Design of Sequencing Batch Reactors for Nitrification/Denitrification

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Acronyms

ACFM	Actual Cubic Feet per Minute
ADWF	Average Dry Weather Flow
COD	Chemical Oxygen Demand
BNR	Biological Nutrients Removal
BOD	Biochemical Oxygen Demand
CBOD	Carbonaceous Biochemical Oxygen Demand
DOB	Depth of Blanket
F/M	Food-to-Microorganism Ratio
HDT	Hydraulic Detention Time
MCRT	Mean Cell Residence Time
mg/L	milligram per liter
MGD	Million Gallons per Day
MLSS	Mixed-Liquor Suspended Solids
MLVSS	Mixed-Liquor Volatile Suspended Solids
NH_3-N	Ammonia-Nitrogen
NH_4-N	Ammonium-Nitrogen
NO_3-N	Nitrate-Nitrogen
NO_2-N	Nitrite-Nitrogen
ORP	Oxidation Reduction Potential
OUR	Oxygen-Uptake Rate
PDWF	Peak Dry Weather Flow
PWWF	Peak Wet Weather Flow
PO_4-P	Phosphate-Phosphorus
SBR	Sequencing Batch Reactor
SOUR	Specific Oxygen-Uptake Rate
SRT	Solids Retention Time
SS	Suspended Solids
SSV	Settled-Sludge Volume
SVI	Sludge Volume Index
SSVI	Stirred Sludge Volume Index
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TSS	Total Suspended Solids
VSS	Volatile Suspended Solids
WAS	Waste-Activated Sludge
WW	Wastewater
WWTP	Wastewater Treatment Plant

INTRODUCTION

SBRs are used all over the world and have been around since the 1920s. With their growing popularity in Europe and China as well as the United States, they are being used successfully to treat both municipal and industrial wastewaters, particularly in areas characterized by low or varying flow patterns. Municipalities, resorts, casinos, and a number of industries, including dairy, pulp and paper, tanneries and textiles, are using SBRs as practical wastewater treatment alternatives.

Improvements in equipment and technology, especially in aeration devices and computer control systems, have made SBRs a viable choice over the conventional activated sludge system. These plants are very practical for a number of reasons:

- In areas where there is a limited amount of space, treatment takes place in a single basin instead of multiple basins, allowing for a smaller footprint. Low total suspended solid values of less than 10 milligrams per liter (mg/L) can be achieved consistently through the use of effective decanters that eliminate the need for a separate clarifier.

- The treatment cycle can be adjusted to undergo aerobic, anaerobic, and anoxic conditions to achieve biological nutrient removal, including nitrification, denitrification, and some phosphorus removal. Biochemical oxygen demand (BOD) levels of less than 5 mg/L can be achieved consistently. Total nitrogen limits of less than 5 mg/L can also be achieved by aerobic conversion of ammonia to nitrates (nitrification) and anoxic conversion of nitrates to nitrogen gas (denitrification) within the same tank. Low phosphorus limits of less than 2 mg/L can be attained by using a combination of biological treatment (anaerobic phosphorus-absorbing organisms) and chemical agents (aluminum or iron salts) within the vessel and treatment cycle.

- Older wastewater treatment facilities can be retrofitted to an SBR because the basins are already present.

- Wastewater discharge permits are becoming more stringent and SBRs offer a cost-effective way to achieve lower effluent limits. Note that discharge limits that require a greater degree of treatment may necessitate the addition of a tertiary filtration unit following the SBR treatment phase. This consideration should be an important part of the design process.

CHAPTER 1. CHARACTERISTICS OF SEQUENCING BATCH REACTORS (SBRs)

1.1. Common SBR Characteristics

1.1.1. General

SBRs are a variation of the activated sludge process. They differ from activated-sludge plants because they combine all of the treatment steps and processes into a single basin, or tank, whereas conventional facilities rely on multiple basins. According to a 1999 U.S. EPA report, an SBR is no more than an activated-sludge plant that operates in time rather than space.

1.1.2. Basic Treatment Process

The operation of an SBR is based on a fill-and-draw principle, which consists of five steps—1. fill, 2. react (aeration), 3. settle (sedimentation), 4. decant (draw), and 5. idle as shown in Fig. 1. These steps can be altered for different operational applications as shown in Fig. 2, 3 & 4.

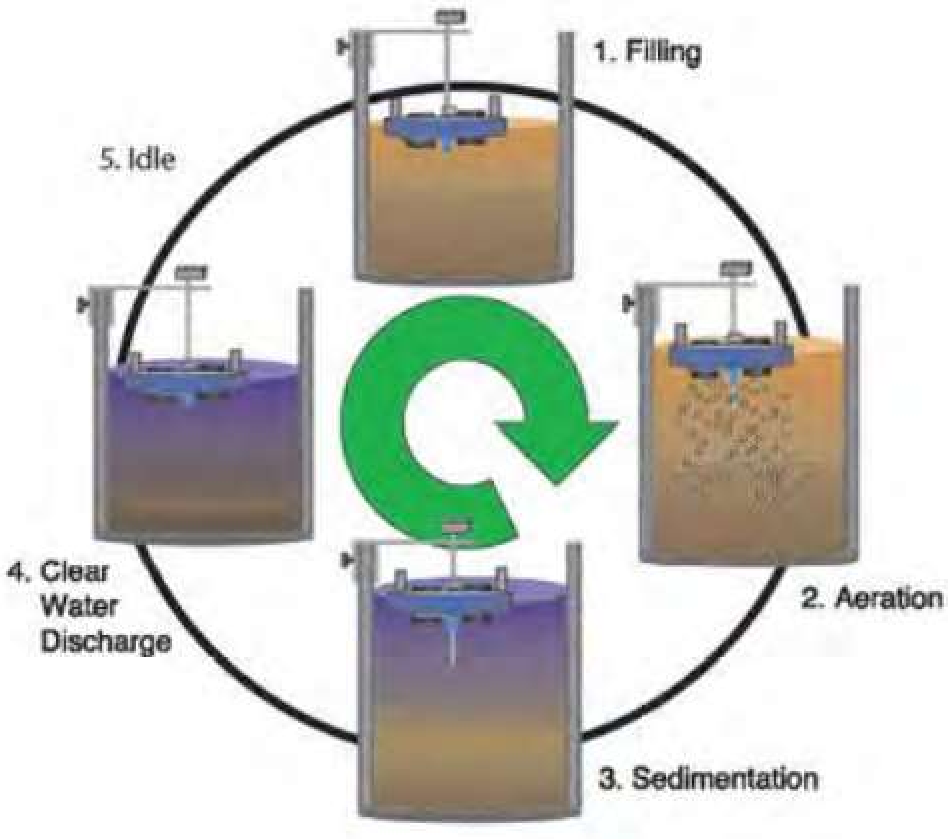

Fig.1. Basic SBR Process.

Fill

During the fill phase, the basin receives influent wastewater. The influent brings food to the microbes in the activated sludge, creating an environment for biochemical reactions to take place. Mixing and aeration can be varied during the fill phase to create the following three different scenarios:

a. Static Fill

Under a static-fill scenario, there is no mixing or aeration while the influent wastewater is entering the tank. Static fill is used during the initial start-up phase of a facility, at plants that do not need to nitrify or denitrify, and during low flow periods to save power. Because the mixers and aerators remain off, this scenario has an energy savings component.

b. Mixed Fill

Under a mixed-fill scenario, mechanical mixers are active, but the aerators remain off. The mixing action produces a uniform blend of influent wastewater and biomass. Because there is no aeration, an anoxic condition is present, which promotes denitrification. Anaerobic conditions can also be achieved during the mixed fill phase. Under anaerobic conditions the biomass undergoes a release of phosphorous. This release is reabsorbed by the biomass once aerobic conditions are reestablished. This phosphorous release will not happen with anoxic conditions.

c. Aerated Fill

Under an aerated fill scenario, both the aerators and the mechanical mixing unit are activated. The contents of the basin are aerated to convert the anoxic or anaerobic zone over to an aerobic zone. No adjustments to the aerated fill cycle are needed to reduce organics and achieve nitrification. However, to achieve denitrification, it is necessary to switch the oxygen off to promote anoxic conditions for denitrification. By switching the oxygen on and off during this phase with the blowers, oxic and anoxic conditions are created, allowing for nitrification and denitrification, respectively. Dissolved oxygen (DO) should be monitored during this phase so it does not go over 0.2 mg/L. This ensures that an anoxic condition will occur during the idle phase.

React

This phase allows for further reduction or "polishing" of wastewater parameters. During this phase, no wastewater enters the basin and the mechanical mixing and aeration units are on. Because there are no additional volume and organic loadings, the rate of organic removal increases dramatically. Most of the carbonaceous BOD removal occurs in the react phase. Further nitrification occurs by allowing the mixing and aeration to continue whilst the majority of denitrification takes place in the mixed fill phase. The phosphorus released during mixed fill, plus some additional phosphorus, is taken up during the react phase.

If REACT phase is designed correctly, no AERATED FILL phase is required for nitrification. The duration of combined SETTLE and DECANT phases, which is 2-3 times longer than that for AERATED FILL, is more than sufficient for complete denitrification during these phases. AERATED FILL phase is applied when the design engineer is not certain if the REACT phase design is capable to completely nitrify. Eq. (14) defined the amount of oxygen required for AERATED FILL phase.

