Chapter 22

Biological Nutrient Removal Processes

OVERVIEW OF BIOLOGICAL NUTRIENT REMOVAL

Treatment plants typically remove nutrients (e.g., nitrogen and phosphorus) from wastewater because of environmental, public health, or economic concerns. In the environment, nutrients stimulate the growth of algae in surface water. Researchers have found that 0.005 mg/L (5 μg/L) of soluble orthophosphate will limit algae growth (WEF, 2001). Other studies have shown that more than 0.05 mg/L of inorganic forms of nitrogen (ammonia-nitrogen and nitrate-nitrogen) may enhance algae growth.

Molecular or free (un-ionized) ammonia can be toxic to certain species of fish. More than 0.2 mg/L of un-ionized ammonia may cause acute toxicity, so it is often controlled via such factors as water pH, temperature, and ammonium ion concentration.

Public health concerns relate to drinking water that contains nitrogen. Regulators typically prefer that drinking water sources contain less than 10 mg/L of nitrate-nitrogen.

Nutrient removal may also reduce a treatment plant's overall operating costs. When aerobic biological treatment processes must nitrify wastewater, denitrifying the effluent (converting nitrate-nitrogen to atmospheric nitrogen) can recover lost oxygen and alkalinity, thereby saving aeration energy. Denitrification also can reduce or eliminate the need for chemicals to maintain an optimum pH for biological treatment. If phosphorus removal is required, biological phosphorus removal (BPR) may reduce chemical needs and eliminate the associated sludge. Finally, biological nutrient removal (BNR) may produce a sludge with better settling properties than the sludge produced via conventional treatment.

Several nutrient removal methods are available (Figure 22.1). One effective method is source control (e.g., reducing the phosphorus used in soap products, especially detergents). Some agencies have eliminated more than 50% of the phosphorus in raw wastewater via good source control. [For more information on source-control programs, see *Developing Source Control Programs for Commercial and Industrial Wastewater* (WEF, 1996).]

Natural systems (e.g., wetlands, overland flow, or facultative lagoons) may also be used to control nutrients. For more information on nutrient removal via natural or land-based systems, see *Natural Systems for Wastewater Treatment* (WEF, 2001).

Nutrients also can be controlled via chemical and biological processes. For more information on chemical–physical BNR systems, see *Biological and Chemical Systems for Nutrient Removal* (WEF, 1998a). For information on aerobic fixed-film processes [e.g., trickling filters and rotating biological contactors (RBCs)], see *Aerobic Fixed-Growth Reactors* (WEF, 2000).

This chapter focuses on suspended-growth BNR processes. Limited information on fixed-film nutrient removal processes is also presented. Most involve specialized

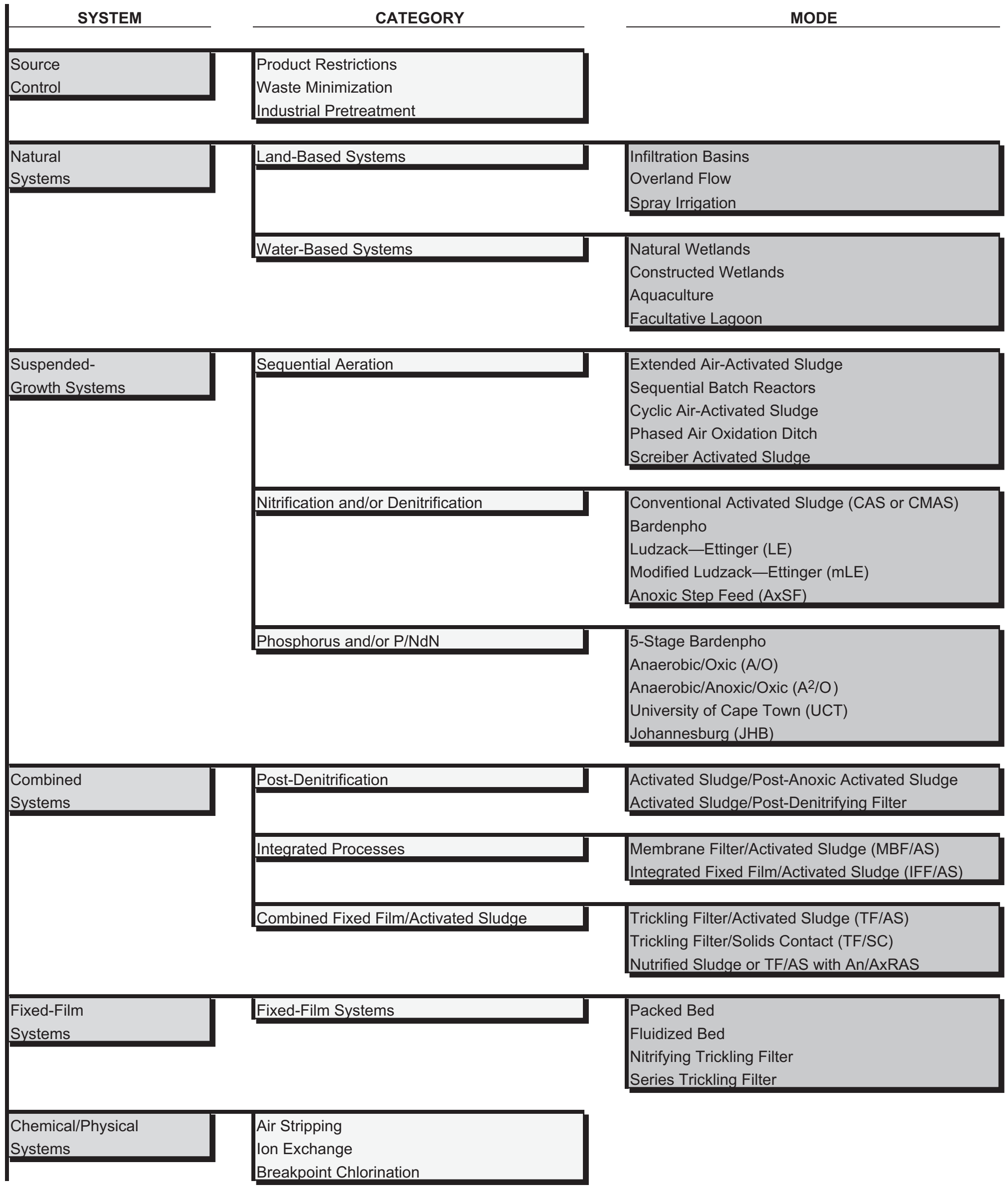


FIGURE 22.1 Nutrient removal alternatives.

reactors with zones, cells, or baffles designed to promote the growth of the bacteria that remove nutrients and the production of a good settling sludge.

Wastewater characteristics also affect both the ability to remove nutrients and the rate of removal (Table 22.1; WEF, 2005). For example, if the influent's inert (non-biodegradable), solids change, operators may need to lengthen the solids retention time (SRT) or mean cell residence time (MCRT) to maintain nitrification. If the wastewater has a high biochemical oxygen demand (BOD) but the oxygen use rate is low, then denitrifying or phosphorus-removing organisms may not be able to compete with other organisms in metabolizing organic material.

Both BNR and BPR depend on sufficient amounts of readily biodegradable organic substrate [chemical oxygen demand (COD) or BOD]. Wastewater treatment professionals have determined that 8.6 mg of COD is needed to remove 1 mg of nitrate-nitrogen from wastewater, but only 0.7 to 1.9 mg of a more readily biodegradable

TABLE 22.1 Biochemistry of BNR processes.

Biological Nitrogen Control Reactions	
1. Biochemical Nutrients Removed by	• 5.0 mg N removed per 100 mg BOD removed • 1 mg P per 100 mg BOD removed • For conventional aerobic process—2.3 mg P/100 mg TSS and 12.2 mg N/100 mg TSS • For biological phosphorous process—3 to 5 mg P/100 mg TSS
2. Biochemical Nitrogen Oxidation (Nitrification)	• 4.57 mg oxygen required per mg nitrogen oxidized • 7.14 mg $CaCO_3$ alkalinity depleted per mg nitrogen oxidized • 0.06 to 0.2 mg net volatile suspended solids formed per mg nitrogen oxidized

3. Biochemical Oxidized Nitrogen Removal (Denitrification)	• 2.86 mg oxygen released per mg oxidized nitrogen removed
	• Carbon source
	  • 1.91 mg methanol per mg oxidized nitrogen removed
	  • 0.7 mg methanol per mg dissolved oxygen removed
	  • 8.6 mg COD per mg oxidized nitrogen removed
	• 3.57 mg $CaCO_3$ alkalinity recovered (added to system) per mg oxidized nitrogen removed
	• 0.5 mg VSS per mg COD (or BOD_5) removed

4. Chlorine Demand due to Nitrite-Nitrogen (Associated with Incomplete Nitrification or Denitrification)	• 5 mg chlorine per mg nitrite-nitrogen, yielding nitrate-nitrogen

substrate (e.g., methanol) is needed. Experiments have indicated that 50 mg of COD is consumed per 1 mg of phosphorus removed from municipal wastewater (Randall, 1992).

Because of the need for sufficient biodegradable organic substrate, numerous treatment plants in cold climates (where BOD constituents break down slowly) enhance or condition wastewater by fermenting sludge or managing recycle streams to ferment byproducts (this is called *primary sludge fermentation*). Primary sludge fermentation typically is done on-site and may eliminate the need for methanol or other commercial, flammable substances. It probably will be unnecessary during warm weather, when natural fermentation in the collection system produces enough volatile fatty acid (VFA) for nutrient removal processes.

As you may have noted, many acronyms are used to describe nutrient-removal processes—so many, in fact, that BNR is often called “the alphabet soup” process (Table 22.2).

BIOLOGICAL SELECTORS. There are dozens of ways to modify or enhance conventional activated sludge or fixed-film systems to remove nutrients, improve sludge settling, and recover oxygen or alkalinity. Most methods used to enhance biological treatment involve specialized reactors or zones called *selectors*.

Growth Zones. Most wastewater treatment professionals are familiar with aerobic or oxic activated sludge processes [Figure 22.2(a)], in which biological growth is managed by controlling the oxygen concentration and recycling flows, such as return activated sludge (RAS) and mixed-liquor recycle (MLR), to the reactor [Figure 22.2(b)]. The wastewater’s oxygen concentration is kept near or above 2.0 mg/L, because nitrification declines when dissolved oxygen concentrations drop below 0.5 mg/L. Also, the oxidation–reduction potential (ORP) is kept near or above +100 mV.

To create an anoxic zone, a baffle or partial wall is installed in the reactor, and the aerators in that area are shut off. Little dissolved oxygen is present (less than 0.5 mg/L) in this zone, but chemically bound oxygen (in nitrite and nitrate) may be present in RAS or MLR flow. Also, ORPs should be between −100 and −200 mV (for rapid denitrification).

Anaerobic zones contain neither dissolved oxygen nor chemically bound oxygen and have ORPs below −300 mV [Figure 22.2(c)]. They typically are created by sending MLR to denitrification selector cells rather than to the head of the anaerobic zone, which would increase chemically bound oxygen levels too much. Sometimes a supplemental source of carbon is necessary to ensure that dissolved and chemically bound oxygen are rapidly removed.

TABLE 22.2 Nutrient removal acronyms and terminology.

	Acronyms and Terms
μ_{max}	Maximum growth rate
2	Secondary
A/O	Anaerobic/oxic process
A^2/O	Anaerobic/anoxic/oxic process
An	Anaerobic
Ax	Anoxic
AxSF	Anoxic step feed
BioP	Biological phosphorus
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
BOD_{2INF}	Biochemical oxygen demand in the secondary influent
BPR	Biological phosphorus removal
CAS	Conventional activated sludge
CBOD	Carbonaceous BOD
CO_2	Carbon dioxide
COD	Biodegradable organic substrate
dN	Denitrification
DO	Dissolved oxygen
EBPR	Enhanced biological phosphorus removal
EFF	Effluent
F	Food expressed as mass of BOD/d
F/M	Food-to-microorganism ratio—with M as mass of TSS
F/M_V	Food-to-microorganism ratio—with M as mass of VSS
HLR	Hydraulic loading rate
HRT	Hydraulic residence time
IFAS	Integrated fixed-film activated sludge
INF	Influent
$iTSS_{2INF}$	Inert TSS in the secondary influent
JHB	Johannesburg process
LE	Ludzack–Ettinger
M	Mass of TSS in the aeration basin
MBR	Membrane bioreactor
MCRT	Mean cell residence time (sometimes referred to as SRT or solids retention time)

TABLE 22.2 Nutrient removal acronyms and terminology (*continued*).

	Acronyms and Terms
ML	Mixed liquor
mLE	Modified Ludzack–Ettinger
MLR	Mixed-liquor recycle, also called internal recycle
MLR_{Ax}	Mixed-liquor recycle from the anoxic zone
MLR_{Ox}	Mixed-liquor recycle from the oxic zone
MLSS	Mixed-liquor suspended solids
MLVSS	Mixed-liquor volatile suspended solids
Mr	Mixed-liquor recycle ratio
M_V	Mass of VSS in the aeration basin
N	Nitrogen or nitrification
N_2	Nitrogen gas
NH_4-N	Ammonia nitrogen
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
NO_X	Nitrite and nitrate
NO_{X2EFF}	Nitrate in the secondary effluent
O_2	Molecular oxygen
ON	Organic nitrogen
ORP	Oxidation–reduction potential
Ox	Oxic
P	Phosphorus or produced or particulate
P_{NO_x}	Produced nitrate
P_x	Produced solids
Q or Q_{INF}	Influent flow
Q_{RAS}	Return activated sludge flow
Q_{WAS}	Waste activated sludge flow
R or RAS	Return activated sludge
RBBOD	Readily biodegradable BOD
Rr	Return activated sludge ratio
SBOD	Soluble BOD
SBR	Sequencing batch reactor
SDNR	Specific dentrification rate
SLR	Solids loading rate
SP	Soluble phosphorus

TABLE 22.2 Nutrient-removal acronyms and terminology (*continued*).

	Acronyms and Terms
SRT	Solids retention time
SVI	Sludge volume index
TKN	Total Kjeldahl nitrogen
TOD	Total oxygen demand
TP	Total phosphorus
TSS	Total suspended solids
TSS_{2EFF}	Total suspended solids in the secondary effluent
TSS_{WAS}	Total suspended solids in the waste activated sludge
UCT	University of Cape Town process
V	Volume of reactor
VSS	Volatile suspended solids
WAS	Waste activated sludge
Xr	Anoxic recycle ratio
Y	Solids yield
Aerobic (oxic) process	Biological treatment that is done in the presence of elemental (O_2) oxygen.
Anaerobic process	Biological treatment that is done with no elemental or combined (NO_2 or NO_3) oxygen.
Anoxic process	Biological treatment that is done with no elemental oxygen but has combined (NO_2 or NO_3) oxygen present.
Attached-growth process	Biological treatment that is done with microorganisms attached or fixed to media such as rocks and plastic (also referred to as fixed-film processes).
Biological nutrient removal	The term applies to removing nutrients (usually nitrogen and phosphorus) by using microorganisms.
Biological phosphorus removal	The term applies to removing phosphorus by encouraging high-uptake of phosphorus by bacteria, followed by wasting the bacteria and the phosphorus contained in their biomass.
Carbonaceous BOD removal	Biological conversion of carbonaceous organic matter to cell tissue and various gaseous end products.
Combined process	Suspended-growth and fixed-growth processes that work in combination with each other.
Denitrification	The biological process by which nitrate is reduced to nitrogen gas.
Facultative processes	Biological processes that can function either with or without oxygen being present.

TABLE 22.2 Nutrient removal acronyms and terminology (*continued*).

	Acronyms and Terms
Fixed-film process	See "attached-growth processes".
nitrification	A two-step biological process in which ammonia is converted to nitrite (NO_2) and then (step-2) nitrite is biologically converted to nitrate (NO_3).
Readily biodegradable BOD	BOD that is rapidly degraded, often consisting of simple organic compounds or volatile fatty acids.
Soluble BOD	BOD on a filtered sample, usually where a sample is vacuumed through a 0.45-µm filter.
Suspended growth processes	A biological process in which the bacteria responsible for treatment are suspended within a liquid.
Substrate	The term used to denote organic matter or other nutrients used by bacteria during their growth.
Volatile fatty acids (VFA)	General term used to describe easily digestible organic compounds such as acetate and other anaerobic fermentation products.

Selector Size and Equipment. Updating a treatment plant for filament control, ammonia removal, denitrification, or BPR involves several changes (Figure 22.3). For example, converting from conventional wastewater treatment to BNR may involve changing gates, baffles, mixers, and recycle pumps; improving aeration equipment and foam control; and adding clarification, RAS pumping, and instrumentation and controls. Also, many BNR facilities operate at long MCRTs, so more aeration basin volume may be required to maintain the necessary residence time to sustain nitrifying bacteria.

