a multi-tank system is to provide time for one reactor to complete its fill cycle before switching to another unit. IDLE is not a necessary phase and can be eliminated. Also, depending on process and treatment goals, aeration, mixing, or sludge wasting can occur during the IDLE period. Length of time in IDLE is determined by the flow rate of wastewater into the plant.



High pressure filter tanks used to treat effluent from SBRs.



Disinfection may be accomplished with ultraviolet treatment (as shown) or chlorination.

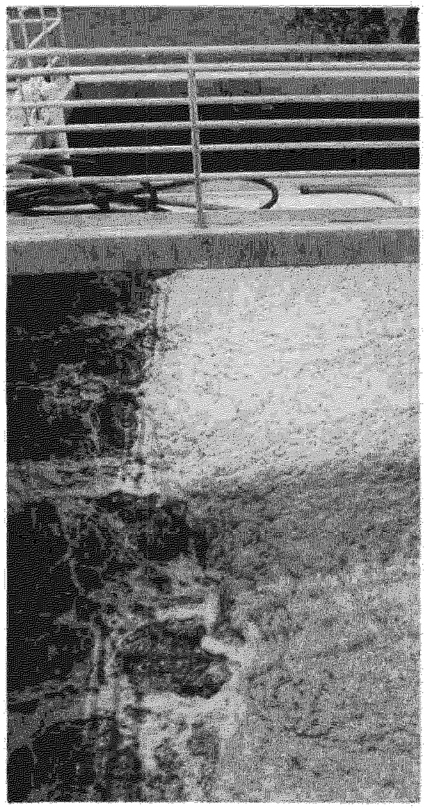


Following treatment, clean effluent either injected to groundwater or released to local stream. Surface release shown here with treatment works in background.

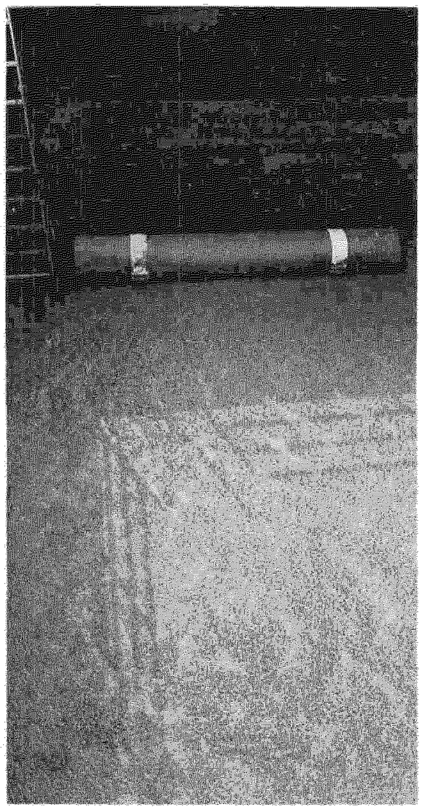
Many modifications can be made to the basin processes described above, to overcome facility constraints or to enhance performance. Examples of these modifications (after suitable physical changes such as additional baffles) include the overlapping of FILL and DRAW under controlled conditions, and the provision of mixing and/or aeration during a period of FILL.

Sludge wasting is another important step in the SBR operation that greatly affects performance. It is not included as one of the five basin processes because there is no set time period within the cycle dedicated to wasting. The amount and frequency of sludge wasting is determined by performance requirements, as with a conventional continuous flow system. In an SBR operation, sludge wasting usually occurs during the SETTLE or IDLE phases. A unique feature of the SBR system is that there is no need for a return activated sludge (RAS) system. Since the aeration and settling occur in the same chamber, no sludge is lost in the REACT phase and none has to be returned from clarifier to maintain the sludge content in the aeration chamber. This eliminates the need for the hardware and controls associated with a conventional RAS system. The sludge volume and, thus, sludge age in the reactor of an SBR system is controlled by sludge wasting only.