Settle

During this phase, activated sludge is allowed to settle under quiescent conditions. No flow enters the basin and no aeration and mixing takes place. The activated sludge tends to settle as a flocculent mass, forming a distinctive interface with the clear supernatant. The sludge mass is called the sludge blanket. This phase is a critical part of the cycle, because if the solids do not settle rapidly, some sludge can be drawn off during the subsequent decant phase and thereby degrade effluent quality. Refer to Eq. (28) for minimum settling time.

Decant

During this phase, a decanter is used to remove the clear supernatant effluent. Once the settle phase is complete, a signal is sent to the decanter to initiate the opening of an effluent-discharge valve. There are floating and fixed arm decanters. Floating decanters maintain the inlet orifice slightly below the water surface to minimize the removal of solids in the effluent removed during the decant phase. Floating decanters offer the operator flexibility to vary fill and draw volumes. Fixed arm decanters are less expensive and can be designed to allow the operator to lower or raise the level of the decanter. It is optimal that the decanted volume is the same as the volume that enters the basin during the fill phase. It is also important that no surface foam or scum is decanted. The vertical distance from the decanter to the bottom of the tank should be maximized to avoid disturbing the settled biomass.

Idle

This step occurs between the decant and the fill phases and may be considered as a safety factor (SF) in the design of SBRs with no flow equalization. In this case, the IDLE time varies based on the influent flow rate and the operating strategy. During this phase, a small amount of activated sludge at the bottom of the SBR basin is pumped out - a process called wasting. Wasted sludge (WS) is collected, dewatered and the resulting liquid called supernatant (or centrate if WS is centrifuged) is pumped back to the SBR.

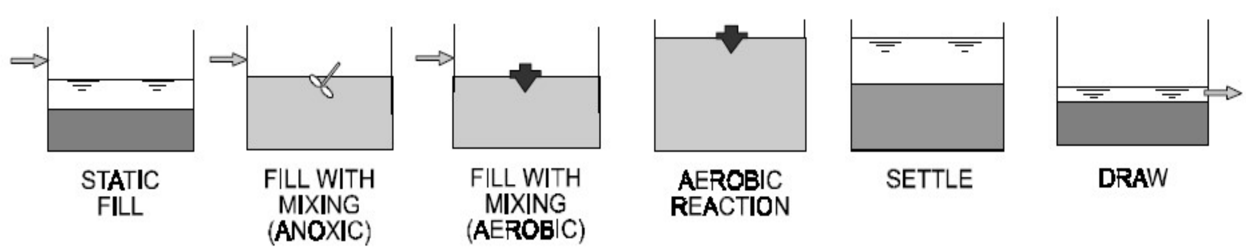

Fig. 2. SBR With Pre-Anoxic Nitrification Zone.

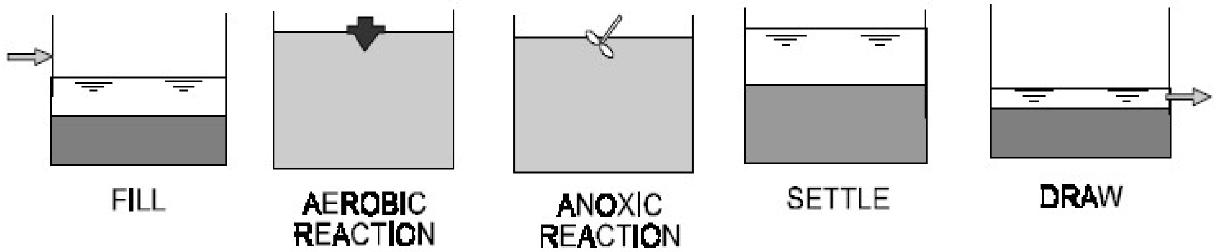

Fig. 3. SBR With Post-Anoxic Nitrification Zone.

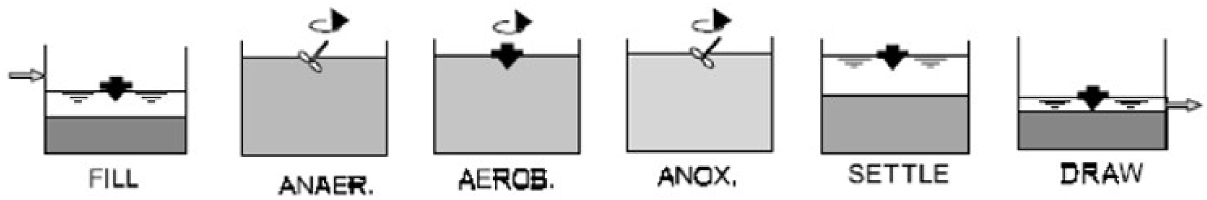

Fig. 4. SBR Sequence for C, N & P Removal

1.1.3 Continuous Flow Systems

SBR facilities commonly consist of two or more basins that operate in parallel but single-basin configurations operating under continuous-flow conditions are not common. In this modified version of the SBR, flow enters each basin on a continuous basis. The influent flows into the influent chamber, which has inlets to the react basin at the bottom of the tank to control the entrance speed so as not to agitate the settled solids. Note that continuous-flow systems are not true batch reactors because influent is constantly entering the basin and as such, cannot be called SBRs. The design configurations of SBRs and continuous-flow systems are, otherwise, very similar. Plants operating under continuous flow should operate this way as a standard mode of operation. A true batch-reaction SBRs operate under continuous flow only under emergency situations.

Plants that have been designed as continuous-inflow systems have been shown to have poor operational conditions during peak flows. Some of the major problems of continuous-inflow systems have been overflows, washouts, poor effluent, and permit violations.

CHAPTER 2. COMMON DESIGN GUIDELINES

2.1. Preliminary/Primary Treatment

Preliminary treatment includes screening, grit removal, and flow monitoring. Primary treatment includes sedimentation and floatation. SBRs generally do not have primary settling tanks; therefore, effective removal or exclusion of grit, debris, plastics, excessive oil or grease, and scum, as well as screening of solids should be accomplished prior to the activated-sludge process.

2.1.1. Screening Influent Wastewater

Bar screens or mechanical screens are used instead of grinders or shredders. Screening influent wastewater is a means of removing rags, sticks, and other debris before they can enter the treatment process. Grinders and shredders pass this material into the SBR where it can become woven together, making it difficult to remove. Removing debris from the wastewater stream before it reaches the basins is beneficial to both the treatment process and the settling phase as excess debris is not present to interfere with the solids that need to settle, resulting in a high-quality sludge blanket. Screens also provide protection for the pumps.

2.1.2. Influent Flow Equalization

Flow equalization is critical where significant variations in flow rates and organic mass loadings are expected. Flow equalization is also important if a plant is expected to receive a significant amount of septage or is taking in a significant amount of industrial wastes. Flow equalization is strongly recommended when the ratio of average dry weather flow to peak hourly flow exceeds 2 and when a plant needs to achieve nitrification and denitrification. The size of the influent equalization basin must be carefully considered because an oversized basin can cause negative downstream treatment process impacts. A plant utilizing an influent equalization basin will be able to have a true batch reaction. Influent-flow equalization benefits the SBR process in the following ways:

- Allows for a smaller SBR basin size because it allows for storage until the process cycle is complete.
- Allows for one basin to be taken off line for maintenance or for seasonal variations. Routine maintenance is necessary for all tanks. For plants that have seasonal

variations, taking one basin off line is cost effective due to a reduced need for electricity, staff hours, and tank maintenance.

- Allows for scum and grease removal at a single point before it enters the SBR tank. Normally, a mechanism or process for removing scum, grease, and floatables is provided in the equalization tank.
- Allows plants that denitrify to ensure that an adequate amount of carbon is available in the denitrification fill phase.
- Allows for an equal flow volume into the basin, keeping the food to microorganism ratio (F/M) fairly stable.

Plants with or without equalization and/or primary clarification must at least have manual and/or mechanical bar screens and, preferably, aerated grit chambers to reduce the amounts of grease, scum, rags, floatables and other debris in wastewater entering the SBR.

Each SBR design is unique and, in some situations, influent flow equalization basins are not needed to obtain optimum treatment unless required by the state. Examples of where influent flow equalization is not needed include but are not limited to plants designed with three or more SBR basins and plants that do not need to nitrify and denitrify. If a plant is operating with a two-basin system without influent-flow equalization, then it must have an adequate supply of essential spare parts onsite for maintenance.

The influent equalization basins have a means of agitation or mixing to keep the solids in suspension. A mechanical mixing unit can be used for this purpose. Maintenance on this basin is normally minimal as the solids are in suspension due to agitation. However, a means to bypass the equalization basin and to dewater the basin must be provided. Pumps that direct influent to the SBRs are in duplicate. Influent flow equalization basins are designed to hold peak flows long enough to allow the active treatment cycle to be completed in at least one SBR. The probability that more than one SBR reactor will be out of service must be determined before sizing the equalization basin.