The size and number of selector zones needed for BNR depends on wastewater characteristics, treatment goals, and other factors. Typically, 20 to 30% of the total basin volume will be dedicated to anoxic or anaerobic zones. Plants with stringent nutrient limits may dedicate as much as 50% of the total basin volume to anoxic or anaerobic zones. Bench or pilot testing may be needed to confirm selector sizing and design criteria. [For details on sizing selectors, see the "Integrated Biological Processes for Nutrient Control" chapter in *Design of Municipal Wastewater Treatment Plants* (WEF, 1998b) or the 4th edition of *Wastewater Engineering* (Metcalf and Eddy, Inc., 2003).]

The wastewater conveyance methods also may need to be changed. Wastewater is often conveyed via pumping or air-entraining devices (e.g., screw pumps, flow-

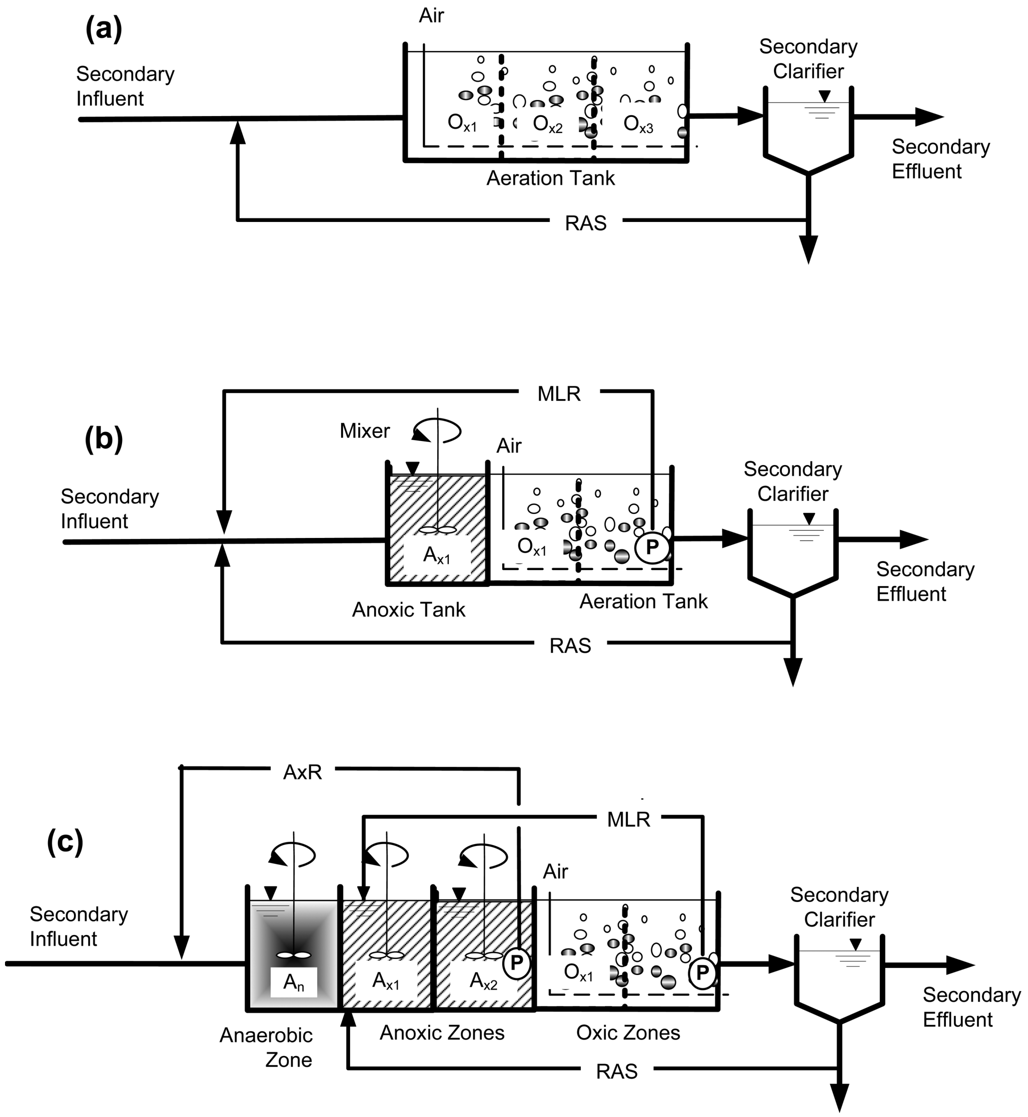
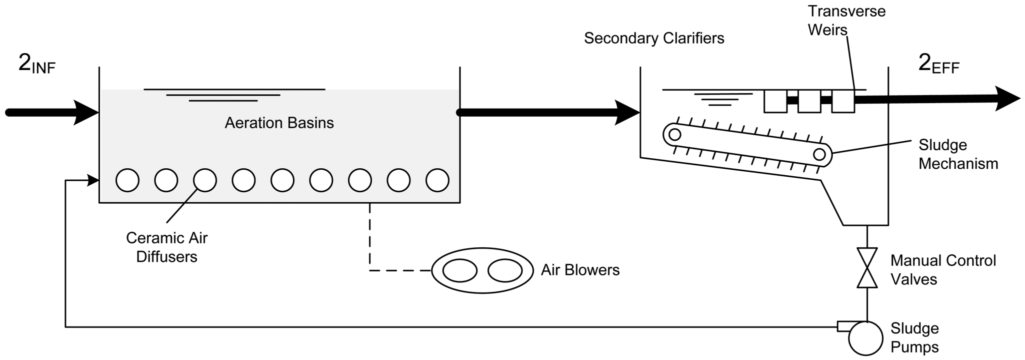


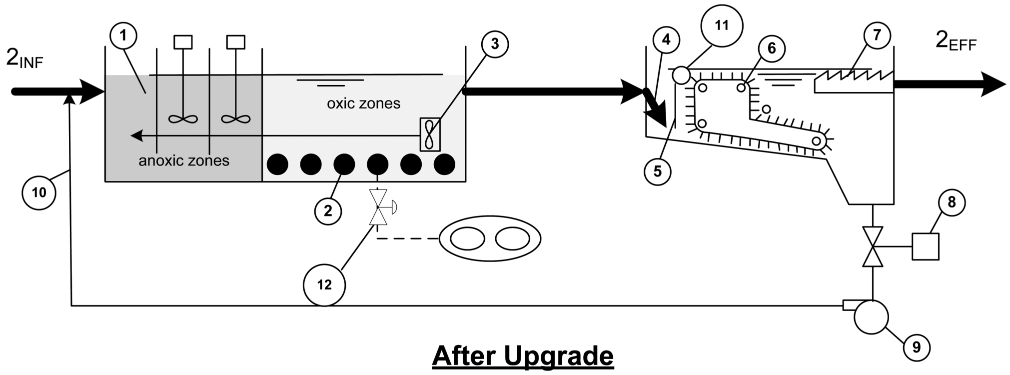
FIGURE 22.2 Selector growth zones.

splitting weirs, or launders), which inject air into the water. Entrained oxygen is detrimental to anoxic or anaerobic conditions, so air-entraining devices should be replaced with submerged weirs, gates, launders, or centrifugal pumps.

The water surface of a BNR reactor and a conventional activated sludge aeration basin look similar, but below the surface, the BNR reactor typically has a series of walls



Before Upgrade



After Upgrade

Major Changes:

1. Anoxic zones with mixers to produce good settling sludge
2. New fine-bubble diffusers to increase aeration efficiency
3. Axial flow pumps for recycle and denitrification
4. Inlet diffuser to evenly distribute flow
5. Baffles to break up flow currents
6. Elevated scrapers to manage scum and foam
7. Longitudinal weirs to even overflow and reduce up-currents
8. Automatic-flow paced sludge drawdown valves
9. Increased sludge pumping
10. Relocate sludge discharge to primary effluent line for pre-RAS dN
11. New automatic scum skimmers
12. Airflow monitorying, distribution, and control system

FIGURE 22.3 Plant changes after BNR upgrade.

or partitions (called *baffles*) that define discrete treatment areas. Baffles are typically made of pressure-treated wood, fiberglass, reinforced concrete, or concrete block. They often include blockouts for piping, tank drainage, main plant flow-through, and maintenance access. The tops of some baffles are below the water surface, while others include overflow weirs that direct water from one zone to the next. Because they are elevated, overflow weirs can force foam into downstream aerated cells, rather than allowing back mixing to occur. During peak flows, however, this elevated water surface prevents the backflow of dissolved oxygen, which would allow readily biodegradable BOD to be consumed. This will interfere with denitrification or phosphorus removal by allowing the ORP to increase.

Numerous devices (e.g., diffused air, pontoon-mounted impellers, submersible impellers, and bridge-mounted turbine impellers) have been used to mix the contents of both anoxic and anaerobic selector zones. However, many wastewater treatment professionals think that diffused air introduces too much entrained oxygen for the zone to be truly anaerobic or anoxic. Some prefer the simplicity of pontoon-mounted impellers because the electrical motors are above the water surface, but most use submersible impellers. Submersible impellers are typically mounted on a vertical rod; they can be raised and lowered, and the horizontal angle can be adjusted for optimum mixing.

Denitrification is an integral part of most BNR systems. It typically involves recycling nitrified mixed liquor via low-head pumps to one of the anoxic cells. Low-head pumps (0.3 to 0.9 m of head) are used because the MLR typically is moved a short distance, needs little or no valving, and enters a wastewater surface only a few inches higher than the one it left. Mixed-liquor recycle pumps may include vertical turbine centrifugal, propeller pumps, or axial flow pumps.

Upgrading to a BNR process often requires a change in aeration equipment. However, more blowers may be unnecessary if the diffusers are very efficient or if the upgrade includes denitrification, which can recover about 63% of the molecular oxygen required to convert ammonia-nitrogen to nitrate-nitrogen. In a multiple-stage BNR process, the first oxic stages typically contain more fine-bubble diffusers because initial oxygen uptake rates are higher than in latter stages of treatment. Diffusers also are installed in the last anoxic zone, which typically is a swing cell. *Swing cells* are zones that have both mixers and diffusers so they can operate as either non-aerated or aerated reactors.

Biological nutrient removal processes may need a long MCRT to allow nitrification and denitrification to occur. However, long MCRTs typically lead to foam or filamentous bacteria problems. To control foam, treatment plants can spray the reactor surface with a chlorine wash or add a cationic polymer or foam suppressant. They also can minimize sidestream recycling that may deposit foam-causing microorganisms or compounds in the reactor. In addition, treatment plant staff should eliminate any hydraulic traps that prevent foam from leaving the reactors. Some plants waste solids directly from the surface of the aeration basin to minimize foaming.

Many wastewater treatment plants originally were sized to remove carbonaceous BOD (CBOD) at 2 to 4 days of MCRT. To nitrify wastewater, the aeration basin may need to be operated at an MCRT that is two to three times longer. Operators can lengthen the MCRT by increasing the mixed-liquor suspended solids (MLSS) concentration. However, increasing the MLSS concentration or RAS flow will increase the solids load to the secondary clarifier, so when upgrading to BNR, both the secondary clarifier and RAS pumping capacity should be evaluated. [For more details on clarifier loading and design, see *Design of Municipal Wastewater Treatment Plants* (WEF, 1998b) and *Wastewater Engineering* (Metcalf and Eddy, Inc., 2003).]

Biological nutrient removal processes typically require more attention to the reactors' instrumentation and control system. Oxygen control can be automated or manual, depending on process needs and plant size. Dissolved oxygen probes in the aerated zones can be used to determine whether these areas have enough oxygen. On the other hand, systems with MLR pumping should reduce or eliminate aeration near the MLR pump suction point to minimize the amount of dissolved oxygen sent to anaerobic or anoxic cells. Oxidation–reduction potential probes can be used to determine the effectiveness of non-oxygenated cells. Other controls can be used to keep the RAS and MLR flows proportional to the influent flow rate.

YARDSTICKS FOR MEASURING BIOLOGICAL NUTRIENT REMOVAL.

The growth of nutrient-removing organisms is affected by many factors. Comparing the growth needs of autotrophic organisms, which nitrify wastewater, with those of heterotrophic bacteria, which oxidize CBOD, can help treatment plant staff better control both processes.

Mean Cell Residence Time. Mean cell residence time (also called *sludge age* or SRT) is the most commonly used parameter when operating a conventional activated sludge system. It measures the average length of time (in days) that microorganisms (sludge) are held in the system, and is calculated as follows:

$$\text{MCRT} = \frac{\text{Mass of MLSS in the aeration basin}}{\text{Mass of total suspended solids (TSS) wasted from the system per day}} \tag{22.1}$$

$$\text{MCRT} = \frac{\text{g MLSS in the aeration basin}}{\text{g/d TSS}_{\text{2EFF}} + \text{g/d TSS}_{\text{WAS}}} \qquad (22.2)$$

If the MCRT is too short, then the biological system will not have enough bacteria to degrade the pollutants, resulting in poor effluent quality (Figure 22.4). The mean cell retention time required depends on the wastewater constituent and the growth rate of the microorganisms consuming it. For example, a simple carbon compound (e.g., acetate) is metabolized by fast-growing heterotrophic organisms; it requires an MCRT of less than 1 day to be synthesized. Conversely, ammonia is oxidized by slow-growing bacteria, so its MCRT is much longer. Many treatment plants that remove CBOD from wastewater may have been designed for 2 to 4 days of MCRT, but to remove ammonia, the MCRT may need to be twice as long, depending on temperature and other factors. If the basin size and MLSS are constant, then the MCRT will shorten as the sludge wasting rate increases and lengthen as the wasting rate decreases.

Calculating MCRT for BNR systems is different because the aeration basin may include anaerobic or anoxic selectors. For example, a sequencing batch reactor (SBR) may not be aerated 35 to 45% of the time. So, process control should include calculating both

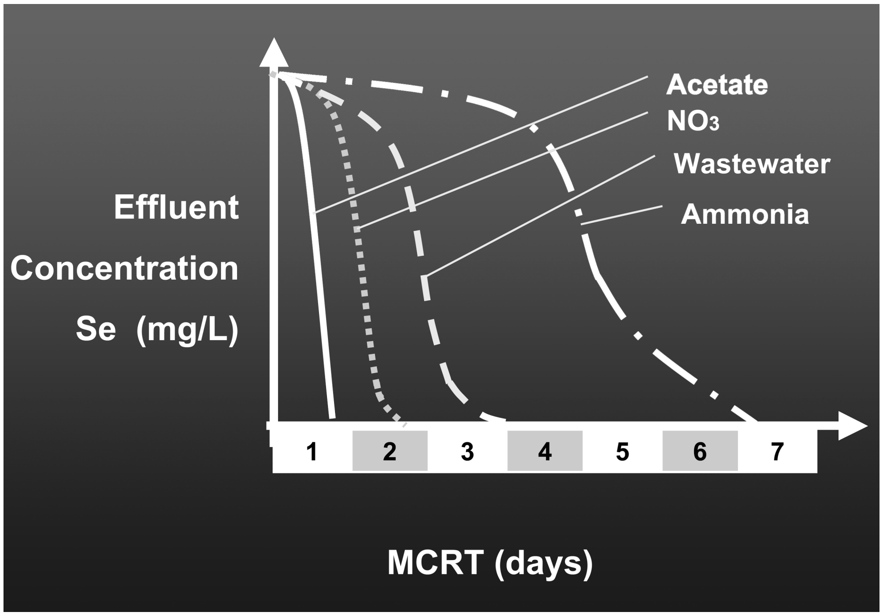


FIGURE 22.4 Effect of MCRT on pollutant removal.

the “aerobic” MCRT (for the aerated portion of the reactor) and the total “system” MCRT. The anaerobic or anoxic selector zones will require separate MCRT calculations. In BPR systems, experts recommend a 1-day anaerobic MCRT for proper growth of *Acinetobacter* organisms (Metcalf and Eddy, Inc., 2003). If the anaerobic contact is too long, the *Acinetobacter* organisms will release their stored phosphorus and take up carbon (this is called *secondary phosphorus release*).

Food-to-Microorganism Ratio. The food-to-microorganism (F:M) ratio measures the amount of food (BOD) available for the amount of mixed-liquor volatile suspended solids (MLVSS) present in the aeration basin:

$$\mathrm{F:M} = \frac{\text{g/d of BOD in secondary influent}}{\text{g MLVSS in the aeration tank}} \tag{22.3}$$

If the treatment plant has primary clarifiers, then *F* is typically based on primary effluent. If not, then *F* is based on the raw wastewater’s BOD load. The *M* for a conventional activated sludge system is typically based on the entire aeration basin’s MLVSS. Most conventional activated sludge systems are designed for F:M ratios ranging from 0.2 to 0.4 (WEF, 1998a). In BNR systems with several cells (Figure 22.5), the selector may be configured to encourage the growth of nonfilamentous (floc-forming) organisms. Or the selector may be configured to encourage the growth of *Acinetobacter* organisms to increase the denitrification rate. In either case, the F:M ratio of each selector zone is important. When calculating the F:M ratio for a BNR system, *F* is based on the secondary influent BOD. If the reactors are operated in series, then the first cell’s *M* is based on its volume and MLVSS concentration. The second cell’s *M* is based on the combined volume of the first and second cells, and so on.