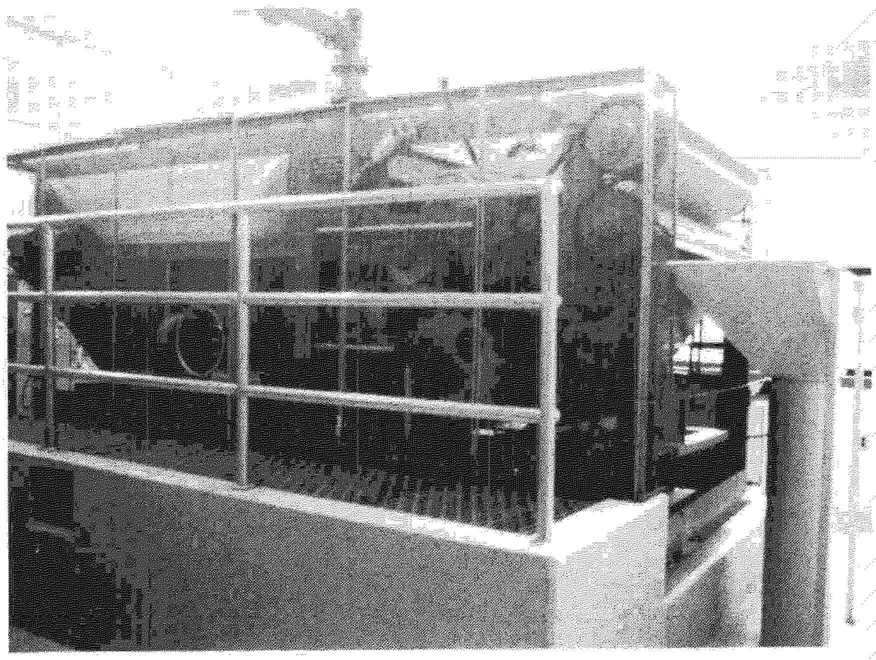
Sludge treatment following removal from SBR



Primary digester—continuous aeration tank



Primary digester—idle tank



Sludge press—sludge comes from idle tank, is processed and then transported and applied to local farmlands.

3.0 Performance

3.1 Biochemical Oxygen Demand (BOD) removal is often used as a traditional measurement of the effectiveness of municipal wastewater treatment. BOD measures the amount of oxygen necessary for removal of the degradable wastewater contaminants by the action of microbiologic organisms. SBR systems consistently achieve more than 90 percent BOD removal in full-scale studies at existing installations. The removal of at least 90 percent is also typical for continuous flow systems currently in use.

Table 2 shows the BOD removal efficiencies of six plants in operation in Canada, Australia, and the U.S. in 1984. As shown in the table, all six plants achieved or surpassed their target effluent BOD.

An important advantage of the SBR system is the control the operator can maintain over microorganism selection. Within a complete treatment cycle, the microorganism selection pressures are highly variable and severe. These pressures include oxygen availability, which ranges from anaerobic through anoxic to high-DO conditions, and substrate availability, which ranges from famine to feast conditions. While certain of these selection pressures can occur in some conventional continuous flow systems, the SBR system provides the ability to easily select and extend or limit preferred conditions through time, allowing the preferential growth of desirable microorganisms.

Two observations have been documented that illustrate the beneficial effects of this control ability. The first is that the RNA content of microorganisms produced by the SBR system is much greater than that found in microorganisms produced in conventional continuous flow systems. The growth rate of microorganisms has been directly linked to the RNA content of the cells. This means that in an SBR system, more microorganisms are capable of processing a greater quantity of substrate at a greater rate than in a conventional system. Secondly, it has been reported that a properly selected aeration strategy can result in the minimizing of the growth of filamentous microorganisms, as is true in continuous flow systems. These microorganisms, whose presence in quantity leads to problems with sludge bulking and foaming, are undesirable in the activated sludge floc in excessive numbers, and their control is an asset to system performance.