2.1.3. Alkalinity Addition

For plants with effluent ammonia limits, facilities are provided with piping for adding alkalinity at both the influent-equalization basin and the SBR basin. It is desirable to be able to measure alkalinity at each stage of the process. Alkalinity addition should be based on the amount measured during the decant phase, not on incoming flow. Alkalinity should be kept in a range of

40-70 mg/L as $CaCO_3$ prior to the decant phase to be sure the nitrification cycle is complete. When nitrification occurs at SBR facilities, it often occurs during periods of diurnal low flow (e.g., very late evening or very early morning) when a plant is not staffed. If no testing or chemical addition is available to compensate for an alkalinity drop, pH in the SBR unit will drop and may cause process upsets.

2.1.3.1. Options for Adding Alkalinity

Sodium Bicarbonate - Baking Soda ($NaHCO_3$). Sodium bicarbonate is most often recommended for alkalinity addition because it is not a strong base and it has a pH of 8.3. It is beneficial to alkalinity addition by providing the bicarbonate species at a pH near neutrality.

Sodium Carbonate - Soda Ash (Na_2CO_3). Soda ash is safer to handle than other alkalis and tends to maintain stable prices over time, hence more and more treatment plants are choosing soda ash for their alkalinity needs. Whilst soda ash is less expensive than sodium bicarbonate, it is generally less effective than sodium bicarbonate and sodium hydroxide. Soda ash is a moderately fast-acting agent, but it generates carbon dioxide, which can lead to foaming problems.

Calcium Oxide - Lime ($Ca(OH)_2$). Lime is available in various forms and is relatively inexpensive. Lime compounds dissolve slowly and require longer contact times than the other chemical options. The use of lime causes more sludge production due to calcium sulfate precipitation. This results in maintenance problems within the basin, especially with pH, DO, and ORP probes.

2.2. Sequencing Batch Reactor

2.2.1. Design Basics

Ideally, SBR plants should have a flow equalization basin. Even with flow equalization, all SBR designs should have a minimum of two SBRs in parallel to allow for redundancy, maintenance, high flows, and seasonal variations. If one basin is off line, the plant is still able to treat influent wastewater because of flow equalization. If the basin microbiology becomes depleted in one basin, the biomass from the remaining basin can be used to restock the basin with depleted biomass. For this to happen, a means of transferring sludge between the two basins must be provided. During storm events and high flow periods, instead of bypassing the basins or blending the stormwater, an additional basin can act as storage if no flow equalization is provided, or certain cycles can be shortened.

The REACT cycle can be shortened under wet weather conditions because of the diluted flow and the reduced time needed to treat the BOD. With higher flows, the FILL phase and the IDLE phase can also be shortened. For domestic wastewater, the combined cycle time varies from 4 hrs to 6 hrs as shown in Fig. 5 and Table 1. It is usually longer for industrial wastewater.

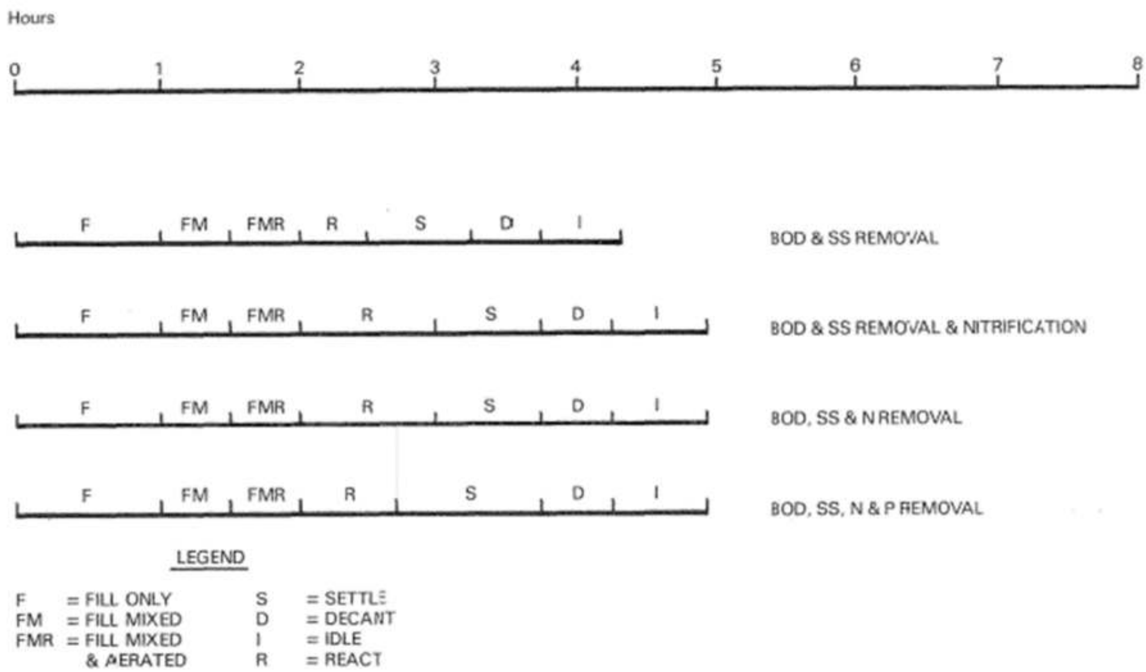

Fig. 5. Typical SBR Cycle Time for Domestic Wastewater.

Stage	Extended aeration BOD removal		Extended aeration BOD and N removal	
	Duration (hour)	% of the total	Duration (hour)	% of the total
Fill	1.0	*23.8*	1.0	*21.3*
Fill with mix	0.5	*11.9*	0.5	*10.6*
Fill with aeration	0.5	*11.9*	0.5	*10.6*
Aerobic/anoxic react	0.5	*11.9*	1.0	*21.3*
Settle	0.7	*16.7*	0.7	*14.8*
Draw	0.5	*11.9*	0.5	*10.6*
Idle	0.5	*11.9*	0.5	*10.6*
Total	**4.2**	***100.0***	**4.7**	***100.0***

Source: EPA (1993)

Table 1. Typical SBR Cycle Time for Domestic Wastewater.

2.2.2. Flow Paced Batch Operation

Flow paced batch operation is preferable to time paced batch or continuous inflow systems. Under a flow paced batch system, a plant receives the same volumetric loading and approximately the same organic loading during every cycle. The SBR basin already has stabilized supernatant in it, which dilutes the batch of incoming influent.

Under a time-paced mode, each basin receives different volumetric and organic loading during every cycle, and the plant is not utilizing the full potential of this treatment method that offers the ability to handle variable waste streams. After each loading, the plant faces a whole new set of treatment conditions, making the operator's job more difficult. Time-paced operation, unless the cycle time is adjusted every time, can lead to under treated effluent. A plant that receives heavy morning loadings, with a flow pattern that drops off after the first cycle, must deal with two different biologies in the basin. For example, one basin could be receiving an early morning load, which has a high organic and volumetric loading. The second basin could be receiving the afternoon loading, which has a lower organic and volumetric loading. Unless the time cycle is adjusted, it becomes difficult to operate under these conditions because the operator is essentially running two separate plants.

Another problem with time-paced operation is that if the plant is required to denitrify, it may not bring in an adequate carbon source needed for the bacteria to strip oxygen from the nitrate. This scenario would be especially problematic during periods of low flow. For an SBR to be effective, the plant must have proper monitoring, allow operators to adjust the cycle time, and have knowledgeable operators who are properly trained to make the necessary adjustments to the cycle.

2.2.3. Blower Design

Several smaller blowers are preferable to one large unit. It is not uncommon for SBR designs to incorporate a single blower per basin to provide aeration. However, operational efficiency can be enhanced when plants utilize several smaller blowers instead of one large blower.

When a single blower per basin is used, it should be sized to provide maximum aeration under worst-case conditions. These conditions typically occur in the summer months, when higher temperatures decrease the amount of oxygen that can be dissolved in wastewater. For facilities that utilize a single blower per basin, a variable frequency drive (VFD) is provided.

In wastewater facilities, pumping and aeration account for a majority of energy consumption. These applications are well suited to the use of VFDs. A VFD is an electronic controller that adjusts the speed of an electric motor by varying the amount of power supplied. A VFD varies both the frequency (hertz) and amplitude (volts) of the alternating current waveform. This allows the motor to continually adjust in order to work just hard enough, rather than running full speed all the time. Wastewater facilities that have installed VFDs have seen a 25 percent reduction in energy costs for pumping and aeration, as well as increased equipment life and decreased maintenance costs. In a plant configured with only one blower per basin, it is difficult to scale back on the aeration provided. With multiple smaller blowers, units can be taken off line when maximum aeration is not required. This results in electrical cost savings.

Fine-bubble membrane diffusers are preferable to coarse-air bubble aeration. Fine-bubble diffusers transfer more oxygen to water due to increased surface area in contact with water. The same amount of air introduced in a big bubble has less surface area in contact with water than an equal amount of air divided into smaller bubbles. The amount of surface area in contact with water is proportional to the amount of oxygen transferred into water. Depth of aerators also plays a part in oxygen transfer due to contact time. The deeper the aerator, the longer it takes for the bubble to come to the surface. Aerator depth is deepest when a tank is filled to the high-water level. If a plant is utilizing time-paced batch reactions, aerator depth is not optimal and oxygen contact time is not maximized.

Blowers in multiple units should are sized to meet the maximum total air demand with the single largest blower out of service.