One recommendation (Albertson, 1987) is that BNR systems have at least three cells to create a high substrate concentration in the initial minutes of contact (Figure 22.5). Food-to-microorganism ratios of 6.0, 3.0, and 1.5 mg/d of BOD per 1.0 mg of MLVSS for the first, second, and third cells, respectively, have been recommended for a plug-flow reactor. However, if the F:M ratio is too high (more than 8.0 mg/d of BOD per 1.0 mg of MLVSS), then a viscous, nonfilamentous organism could dominate the reactor (this is called *slime bulking*).

Wastewater Characteristics. Today, wastewater treatment plants typically are designed based on complicated models that use a perplexing array of wastewater characteristics. In fact, one text lists nearly 40 wastewater constituents as “important” when designing wastewater treatment facilities (Metcalf and Eddy, Inc., 2003). Fortunately, operators of BNR facilities only need a fundamental understanding of the relationship between wastewater characteristics and plant operations to optimize plant performance.

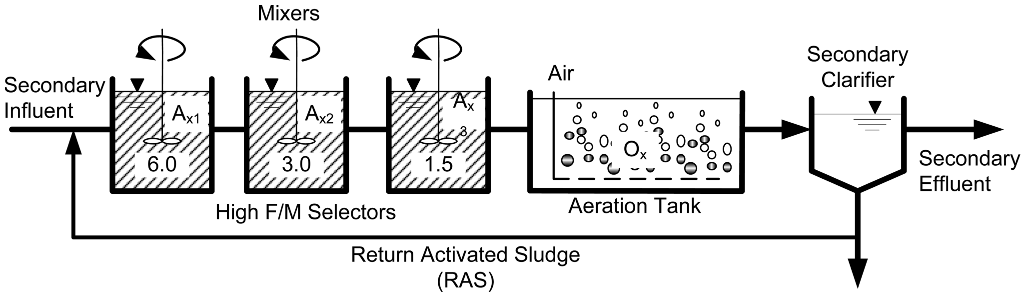


FIGURE 22.5 Selectors for controlling filamentous bacteria.

One of the key characteristics is the amount of inert TSS in biological treatment influent ($iTSS_{2INF}$). A high concentration of inert TSS will increase the percentage of nonbiodegradable solids in the MLSS, so a longer MCRT will be needed to treat the wastewater sufficiently. To calculate $iTSS_{2INF}$,

$$iTSS_{2INF} = TSS_{2INF} - VSS_{2INF} \tag{22.4}$$

Where

TSS_{2INF} = total suspended solids in secondary influent, and
VSS_{2INF} = volatile suspended solids (VSS) in secondary influent.

Operators also should better understand BOD's constituents. The soluble BOD measurement, for example, will indicate how much material is readily biodegradable. Soluble BOD typically is measured based on a 5-day BOD test in which wastewater is passed through a 0.45-μm filter. A 1-day BOD test will provide an estimate of readily biodegradable BOD—including the simple carbon compounds that are available for rapid bioassimilation.

Operators can learn other valuable information by assessing the influent BOD and waste activated sludge (WAS). In a conventional activated sludge system, for example, 5 mg of nitrogen and 1 mg of phosphorus will typically be used for every 100 mg of BOD removed. In a BPR process, 3 to 5 mg of phosphorus may be used for every 100 mg of BOD removed. If the BPR process is operated to remove total phosphorus, then a secondary-influent-BOD-to-total-phosphorus ratio of 20:1 or more may be needed to ensure that the treated effluent will contain less then 1.0 mg/L of phosphorus.

The required BOD-to-total-phosphorus ratio depends on process type and effluent goals. Processes that do not nitrify *and* denitrify [e.g., the anaerobic/oxic (A/O) process]

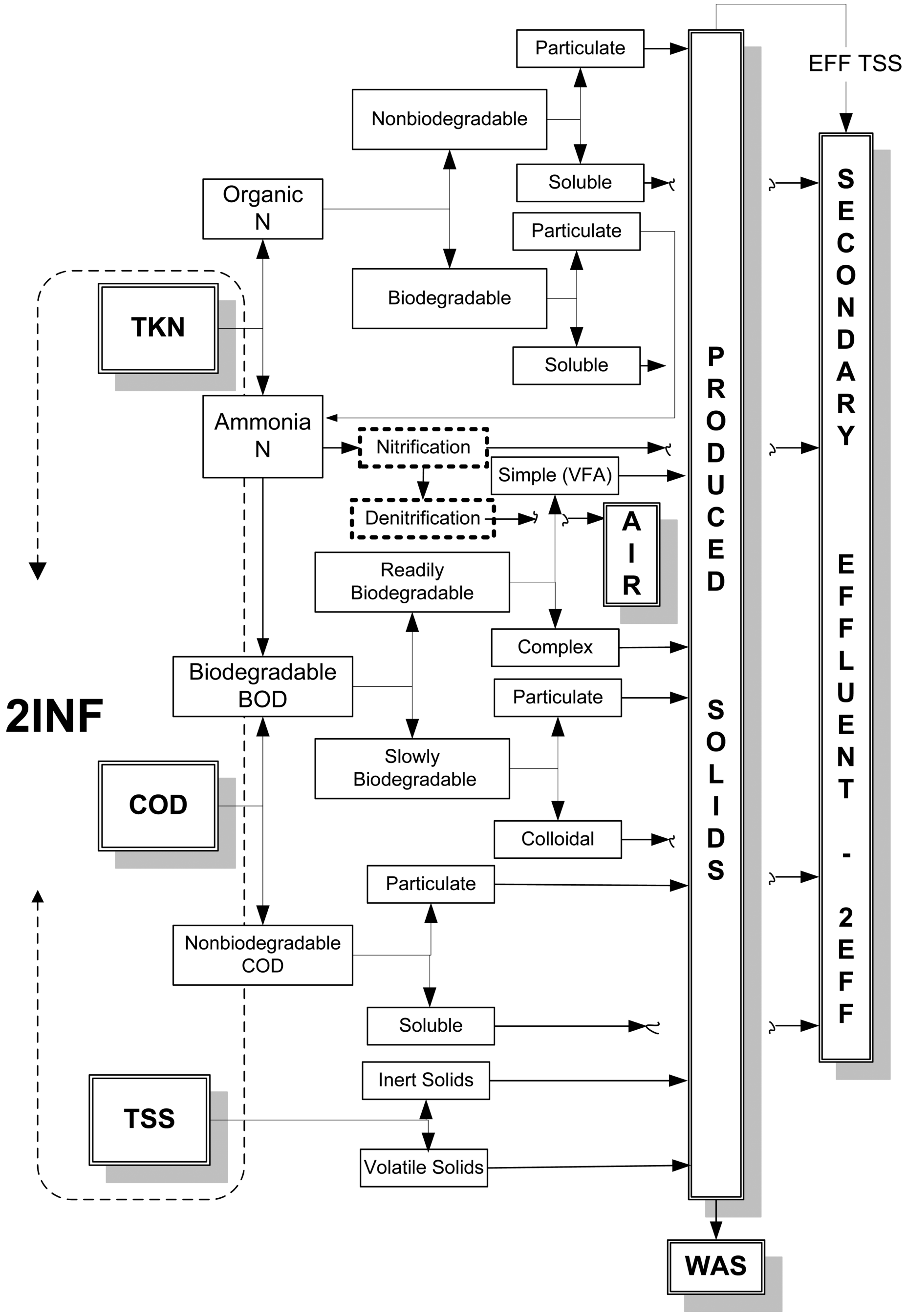


FIGURE 22.6 Interaction of nutrients.

may require a BOD-to-total-phosphorus ratio of 15 : 1, while those with full nitrification and denitrification may require a BOD-to-total-phosphorus ratio of 25 : 1 or more.

Aeration Requirements. Aeration systems designed for CBOD removal may need to be enlarged by 30 to 50% to provide enough oxygen to nitrify ammonia. Some plants accommodate the increased demand by replacing air diffusers with fine-bubble systems or other more efficient aerators. Some incorporate denitrification (the reduction of nitrate-nitrogen to nitrogen gas) into the BNR process because denitrification can theoretically reclaim 63% of the oxygen needed for nitrification. However, because denitrification typically only reduces about half of the nitrate-nitrogen in the wastewater (denitrification effluent typically contains 6 to 8 mg/L of nitrate-nitrogen), the actual amount of oxygen reclaimed may be closer to 30 to 40%.

Sludge Settleability and Foam. Many BNR facilities operate at a high MCRTs (more than 8 days) to fully nitrify and allow for denitrification. As a result, the facilities frequently have sludge-settleability or foam problems. Wastewater constituents (e.g., soap, oil, and grease) and streams recycled from solids handling processes can exacerbate these problems. If so, the facility may need spray nozzles to spread antifoaming chemicals.

Before RAS flows are raised to increase the basin MLSS concentration, plant staff should evaluate the solids loading ($g/m^2 \cdot d$) on the secondary clarifiers to determine if the capacity is adequate. Larger RAS pumps may be needed to obtain the higher MLSS concentration often desired in a BNR system.

Return Flows. Conventional activated sludge systems typically have only one return flow: RAS. Biological nutrient removal processes, on the other hand, may have more return flows (e.g., MLR). The return activated sludge pumping rates are typically 30 to 100% of the influent flow (Q). The MLR pumping rates may be 100 to 400% of the influent flow, depending on such factors as the target effluent nitrate concentration. They also may be transferred from an aerobic or oxic zone (MLR_{OX}) or from an anoxic zone (MLR_{AX}). The source of the MLR—and which zone receives it—often distinguishes one BNR process from another.

Alkalinity and pH. Biological nutrient removal systems also may need pH control or added chemicals (e.g., hydrated lime, soda ash, or caustic soda) to supplement the available alkalinity. Because alkalinity is consumed during nitrification, the chemicals can help maintain the minimum alkalinity level needed (typically, 60 to 100 mg/L of alkalinity as calcium carbonate). Low alkalinity not only lowers pH but may limit the growth of nitrifying organisms because they lack enough inorganic carbon to produce new cells.

Hydraulic Retention Time. The hydraulic retention time (HRT) required to maintain BNR depends on the size of the reactor, which in turn depends on the MCRT necessary for growth. Once the reactor size is known, then the HRT can be found by dividing the volume of the reactor (V) by the secondary influent flow (Q_{2INF}):

$$\underset{\text{(hours)}}{\text{Nominal HRT}} = \frac{V\ (m^3) \times 24\ \text{hr/d}}{Q_{2INF}\ (m^3/d)} \tag{22.5}$$

The result is a nominal value used to relate basin size to plant flow. The nominal value is typically used because internal recycle streams do not affect most of the reactions that are important to plant operators. For some parameters, however, the actual HRT may be affected by recycle streams, in which case, recycle flows (i.e., RAS and MLR) should be added to the denominator in Equation 22.5.

BIOLOGICAL NITROGEN REMOVAL PROCESSES

During secondary treatment, nitrogen's ultimate fate depends on the carbon compounds (measured as BOD and COD) involved, the type of sludge (measured as TSS and VSS) involved, and the oxidation methods used (Figure 22.4).

When nitrogen [total Kjeldahl nitrogen (TKN)] enters the wastewater treatment plant, it is composed of both organic nitrogen and ammonia-nitrogen. Domestic wastewater typically contains 40 mg/L of TKN, which consists of 25 mg/L of ammonia-nitrogen and 15 mg/L of organic nitrogen. Biological treatment of ammonia-nitrogen involves either incorporating it to the biological cells (MLVSS) or oxidizing it to nitrate (Figure 22.7). If incorporated to biological cells, then ammonia and the organic nitrogen are discharged with the WAS. If oxidized to nitrate, then the oxidized ammonia (nitrate) may be converted to nitrogen gas via denitrification and emitted to the atmosphere.

Wastewater characteristics can affect nutrient behavior. For example, if about 20% of the organic nitrogen (15 mg/L) hydrolyzes to become ammonia, then the total ammonia-nitrogen available for cell synthesis is:

$$(15\ \text{mg/L})(0.2) + 25\ \text{mg/L} = 3.0\ \text{mg/L} + 25\ \text{mg/L} = 28\ \text{mg/L} \tag{22.6}$$

Typical effluent from the primary treatment process contains 160 mg/L of BOD. During secondary treatment, the equivalent of about 80 mg/L of biological VSS is produced (0.5 mg VSS/mg BOD). Ammonia is consumed during the production of VSS, as are 8 mg/L of nitrogen [(80 mg/L)(10/100)] and 1.6 mg/L of phosphorus [(80 mg/L)(2/100)]. The resulting biological sludge contains approximately 10% nitrogen and 2% phosphorus.

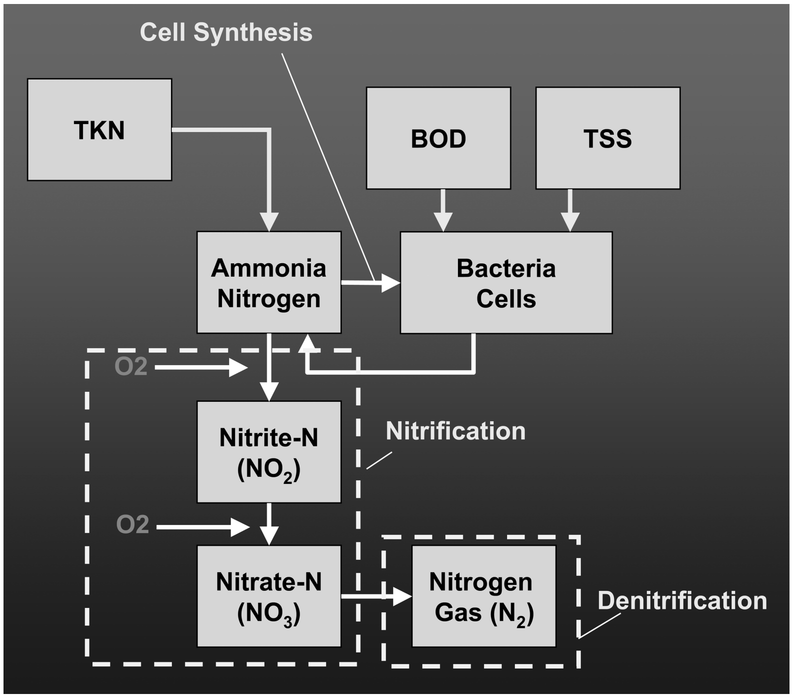


FIGURE 22.7 Nitrogen removal in wastewater treatment systems.

Treatment plant staff also should keep the following in mind:

- For a total nitrogen balance, staff should account for TKN;
- Because biological sludge consumes nitrogen, not all of the influent ammonia-nitrogen will need to nitrified. However, because organic nitrogen hydrolyzes, some more ammonia will become available.
- Changes in the influent BOD-to-nitrogen ratio will change the amount of ammonia requiring oxidation. As BOD increases, so will produced biosolids. An increase in biosolids production translates into more ammonia uptake for cell growth and less ammonia to nitrify.

If the wastewater characteristics are not "typical", then treatment plant staff will have to adjust the target MCRT, F:M ratio, or other criteria.

The difference between conventional activated sludge and BNR systems is that a conventional activated sludge system only removes nitrogen via sludge wasting. A biological nutrient removal facility can remove nitrogen via sludge wasting and a combined biological reaction to oxidize the remaining ammonia (nitrification) and reduce oxidized nitrogen (denitrification). If the treatment plant only has an ammonia limit, it may only nitrify the wastewater. If the plant has both ammonia and oxidized nitrate limits, then it will need to both nitrify and denitrify the wastewater.

NITRIFICATION.

Nitrification is the biological conversion of ammonia-nitrogen to nitrate-nitrogen.

Biochemistry.

Nitrification is done by *autotrophic microorganisms*—organisms that use inorganic materials as a source of nutrients and photosynthesis or chemosynthesis as a source of energy. They oxidize ammonia-nitrogen and reduce carbon dioxide to produce new biomass, typically requiring 6 to 9 days of MCRT to produce up to 0.2 mg of VSS per 1.0 mg of ammonia removed.

The first step in nitrification is oxidizing ammonia-nitrogen to nitrite-nitrogen via *Nitrosomonas* bacteria. Then *Nitrobacter* bacteria oxidize nitrite-nitrogen to nitrate-nitrogen. The following equations illustrate the nitrification process:

$$2NH_4^+\text{-N} + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+ \tag{22.7}$$

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2\ NO_3^-\text{-N} \tag{22.8}$$

$$NH_4^+\text{-N} + 2O_2 \xrightarrow{\text{Nitrifiers}} NO_3^-\text{-N} + 2H^+ + H_2O \tag{22.9}$$

Nitrification is typically a complete reaction—meaning that the result is predominantly nitrate (little or no nitrite). However, treatment plants that nitrify seasonally may find that nitrite will accumulate until the slow-growing *Nitrobacter* becomes an established population. The nitrite buildup may lead to *nitrite lock*—excessive chlorine demand by incompletely oxidized nitrite (5 mg of chlorine per 1 mg of nitrite-nitrogen, Table 22.1).