Table 2

Plants Evaluation Summary

	Canada		United States				Australia		
Parameter	Rivercrest, Manitoba (a)	Glenlea, Manitoba (a)	Choctaw, Oklahoma	Grundy Center, Iowa	Eldora, Iowa	Culver, Indiana (b)	Tamworth, New South Wales	Yamba, New South Wales	Remarks
Design Firm	Topnik & Assoc. Ltd.	Topnik & Assoc. Ltd.	Rea Engg. & Assoc.	Clapsaddle Garber Assoc.	Jensen, Carry & Shott, Inc.	University of Notre Dame	Laurie, Montgomeria & Petit Pty. Ltd.	Austgen-Biojet	a. Rivercrest and Glenlea data obtained from reference (20)
Date of first visit	5/16/84	5/16/84	5/30/84	6/11/84	6/12/84	6/14/84	7/10/84	7/11/84	b. Culver data obtained from reference (15).
Design avg. flow, gpd	24,000	2,000	500,000	832,000	220,000	—	535,000	253,000	c. Actual operating data.
Design loading BOD, mg/l SS, mg/l NH_3, mg/l	236(c) 200(c) 37(c)	251(c) 152(c) 55(c)	260,366(c) 260,350(c) 19(c)	200 — 15	250,120(c) — 25	170(c,d) 150(c,d) 20(c,d)	260 — 35–40	260(d) — —	d. Raw Sewage e. Jet motive pumps on all the time, but air on and off for 40 and 10 mins, respectively repeated three times during the 150 minutes fill & react periods.
Current avg. flow, gpd	60,000	1,165	200,000 283,000 (equivalent)	800,000	220,000 106,000 (equivalent)	353,000	535,000(est)	—	
Desired eff. qual. BOD, mg/l SS, mg/l NH_3, mg/l	TOC-40 30 —	30 30 —	20 20 15	30 30 6 (summer), 11 (winter)	30 30 8(summer), 10(winter)	10 10	30 30	30 30	
Actual eff. qual BOD, mg/l SS, mg/l NH_3, mg/l	11 15 10	5 6 2	8 18 —	Not being met because of decanter problems. See discussion.	Data was not available. Effluent appeared to be satisfactory.	10 5 1.0	5 to 10 5 to 10 2.2	6 to 10 10 to 15 1.0	
Mode of operation at design flow Fill time R time S time D time I time	 90 min 45 min 20–60 min —	 22 hrs 1 hr 1 hr —	 18 hrs 3 hrs 3 hrs —	40 min (w/o air/pumps) 120 min (w/air/pumps) 60 min 40 min 60 min	 150 min(e) 80 min 50 min 45 min	180 min 42 min 42 min 42 min 60 min Fill 30% mixed 70% aerated	continuous 120–150 min 45 min 45 min —	continuous 150 min 180 min 45 min —	
Important design parameters DT, hours F/M, kg BOD/kg ML SS SRT, days	7.6 0.18(c) 43(c)	4.9 0.032(c) 18.80(c)	48 0.037, 0.028(c) Sludge wasted twice in 10 months	20.4 0.078 0.067(c) 25.30(c)	43 0.05 Sludge not wasted in last 2 months	16.5(c) 0.08:0.16 15.45(c)	46 0.04 —	36 0.05 —	
Power usage kwh/kg BOD applied	0.8	22.9	2.9	0.8 to 1.3	2.2	2.1	1.9	1.5	
Unit Processes Trash Rack Mech. Screens Comminutor Grit Removal Equalization Primary Treat. SBR Disinfection Sludge Treat.	Yes — — — Yes — Yes — Holding tank & land application	— — — — Lift station wet well — Yes — Agriculture farm	Yes (bypass) — Yes — Emergency holding pond — Yes Yes Holding pond & land appl.	Yes (bypass) Yes Yes, aerated Sideline equilization — Yes Yes Aerated sludge holding & sludge beds	— Yes — Yes, aerated — — Yes — Anaerobic digestors & sludge beds	— Yes or Yes — — Yes Yes Yes Aerobic digesters & sludge beds	— Yes or Yes — — — Yes Polishing lagoon Sludge lagoon	Yes — — Yes — Yes Yes Polishing lagoon Aerobic lagoon	
Reasons for providing this technology	Capital cost savings & simple operation	Capital cost savings & simple operation	8.4 percent savings in life cycle costs	19% capital cost savings in secondary treatment process or 8 percent savings in overall plant cost	Capital cost savings & simple operation (100% city funding)	Full scale study funded by EPA	Capital cost savings	Capital cost savings	

Table from Arora, p. 4–2.

3.2 Suspended solids removal is a second traditional measure of wastewater treatment plant performance. Suspended solids removal has also been proven to be effective in SBR systems. As shown in Table 2, removal efficiencies of greater than 90 percent are characteristic of SBR systems as well as conventional continuous flow systems. In addition, the SBR system has two major advantages over the continuous systems. First, suspended solids removal occurs during the SETTLE phase of the operational cycle. As a physical rather than a chemical process, the solids separation depends on floc size and density as well as on turbulence and currents within the settling tank. The more quiescent the tank, the better the solids separation. One of the advantages of the SBR system is that by stopping the flow into and out of the tank, as well as by stopping the aeration and mixing, settling takes place under almost perfectly quiescent conditions. This yields a faster and more defined solids separation. Conventional continuous flow systems, by definition, cannot stop the inflow and outflow of the clarifier unit. Thus, settling must take place in conditions where water currents and possible short-circuiting are occurring.