2.2.4. Decanting

During the decant phase, operating under a flow-paced batch operation, no more than one-third of the volume contained in the basin (i.e., the tank contents) should be decanted each time in order to prevent disturbance of the sludge blanket. The decant phase should not interfere with the settled sludge, and decanters should avoid vortexing and taking in floatables. The problem with decanting more than one-third is that it increases the chance that solids will be decanted into the effluent, thereby impairing the effluent quality. For the plant to run optimally, it is important that the decant volume is the same as the volume added during the FILL phase. The length of the decant weir can have an impact that is very similar to that of the over flow weir found in a clarifier. The flux (upward forces) caused by the discharge of the decant creates an upward force that may pull poorly settled solids up and out the discharge.

2.2.5. Bottom Slope

All basins have a sloped bottom with a drain and sump for routine tank maintenance and ease of cleaning. Rectangular basins are slightly sloped to one corner to allow for hosing down the unit. Circular basins are sloped toward the middle for maintenance. All SBR designs include a means for completely emptying each SBR unit of all grit, debris, liquid, and sludge.

2.3. Post Basin - Effluent Equalization

Post basin for effluent equalization smoothes out flow variations prior to downstream processes, such as disinfection. By providing storage and a constant smooth flow, the disinfection process is more effective. If post flow equalization is not utilized, the effluent might not receive the designed amount of treatment. Post basin effluent equalization also allows downstream processes to be sized smaller, since the flow from the basin is metered out and does not hydraulically surge the downstream processes.

Effluent equalization also ensures that there are no large variations in operating ranges for the metering pumps and chlorine analyzers. Ideally, the basin holds a minimum of two decantable volumes. There is a means of returning the liquid from the post flow equalization basin to the headworks if a poor decant occurs. Post basins also have a means of removing solids from the bottom of the unit, such as a sloped bottom with a drain or sump.

CHAPTER 3. OPERATIONAL SUGGESTIONS

3.1. Parameters to Be Monitored by the SCADA System

Oxidation reduction potential (ORP), dissolved oxygen (DO), pH, and alkalinity are parameters that are usually monitored by the Supervisory Control and Data Acquisition (SCADA) system. SCADA is a computer-monitored alarm, response, control, and data acquisition system used by operators to monitor and adjust treatment processes and facilities.

The design engineer determines what parameters can be monitored and controlled by the SCADA system. Monitoring of certain parameters is important, and the ability to adjust these parameters from a remote location is ideal. The operator needs to be able to add chemicals to raise the alkalinity and subsequently the pH. The set point should be an alkalinity value rather than pH based. In most of the states, the operators have the ability to fully control and modify the plant operating parameters, such as cycle time, volume, level set point, chemical dosage, etc.

Alkalinity monitoring and addition ensures that a pH of less than 7.0 does not occur. Nitrification consumes alkalinity, and with a drop in alkalinity, pH also drops. If a plant has adequate alkalinity, pH does not change, so it does not need to be raised. Chemicals that raise alkalinity, such as sodium bicarbonate and soda ash, are recommended over sodium hydroxide. Sodium hydroxide does not raise alkalinity but it does raise pH. Refer to the author's class "Lead & Copper Corrosion Control in Potable Water" for a discussion of the pros and cons of various chemicals used to increase alkalinity.

For plants that nitrify and denitrify, ORP monitoring is desirable. ORP is the measure of the oxidizing or reducing capacity of a liquid. DO varies with depth and location within the basin. ORP can be used to determine if a chemical reaction is complete and to monitor or control a process.

Operators need to have the ability to make changes that will modify these readings to achieve appropriate nutrient removal. ORP readings have a range and are site specific for each facility. General ranges are: carbonaceous BOD (+50 mV to +250 mV), nitrification (+100 mV to +300 mV), and denitrification (+50 mV to -50 mV).

Online dissolved oxygen meters allow operators to adjust blower times to address the variable organic loads that enter the plant. Lack of organic strength reduces the react time during which aeration is needed to stabilize the wastewater. DO probes are used to control the aeration blower run time during the cycle, which, in turn, reduces the energy cost of aeration. It is desirable to locate DO, pH, and/or ORP probes in a place that can be reached easily by operators. These probes often clog and foul and need cleaning and calibration. If they are not easily accessible, proper maintenance may not occur.

Usually, the plant operators are trained to modify the SCADA system setting to increase or decrease blower speed. Allowing the operator to adjust the blower speed, through the SCADA system, gives the operator much more control over the DO in the SBR.

Annunciator panels normally indicate the following alarm conditions as a minimum:

a) High- and low-water level in each tank
b) Valve - failure of all automatically operated valves
c) Decanter - failure
d) Blower - low pressure, high temperature and failure
e) Pump - high pressure and failure
f) Mixer - failure
g) Effluent - high turbidity.

3.2. Cold Climate Adjustments

In general, sewage temperatures are above freezing, but the batch mode of operation exposes the SBR basin to cold winter temperatures. The long, cold ambient air temperature in winter cools the contents of a basin below the optimal temperature of 20-25 °C, which is the ideal temperature for advanced treatment to occur.

Based on the USEPA, SBRs in the northeastern United States respond appropriately against extreme cold temperatures. Where practical, basins for small or very small systems or facilities are housed in a garage type structure to ensure that there is no freezing. Larger basins are also covered to minimize heat loss.

Some facilities use earth insulation. Exposed piping is wrapped in heat tape and insulated to protect from freezing. Provisions to minimize the freezing of discharge pipes, controllers, decanter valves and ice buildup on decanters and chemical lines are implemented.

3.3. Sampling

3.3.1. Proper Sampling Points

As with all wastewater treatment plants, SBR samples are collected and analyzed for both process control and compliance reporting. Sampling locations are carefully chosen. SBRs that utilize influent equalization basins have more representative flow paced composite samples because the discharge is consistent in volume. In other words, flow equalization and true batch reactions allow for easier composite sampling because the same volume is entering and exiting the basin during each cycle.

Twenty-four-hour effluent composite samples are flow paced and include samples collected at the beginning and end of each decant event.

3.3.2. Parameters to Monitor

Numerous parameters can be monitored for process control. Except for BOD_5, multiple manufacturers provide online monitors including COD, TOC, alkalinity, ORP, TDS, ammonia, etc. which makes the design and operation much easier than 20 years ago. Testing and monitoring of process control parameters, however, requires planning and organization so that variances from the targeted performance goals are easily recognized.

3.4. Solids Retention Time (SRT)

Solids retention time is the ratio of the mass of solids in the aeration basin divided by the solids exiting the activated sludge system per day. Exiting solids are equal to the mass of solids wasted from the system plus the mass of solids in the plant effluent.

Ensuring an adequate SRT is very critical to the SBR biological nutrient removal (BNR) design process. The design SRT for nitrifying systems should be based on the aeration time during the cycle, not the entire cycle time as discussed in Chapter 5.

3.5. Sludge Wasting

Sludge wasting normally occurs during the IDLE cycle to provide the highest concentration of mixed liquor suspended solids (MLSS). The plants are operated on pounds of MLSS rather than concentration.

Sludge from the SBR basins can be wasted to a digester and/or holding tank for future processing and disposal. The digester and sludge holding tanks are sized based on the sludge treatment and disposal method.

Supernatant from the sludge digester and/or holding tank is returned to the headworks or influent equalization basin so that it receives full treatment. The storage facility is designed so that the supernatant volume and load do not adversely affect the treatment process.

A high level alarm and interlock are provided to prevent sludge waste pumps from operating during high level conditions in the digester and/or holding tanks. Controls are provided to prevent overflow of sludge from digester and/or holding tanks.

CHAPTER 4. OTHER SUGGESTIONS

4.1. On Site Manufacturer Training

A complete and comprehensive SBR operation and maintenance manual are normally provided as formal training, specific to SBR functions and operations, is essential for operators. Details of the training program are usually provided in the engineer's design report and/or the operation and maintenance manual. A facility design engineer may need to be retained to provide technical assistance and modify the SBR operation and maintenance manual and/or plant controls, as needed, during the first year of operation or until consistent compliance is achieved.

4.2. Wet/Cold Weather Operating Plans

SBRs that have flows from combined collection systems or systems prone to sanitary sewer overflows during wet weather, would normally develop wet-weather operating plans or standard operating procedures (SOPs). This plan provides operators with a guide to minimize the discharge of pollutants during wet weather and protect their facility from upset.

These plans or SOPs typically focus on determining performance during wet weather as compared to dry weather, determining a facility's capability to operate at incremental increases in wet-weather flow, and assessing whether unused facilities at the plant can be used to store or treat wet-weather flows. Also, by keeping accurate records, correlations can be developed between weather events and flows, which is helpful in predicting the impacts of storm events and preparing for expected weather conditions.

Snow melt, rain, and infiltration and inflow (I&I) can drastically affect the way an SBR functions from a microbial standpoint. Influent oxygen levels as high as 5 mg/L, diluted BOD, and cold sewerage temperatures are all long-term spring occurrences and need to be given serious consideration during the SBR design process. The function of the SBR for nutrient removal requires control over the oxygen level during the various SBR phases. Loss of this control due to long periods of I&I can limit the effectiveness of the nutrient-removal process. Some facilities develop cold weather operating plans or SOPs to mitigate treatment impacts during winter months.