Effective nitrification depends on sufficient oxygen and alkalinity (to maintain a suitable wastewater pH). *Nitrosomonas* and *Nitrobacter* require 4.57 mg of oxygen and 7.14 mg of alkalinity (as calcium carbonate) for each 1.0 mg of nitrate-nitrogen formed. They yield about 0.06 to 0.20 mg of VSS for each 1.0 mg of nitrate-nitrogen formed.

Influences.

Autotrophic bacteria typically grow two to three times more slowly than heterotrophic bacteria, which are the predominant organisms in a biological treatment system. Understanding the relationship between the bacteria's "growth rate" and MCRT (sludge age) can help treatment plant staff determine whether and how temperature, dissolved oxygen, and other factors affect biological treatment. The *biomass growth rate* (μ) is calculated as follows:

$$\mu = \frac{\text{amount of bacteria grown per day}}{\text{amount of bacteria present}} \tag{22.10}$$

The *maximum growth rate* (μ_{max}) for nitrifying bacteria at 20 °C is typically between 0.14 and 0.23 kg/d (0.3 and 0.5 lb/d). To put this in terms more familiar to plant staff, for a treatment system in equilibrium:

$$\mu = \frac{P_x}{MLSS_x} = \frac{TSS_{2EFF} + TSS_{WAS}}{MLSS_x} \tag{22.11}$$

Where

P_x = the amount of sludge produced per day (sludge wasted in the secondary effluent and planned WAS), and
$MLSS_x$ = amount of TSS in the aeration basin.

In other words, μ is the inverse of MCRT, which is used for process control:

$$MCRT = \frac{MLSS_X}{TSS_{2EFF} + TSS_{WAS}} \tag{22.12}$$

The minimum MCRT is the inverse of the maximum growth rate:

$$MCRT_{MIN} = \frac{1}{\mu_{MAX}} \tag{22.13}$$

Nitrification depends on the ammonia-nitrogen concentration, the dissolved oxygen concentration, and the wastewater temperature (Figure 22.8). Standard conditions used to describe the rate of removal are 20 °C, 2 mg/L of dissolved oxygen, and 10 mg/L of ammonia-nitrogen. If dissolved oxygen or ammonia concentrations drop, then nitrifier growth will slow down. If the conditions are not toxic, then lowering temperature below the standard will probably will have the most significant effect on reducing nitrifier growth rate.

Most wastewater treatment plants are designed based on the maximum growth rates at a given range of operating temperatures. When designing a plant, engineers are encouraged to use an MCRT that is 1.5 to 2.0 times greater than the MCRT theoretically

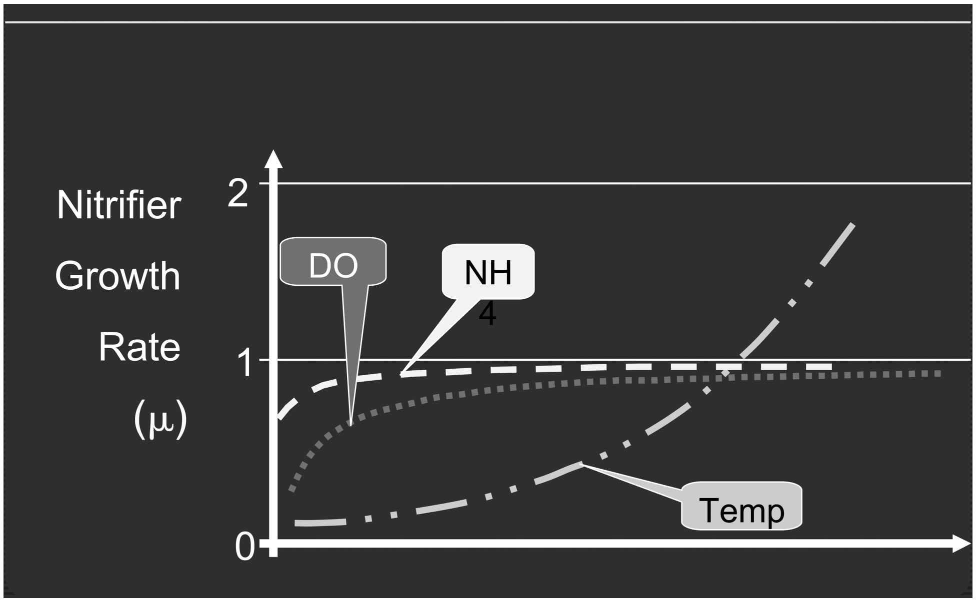


FIGURE 22.8 Key factors that affect nitrification.

needed for nitrification (Figure 22.9). For example, the calculated MCRT (using μ_{max}) may be 10 days at 10 °C, but a design engineer would probably make the aeration basin large enough to operate at a 15-day MCRT (factor of safety = 1.5) or a 20-day MCRT (factor of safety = 2.0). So, operators may find that the process nitrifies reliably at a shorter MCRT. (The actual "best" MCRT is plant-specific because of the number of variables involved.)

Nitrification is also affected by pH. The optimum pH is typically about 7.5. As the pH drops, so do the nitrifiers' growth rate and activity. Nitrification may be inhibited when the pH is less than 6.5, but some information sources have indicated that nitrifiers can acclimate to low pH.

Some metal, organic, and inorganic compounds can inhibit the growth of autotrophic bacteria. If plant personnel suspect that toxics are inhibiting bacteria growth, they should conduct a bench-scale test assessing the nitrification rate. Such tests can be conducted onsite, or samples may be sent to a contract laboratory for testing.

DENITRIFICATION. In denitrification, bacteria reduce nitrate to nitrogen gas (Figure 22.6). Nitrogen gas is not very water-soluble, so it is released into the atmosphere. The

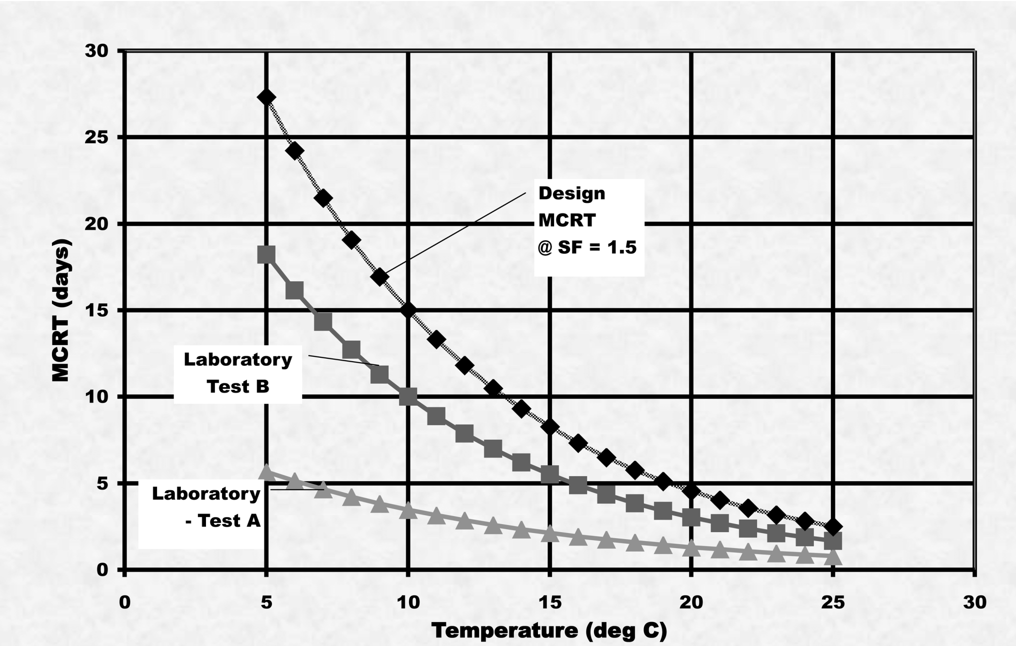


FIGURE 22.9 Design MCRT for nitrification.

atmosphere naturally consists of more than 70% nitrogen, so the emissions do not harm the environment.

Biochemistry. Denitrification is done by *heterotrophic microorganisms*—organisms that use organic materials as a source of nutrients and metabolic synthesis as a source of energy. Heterotrophic organisms spend less energy on synthesis than autotrophic organisms do, so they grow more quickly and yield more cell mass. They typically require 2 to 4 days of MCRT to produce 0.5 mg of VSS per 1.0 mg of BOD removed.

Numerous heterotrophic bacteria can denitrify wastewater. *Denitrifiers*—the bacteria that reduce nitrate—are "facultative" bacteria, meaning they can function in both oxic and anoxic environments. Denitrifiers prefer to use molecular oxygen, but if the environment contains less than 0.3 to 0.5 mg/L of dissolved oxygen, they will cleave the oxygen from nitrate-nitrogen molecules to synthesize carbon compounds (e.g., BOD) (Daigger et al., 1988):

$$\begin{aligned}\mathrm{NO_3^-\text{-}N} + \text{carbon source} + \text{facultative bacteria} &= \mathrm{N_2 + CO_2 + H_2O + OH^-} \\ &\quad + \text{new bacterial cells} \qquad (22.14)\end{aligned}$$

The biochemical reactions associated with denitrification are key factors in operating wastewater treatment plants (Table 22.1). For example, reducing nitrate-nitrogen eliminates some of the BOD demand, so the anoxic reactors help remove CBOD. If CBOD is the only treatment consideration, then MCRT and F:M ratio calculations could include the biomass in the denitrification process.

Theoretically, 2.86 mg of oxygen is recovered for every 1.0 mg of nitrate-nitrogen reduced to nitrogen gas. This is more than 60% of the oxygen needed for nitrification, so this recovered oxygen could be used to greatly reduce the amount of aeration equipment needed in other areas of the treatment plant.

Denitrification also results in new bacterial cells. The cell yield depends on the carbon source. For example, if methanol is the carbon source, then the cell yield is about 0.5 mg VSS per 1.0 mg of nitrate-nitrogen removed. If BOD is the source, then the cell yield is about 1.5 mg VSS per 1.0 mg of nitrate-nitrogen removed.

In addition, about 3.57 mg of alkalinity (as calcium carbonate) is produced for each 1.0 mg of nitrate-nitrogen removed. So, about 50% of the alkalinity lost during nitrification can be recovered during denitrification.

Influences. Denitrifiers are less sensitive than nitrifiers, so if the treatment plant environment does not inhibit the nitrifiers, then the denitrifiers should have no problem functioning at optimal growth rates.

The rate at which denitrifiers remove nitrate is the *specific denitrification rate* (SDNR):

$$\mathrm{SDNR} = \frac{\text{kg NO}_3\text{-N removed per day}}{\text{kg VSS}} \tag{22.15}$$

This rate varies, primarily depending on the type of carbon source and amount of carbon available (as measured by the F:M ratio).

Nitrification and dentirification can occur in one treatment unit [this is called *simultaneous nitrification/denitrification* (SNDN)], or denitrification may occur separately in either post- or pre-anoxic reactors. In the 1970s, BNR and denitrification typically were done via post-anoxic reactors [Figure 22.10(a)] (Stensel, 2001). Methanol was the carbon source for denitrification (methanol's SDNR ranges from 0.1 to 0.3 mg NO_3-N/d·mg VSS). A relatively small post-aeration reactor followed the denitrification process to oxidize any remaining organics.

In the 1980s, many wastewater treatment plants were upgraded with selectors for controlling filamentous organisms [Figure 22.10(b)]. Those that nitrified their wastewater found that the anoxic zone was denitrifying RAS as well as controlling filaments. Because methanol is expensive and a hazardous material, most plants took advantage

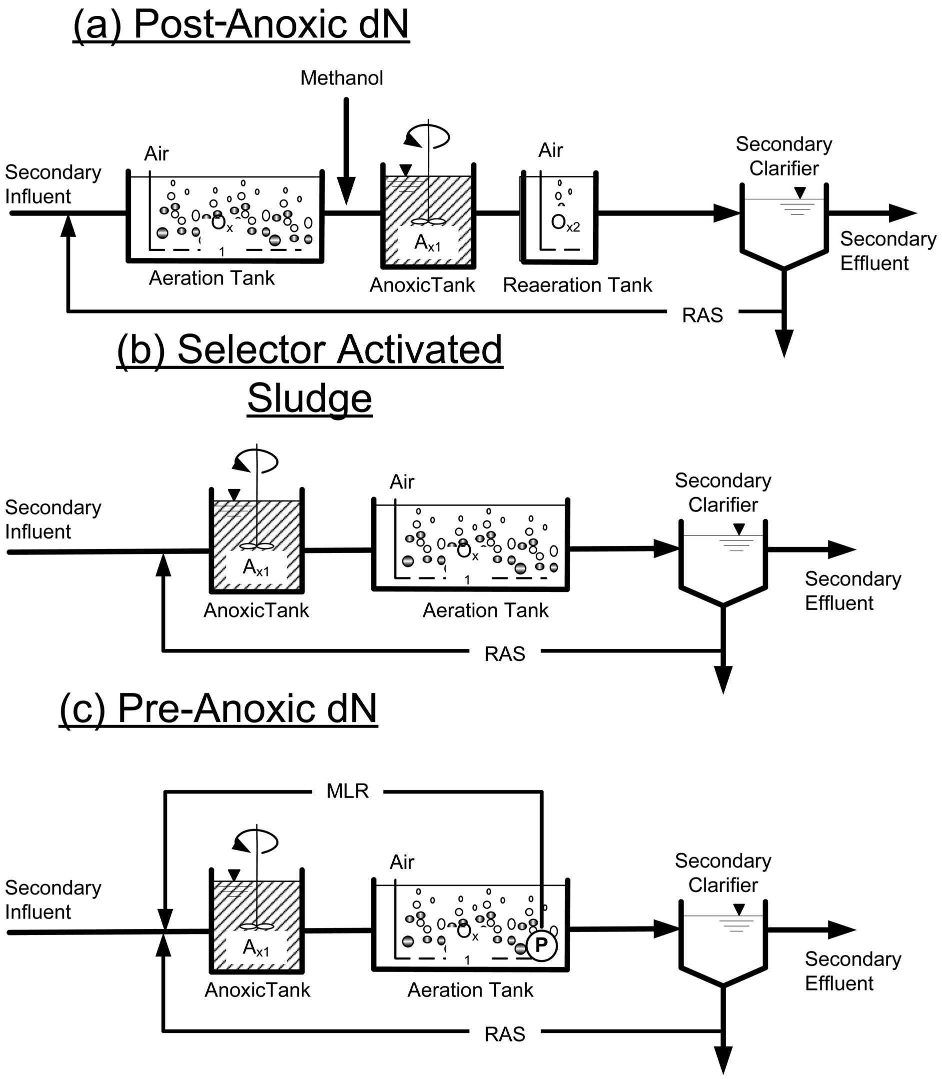


FIGURE 22.10 Selectors for denitrification.

of this lesson. They added an MLR system and used a pre-anoxic selector for denitrification [Figure 22.10(c)]. In this selector, either raw wastewater or primary effluent is used as the carbon source for denitrification (wastewater's SDNR typically ranges from 0.03 to 0.12 mg NO_3-N/d·mg VSS).

Overall, the denitrification rate drops as wastewater passes through various anoxic cells because less readily biodegradable BOD is available in downstream anoxic zones than in upstream ones. When the denitrification process depends on endogenous respiration for nitrate reduction (i.e., has no external source of carbon), its SDNR ranges from 0.005 to 0.03 mg NO_3-N/d·mg VSS (U.S. EPA, 1993). Such rates may apply when denitrification occurs after a trickling filter or in a post-anoxic reactor without an added carbon source.

Temperature and pH also influence denitrification rates, but the most important parameter is molecular oxygen. Treatment plant staff should minimize the concentration of molecular oxygen in the wastewater. Selector cells should be sized to promote high F:M ratios, and MLR may need to be introduced in the second or third cell to avoid oxygen overload.