The second advantage to the solids separation process in the SBR system is the flexibility afforded to alter the time dedicated to the process. An SBR unit can easily be adjusted to give more time to the SETTLE phase if it is necessary to achieve sufficient solids separation. During high flow conditions, the SETTLE time can be reduced to the minimum necessary to achieve solids separation, cutting down on the overall cycle time and treating more flow. Decanting can also be initiated during SETTLE, if necessary, to further reduce the overall time requirements. Conventional continuous flow systems exhibit none of this flexibility.

3.3 Nitrogen removal can be achieved in the SBR system without additional equipment or chemicals. Nitrogen enters the system in the raw wastewater in the form of organic nitrogen and ammonia (NH_4). It is removed from the system in the form of nitrogen gas (N_2). The process by which ammonia nitrogen is converted to nitrogen gas involves three steps. First is the conversion (nitrification) of ammonia nitrogen to nitrite (NO_2). Second is the conversion of nitrite to nitrate (NO_3). Third is the conversion (denitrification) of nitrate nitrogen to nitrogen gas. All of these steps are accomplished by microbiological action. However, the differing nature of the reactions, oxidizing or reducing, demands different microorganisms and reactor conditions.

Nitrification, the process of converting ammonia-nitrogen through nitrite-nitrogen to nitrate nitrogen (steps 1 and 2), can only occur under conditions of adequate DO. In the SBR system, nitrification takes place during REACT and any periods of aerated FILL. If the nitrification process is to be effective, the combined aeration time during FILL and REACT must be sufficiently long and the DO sufficiently high (greater than 0.5 g/m^3) to allow for both the development of nitrifiers (those microbes performing the nitrification) in the system and the completion of ammonia-nitrogen oxidation.

Denitrification (step 3), the process of converting nitrate-nitrogen to nitrogen gas, only occurs in the absence of DO. In an SBR system, denitrification can occur during the unaerated portion of FILL and during the latter stages of SETTLE, DRAW, and IDLE after the DO content has dropped off. As with nitrification, these conditions must last sufficiently long to allow the desired nitrogen reduction to take place.

Nitrogen removal in an SBR system can be considerably greater in efficiency than conventional continuous flow systems. The advantage of the SBR system is that the conditions necessary to achieve nitrogen removal can be created by simple changes to the plant operation (modifications to periodicity and duration of aeration) rather than by major modification of the physical plant. Figure 2 shows suggested operating strategies for achieving different water quality objectives through SBR operations.

3.4 Phosphorus removal by microbiological methods in SBR systems has also been documented. The addition to the reactor of a chemical coagulant that precipitates the phosphorus into the sludge is a common phosphorus removal process applicable to both conventional continuous flow and SBR systems. The microbiological removal of phosphorus first requires an anaerobic period (the absence of dissolved oxygen and oxidized nitrogen) during which substrate (raw waste) is present. This period should be followed by an aerobic period (high DO) that promotes the uptake of excess phosphorus by the sludge mass. Excess sludge should be removed from the reactor in suitable quantities before the onset of the next anaerobic period. In terms of SBR operation, anaerobic conditions must be available during FILL, and sufficient aeration must be provided during REACT to achieve phosphorus uptake by the biomass. The flexibility of the SBR system is again shown by its ability to achieve these conditions with simple operational modifications. Figure 2 shows a recommended strategy for accomplishing both nitrogen and phosphorus removal in an SBR system.