4.3. SBR Performance

The performance of SBRs is typically comparable to conventional activated sludge systems and depends on system design and site specific criteria. According to the USEPA, depending on their mode of operation, SBRs can achieve good BOD and nutrient removal. For SBRs, the BOD removal efficiency is generally 85 to 95 percent.

SBR manufacturers will typically provide a process guarantee to produce an effluent of less than

- 10 mg/L BOD
- 10 mg/L TSS
- 5 - 8 mg/L TN
- 1 - 2 mg/L TP.

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 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 to 7 hours or, on the other end of the spectrum, an extended aeration treatment system with a typical HRT of 18 to 36 hours. For a BNR plant, the AERATED REACT (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 where 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.

CHAPTER 5. SBR DESIGN FOR NITRIFICATION/DENITRIFICATION

5.1. Simplified Design Approach

The most simplified design approach for a domestic wastewater SBR system includes the following steps:

Step 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 (θ_c or 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 comply with applicable Federal and local discharge regulations and codes.

Step 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 = BOD mg/L x 8.33 lb/gal x flow (10^6 gal/day)
M = F/F/M

Step 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.

Volume = M x (10^6gal/day)/(8.33 x MLSS concentration)

Step 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.

Step 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 less 1 since one tank may be out of service. 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 can achieve required performance levels.

Step 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 -1)

Step 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 FB, usually 3 to 4 feet, and a 2-3 ft buffer zone BZ between the mixed liquor and decant volumes.

Volume of tank = Volume mixed liquor + Volume decant + FB + BZ

Area of tank = Volume of tank/Tank depth

Step 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 S8R 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. For aerated depths less or over 12 ft, Fig. 6 can be used to adjust the design air flow rate depending on hydrostatic pressure. From Fig. 6, for a 15 ft deep basin, the adjusted air flow rate is the air rate divided by 0.8.

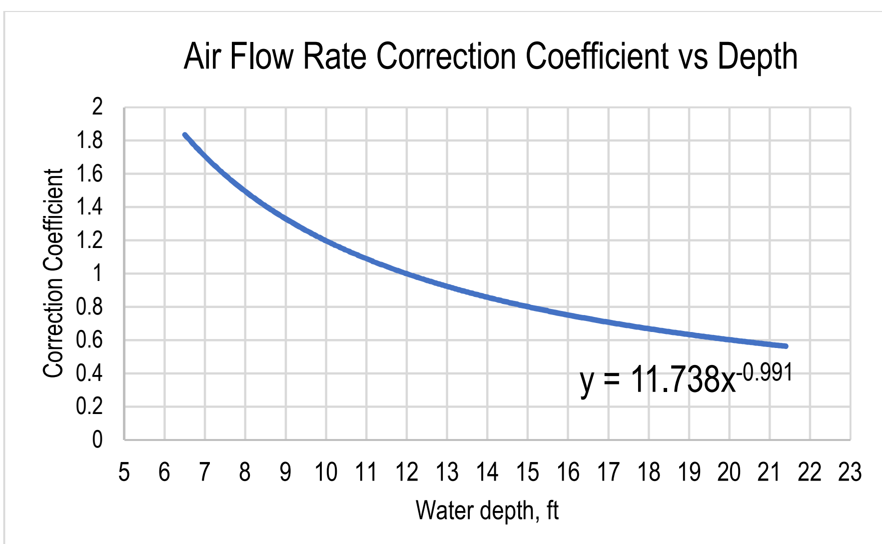

Fig. 6. Air Flow Rate Adjustment Coefficients vs Basin Depth.

Step 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 (Fig. 5).

The design steps outlined above present 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).

5.2. Extended Simplified Design Approach

This approach is an expanded version of the simplified design approach presented in Part 5.1. The difference between the two is that the latter is based on F/M and the former is based on both F/M and SRT, i.e. θ_c. The designer will need to choose F/M or θ_c or both to compare the results using the two methods. The steps to follow and the design formulas are given in Table 4 except for oxygen transfer discussed in Part 5.3. Tables 2, 3 and 5 provide additional information to aid in the Table 4 calculations. The amount of alkalinity required to complete the nitrification-denitrification process for SBRs with ammonia discharge limitations is given in Table 3. A large amount of alkalinity is required and may need to be added for nitrification to complete of which 50% is returned during denitrification. Some phosphate may also be required. From Table 2 for the purpose of sludge volume determination, there are 0.5 g of VSS (cells) and 0.2 g of VSS for each g of BOD_5 (food or substrate) and ammonium oxidized, respectively.

Coefficient or Rate	Unit	Range	Typical value
Fraction of readily biodegradable effluent, (f_{rb})		0.15 – 0.30 (raw sewage) 0.2-0.35 (settled sewage)	0.2
Biodegradable fraction of VSS ($X_b/X_v = X_b/X_0 = f_b$); X_0 influent TSS	gSS_b /gVSS	0.55-0.70 (conventional AS) 0.4-0.65 (extended aeration)	0.65
VSS/SS ($X_v/X = f_v$) = MLVSS/MLSS	gVSS/ gSS	0.70-0.85 (convent. AS) 0.60-0.75 (extended aeration)	0.8
COD/BOD_5 in influent	$gCOD/gBOD_5$	1.7-2.4 (domestic sewage)	2.1
Yield coef. (Y_S) for BOD_5	$gVSS/gBOD_5$	0.3-0.9	0.5
Yield coef. (Y_N) for NH_3	$gVSS/gNH_4^+$-N	0.1-0.3	0.2
Coef. of endogenous respiration of biodegradable SS, K_d	d^{-1}	0.03-0.09	0.05
pH	su	7.2-9	
F/M	$gBOD_5/gMLVSS \cdot d$	0.05-0.30	0.1

Volumetric loading rate	$lbBOD_5/10^3ft^3\cdot d$	5-15	10
MLSS, X	mg/l	1500-5000	3500
$V_{reactor}/Q_{PWWF}$ = HDT	hrs	12-50	24
Cycle time	hrs	4-6 (domestic ww) 6-12 (industrial ww)	4
DO in reactor	mgO_2/l	2.0-2.5	2
θ_c sludge age or SRT	day	5-30	20
BOD_5/TKN and nitrifiers fraction f_N (assume f_N = 0.05)	>5	nitrifier fraction f_N <0.054 (i.e. < 5.4%)	3% nitrogen (w/w) in sludge
Fraction of decant volume, $f_d = V_d/V_{reactor}$		0.3-0.6	0.5 max

Table 2. Kinetic rates and coefficients for BOD & ammonia removal in SBRs.

Parameter	Unit	Balance
Alkalinity as $CaCO_3$	7.14 g/g NH_4^+-N oxidized	Lost
Alkalinity as $CaCO_3$	3.57 g/g NH_4^+-N oxidized to N_2	Gained
Oxygen	3.43 g/g NH_4^+-N oxidized to NO_2^-	Lost
Oxygen	1.14 g/g NO_2^- oxidized to NO_3^-	Lost
Oxygen	4.57 g/g NH_4^+-N oxidized	Lost
PO_4^{2-}	0.3 g/ g NH_4^+-N oxidized to N_2	Lost
Oxygen as COD	1.42 g/g biomass	Lost
Oxygen as COD	1.99 g/g ww organic matter	Lost

Table 3. Major SBR Process Demand Parameters.

Item to be calculated	Unit	Equation
Number of cycles per day	–	m (adopt)
Total cycle time	hour	$T_{total} = \frac{24}{m}$
Time of arrival of influent during the cycle	hour	$T_{arrival\ of\ influent\ during\ cycle} = T_{arrival\ influent\ during\ day}/m$
Biodegradable fraction of the MLVSS	–	$f_b = \frac{0.8}{1+0.2 \cdot K_d \cdot \theta_c}$
Volume for reaction	m^3	$V_{react} = \frac{Y \cdot \theta_c \cdot Q \cdot (S_o - S)}{X_v \cdot (1 + f_b \cdot K_d \cdot \theta_c)}$
Fill volume	m^3	$V_{fill} = \frac{Q}{m}$
Transition volume	m^3	$V_{trans} = f_{Hfill} \cdot V_{fill}$
Sludge volume	m^3	$V_{sludge} = V_{react}$
Total reactor volume	m^3	$V_{tot} = V_{react} + V_{fill} + V_{trans}$
Total reactor height	m	H_{tot} (adopt)
Fill height	m	$H_{fill} = \frac{V_{fill}}{Area} = \frac{V_{fill}}{(V_{tot}/H_{tot})}$
Transition height	m	$H_{trans} = f_{Hfill} \, . \, H_{fill}$
Sludge height	m	$H_{sludge} = H_{tot} - (H_{fill} + H_{trans})$
MLSS concentration	mg/L	$X = \frac{X_v}{(SSV/SS)}$
MLSS mass in the reactor	kg	$M_x = \frac{X \cdot V_{tot}}{1000}$
SS concentration in the settled sludge	mg/L	$X_r = \frac{M_x \cdot 1000}{V_{sludge}}$
Number of reactors	–	n (adopt)
Volume of each reactor	m^3	$V_{reactor} = \frac{V_{tot}}{n}$
Fill time within cycle	hour	$T_{fill} = T_{arrival\ of\ influent\ during\ cycle}/n$
Active time within cycle (= fill time + react time)	hour	$T_{active} = T_{total} \cdot \frac{V_{react}}{V_{tot}}$
Reaction time within cycle	hour	$T_{react} = T_{active} - T_{fill}$
Settling velocity of the sludge interface	m/hour	$v = v_o \cdot e^{-K \cdot X}$
Settle time within cycle	hour	$T_{settle} = \frac{(H_{trans} + H_{fill})}{v}$
Supernatant withdrawal time within cycle	hour	T_{draw} (adopt; $\leq T_{total} - T_{fill} - T_{react} - T_{settle}$)
Idle time within cycle	hour	$T_{idle} = T_{total} - (T_{fill} + T_{react} + T_{settle} + T_{draw})$
Number of effluent removals per day	–	Number removals per day = m·n
Volume of effluent in each removal	m^3	Vol. each removal = Q/(m·n)
Flow of effluent in each removal	m^3/hour	Flow each removal = Vol. each rem./T_{draw}