There is a practical limit to denitrification. Nitrate removal is a function of the nitrate produced in both the aerobic zone (P_{NO_X}) and in secondary effluent (NO_{X2EFF}). Increasing the MLR to lower the NO_X is subject to the law of diminishing returns. The mass of produced nitrate must equal the mass of effluent nitrate associated with the plant's effluent flow (Q), MLR, and RAS flow (Equation 22.15):

$$(Q)(P_{NO_X}) = NO_{X2EFF}(Q + MLR + RAS) \tag{22.16}$$

$$P_{NO_X} = \frac{NO_{X2EFF}\,(Q + MLR + RAS)}{Q} \tag{22.17}$$

$$P_{NO_X} = NO_{X2EFF}(1 + Mr + Rr) \tag{22.18}$$

Where

Mr = MLR/Q and
Rr = RAS/Q.

$$Mr = \frac{P_{NO_X}}{NO_{X2EFF}} - 1.0 - Rr \tag{22.19}$$

So, given the treatment plant illustrated in Figure 22.11, an Rr of 0.5, and 25 mg/L of produced nitrate, an Mr of 1.0 (MLR = Q) will result in an effluent nitrate concentration of about 11 mg/L. If the effluent nitrate limit is 5 mg/L, then Mr will need to be 3.5 (i.e., 350% of the treatment plant's influent flow) to achieve this limit. When effluent nitrate limits are less then 5 mg/L, a post-anoxic selector may be necessary to achieve the limit without having a Mr that is excessively large.

COMMON NITROGEN REMOVAL PROCESSES. Optimal operating parameters for nitrogen removal processes are plant-specific, but the parameters typically used for operation at design conditions are listed in Table 22.3. The advantages and

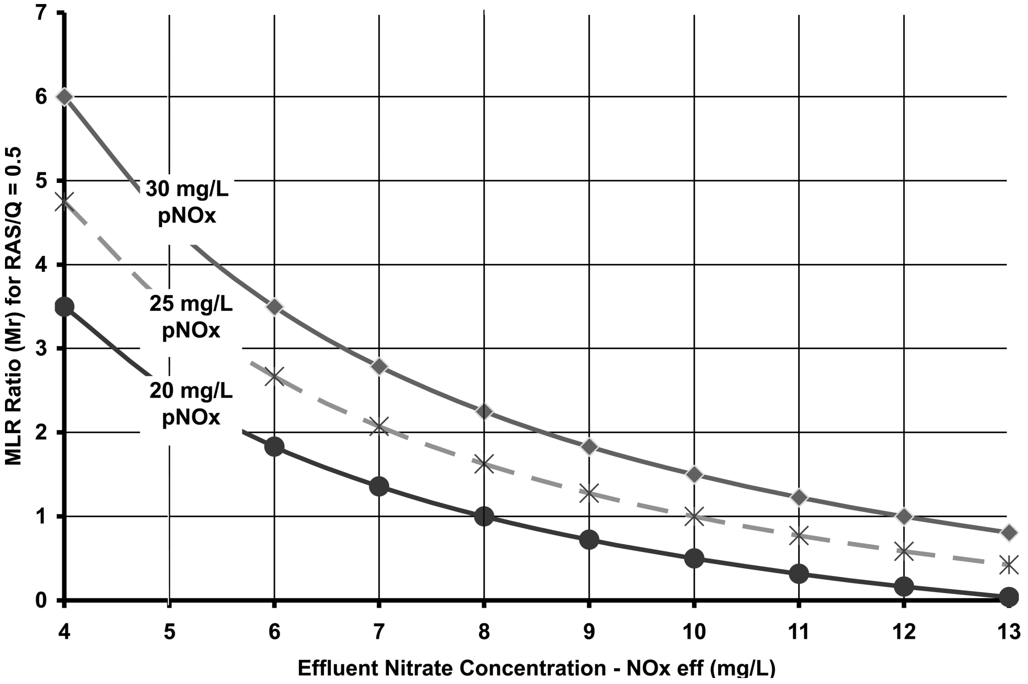


FIGURE 22.11 Effect of MLR ratio on affluent nitrate.

limitations of nitrogen removal processes are listed in Table 22.4 (Metcalf and Eddy, Inc., 2003). Descriptions of common nitrogen removal processes follow.

Ludzack–Ettinger Process. In the 1960s and 1970s, engineers made a number of modifications to the conventional activated sludge process to improve nitrogen removal. For example, researchers Ludzack and Ettinger developed a version in which RAS and secondary influent are combined in an anoxic zone that is followed by an aerobic zone [Figure 22.12(a)]. The nitrate formed in the aerobic zone is returned to the anoxic zone via RAS for denitrification.

Because the anoxic zone's only source of nitrate is the RAS, denitrification is limited by the amount of RAS flow. If the influent NO_X is 20 mg/L, the effluent nitrate concentration will be 15 mg/L, 13 mg/L, or 10 mg/L depending on whether the RAS recycle flow ratio is 0.3, 0.5, or 1.0, respectively. So, the process is only suitable for denitrification if nitrate limits are liberal or high RAS flows can be maintained.

Modified Ludzack–Ettinger Process. The difference between the modified Ludzack–Ettinger (MLE) process and the Ludzack–Ettinger (LE) process is that the MLE process

TABLE 22.3 Typical parameters for nitrogen removal.

Process	MCRT (days)	MLSS (mg/L)	HRT (hours) Total System	HRT (hours) Ax Zone	HRT (hours) Ox Zone	RAS (% of Q)	MLR (% of Q)
mLE	7–20	3000–4000	5–15	1–3	4–12	50–100	100–200
SBR	10–30	3000–5000	20–30	Variable	Variable		
4-Stage Bardenpho	10–20	3000–4000	8–20	1–3 (1st stage) 2–4 (3rd stage)	4–12 (2nd stage) 0.5–1 (4th stage)		
Oxidation Ditch	20–30	2000–4000	18–30	Variable	Variable	50–100	
Anoxic Step Feed	7–20	2000–6000	4–12	0.5–2	3.5–10	30–75	

recycles mixed liquor from the oxic zone to the anoxic zone [Figure 22.12(b)]. The mixed-liquor flow may equal 100 to 300% of the secondary influent flow, depending on how much denitrification is desired. Effluent nitrate concentrations typically range from 4 to 7 mg/L.

The mixed-liquor pumps may be relatively small because short distances and large transfer pipes typically result in pumping heads of less than 0.9 m (3 ft). They also may resemble a fan rather than the conventional centrifugal pumps used at wastewater treatment facilities.

This design [Figure 22.12(b)] is the cornerstone of many other BNR processes, including those used for BPR, so the MLE process will be referred to in many subsequent process descriptions. Although Figure 22.12 shows the anoxic (or anaerobic) selector as one reactor, it probably consists of two or more cells, zones, or compartments operated in series. If nitrified effluent is recycled for denitrification, the MLR is typically transferred to the second or third cell in the anoxic selector to minimize dissolved oxygen in the first compartment, thereby better controlling filamentous bacteria and providing optimal conditions for *Acinetobacter* organisms.

Four-Stage Bardenpho Process. The four-stage Bardenpho process is an MLE process with subsequent anoxic and oxic zones [Figure 22.12(c)]. Developed by James Barnard, the process was originally used for both denitrification and BPR. (The process' name is a compilation of the first three letters of the inventor's name and the words *denitrification* and *phosphorus*.) Its original carbon source was acetic acid or methanol, but a later adaptation—called the enhanced MLE process—uses wastewater instead and is con-

TABLE 22.4 Advantages and limitations of nitrogen removal processes.

	Advantages	Limitations
General	Saves energy; BOD is removed before aerobic zone	
	Alkalinity is produced before nitrification Design includes an SVI selector	
MLE	Very adaptable to existing activated-sludge processes	Nitrogen-removal capability is a function of internal recycle
	5 to 8 mg/L TN is achievable	Potential *Nocardia* growth problem. Dissolved oxygen control is required before recycle
Step Feed	Adaptable to existing step-feed activated sludge processes	Nitrogen-removal capability is a function of flow distribution
	With internal recycle in last pass, nitrogen concentrations less than 5 mg/L are possible	More complex operation than mLE; requires flow split control to optimize operation
	5 to 8 mg/L TN is achievable	Potential *Nocardia* growth problem
		Requires dissolved oxygen control in each aeration zone
Sequencing Batch Reactor	Process is flexible and easy to operate	Redundant units are required for operational reliability unless aeration system can be maintained without draining the aeration tank
	Mixed-liquor solids cannot be washed out by hydraulic surges because flow equalization is provided	
	Quiescent settling provides low effluent TSS concentration	
		More complex process design Effluent quality depends upon reliable decanting facility
	5 to 8 mg/L TN is achievable	May need effluent equalization of batch discharge before filtration and disinfection
Batch Decant	5 to 8 mg/L TN is achievable Mixed-liquor solids cannot be washed out by hydraulic surges	Less flexible to operate than SBR Effluent quality depends on reliable decanting facility

TABLE 22.4 Advantages and limitations of nitrogen removal processes (*continued*).

	Advantages	Limitations
Bio-denitro™	5 to 8 mg/L TN is achievable	Complex system to operate
	Large reactor volume is resistant to shock loads	Two oxidation ditch reactors are required; increases construction cost
Nitrox™	Large reactor volume is resistant to shock loads	Nitrogen-removal capability is limited by higher influent TKN concentrations
	Easy and economical to upgrade existing oxidation ditch processes	Process is susceptible to ammonia bleed-through
	Provides SVI control	Performance is affected by influent variations
Bardenpho (4-stage)	Capable of achieving effluent nitrogen levels less than 3 mg/L	Large reactor volumes required
		Second anoxic tank has low efficiency
Oxidation Ditch	Large reactor volume is resistant to load variations without affecting effluent quality significantly	Nitrogen-removal capability is related to skills of operating staff and control methods
	Has good capacity for nitrogen removal; less than 10 mg/L effluent TN is possible	
Post-Anoxic with Carbon Addition	Capable of achieving effluent nitrogen levels less than 3 mg/L	Higher operating cost due to purchase of methanol
	May be combined with effluent filtration	Methanol feed control required
Simultaneous Nitrification/ Denitrification	Low effluent nitrogen level possible (3 mg/L lower limit)	Large reactor volume; skilled operation is required
	Significant energy savings possible Process may be incorporated into existing facilities without new construction	Process control system required
	SVI control enhanced Produces alkalinity	

figured with denitrification (rather than phosphorus removal) as the primary goal. Both processes can achieve effluent nitrate concentrations of less than 3 mg/L.

Anoxic Step-Feed Process. Anoxic zones can be established in a conventional step-feed process to increase mixed-liquor concentrations in the early stages, resulting in a four-stage BNR step-feed process with a 30 to 40% longer MCRT than that of a conventional plug-flow arrangement [Figure 22.12(d)]. If the anoxic and oxic reactors are the

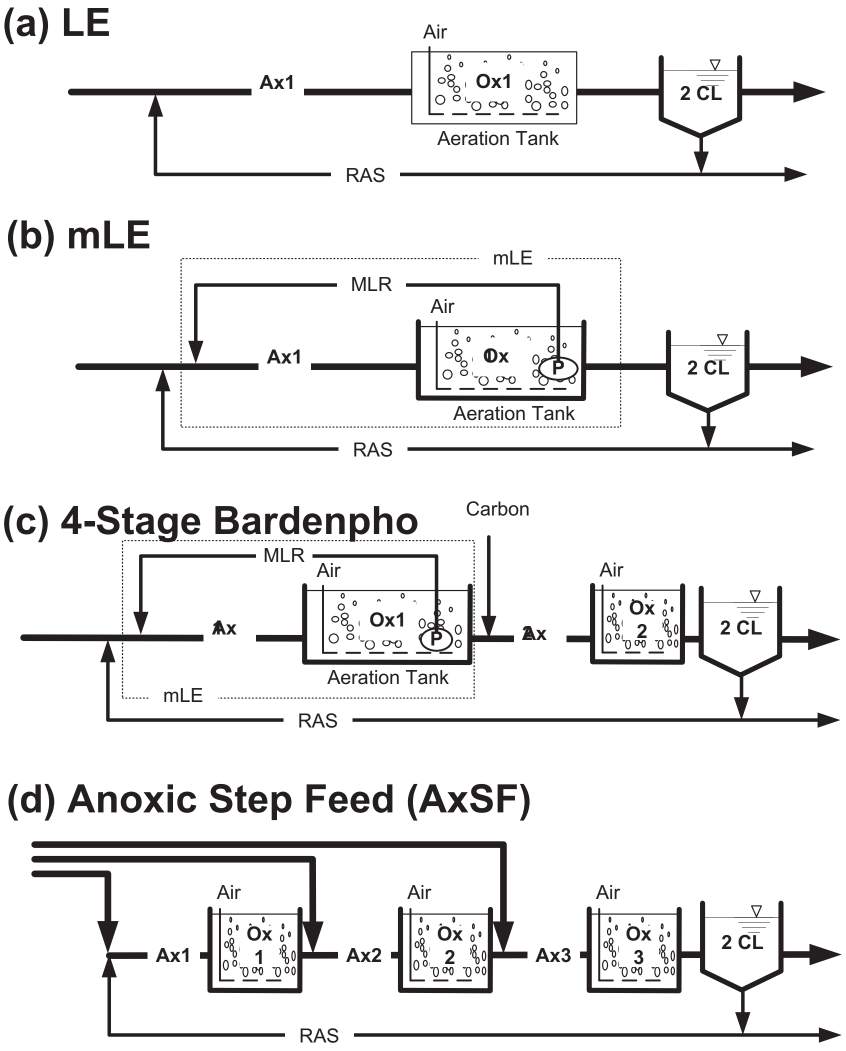


FIGURE 22.12 Suspended-growth pre-anoxic processes.

same size, a four-stage system should have an influent flow split of about 15 : 35 : 30 : 20% so the F : M ratio will be the same in each step. Each stage should have its own influent controls. The flow into the last step is critical because the nitrate produced there will not be reduced. So, the anoxic step-feed process is best used when the effluent nitrate limit is more than 6 to 8 mg/L.

Sequencing Batch Reactors. A conventional SBR, which is designed to remove CBOD, consists of four phases: fill, react, settle, and decant (Figure 22.13). To denitrify wastewater, the fill phase is adjusted to "mixed fill", in which the influent is stirred (but not aerated). At facilities with effluent nitrate limits less than 5 mg/L, a second anoxic phase may be added after the react cycle, and a carbon source (e.g., methanol) may be added to enhance denitrification before the settling and decant phases.

Oxidation Ditches. Oxidation ditches are typically sized based on long aerobic MCRTs (20 to 25 days), so excess volume is available for denitrification (Figure 22.14). This is typically achieved by turning off one or more aeration rotors to create an anoxic zone [Figure 22.14(a) and (b)]. Because the SDNRs are low, the zone must be large enough to provide the needed anoxic time.

Another approach is to cycle the aeration by turning the aerators off at least twice a day [Figure 22.14(c)]. Submerged mixers maintain recirculation in the ditch during the anoxic phases. A variation of cyclic aeration, called the Nitrox™ process, involves using ORP for control.

A third approach is phased ditch operation [Figure 22.14(d)]. In this process, two oxidation ditches are operated in series, and secondary influent is alternately pumped into them. When the influent enters the ditch, its aeration equipment is turned off, and the reactor becomes anoxic. Submerged mixers maintain recirculation. After a period of time (typically 1 to 2 hours), the influent is sent to the second ditch. At the time of the switch, the aerators are turned on in the first ditch, making it oxic, and the aerators on the second ditch are turned off. This cycle continues, allowing periods of aeration and anoxic fill to occur. A variation of phased ditch operation, called the Bio-denitro™ process, uses four phases to enhance oxidation and denitrification (Stensel and Coleman, 2000).

OTHER OR EMERGING NITROGEN REMOVAL PROCESSES.

The following nitrogen removal processes are either emerging or not widely used.

Membrane Bioreactors. Membrane bioreactors (MBRs) combine activated sludge and membrane filtration systems (WERF, 2000a). The semi-permeable membranes used typically provide either ultrafiltration or microfiltration. An aeration basin converted into an MBR can operate at 8000 to 10 000 mg/L of MLSS. Its MCRT is typically 20 days or more to minimize biofouling of the membranes.

The system configuration and equipment involved depends on the manufacturer. One manufacturer installs the membranes directly in the aeration basin, drawing treated wastewater through the filters via a permeate pump. Another manufacturer installs the membranes in a tank outside the aeration basin. In this case, MLSS is pumped to the "membrane tanks", and separate vacuum pumps pull permeate through the membranes.