Figure 2

Suggested Operating Strategies for Different Water Quality Objectives

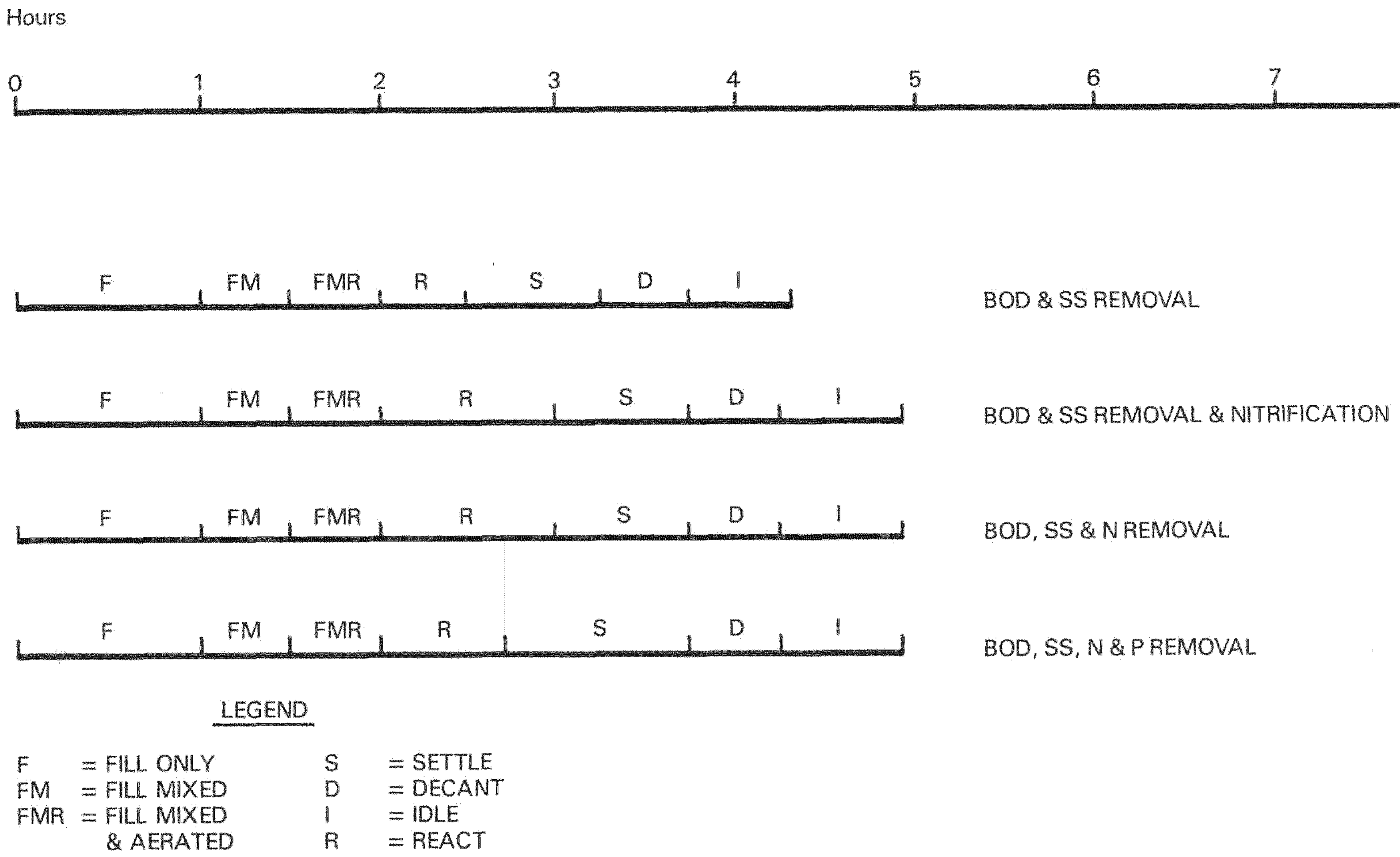


Figure from Arora, p. 7-4

4.0 Design

4.1 Design of municipal SBR systems to handle industrial wastewater would generally require an extensive treatability study, as would conventional continuous flow systems. On the other hand, system design for typical domestic wastewater is relatively simple, centering around the selection of the proper tank sizes, the inlet configuration, the aeration system, and the control mechanism. With knowledge of such factors as average daily wastewater flow, peak daily flow, average influent BOD, average influent suspended solids, average influent ammonia nitrogen, and effluent requirements, an initial design for an SBR system can be easily developed.

4.2 One suggested design approach for a domestic SBR system includes the following steps:

1. Decide if primary treatment is needed. Primary treatment is unnecessary in most SBR systems, especially if the design sludge age or sludge retention time (SRT) is high (more than 20 days). A high SRT system will also accomplish some sludge digestion aerobically in the reactor. The treatment selected must, of course, comply with applicable Federal and local discharge regulations and codes.