Y = yield coefficient (gMLVSS/gBOD$_5$ removed) S = total effluent soluble BOD (mg
θ_c = sludge age (d) X_v = MLVSS concentration (mgL^{-1}
Q = inflow ($m^3 d^{-1}$) K_d = decay coefficient (d^{-1})
S_o = total influent BOD (mgL^{-1}) v_o,K= settling velocity equation coeffi

Table 4. SBR Design Formulas.

Constituent[a]	Change of oxidation state	COD equivalent[b]
Biomass, $C_5H_7O_2N$	C to +IV	1.42 g COD/g $C_5H_7O_2N$, 1.42 g COD/g VSS, 1.20 g COD/g TSS
Oxygen (as e^- acceptor)	O(0) to O(−II)	−1.00 g COD/gO_2[c]
Nitrate (as e^- acceptor)	N(+V) to N(0)	−0.646 g COD/g NO_3^-, −2.86 g COD/g N
Nitrate (as N source)	N(+V) to N(−III)	−1.03 g COD/g NO_3^-, −4.57 g COD/g N
Sulfate (as e^- acceptor)	S(+VI) to S(−II)	−0.667 g COD/g $SO_4^=$, −2.00 g COD/g S
Carbon dioxide (as e^- acceptor)	C(+IV) to C(−IV)	−1.45 g COD/g CO_2, −5.33 g COD/g C
CO_2, HCO_3^-, $H_2CO_3^=$	No change in an oxidizing environment	0.00
Organic matter in domestic wastewater, $C_{10}H_{19}O_3N$	C to +IV	1.99 g COD/g organic matter
Protein, $C_{16}H_{24}O_5N_4$	C to +IV	1.50 g COD/g protein
Carbohydrate, CH_2O	C to +IV	1.07 g COD/g carbohydrate
Grease, $C_8H_{16}O$	C to +IV	2.88 g COD/g grease
Acetate, CH_3COO^-	C to +IV	1.08 g COD/g acetate
Propionate, $C_2H_5COO^-$	C to +IV	1.53 g COD/g propionate
Benzoate, $C_6H_5COO^-$	C to +IV	1.98 g COD/g benzoate
Ethanol, C_2H_5OH	C to +IV	2.09 g COD/g ethanol
Lactate, $C_2H_4OHCOO^-$	C to +IV	1.08 g COD/g lactate
Pyruvate, CH_3COCOO^-	C to +IV	0.92 g COD/g pyruvate
Methanol, CH_3OH	C to +IV	1.50 g COD/g methanol
$NH_4^+ \rightarrow NO_3^-$	N(−III) to N(+V)	3.55 g COD/g NH_4^+, 4.57 g COD/g N
$NH_4^+ \rightarrow NO_2^-$	N(−III) to N(+III)	2.67 g COD/g NH_4^+, 3.43 g COD/g N
$NO_2^- \rightarrow NO_3^-$	N(+III) to N(+V)	0.36 g COD/g NO_2^-, 1.14 g COD/g N
$S \rightarrow SO_4^=$	S(0) to S(+VI)	1.50 g COD/g S
$H_2S \rightarrow SO_4^=$	S(−II) to S(+VI)	1.88 g COD/g H_2S, 2.00 g COD/g S
$S_2O_3^= \rightarrow SO_4^=$	S(+II) to S(+VI)	0.57 g COD/g $S_2O_3^=$, 1.00 g COD/g S
$SO_3^= \rightarrow SO_4^=$	S(+IV) to S(+VI)	0.20 g COD/g $SO_3^=$, 0.50 g COD/g S
H_2	H(0) to H(+I)	8.00 g COD/g H

Table 5. Oxygen Demand as COD for WW Oxidation-Reduction Reactions.

5.3. Author's Design Approach

5.3.1. Sludge Production

The quantity of sludge produced per reactor per cycle can be estimated using the following expression:

$$SP^{PDWF} = \frac{8.34Q^{PDWF}HDT}{(n-1)m}\left[X_0(1-f_b) + \frac{S_0 f_d}{HDT(\frac{F}{M})f_v} + Y(S_0 - S(1-f_b)) - \frac{K_d S_0}{\frac{F}{M}}\right] \quad (1)$$

where the parameters are defined in Tables 2 and 4.
SP^{PDWF} in lb/reactor/cycle for peak dry weather flow (PDWF) in MGD.
S_0 and S are influent and effluent BOD_5
8.34 is the conversion factor from MGD and mg/L to lb/day
m – number of cycles per day
n – number of parallel SBR reactors.

The volume of an SBR reactor in million gallons (MG) for PDFW is given as follows:

$$V_R^{PDWF} = \frac{(1+f_d)Q^{PDWF}HDT}{(n-1)\,m} \quad (2)$$

With no flow equalization, the SBR volume in MG is as follows:

$$V_R^{PWWF} = \frac{(1+f_d)Q^{PWWF}HDT}{(n-1)\,m} \quad (3)$$

and $V_R^{PWWF} > V_R^{PDWF}$, $SP^{PWWF} < SP^{PDWF}$

Since the activated sludge centrate or supernatant goes back to the plant after dewatering and assuming that its volume is the same for each SBR, Eq. (3) becomes

$$V_R^{PWWF} = \frac{(1+f_d)(q_c+Q^{PWWF})HDT}{(n-1)\,m} \quad (4)$$

where q_c is activated sludge centrate. For some SBR cycles, $q_c = 0$.

The decanter mechanism capacity is defined as follows:

$$C = \frac{f_d(q_c+Q^{PWWF})HDT}{(n-1)\,m\,t_d} \quad (5)$$

where t_d – DECANT phase time.

The amount of biomass per reactor per cycle can also be estimated from Eq. (6) and compared to the results obtained using Eq. (1):

$$SP\ (lb/cycle) = \frac{8.34(q_c+Q^{PDWF})HDT}{(n-1)\ m}((N_0 - N)Y_N + (S_0 - S)Y_S) \qquad (6)$$

where Y_N and Y_S are yield coefficients from Table 2 and S and N are influent and effluent ammonia and BOD_5 concentrations.

As a very rough estimate, the weight of dry biomass in an SBR reactor sludge is given as

$$SP\ (lb/cycle) = 750\,\frac{(q_c+Q^{PDWF})HDT}{(n-1)\ m} \qquad (7)$$

5.3.2. Detention Time

The following expressions can be used to estimate the reactor detention times (hr) for carbonaceous (BOD) removal and nitrification-denitrification:

$$\theta^{BOD5} = \frac{24(S_0-S)Y_S}{X_v(\frac{1}{\theta_c}+K_d)} \qquad (8)$$

$$\theta^{NH} = \frac{24(N_0-N)Y_N}{X_v(\frac{1}{\theta_c}+K_d)f_N} \qquad (9)$$

The average θ_c, K_d, f_N, Y_S and Y_N values from Table 2 are 20 d, 0.05 d^{-}, 0.05, 0.5 and 0.2, respectively. It is strongly recommended that these values be defined based on a bench-scale or pilot study conducted for representative wastewater samples and at similar hydraulic and organic loading rates.

The ratio of detention times is

$$R = \frac{\theta^{BOD5}}{\theta^{NH}} = \frac{(S_0-S)Y_S f_N}{(N_0-N)Y_N} \qquad (10)$$

Depending on whether R is above or below 1, the process is BOD or ammonia controlled.

5.3.3. Oxygen Requirements

Eq. (11) estimates the oxygen requirement per cycle per reactor:

$$O_2^{PDWF}\ (lb) = \frac{8.34(1+f_d)(q_c+Q^{PDWF})HDT}{(n-1)\ m}(4.57(N_0 - N) + 1.25(S_0 - S)) \quad (11)$$

where the coefficient 4.57 is from Table 3 and 1.25 is a commonly used safety factor in place of 1.0.