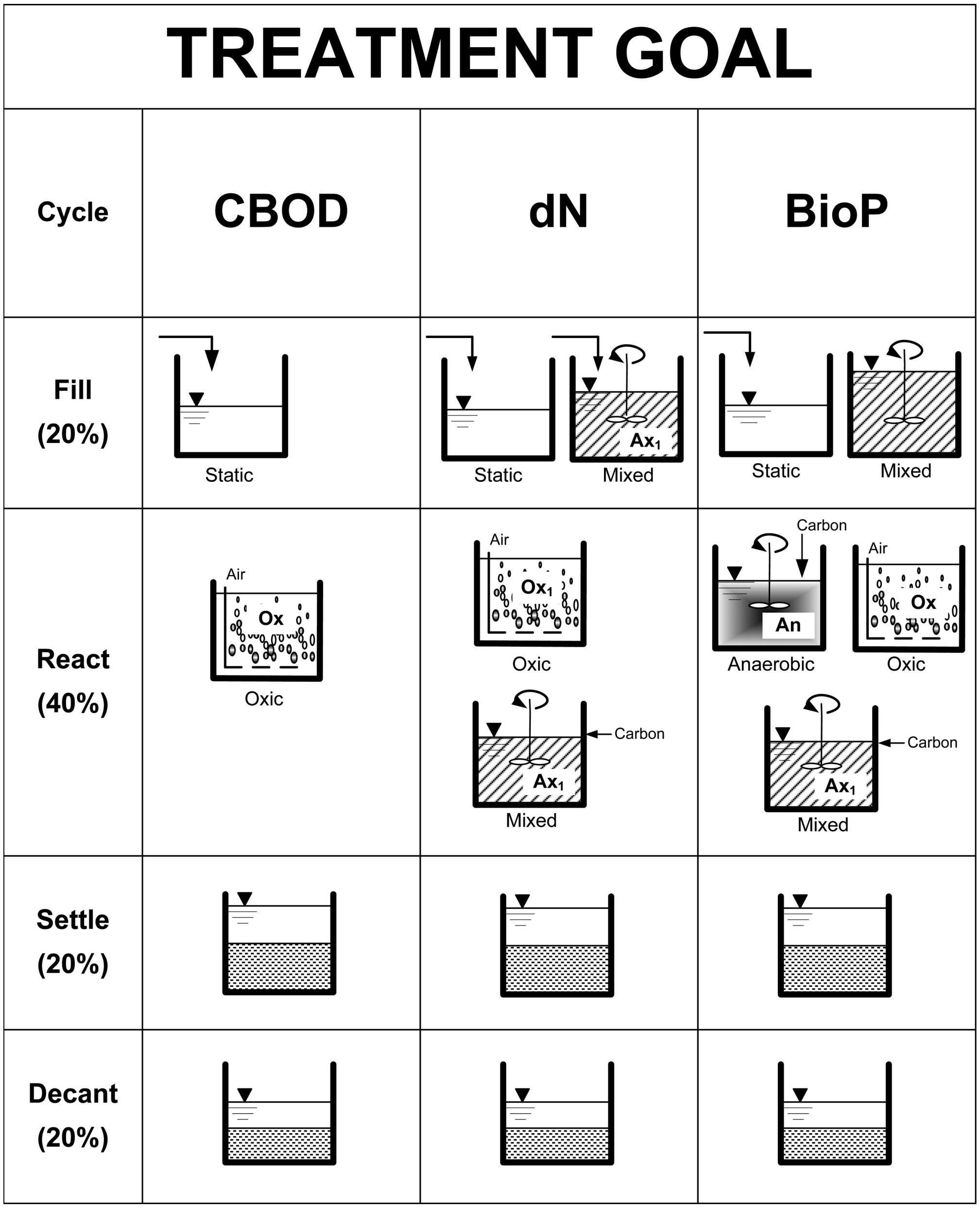


FIGURE 22.13 Sequencing batch reactor processes.

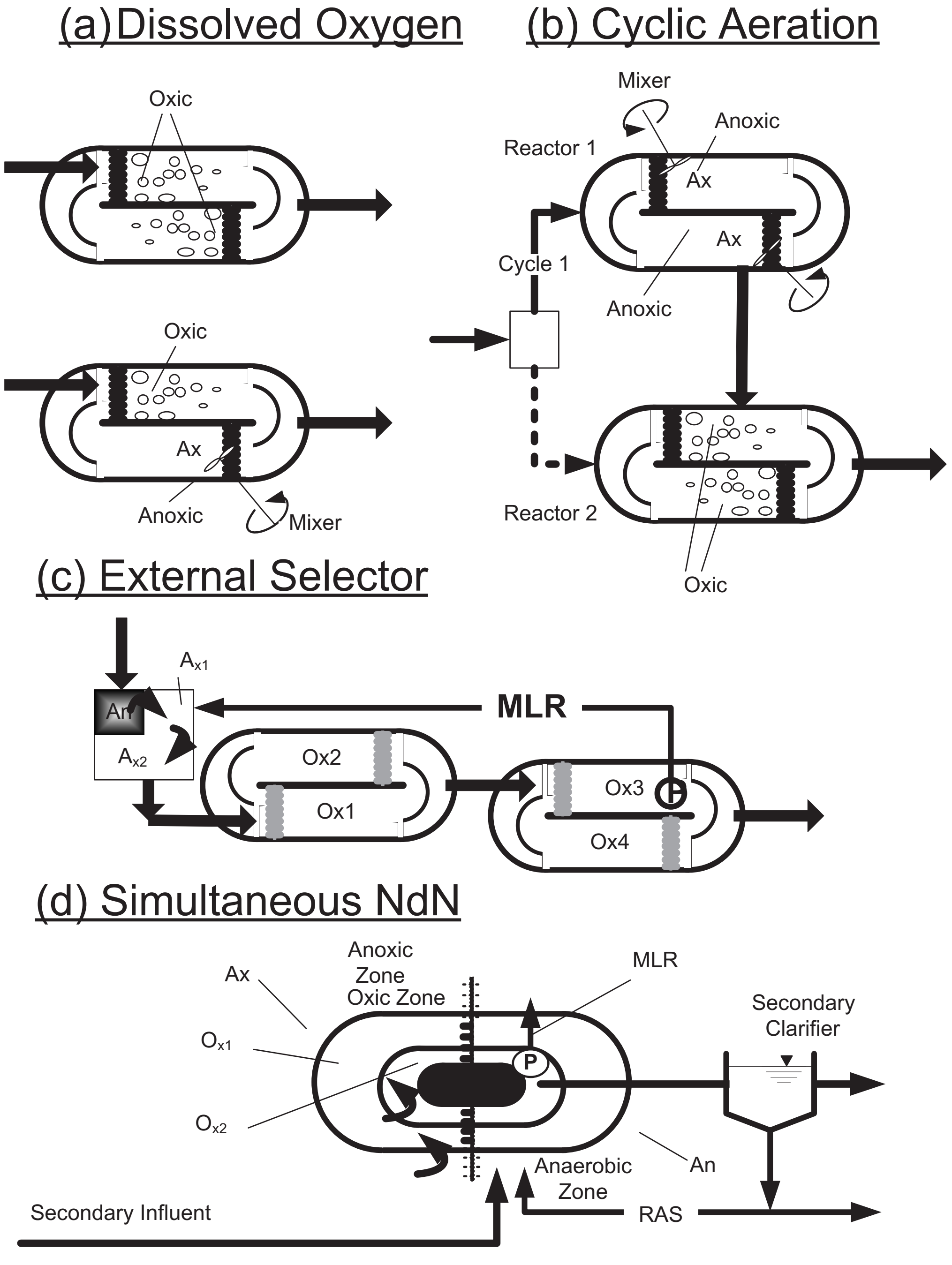


FIGURE 22.14 Oxidation ditch processes.

One benefit of MBRs is that their effluent requires no further biological treatment or filtration to meet water reuse standards.

Lagoons. Lagoons are probably one of the oldest nutrient removal technologies. However, their large size and loss of nitrification during cold weather have typically limited their use.

A number of facultative or partially aerated lagoons have been upgraded to *activated lagoons* by converting the lined earthen basins to aeration basins and adding secondary clarifiers and an RAS system. Conventional secondary clarifiers and RAS pumps can be used, but several manufacturers supply in-basin clarifiers with traveling-bridge sludge collectors and airlift RAS pumping.

Activated lagoons operate at 40 to 80 days of MCRT and 2000 to 3000 mg/L of MLSS. They can nitrify wastewater reliably and do not have the algae problems of conventional lagoons.

Fixed-Film Processes. Fixed-film (attached-growth) processes, such as trickling filters, biotowers, and RBCs, may be used to treat nitrogen alone or both nitrogen and BOD. They typically nitrify wastewater at about half of the organic loading needed for BOD removal. Nitrification is promoted when fixed-film reactors are operated in series (often called stages) and the oxygen concentration is high in the last stage. With series or staged configuration, BOD removal occurs in the first reactor whereas the majority of nitrifiers grow in the second-stage reactor. In the second stage, nitrifying organisms have little competition from heterotrophic bacteria and are able to convert ammonia to nitrate-nitrogen.

Fixed-film reactors are rarely used for denitrification or BPR because of the difficulty maintaining an anaerobic/anoxic environment using the relatively little carbon typically found in municipal wastewater. For detailed descriptions of fixed-film reactors, see *Aerobic Fixed-Growth Reactors* (WEF, 2000).

Combined Fixed-Film and Suspended-Growth Processes. A combination of fixed-film and suspended-growth processes has been used to remove both nitrogen and phosphorus from wastewater (Harrison, 1999). In such systems, the suspended-growth reactor typically is preceded by a biotower containing plastic filter media. If denitrification or phosphorus removal is required, then selector zones may be added in the RAS stream or the anaerobic/anoxic zones that precede the biotower. When the selector zones precede the biotower, the filter media are “activated” by pumping the mixed liquor over them. Both biotower and RBC media can be activated so long as the media are strong enough to accommodate added weight and provisions are made for enhanced sloughing.

Deep-Bed Effluent Filters. Deep-bed effluent filters—typically downflow units containing about 1.8 m (6 ft) of sand, anthracite, or another coarse media—may be used for denitrification and TSS removal. Methanol or another carbon source typically is added to encourage denitrification. The units follow a biological treatment system (including secondary clarification) that provides nitrification.

Because the filter media are large, more solids can be stored in the filter bed, and filter runs between backwashes may be longer than those of a conventional effluent filter. Effective cleaning typically involves a combination of air and water scouring.

Fluidized Beds. A fluidized bed is an attached-growth reactor filled with sand, on which the biomass grows. Wastewater enters the bottom of the reactor and flows upward with enough velocity to expand (fluidize) the sand bed. Rather than backwashing the entire filter, a small volume of media is continuously removed from the reactor, separated from treated wastewater, and then scoured to remove the biomass.

Although fluidized beds can nitrify or denitrify wastewater at biomass concentrations ranging from 25 000 to 30 000 mg/L, thereby minimizing space requirements, they are often difficult to operate. Difficulties have included loss of media, difficulty separating biogrowth from the media, and high maintenance.

Integrated Fixed-Film Activated Sludge Processes. In an integrated fixed-film activated sludge (IFAS) process, filter media are added to an aeration basin to increase the overall microbe population (WERF, 2000b). Like a conventional activated sludge process, an IFAS process uses a secondary clarifier to settle sludge and recirculate RAS. However, its MCRT is 40 to 50% longer than a conventional activated sludge process with the same MLSS and volume, according to tests.

The filter media could be made of rope (tassels tied to a main string), sponge (cubes suspended in some type of housing), or plastic (corrugated sheets, specially designed webs, or cubes). They often are placed over conventional coarse-bubble air diffusers, which should be sized to both meet the process' oxygen demand and control biomass on the filter media. Also, fine-mesh screens should be installed at the influent end to minimize hair, plastic, and other materials that could blind the filter media.

ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL

A conventional activated sludge system removes phosphorus from wastewater naturally when its microorganisms take up soluble phosphorus to generate new biomass. Each milligram of VSS (dry weight) produced in such systems contains about 2% phosphorus. If 0.5 mg of VSS is produced per 1 mg of BOD removed, then about 1.0 mg of phosphorus is converted to cell mass per 100 mg of BOD removed (Table 22.1). So, traditional sludge wasting reduces phosphorus by about 1 to 2 mg/L.

Acinetobacter (BioP) microorganisms consist of up to 35% phosphorus, so mixed liquor with a high percentage of *Acinetobacter* organisms may contain about 6% phosphorus. Systems designed to select for such organisms are called *enhanced biological phosphorus removal* (EBPR) systems. They can reduce phosphorus concentrations by 3 to 6 mg/L.

Chemicals can also be used to precipitate phosphorus, but EBPR minimizes the need for them, thereby reducing their side effects: alkalinity loss and extra sludge production. Enhanced biological phosphorus removal systems also produce a better settling sludge.

The disadvantages of EBPR include a higher capital cost (for baffles and mixers to create selector zones), sensitivity to nitrate or oxygen toxicity, and more complex operations (WEF, 1998a).

BIOCHEMISTRY. Enhanced biological phosphorus removal works because *Acinetobacter* organisms, which are heterotrophic, have a metabolic quirk: they can absorb soluble BOD under anaerobic conditions and store it until they are in an aerobic environment, where they then metabolize it. (Most heterotrophic bacteria cannot transfer soluble BOD under anaerobic conditions.) So, in the right environment with the right type and amount of BOD—they prefer short-chain carbon compounds—*Acinetobacter* organisms will predominate.

Enhanced biological phosphorus removal is a two-step process in which an anaerobic environment is followed by an aerobic one (Figure 22.15). In the anaerobic selector, *Acinetobacter* organisms release phosphorus, thereby obtaining the energy to uptake readily biodegradable organics. This ability enables *Acinetobacter* organisms to become dominant. It also tends to result in orthophosphorus concentrations as high as 40 mg/L. Phosphorus release typically occurs within 0.5 to 1 hour of HRT.

When the mixed liquor enters the aerobic zone, *Acinetobacter* organisms grow new biomass and take up phosphorus—typically more than the amount they released in the anaerobic zone. EBPR effluent may contain less than 1.0 mg/L of soluble phosphorus. Soluble BOD also drops from between 70 and 80 mg/L to 1.0 mg/L (Figure 22.15). In addition, some wastewater facilities have reported that operating in the EBPR mode provides superior sludge settling

Acinetobacter organisms grow slowly, but faster than nitrifying bacteria. To avoid washout, the process' overall MCRT should be between 2 and 3 days. Longer MCRTs (up to 40 to 60 days) do not hurt *Acinetobacter* organisms, but the RAS' nitrate concentration could prevent the first zone from being truly anaerobic. Ideally, an EBPR facility

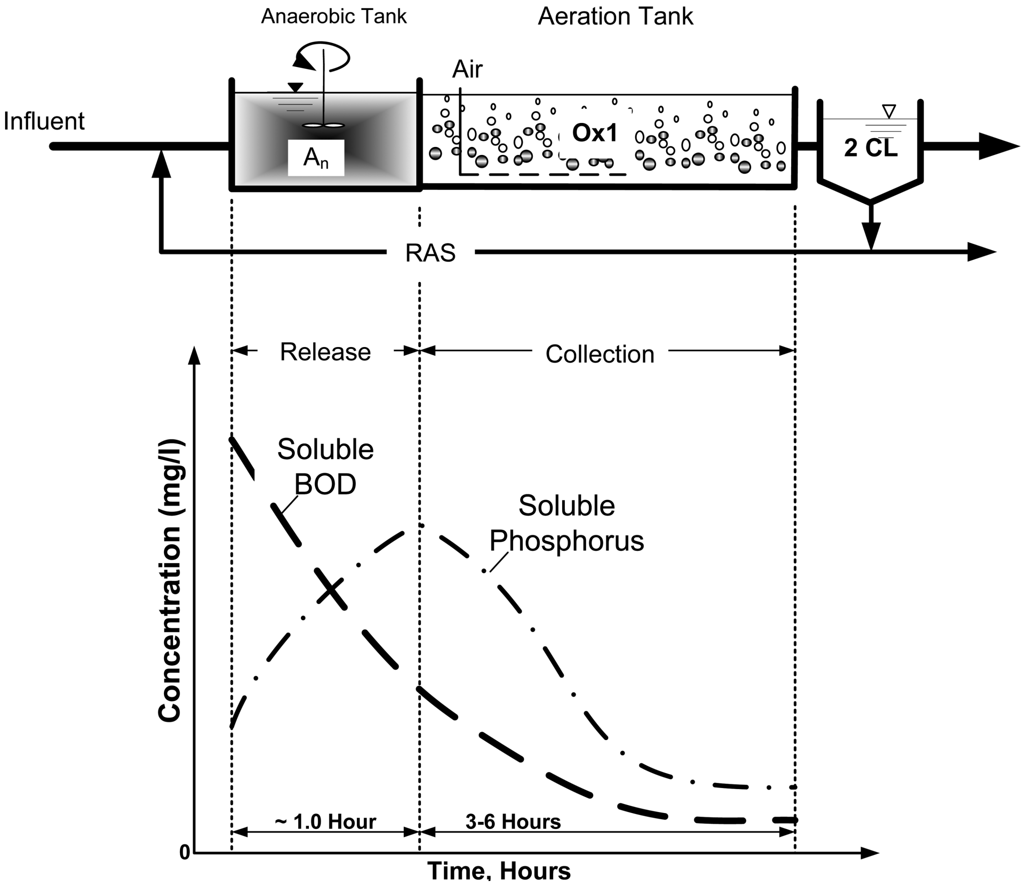


FIGURE 22.15 Biological phosphorus timeline.

should avoid nitrification, but if both nitrification and BPR are necessary, then plant staff should take steps to eliminate interference from combined oxygen.

Settled or waste sludge from EBPR processes must be managed carefully to avoid *secondary release*—phosphorus emitted from sludge when it is held under anaerobic conditions. Such phosphorus can be inadvertently recycled to the process reactors.