2. Select the desired food/microorganism (F/M) ratio. The selection of the design F/M ratio should be based on considerations such as nitrification requirements and desired SRT. From a given influent BOD, F can be calculated in pounds of BOD/-day, and application of the selected F/M ratio yields the design M or sludge mass.

   $F = \text{BOD mg/l} \times 8.33 \text{ lb/gal} \times \text{flow } (10^6 \text{ gal/day})$

   $M = F \div \text{F/M ratio}$

3. Select a value of Mixed Liquor Suspended Solids (MLSS) concentration in the reactor at the end of DRAW. This is slightly different from designing a conventional continuous flow system. The MLSS concentration in an SBR design corresponds to a particular period in the SBR operating cycle, since the concentration changes throughout the cycle. In an SBR, the MLSS concentration is lowest at the end of FILL and highest at the end of DRAW. With most SBR systems, the MLSS concentration at the end of DRAW should be higher than the corresponding value used in the design of a conventional continuous flow system, because the MLSS concentration in the SBR system at the end of DRAW represents a completely settled mixed liquor, similar to that in a conventional clarifier underflow. The design mixed liquor volume can then be calculated from the selected MLSS concentration.

   $\text{Volume} = M \times (10^6 \text{ gal/day}) / (8.33 \times \text{MLSS concentration})$

4. Select the number of SBR tanks. The number selected will depend on the mixed liquor volume determined in step 3, as well as on considerations of area, unit availability, projected maintenance, and operational flexibility. There are no basic rules of judgment in this regard, except that in most cases it is desirable to provide at least two tanks.

5. Select a cycle length, comprised of FILL, REACT, SETTLE, DRAW, and IDLE, for each "batch" treatment. The total time for a cycle will be the sum of the times allowed for the cycle phases.

   $$T = t_f + t_r + t_s + t_d + t_i$$

   The time for FILL, t_f, can be calculated from the peak daily flow divided by the number of tanks. The combined time for SETTLE, t_s, and the time for DRAW, t_d, can be estimated to be less than 3 hours. The time for REACT, t_r, should be determined from kinetic studies, but for domestic wastewater the range of time for REACT will generally be between 1/2 and 2 hours. The final time factor for IDLE, t_i, is selected to provide the operating characteristics needed so that the active part of the cycle will achieve required performance levels (see Section 3, Performance).

6. Calculate the volume of liquid per tank per decant.

   Volume per decant (V_d) = Average Flow/cycles

   Volume per tank per decant = V_d/no. of tanks

7. Calculate the tank size. The total volume required per tank is the sum of the volume of mixed liquor per tank at the end of DRAW and the volume of liquid decanted per tank per cycle.

   The final dimensions of the tanks can be developed by selecting a reasonable tank depth. In most cases a depth of 15 feet or less is practical from the standpoint of oxygen transfer efficiency. Also, allowance must be made for appropriate freeboard, usually 3 to 4 feet.

   Volume of tank = Volume mixed liquor + Volume decant

   Area of tank = Volume of tank ÷ Tank depth

8. Size the aeration equipment. This is done in the same manner as in a conventional continuous flow system, except that since the aeration equipment runs for only a portion of the operating cycle in an SBR system (REACT, or REACT and a part of FILL), the calculated daily oxygen requirement must be met in this shorter time frame. The size of the aeration equipment is therefore increased over that of a conventional continuous flow system of the same capacity.

9. Size the decanter and associated piping. The decant rate is calculated from the maximum volume of liquid decanted per tank per cycle. This volume is then divided by the desired decant or DRAW time. The DRAW period is typically chosen to be approximately 45 minutes.

4.3 Factors to be considered that can place constraints on the design process are the ability to maintain treatment quality in a single tank system, the optimum or maximum sizes for an individual reactor unit in a multi-tank system, and desired sludge storage volume.

The design steps outlined above illustrate a simplified approach. In a real situation, many iterative calculations may be necessary to accommodate several conditions (different MLSS concentrations, different number of operating cycles to achieve flexibility during actual plant operation, diurnal flow variations, and different decant heights to correspond to different conditions of sludge settleability).

5.0 Currently Operating Plants

SBR wastewater treatment plants are currently operating at several sites in Australia, Canada, and the United States. They include plants at Rivercrest and Glenka, Manitoba, Canada; Choctaw, Oklahoma; Grundy Center and Eldora, Iowa; Culver, Indiana; Poolesville, Maryland; and Tamworth and Yamba, New South Wales, Australia. The designs of these plants differ in several aspects, including inlet design, aeration/mixing system design, and decanter design, but they all operate on sequencing batch principles.