From Eq. (11)

$$R' = \frac{O_2^{BOD5}}{O_2^{NH3}} = \frac{1.25(S_0-S)}{4.57(N_0-N)} \quad (12)$$

To match BOD_5 and NH_3 detention times and oxygen requirements to complete oxidation, R = R'. From Eq. (10) and (12) obtain

$$0.274 = \frac{f_N Y_S}{Y_N} \quad (13)$$

Nitrification is not complete during REACT cycle if the right side of Eq. 13 is less than 0.274. Additional aeration is required which is done during AERATED FILL cycle. The oxygen requirement for AERATED FILL cycle is obtained from Eq (11) and (13):

$$O_2^{\Delta N}(lb) = \frac{10.43(1+f_d)(q_c+Q^{PDWF})HDT}{(n-1)m}(N_0 - N)(\frac{Y_N}{f_N Y_S} - 3.67) \quad (14)$$

If the right side of Eq. 13 exceeds 0.274, the reactor volume time is larger than required and may need to be downsized.

From Table 2 and Eq. (13) obtain

0.274(0.1-0.3) = (<0.054)(0.3-0.9) (15)

This equality is satisfied for f_N = (0.054-0.05), Y_N = (0.1-0.16) and Y_S = (0.5-0.9), i.e. the approach presented by Eq. (12) & (13) is valid even with the SF of 1.25 in Eq. (11). With no safety factor, Eq. (13) is valid for broader ranges of f_N, Y_N and $Y_{S.}$

The following expression, obtained by combining Eq. (11) and (13), defines the oxygen requirement per SBR per cycle if the equality in Eq. (13) is satisfied, i.e. the REACT phase is capable of completely oxidizing BOD_5 and nitrifying:

$$O_2^{PDWF}\ (lb) = \frac{10.43(1+f_d)(q_c+Q^{PDWF})HDT}{(n-1)\ m}((N_0 - N)\left(\frac{Y_N}{f_N Y_S}\right) + (S_0 - S)) \quad (16)$$

The volume of required air can be calculated based on the air density, range of temperatures, friction loss (3%-6%), 21% of oxygen in air, Fig. 1 and Eq. (11) or Eq. (15) if the kinetic rates are available. Normally, the air blower pressure requirement is in the range from 7 to 12 psi.

The density of oxygen in air is given as follows:

$$d_{O2}\left(\frac{lb}{ft^3}\right) = \frac{2.7P(psi)}{460+T_{ambient}(^0F)}\left(1-6.73\cdot 10^{-6}Z\right)^{5.528}\frac{1+\omega}{1+1.61\omega} \qquad (17)$$

where Z – altitude (ft)

ω – lb water/lb dry air (from the psychometric chart).

The volume of air from Eq. (16) and (17) is

$$V_{air}(actual\ ft^3) = \frac{O_2^{PDWF}}{d_{O2}} \qquad (18)$$

The average air flow rate for Eq. (16) is

$$r_{aver}^{air}(acfm) = \frac{V_{air}}{t_r} \qquad (19)$$

Based on Fig. (7), most of the oxygen is consumed during the first half of REACT cycle (from 241 hr to 243 hr). BOD_5 would normally drop exponentially from its maximum in the beginning of REACT cycle to little or none by the end. The dissolved oxygen (DO) would normally increase from less than 0.2-0.25 mg/l (the DO of unaerated FILL cycle) to its saturation value. The DO saturation values in treated wastewater are less than those for clean water and range from 5 mg/L to 7 mg/L.

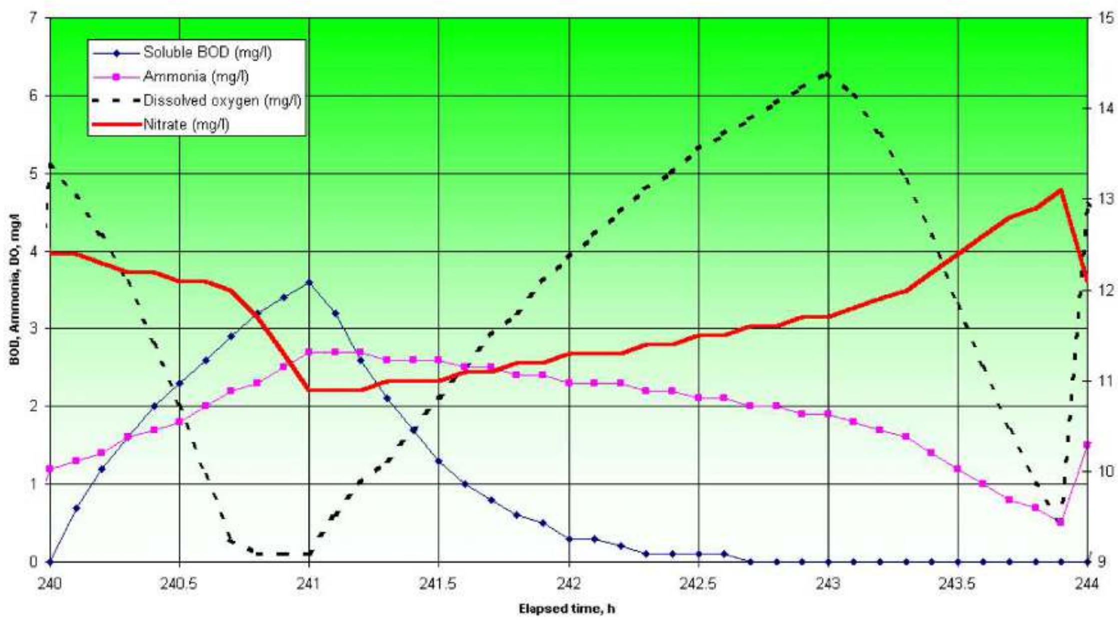

Fig. 7. Major SBR Operating Parameters During a Full Cycle (4 hrs).

Based on Fig. 7, both a BOD_5 decay and a DO increase functions during REACT cycle have a triangular shape. The air delivery volume then can be described as follows:

$$V_{air} = 0.5q'_{max}t_r \quad (20)$$

where

q_{max} – maximum air flow requirement (acfm) during REACT cycle (when FILL phase is unaerated)
t_r – REACT cycle time, min.

The value of q_{max} can be determined by combining Eq. (18) and Eq. (20)

$$q'_{max}(acfm) = \frac{2\,O_2^{PDWF}}{d_{O2}t_r} \quad (21)$$

It defines the maximum air flow rate as a function of the REACT phase time when FILL phase is not aerated. Air blowers for REACT cycle require a VFD (VSP) to program speed (rpm) using Eq. (21). The blower stops when the DO level in reactor during REACT cycle has been at its saturation value for 5 min or constant for 10 min. A safety factor (SF) of 1.25-1.5 is normally applied in Eq. (21) for blower capacity determination.

5.3.3.1. MKMAX Algorithm for REACT Phase

A more complex solution to finding the maximum required air flow rate linearly defined in Eq. (21) is to recognize that BOD_5 decay is an exponential function. As such, the air rate would exponentially decline to a minimum by the end of REACT cycle as shown in Fig. 8.

The decay function in Fig. 8 can be described as follows:

$$q^{REACT}(acfm) = q_{max}e^{-0.027t} \quad (22)$$

where t is time in minutes during REACT cycle.

The air volume for REACT cycle then is

$$V_{air}^{REACT}(acf) = \int_0^{t_r} q_{max}e^{-0.027t}dt = 37q_{max}(1 - e^{-0.027t_r}) \quad (23)$$

where t_r is REACT cycle time (min).

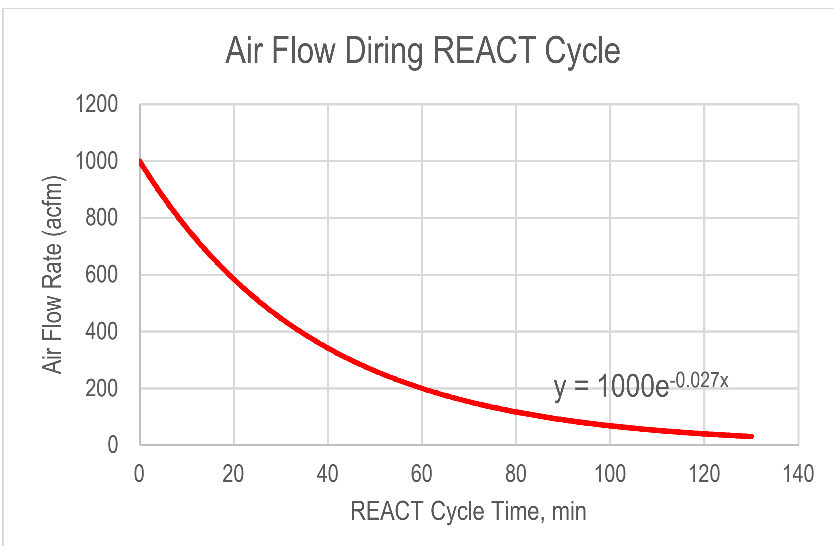

Fig. 8. Air Remand During REACT Cycle.