INFLUENCES. Good BPR depends on the right environment (low ORP) and the right type and amount of organic matter. Most wastewater will contain enough readily biodegradable BOD to allow EBPR. *Acinetobacter* organisms prefer short-chain carbon compounds, also called VFAs. If the treatment plant is in a warm climate or the collection system has an extended retention time so septic conditions can occur, then the wastewater typically will have enough VFAs.

In areas with colder climates or wastewater diluted by infiltration and inflow (I/I), staff may need to supplement naturally occurring VFAs. Some treatment plants generate VFAs by holding primary sludge (only 20 or 30% may need processing) in a gravity-based thickener called a *primary sludge fermenter*. Others maintain a sludge blanket in the primary clarifier. In either approach, staff maintain a sludge blanket with a 1- to 3-day MCRT to generate enough VFAs so the overflow can supplement the treatment plant influent and allow EBPR to occur.

To optimize EBPR, either nitrate-nitrogen must be removed from the RAS, or the RAS flow must be reduced (typically 20 to 30%) to minimize dissolved oxygen entrainment. The ratio of BOD to total phosphorus is also important. A ratio of 25 : 1 or more is considered necessary to achieve good phosphorus removal (the actual BOD-to-total phosphorus ratio needed depends on the process involved).

Suspended solids at an EBPR facility may have a phosphorus concentration of 6% or more, compared to 2% at a conventional biological treatment system. Likewise, a secondary effluent with 30 mg/L of TSS will contain 1.8 mg/L of particulate phosphorus at an EBPR facility, but only 0.6 mg/L at a conventional plant. So, effluent filtration may be necessary to meet low total phosphorus limits.

COMMON COMBINED NITROGEN AND PHOSPHORUS REMOVAL PROCESSES. Optimal operating parameters for BPR processes are plant-specific, but the parameters typically used for operation at design conditions are listed in Table 22.5. The advantages and limitations of BPR processes are listed in Table 22.6 (Metcalf and Eddy, Inc., 2003). Descriptions of common BPR processes follow. Most remove both nitrogen and phosphorus.

Anaerobic/Oxic Process. Developed in the 1970s and patented in the early 1980s, the A/O process has a similar flow scheme to that of the LE process [Figure 22.12(a)] except it uses an anaerobic zone rather then an anoxic one. The main difference between the LE process and the A/O process is that A/O does not nitrify. Typically, its anaerobic zone's HRT is between 30 and 60 minutes to select for *Acinetobacter* organisms, and its oxic zone's MCRT is between 2 to 4 days to discourage nitrification. The A/O process typically is not used at treatment plants that need both nitrogen and phosphorus removal because other processes do both more effectively.

Anaerobic/Anoxic/Oxic Process. The proprietary anaerobic/anoxic/oxic (A^2/O^{TM}) process is a modification of the A/O process in which an anoxic zone denitrifies the MLR. Essentially, it is an MLE process preceded by an anaerobic zone [Figure 22.16(a)].

TABLE 22.5 Typical parameters for phosphorus removal processes.

			HRT (hours)				
Process	**MCRT (days)**	**MLSS (mg/L)**	**An Zone**	**Ax Zone**	**Ox Zone**	**RAS (% of Q)**	**MLR (% of Q)**
A/O	2–5	3000–4000	0.5–1.5	—	1–3	25–100	
A^2/O	5–25	3000–4000	0.5–1.5	0.5–1	4–8	25–100	100–400
UCT	10–25	3000–4000	1–2	2–4	4–12	80–100	200–400 (Ax) 100–300 (Ox)
VIP	5–10	2000–4000	1–2	1–2	4–6	80–100	100–200 (Ax) 100–300 (Ox)
Bardenpho (5-stage)	10–20	3000–4000	0.5–1.5	1–3 (1st stage) 2–4 (2nd stage)	4–12 (1st stage) 0.5–1 (2nd stage)	50–100	200–400
SBR	20–40	3000–4000	1.5–3	1–3	2–4		

Typically, its anaerobic zone is about the same size as that in the A/O process, while the anoxic zone has an HRT of 1 hour and the MLR is 100 to 400% of the secondary influent.

The A^2/O process allows *Acinetobacter* organisms to be competitive in the anaerobic zone—even while nitrification is occurring—by lowering the nitrate content in the RAS. It can achieve good denitrification via proper sizing of the anoxic zone.

Modified University of Capetown Process. The modified University of Capetown (UCT) process has anaerobic and anoxic zones preceding what is essentially an MLE process [Figure 22.16(b)]. It returns denitrified mixed-liquor recycle (MLR_{Ax}) from the first anoxic zone to the anaerobic zone to maintain nitrates at a lower concentration than most other EBPR processes can achieve. The UCT process is especially beneficial when treating weak wastewater, which may lack the proper nutrient ratios, because it allows *Acinetobacter* organisms to compete with other microorganisms in dilute wastewater.

Sometimes the UCT process is modified with selector zones to operate at higher hydraulic rates. In this case, the HRT may be 1 to 2 hours because the mixed liquor in the anaerobic zone will be less than in a comparable A/O process. The flow rate for the MLR_{Ax} is typically twice the secondary influent flow.

A variation of the modified UCT process is the Virginia Initiative Plant (VIP) process, which has a similar flow schematic [Figure 22.16(b)] but its anoxic and oxic zones are staged to allow operation at a lower MCRT. In this process, the RAS is mixed with the MLR_{Ox} before the anoxic zone to minimize dissolved oxygen recycle.

TABLE 22.6 Advantages and limitations of phosphorus removal processes.

	Advantages	**Limitations**
A/O	Operation is relatively simple when compared to other processes	Phosphorus removal declines if nitrification occurs
	Low BOD/P ratio possible	Limited process control flexibility is available
	Relatively short hydraulic retention time	
	Produces good settling sludge	
	Good phosphorus removal	
A^2/O	Removes both nitrogen and phosphorus	RAS containing nitrate is recycled to anaerobic zone, thus affecting phosphorus-removal capability
	Provides alkalinity for nitrification	
	Produces good settling sludge	
	Operation is relatively simple	Nitrogen removal is limited by internal recycle ratio
	Saves energy	Needs higher BOD/P ratio than the A/O process
UCT	Nitrate loading on anaerobic zone is reduced, thus increasing phosphorus-removal capability	More complex operation
		Requires additional recycle system
	For weaker wastewater, process can achieve improved phosphorus removal	
	Produces good settling sludge	
	Good nitrogen removal	
VIP	Nitrate loading on anaerobic zone is reduced, thus increasing phosphorus-removal capability	More complex operation
		Requires additional recycle system
	Produces good settling sludge	More equipment required for staged operation
	Requires lower BOD/P ratio than UCT	
Bardenpho (5-stage)	Can achieve 3 to 5 mg/L TN in unfiltered effluent	Less efficient phosphorus removal
	Produces good settling sludge	Requires larger tank volumes
SBR	Both nitrogen and phosphorus removal are possible	More complex operation for N and P removal
	Process is easy to operate	Needs larger volume than SBR for N removal only

TABLE 22.6 Advantages and limitations of phosphorus removal processes (*continued*).

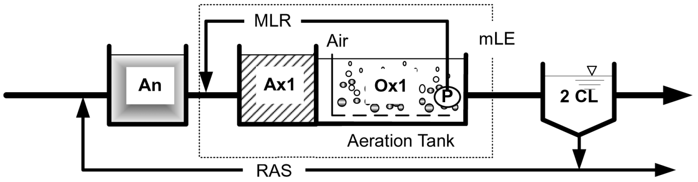
	Advantages	Limitations
	Mixed-liquor solids cannot be washed out by hydraulic surges	Effluent quality depends on reliable decanting facility
	Quiescent settling may produce lower effluent TSS concentration	Design is more complex
	Flexible operation	Skilled maintenance is required
		More suitable for smaller flowrates
PhoStrip	Can be incorporated easily into existing activated sludge plants	Requires lime addition for phosphorus precipitation
	Process is flexible; phosphorus-removal performance is not controlled by BOD/phosphorus ratio	Requires higher mixed-liquor dissolved oxygen to prevent phosphorus release in final clarifier
		Additional tank capacity required for stripping
	Significantly less chemical usage than mainstream chemical precipitation process	Lime scaling may be a maintenance problem
	Can achieve reliable effluent orthophosphate concentrations less than 1 mg/L	

Five-Stage Bardenpho Process. When an anaerobic zone precedes the four-stage Bardenpho process [Figure 22.12(c)], the resulting five-stage process can be used to encourage the growth of *Acinetobacter* organisms. The flow schematic of a five-stage (modified) Bardenpho process resembles the A^2/O process followed by a second anoxic zone and a reaeration (oxic) zone [Figure 22.16(c)]. This process is typically designed to operate with a total HRT of about 22 hours, although the HRTs vary for each zone: anaerobic (2 hours), anoxic (3 hours), aerobic (12 hours), secondary anoxic (2 hours), and reaeration (1 hour).

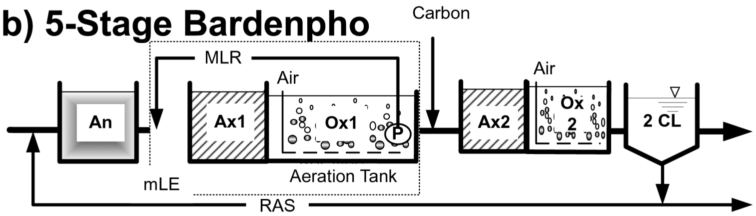
Johannesburg Process. Originally used in Johannesburg, South Africa, this process is essentially a simpler version of the modified UCT process. The Johannesburg (sidestream denitrification) process minimizes the amount of nitrate fed to the anaerobic zone by including an anoxic zone in the RAS flow pattern [Figure 22.16(d)]. It uses the bacteria's endogenous respiration to denitrify the RAS, while a second (mainstream) anoxic zone denitrifies the MLR. Its anaerobic zone can operate at a higher MLSS concentration than the modified UCT process, thereby reducing the HRT necessary for BPR.

OTHER OR EMERGING PHOSPHORUS REMOVAL PROCESSES. The following phosphorus removal processes are either emerging or not widely used.

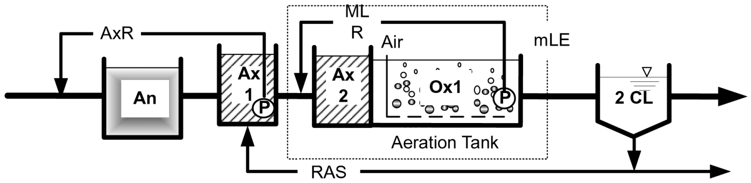
(a) A^2/O



(b) 5-Stage Bardenpho



(c) Modified UCT



(d) Johannesburg (JHB)

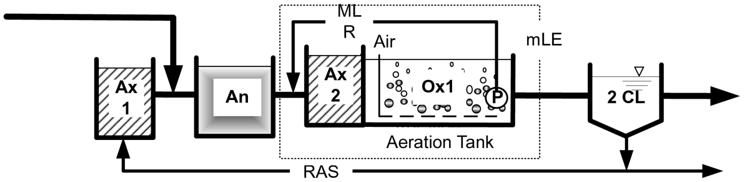


FIGURE 22.16 Suspended-growth processes for phosphorous removal.

Sequencing Batch Reactors. Typically used for denitrification and CBOD removal, SBRs can also be modified to remove phosphorus (Figure 22.13). This is done by inserting an anoxic period and adding carbon (typically methanol) after the aerated react period. This ensures that little nitrate remains during the fill period, so the following anaerobic period will encourage the growth of *Acinetobacter* organisms. Adding methanol after the react period (while aeration is shut off) allows nitrate to be consumed. The following short aerated react period ensures that the methanol is totally consumed and will not contribute to BOD in the final effluent. To ensure that enough VFAs are available, a carbon source is also added during the initial mix–react period.

These modifications typically cut the SBR's cycles to three to four per day. The reduced cycles and extra complexity make BPR difficult to achieve, compared to conventional, constant-flow BNR processes.

Oxidation Ditches. Oxidation ditches (Figure 22.14) typically are not considered a BPR process because of the difficulty associated with achieving truly anaerobic conditions when nitrates are being recycled (Stensel and Coleman, 2000). However, good BPR can be achieved by constructing an external selector, which may incorporate flexible cells allowing a mainstream BPR process to be used with the oxidation ditch [Figure 22.14(c)]. One oxidation ditch manufacturer promotes dissolved oxygen control in the outer reactor ring as a means of accomplishing BPR [Figure 22.14(d)].

PhoStrip Process. The "PhoStrip" process, which removes phosphorus via a sidestream process, was first introduced in the 1970s before any mainstream BPR processes existed. Although seldom used today because of its chemical requirements and complex operations, the PhoStrip method of removing phosphorus from RAS deserves description. It involves transferring about one-third of the RAS to an anaerobic stripper tank (typically a gravity thickener) for a HRT of between 8 and 12 hours. A small amount of primary effluent or raw wastewater may be added to the tank to enhance anaerobic conditions. After fermentation, supernatant from the stripper tank is transferred to a separate reactor, where lime is added to raise the pH and precipitate soluble phosphorus (Figure 22.15).

Although it uses lime, PhoStrip is considered a biological process because the RAS in the stripper tank promotes the proliferation of *Acinetobacter* organisms.

Combined Fixed-Film and Suspended-Growth Processes. Although uncommon, BPR may also be incorporated into flow schemes using fixed-film reactors, including rock-media trickling filters. For example, a trickling filter/solids contact (TF/SC) process used an anaerobic selector in the RAS stream and added a carbon source to reduce nitrates and enhance the growth of *Acinetobacter* organisms. After the enhancement, the RAS is returned to the mainstream (solids contact reactor) after the rock trickling filter. Biological phosphorus removal has also been successful in biotowers when anoxic and anaerobic selectors preceded the fixed-film reactor. In this case, MLSS from the suspended-growth selector processes was pumped to the biotower. The biotower may also be followed by a solids contact or activated sludge aeration basin if nitrification is required.

PROCESS CONTROL

Operators of BNR facilities need more process-control knowledge than those of conventional treatment facilities to keep them operating smoothly. The key operating parameters for a BNR facility typically include

- MCRT,
- F:M ratio,
- HRT,
- Oxygen levels,
- Alkalinity and pH control,
- Denitrification,
- Recycle flows, and
- Secondary clarification.

MEAN CELL RESIDENCE TIME. The mean cell residence time (defined in Equation 22.2) is the key to understanding whether the BNR process has enough time to function effectively. When evaluating MCRT, operators should answer such questions as

- Is the MCRT long enough to establish nitrification?
- How much sludge should be wasted to maintain a desired MCRT?
- Can the MCRT be increased by maintaining a higher MLSS?

Nitrifying facilities, such as conventional activated sludge, A^2/O, and MLE processes, typically need between 5 and 15 days of MCRT. Facilities with intricate recycling patterns, such as the UCT process, need between 10 and 25 days of MCRT. Other processes, such as extended aeration systems, SBRs, and oxidation ditches, need between 15 and 30 days of MCRT. In cold climates (less than 12 °C), nitrification systems need at least 30 days of MCRT to function reliably.

$$\text{MCRT} = \frac{\text{MLSS}}{\text{TSS}_{\text{2EFF}} + \text{TSS}_{\text{WAS}}}$$

Where

MLSS = TSS in the aeration basin,
TSS_{2EFF} = TSS in secondary effluent, and
TSS_{WAS} = TSS in WAS.

Example 22.1: Determine Whether the MCRT is Sufficient for Nitrification. Given the plant shown in Figure 22.17, what is its MCRT? Will it nitrify wastewater reliably at 12 °C? Assume that MLSS = 2000 mg/L, TSS_{WAS} = 7000 mg/L, and Q_{WAS} = 31 000 gpd.