6.0 Economics

Table 3 shows estimated costs for constructing SBR systems to handle flow rates of 379, 1893, 3785, and 18,925 m^3/d (or 1, 5, 10 and 50 MGD, respectively). In constructing this table, floating aerators were considered, to allow for comparison to other activated sludge systems. Table 4 further defines the operation and maintenance costs. A two tank system was used for the 379 m^3/d plant, and three tank systems for the other three daily flow rates. The design criteria for cost purposes can be summarized as follows:

Flow (M^3/d)	Flow (MGD)	Sets of Tanks	Tanks per Set	Total Volume (M^3)
379	1	2	1	252
1,893	5	3	1	947
3,785	10	3	1	1,893
18,925	50	3	4	9,465

Costs are developed as per January 1983. While the modular design notion provides reasonable costs for the three lower flow rate systems, this approach results in unreasonable costs for the 18,925 m^3/d facility. In particular, any appreciable economy of scale is lost with respect to items such as the inlet and discharge structures and excavation and concrete work. A more detailed approach to design in this area would likely result in additional savings.

Tables 5–8 show cost comparisons between SBR systems, and conventional oxidation ditch and activated sludge systems. The cost estimates for the SBR are conservative and do not necessarily reflect the full potential of that technology, because the information available on SBR systems is limited. Even at these conservative estimates, however, the SBR system is competitive.

Table 3.

Cost Estimates for SBR for Four Average Daily Flow Rates

Process Unit	Flow Rates (m^3/d; MGD in parentheses) 379 (1)	1893 (5)	3785 (10)	18,925 (50)
Inlet Control System	$ 2,000	$ 3,000	$ 4,000	$ 20,000
Contact Chamber Baffle Walls	2,000	4,000	5,000	24,000
Aerators	25,000	50,000	60,000	256,000
Excavation, Concrete and/Handrail	70,000	150,000	250,000	840,000
Microprocessors	10,000	10,000	10,000	10,000
Level Control/Monitoring	2,000	4,000	4,000	16,000
Decant System	9,000	16,000	18,000	90,000
Subtotal (1)	$120,000	$237,000	$351,000	$1,256,000
Noncomponent Costs*	30,000	59,000	88,000	314,000
Subtotal (2)	$150,000	$296,000	$439,000	$1,570,000
Engineering, Construction on Supervision and Contingencies**	45,000	89,000	132,000	471,000
Total Installed Capital Costs	$195,000	$385,000	$571,000	$2,041,000
Annual Operation and Maintenance Costs	13,000	24,000	40,000	148,000
Present Worth Costs***	$329,000	$632,000	$983,000	$3,564,000
Costs/(m^3/d)	$ 870	$ 330	$ 260	$ 190

* At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

** At 30 percent of subtotal (2).

*** Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

Source: Reference 2.

Table 4.

Operation and Maintenance Cost Estimates for the SBR for Four Average Daily Flow Rates

Costs (dollar/yr)	Flow Rates (m^3/d; MGD in parentheses)			
	379 (1)	1893 (5)	3785 (10)	18,925 (50)
Operation Labor	$ 7,885	$10,046	$15,518	$ 33,208
Maintenance Labor	1,319	1,941	2,346	5,062
Power*	2,232	9,660	18,900	96,600
Material	1,890	2,640	3,722	13,136
TOTAL O & M (rounded)	$13,000	$24,000	$40,000	$148,000

* Includes mixing, aeration and decanting at a power rate of $0.06/kWh.

Source: Reference 2.

Table 5.

Cost Comparison — 379 m^3/d (1 MGD) Facility

Process Unit	Oxidation Ditch	SBR
Raw Sewage Pumping	$ 40,000	$ 40,000
Preliminary Treatment	24,000	24,000
Aeration/Clarification	240,000	120,000
Chlorination	48,000	48,000
Aerobic Digestion	—	40,000
Sludge Lagoons	7,000	7,000
Subtotal (1)	$ 359,000	$ 279,000
Noncomponent Costs*	90,000	70,000
Subtotal (2)	$ 449,000	$ 349,000
Engineering, Construction Supervision and Contingencies**	135,000	105,000
Total Installed Capital Cost	$ 584,000	$ 454,000
Annual Operation and Maintenance Costs	65,000	58,000
Present Worth Costs***	$1,253,000	$1,051,000

* At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

** At 30 percent of subtotal (2).

*** Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

Source: Reference 2.