From Eq. (23) and Eq. (18) obtain

$$q_{max}^{MK}(acfm) = \frac{O_2^{PDWF}}{37d_{O2}(1-e^{-0.027t_r})} \quad (t_r > 0) \quad (24)$$

The expression presented in Eq. (24) is named MKMAX algorithm. The d_{02} and O_2 values are defined by Eq. (16) or (11) and Eq. (17). Since the only unknown in Eq. (24) is t_r, the maximum air flow rate to size the blowers can be modeled as a function of the REACT cycle time and air blower speed range. The blower serving REACT cycle needs to be on VFD (VSP) to program. DO control should be used to avoid over aeration during period of low organic and hydraulic loading. Blower stops when the DO level in REACT cycle has been at its saturation value for 5 min or constant for 10 min. The results of Eq. (24), Eq. (21), Eq. (20), Eq. (23) and Eq. (19) can be compared to check for correctness such that Eq. (23) > Eq. (20), Eq. (24) > Eq. (20), Eq. (24) > Eq. (19), and Eq. (24) ≈ Eq. (21).

5.3.3.2. MKIO2 Algorithm for AERATED FILL Phase

A rough estimate of the maximum air volume for AERATED FILL phase, if required, can be calculated as the product of the ratio of Eq. (14) to Eq. (16) and Eq. (20):

$$V_{NH_3}^{AERFILL}(acf) = \frac{0.5q'_{max}t_r(N_0-N)(\frac{Y_N}{f_N Y_S}-4)}{(N_0-N)\left(\frac{Y_N}{f_N Y_S}\right)+(S_0-S)} \qquad (25)$$

The ratio of air volume in Eq. (25) to the SBR liquid volume, given by Eq. (2) or (3), may vary from 2% to 8% (average 5%) but cannot be higher than 10%. For water temperatures in the range 60^oF-70^oF and air pressure of 10 psig, the average degree of air in water saturation is less than 3%. As such, the combined air volume, both diffused and in air bubbles, is less than 8%. To check your previous calculations, refer to the following expression:

$$\frac{V_{NH_3}^{AERFILL}}{V_{SBR}^{PDWF}} \leq 0.08 \qquad (26)$$

From Eq. (21) and (25)

$$V_{NH_3}^{AERFILL}(acf) = \frac{0.5q'_{max}t_r(N_0-N)\left(\frac{Y_N}{f_N Y_S}-3.67\right)}{(N_0-N)\left(\frac{Y_N}{f_N Y_S}\right)+(S_0-S)} = \frac{\alpha O_2^{PDWF}}{d_{O_2}} \qquad (27)$$

where

$$\alpha = \frac{(N_0-N)\left(\frac{Y_N}{f_N Y_S}-3.67\right)}{(N_0-N)\left(\frac{Y_N}{f_N Y_S}\right)+(S_0-S)} \qquad (28)$$

From Eq. (4), the FILL volume is

$$V_R^{PWWF} = \frac{f_d(q_c+Q^{PWWF})HDT}{(n-1)\,m} \tag{29}$$

From Eq. (26), (27) and (29) follows that

$$\frac{\alpha(n-1)mO_2^{PDWF}}{d_{O_2}f_d(q_c+Q^{PWWF})HDT} < 0.08 \tag{29}$$

which allows to adjust f_d and q_c.

From Eq. (27), the average air flow rate for FILL phase is

$$q_{O_2}^{AERFILL}(acfm) = \frac{\alpha O_2^{PDWF}}{t_f d_{O_2}} \tag{30}$$

If the SBR is continuously filled with wastewater at a constant flow rate, from Eq. (30) obtain the following expression that defined the FILL phase air flow rate for a time interval:

$$q_{IO_2}^{AERFILL}(acfm) = \frac{\alpha O_2^{PDWF}\tau}{t_i d_{O_2}\sigma\sum_1^{\sigma}\sigma} \tag{31}$$

where

t_i – aerated interval duration within the FILL phase (min)
τ- interval number
σ – number of aerated intervals ($\sigma \geq \tau$, e.g. interval No. 3 in a 5- interval aeration sequence).

Eq. (31) is named MK2 Algorithm.

5.3.6. Sludge Settling Time

With no flow equalization and with sludge decant, centrate or supernatant returned to the reactor, the SBR volume in MG from Eq. (3) is as follows:

$$V_R^{PWWF} = \frac{(1+f_d)(q_c+Q^{PWWF})HDT}{(n-1)\,m} \tag{26}$$

where q_c – sludge decant or centrate.

One of the most practical and well-known models describing the settling of activated sludge is the Vesilind model (1986) that has the following form:

$$V_S = V_0 e^{-zX} \qquad (27)$$

where

V_S – settling velocity (m/h)

V_0 – maximum settling velocity (m/h)

X – MLSS concentration (l/g)

z - parameter describing settling velocity (g/l), given in Table 8.

SSVI*	V_0	z
35-50	10.5	0.3
50-65	8.06	0.31
65-75	7.82	0.34
75-85	7.03	0.37
85-95	6.40	0.40
95-110	5.63	0.44
110-120	5.09	0.48
120-150	4.47	0.52

Table 8. Typical Values of V_S and z for a range of SSVI by Pitman (1984).

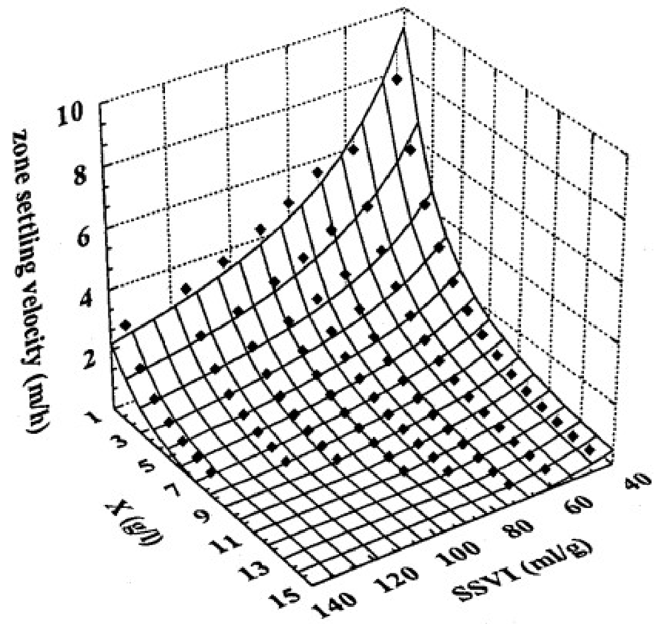

Fig. Plot of Eq. (27).

The minimum sludge settling time, hrs, is obtained by combining Eq. (27) and (4) as follows:

$$t_S^{min} = \frac{V_R^{PWWF}}{A_R V_S} \tag{28}$$

where A_R is the SBR area.

5.3.7. Design Deviations

Since the cycle time is

$$T_c = t_f + t_r + t_s + t_d + t_i \tag{29}$$

the deviation *x* from the design cycle time can be presented in the following form

$$\frac{Actual\ time}{Design\ time} x = ax\ (\rightarrow 1\ for\ ideal\ phases) \tag{30}$$

For municipal sewage treatment, usually there are 4 to 6 cycles per day, i.e. 5 on the average. For 5 parallel SBR reactors, Eq. (30) can be presented in the following format:

$$\begin{pmatrix} a_f^1 & a_r^1 & a_s^1 & a_d^1 & a_i^1 \\ a_f^2 & a_r^2 & a_s^2 & a_d^2 & a_i^2 \\ a_f^3 & a_r^3 & a_s^3 & a_d^3 & a_i^3 \\ a_f^4 & a_r^4 & a_s^4 & a_d^4 & a_i^4 \\ a_f^5 & a_r^5 & a_s^5 & a_d^5 & a_i^5 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} = \begin{pmatrix} 5 \\ 5 \\ 5 \\ 5 \\ 5 \end{pmatrix} \quad (31)$$

The *x* values can be obtained with the help of free online calculators using the inverse or Cramer methods. The determinant is zero so there no solution if the actual times match the design times. Ideally, *a* = *x* = 1 and the mathematical limit of the sum of the five linear equations in Eq. (31) is 25.

The values of *x* representing various hydraulic and organic loading conditions during several days will help define the extent of deviation from the design conditions and fix long-term problems. They can also be used by regulatory agencies for compliance purposes. The negative and positive *x* sign in Eq. (32) indicates an over- or under design, respectively. The minimum detention and settling times for REACT and SETTLE cycles in Eq. (29) are defined by Eq. (8, 9) and (28).

Some states require that the minimum REACT and SETTLE times be fixed in the PLC algorithm so that no batch can bypass treatment. For instance, the PADEP requires a minimum of 20 min of REACT time. The IDLE time varies depending on the preceding cycles and whether it was designed as an additional anoxic zone for phosphorus removal. With no flow equalization, the FILL time varies which affects the rest of the cycles. The DECANT time is normally fixed when there is a REACT cycle. However, if the batch bypasses treatment due to peak flow, the DECANT time is also reduced. The T_c in Eq. (29) for an undersized SBR becomes T_c/Flow Peaking Factor.

6. SUMMARY

This paper was intended to provide an overview of the most common regulatory design guidelines and criteria for SBRs and introduce my personal design approach to achieve a complete nitrification and BOD destruction in a single REACT phase. Chapters 1 to 4 present general information on SBRs as well as a compilation of various design criteria by various state and Federal agencies. Chapter 5 is a step by step SBR design guide that can be used by both mature and inexperienced designers to hydraulically and biologically design an SBR capable of BOD and ammonia destruction. The author presents two oxygen delivery rate algorithms that may change the traditional ways of designing and programming SBRs.

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