Table 6.

Cost Comparison — 1,893 m³/d (5 MGD) Facility

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	$ 248,000	$ 248,000	$ 248,000
Preliminary Treatment	36,000	36,000	36,000
Primary Clarification	128,000	—	—
Aeration/Clarification	448,000	416,000	237,000
Chlorination	80,000	80,000	80,000
Gravity Thickening	64,000	64,000	64,000
Aerobic Digestion	208,000	152,000	208,000
Vacuum Filtration	272,000	272,000	272,000
Sludge Lagoons	12,000	12,000	12,000
Chemical Feed Systems	44,000	44,000	44,000
Subtotal (1)	$1,540,000	$1,324,000	$1,201,000
Noncomponent Costs*	385,000	331,000	300,000
Subtotal (2)	$1,925,000	$1,655,000	$1,501,000
Engineering, Construction Supervision and Contingencies**	578,000	497,000	450,000
Total Installed Capital Costs	$2,503,000	$2,152,000	$1,951,000
Annual Operation and Maintenance Costs	166,000	150,000	150,000
Present Worth Costs***	$4,212,000	$3,696,000	$3,495,000

* At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

** At 30 percent of subtotal (2).

*** Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

Source: Reference 2.

Table 7.

Cost Comparison — 3,785 m^3/d (10 MGD) Facility

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	$ 312,000	$ 312,000	$ 312,000
Preliminary Treatment	56,000	56,000	56,000
Primary Clarification	164,000	—	—
Aeration/Clarification	624,000	576,000	351,000
Chlorination	104,000	104,000	104,000
Gravity Thickening	68,000	68,000	68,000
Aerobic Digestion	264,000	160,000	264,000
Vacuum Filtration	288,000	272,000	288,000
Sludge Handling and Landfilling	76,000	68,000	76,000
Chemical Feed Systems	44,000	44,000	44,000
Subtotal (1)	$2,000,000	$1,660,000	$1,563,000
Noncomponent Costs*	500,000	415,000	391,000
Subtotal (2)	$2,500,000	$2,075,000	$1,954,000
Engineering, Construction Supervision and Contingencies**	750,000	623,000	586,000
Total Installed Capital Costs	$3,250,000	$2,698,000	$2,540,000
Annual Operation and Maintenance Costs	230,000	190,000	190,000
Present Worth Costs***	$5,617,000	$4,654,000	$4,496,000

* At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

** At 30 percent of subtotal (2).

*** Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

Source: Reference 2.

Table 8.

Cost Comparison — 18,925 m^3/d (50 MGD) Facility

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	$ 600,000	$ 600,000	$ 600,000
Preliminary Treatment	148,000	148,000	148,000
Primary Clarification	352,000	—	—
Aeration/Clarification	1,720,000	1,952,000	1,256,000
Chlorination	160,000	160,000	160,000
Gravity Thickening	88,000	88,000	88,000
Aerobic Digestion	624,000	256,000	624,000
Vacuum Filtration	496,000	280,000	496,000
Sludge Handling and Landfilling	88,000	72,000	88,000
Chemical Feed Systems	56,000	44,000	56,000
Subtotal (1)	$ 4,332,000	$ 3,600,000	$ 3,516,000
Noncomponent Costs*	1,083,000	900,000	879,000
Subtotal (2)	$ 5,415,000	$ 4,500,000	$ 4,395,000
Engineering, Construction Supervision and Contingencies**	1,625,000	1,350,000	1,319,000
Total Installed Capital Costs	$ 7,040,000	$ 5,850,000	$ 5,714,000
Annual Operation and Maintenance Costs	490,000	455,000	455,000
Present Worth Costs***	$12,083,000	$10,533,000	$10,397,000

* At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

** At 30 percent of subtotal (2).

*** Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

Source: Reference 2.

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The photographs in this report (except the cover photograph) show the Poolesville, MD SBR Facility. These were provided by John A. Hart of Hart's Custom Photographic Services, Poolesville, MD. The cover photograph was provided by Austgen Biojet, San Francisco, CA, showing one of their facilities.