1. Determine the biomass in the system:

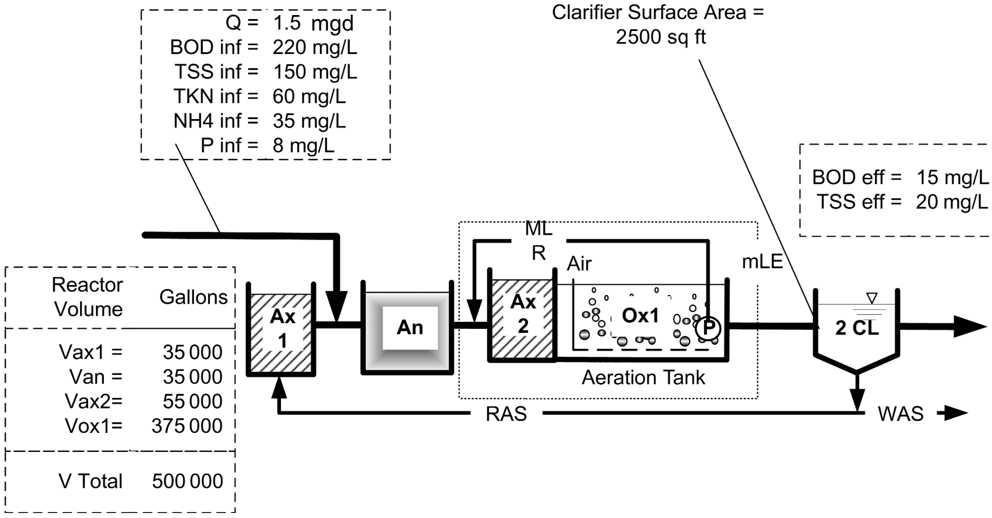
M_{AX1} = (0.035 mil. gal)(8.34)(2000 mg/L) = 584 lb TSS
M_{AX1} = (0.035 mil. gal)(8.34)(2000 mg/L) = 584 lb TSS
M_{AX2} = (0.055 mil. gal)(8.34)(2000 mg/L) = 917 lb TSS
M_{Ox} = (0.375 mil. gal)(8.34)(2000 mg/L) = 6255 lb TSS

Total M = 8340 lb TSS

2. Determine the biomass wasted each day:

TSS_{WAS} = (0.031 mgd)(8.34)(7000 mg/L) = 1810 lb/d
TSS_{2EFF} = (1.5 mgd)(8.34)(20 mg/L) = 250 lb/d

Total wasted TSS = 2060 lb/d



Q = 1.5 mgd
BOD inf = 220 mg/L
TSS inf = 150 mg/L
TKN inf = 60 mg/L
NH4 inf = 35 mg/L
P inf = 8 mg/L

Clarifier Surface Area = 2500 sq ft

BOD eff = 15 mg/L
TSS eff = 20 mg/L

Reactor Volume	Gallons
Vax1 =	35 000
Van =	35 000
Vax2=	55 000
Vox1=	375 000
V Total	500 000

FIGURE 22.17 Biological nutrient removal example.

3. Determine the MCRT

   a. For the entire system:

$$\text{MCRT} = \frac{8340 \text{ lb TSS}}{2060 \text{ lb/d TSS}} = 4.05 \text{ days}$$

   b. For the aerobic (oxic) treatment process:

$$\text{MCRT}_{\text{Ox}} = \frac{6255 \text{ lb TSS}}{2060 \text{ lb/d TSS}} = 3.04 \text{ days}$$

4. Evaluate MCRT_{Ox} for nitrification potential:

   a. Figure 22.9 indicates that under optimal laboratory conditions, nitrification could occur if the MCRT is between 2.5 and 8 days. At 12 °C, however, the process needed an MCRT of about 11 days (using a safety factor = 1.5).

   b. Calculations showed that the MCRT_{Ox} is about 3 days.

   c. Conclusion: Nitrification will NOT occur at 12 °C.

Example 22.2: Increase the MCRT. Again, given the plant shown in Figure 22.17, how much should operators reduce the waste flow (Q_{WAS}) to increase the MCRT_{Ox} from about 3 days to 5.5 days over a 5-day period?

Start by determining how many pounds of MLSS must be maintained to achieve the desired MCRT:

$$\begin{aligned}\text{Target } \text{TSS}_{\text{WAS}} + \text{TSS}_{\text{2EFF}} &= M_{\text{Ox}}/\text{MCRT}_{\text{Ox}} \\ &= 6255 \text{ lb TSS}/5.5 \text{ days} \\ &= 1137 \text{ lb/d TSS}\end{aligned}$$

$$\begin{aligned}\text{Target } \text{TSS}_{\text{WAS}} &= 1137 \text{ lb/d TSS} - 250 \text{ lb/d TSS} \\ &= 887 \text{ lb/d TSS}\end{aligned}$$

$$\begin{aligned}\text{Target } Q_{\text{WAS}} &= (887 \text{ lb/d}/8.34)(7000 \text{ mg/L}) \\ &= 0.0152 \text{ mgd } (15\,200 \text{ gpd})\end{aligned}$$

$$\begin{aligned}\text{Change in } Q_{\text{WAS}} &= 31\,000 \text{ gpd} - 15\,200 \text{ gpd} \\ &= 15\,800 \text{ gpd}\end{aligned}$$

$$\begin{aligned}\text{Amount to reduce per day} &= 15\,800 \text{ gpd}/5 \text{ days} \\ &= 3160 \text{ gpd}\end{aligned}$$

Operators should evaluate the process and recheck their calculations before making process changes.

Example 22.3: Determine the MCRT an SBR Needs to Achieve Nitrification. A sequencing batch reactor facility has the following characteristics:

- Total basin volume (V_B) = 0.5 mil. gal,
- Influent flow (Q) = 425 000 gpd,
- Influent BOD (BOD_{2INF}) = 220 mg/L,
- Aerobic react time = 60%,
- Produced solids (P_X) = 700 lb/d TSS,
- Temperature = 12 °C, and
- MLSS = 2000 mg/L.

The facility does not meet its ammonia limit when winter temperatures are 12 °C or lower. What MCRT would ensure that nitrification occurs?

1. Determine the existing MCRT:

$$\text{MCRT} = \frac{M}{P_x} = \frac{(0.5)(8.34)(2000\text{ mg/L})}{700\text{ lb/d}} = \frac{8340\text{ lb TSS}}{700\text{ lb/d}}$$

$$\text{MCRT} = 11.9\text{ days}$$

2. Determine MCRT_{Ox} and compare it to the target values suggested to maintain nitrification in Figure 22.9:

$$\begin{aligned}\text{MCRT}_{\text{Ox}} &= \frac{\text{MCRT (percent time or volume oxic)}}{100}\\ &= \frac{11.9\text{ days }(60\%)}{100}\\ &= 7.14\text{ days}\end{aligned}$$

According to Figure 22.9, the target MCRT_{Ox} should be 12 days when the temperature is 12 °C.

3. Adjust the MCRT for oxic conditions at 12 days:

$$\begin{aligned}\text{MCRT} &= \frac{\text{MCRT}_{\text{Ox}}\ (100)}{\text{(Percent time)}} = \frac{12\text{ days }(100)}{60\%}\\ &= 20\text{ days required for nitrification}\end{aligned}$$

FOOD-TO-MICROORGANISM RATIO. The F:M ratio measures the amount of "food" (*F*; typically BOD) available for the population of "bugs" (*M*; MLVSS) present in the aeration basin. *F* is typically based on the BOD load in primary effluent, or in raw wastewater if the treatment plant lacks primary clarifiers. When the reactors operate in series, the first cell's *M* is calculated using the first cell's volume and MLVSS concentration; the second cell's *M* is calculated using the combined volume and MLVSS concentrations of the first and second cells, etc.

$$\mathrm{F:M} = \frac{\text{BOD of secondary influent}}{\text{MLVSS in the reactor}}$$

The F:M ratio is a good indicator of how well selector reactors will promote the growth of floc-forming bacteria. When the F:M ratio is high, floc-forming bacteria have a competitive advantage over filamentous bacteria.

Selector loading also helps ensure that nuisance bacteria will not cause operating problems. The selector cells should be arranged so BOD is taken up rapidly.

Example 22.4: Determine the F:M Ratio of a BNR Facility. Given the BNR facility described in Figure 22.17, determine its F:M ratio.

1. Determine the incoming BOD load (*F*):

$$\begin{aligned} F &= (8.34)(1.5\ \text{mgd})(220\ \text{mg/L BOD}) \\ &= 2752\ \text{lb BOD/d} \end{aligned}$$

2. Determine *M* for each treatment zone. If the MLSS is 80% volatile, then the cumulative *M* is:

	Zone *M*	Cumulative *M*
M_{Ax1} = (0.035 mil. gal)(8.34)(2000 mg/L)(0.8) =	467	467
M_{An1} = (0.035 mil. gal)(8.34)(2000 mg/L)(0.8) =	467	934
M_{Ax2} = (0.055 mil. gal)(8.34)(2000 mg/L)(0.8) =	734	1668
M_{Ox} = (0.375 mil. gal)(8.34)(2000 mg/L)(0.8) =	5004	6672
Total M =	**6672 lb**	

3. Calculate the F : M ratio in each selector zone and for the entire system:

$$\mathrm{F:M_{An1}} = \frac{2752\ \mathrm{lb/d\ BOD}}{467\ \mathrm{lb\ VSS}} = 5.9\ \mathrm{d}^{-1}$$

$$\mathrm{F:M_{Ax1}} = \frac{2752\ \mathrm{lb/d\ BOD}}{934\ \mathrm{lb\ VSS}} = 2.9\ \mathrm{d}^{-1}$$

$$\mathrm{F:M_{Ax2}} = \frac{2752\ \mathrm{lb/d\ BOD}}{1668\ \mathrm{lb\ VSS}} = 1.6\ \mathrm{d}^{-1}$$

$$\mathrm{System\ F:M} = \frac{2752\ \mathrm{lb/d\ BOD}}{6672\ \mathrm{lb\ VSS}} = 0.41\ \mathrm{d}^{-1}$$

With consecutive cells (e.g., An_1, Ax_1, $Ax_{2,}$ or O_x), *F* is the "applied" BOD in the first compartment. *M* increases as greater portions of the reactor are considered in F/M calculations.

HYDRAULIC RETENTION TIME. The hydraulic retention time for maintaining BNR depends on reactor size, which is determined by the MCRT necessary for growth. Once the biological reactor or basin size is known, then the HRT can be calculated by dividing the reactor volume (*V*) by the secondary influent flow (*Q*):

$$\mathrm{HRT} = \frac{(\mathrm{mil.\ gal\ of\ V})(24\ \mathrm{hr/d})}{\mathrm{mgd\ of\ Q}}$$

Although not used in daily BNR operations, HRT indicates whether the plant is operating within a normal contact time. Nitrifying facilities, such as conventional activated sludge, A^2O, and MLE processes, typically have an HRT between 5 and 15 hours. Facilities with more intricate recycle patterns, such as the UCT process, typically have HRTs between 10 and 18 hours. Other processes, such as extended aeration, SBR, and oxidation ditch systems, have HRTs between 18 and 36 hours.

Example 22.5: Determine the HRT of a BNR Facility. Given the BNR facility shown in Figure 22.17, calculate the HRT of each zone. Assume that RAS = 0.5 mgd and MLR = 3.0 mgd.

Zone No.	Volume (mil. gal)	Cumulative volume (mil. gal)	Incoming flow Q + RAS + MLR	Nominal HRT (hr)	Actual HRT (hr)
An1	0.035	0.035	2.0	0.56	0.42
Ax1	0.035	0.070	2.0	0.56	0.42

Ax2	0.055	0.125	5.0	0.88	0.16
Ox1	0.375	0.500	5.0	6.00	1.13
Total	**0.500**			**8.00**	

OXYGEN REQUIREMENTS AND AERATION EQUIPMENT. When a conventional activated sludge system is converted into a BNR facility, its dissolved oxygen requirements typically increase, requiring changes in the aeration equipment or diffuser layout. A maximum of 1.2 mg of oxygen is required to treat 1.0 mg of 5-day BOD (BOD$_5$). Approximately 4.57 mg of oxygen is required to oxidize 1.0 mg of ammonia-nitrogen (Table 22.1). If the plant also denitrifies, however, then 2.86 mg of oxygen is recovered for each 1.0 mg of nitrate-nitrogen removed.

When determining aeration equipment needs, treatment plant staff should begin by consulting with equipment suppliers or environmental engineers, because aeration efficiency varies widely. The equipment should be assessed based on field conditions, not laboratory or "standard" conditions (aeration rates in clean water, which may be more than twice the rate possible in wastewater). The field rates for high-speed surface aerators, for example, can range from 1.0 to 2.0 lb of oxygen/hp/hr.

Diffuser equipment calculations are more complicated because of the wide variety of diffusers available. However, the typical field rate for coarse-bubble diffusers in domestic wastewater is 0.375% per foot of submergence. The standard rate for fine-bubble diffusers in clean water is about 0.66% per foot of submergence.

Following are other useful conversion factors:

- 1 standard cu ft of air = 0.0173 lb of oxygen,
- Blower horsepower = (cu ft/min)(lb/sq in. at blower)(0.006), and
- The annual power cost of an aerator or diffuser = \$650/hp if electricity costs \$0.10/kWh.

Example 22.6: Determine the Oxygen Demand for a BNR Facility. If a 2.3-mgd BNR facility nitrifies completely, its influent ammonia = 25 mg/L, and its $\text{BOD}_{2\text{INF}}$ = 140 mg/L, then:

- What is the oxygen demand for BOD removal alone,
- What is the oxygen demand for BOD removal and nitrification, and
- How much money will the facility save in aeration costs if electricity costs \$0.12/kWh and the plant denitrifies to 8 mg/L of nitrous oxides?

1. Calculate the amount of oxygen required for CBOD removal:

$$O_2 = \frac{(140\text{ mg/L BOD})(1.2\text{ mg/L }O_2)(2.3\text{ mgd})(8.34)}{1.0\text{ mg/L BOD}}$$

$$= 3223\text{ lb/d }O_2$$

2. Calculate the oxygen demand after nitrification (without denitrification):

   a. $\text{NOD} = (25\text{ mg/L }NH_4\text{-N})(8.34)(4.57\text{ mg oxygen/mg }NH_4\text{-N})(2.3\text{ mgd})$

   $= 2192\text{ lb/d }O_2$

   b. $\text{TOD} = \text{CBOD} + \text{NOD}$

   $= 3223\text{ lb/d }O_2 + 2192\text{ lb/d }O_2$

   $= 5415\text{ lb/d }O_2$

   (Note: The above is a simplified approach for a rough approximation.)

3. Calculate how much aeration energy will be saved if the plant also adds denitrification.

   a. Determine how much nitrate will be produced:

   $P_{NO_x} = NH_4\text{-}N_{2INF} - NO_{X2EFF}$

   $NO_x = (25\text{ mg/L }NH_4\text{-N} - 8\text{ mg/L }NO_3\text{-N})(8.34)(2.3\text{ mgd})$

   $= 326\text{ lb/d }NO_3\text{-N}$

   b. Calculate the amount of oxygen saved:

$$\text{lb }O_2 = \frac{326\text{ lb }NO_X}{1\text{ day}} \times \frac{2.9\text{ lb }O_2\text{ recovered}}{1\text{ lb }P_{NO_X}}$$

$$= 946\text{ lb/d }O_2\text{ recovered}$$

   c. Determine how much money is saved each year if electricity costs \$0.12/kWh (assume the facility uses surface high-speed aerators with a field transfer rate of 1.3 lb O_2/hp/hr):

$$\text{Electricity} = \frac{(946\text{ lb }O_2)}{1\text{ day}} \times \frac{1\text{ hp-hr}}{1.3\text{ lb }O_2} \times \frac{1\text{ day}}{24\text{ hrs}}$$

$$= 30.3\text{ hp saved}$$

$$\begin{aligned}\text{Savings} &= 30.3\ \text{hp} \times \frac{\$650}{\text{hp}\cdot\text{year}\cdot\$0.10/\text{kWh}} \times \frac{\$0.12}{\text{kWh}} \\ &= \$23,630/\text{yr}\end{aligned}$$

Example 22.7: Determine How Much More Air Blower Capacity a Treatment Plant Needs to Nitrify Wastewater. Suppose an activated sludge plant must nitrify its wastewater (its previous limits were for CBOD only), and its aeration basin has coarse-bubble diffusers that are 14 ft below the water surface. Plant staff already know that they need 1600 lb/d more oxygen to nitrify the wastewater. So, how much more horsepower is needed?

1. Calculate the coarse-bubble diffusers' efficiency at 14-ft submergence:

$$\begin{aligned}\text{Percent efficiency} &= (0.375\%/\text{ft})(14\ \text{ft}) \\ &= 5.25\%\ \text{field transfer for coarse bubble}\end{aligned}$$

[Note: For fine-bubble diffusers, the percent efficiency = (0.66%/ft)(14 ft) = 9.24%]

2. Then determine the required airflow rate:

$$\text{Airflow} = \frac{(100)(\text{lb/d O}_2\ \text{Required})}{(0.0173\ \text{lb O}_2/\text{cu ft})(\text{Percent efficiency})(1440\ \text{min/d})}$$

$$\begin{aligned}\text{Airflow} &= \frac{(100)(1600\ \text{lb/d O}_2)}{(0.0173\ \text{lb O}_2/\text{cu ft})(5.25\%)(1440\ \text{min/d})} \\ &= \frac{1600\ \text{lb/d O}_2}{(0.2491)(5.25)} \\ &= 1220\ \text{cfm}\end{aligned}$$

3. Estimate the discharge pressure at the blower [assume 4-ft headlosses in air piping and equipment (line losses)]:

$$\begin{aligned}\text{Total head at blower} &= \text{Static} + \text{Line headloss} \\ &= 14\ \text{ft} + 4\ \text{ft} \\ \text{Total head} &= 18\ \text{ft or } 7.8\ \text{psi}\end{aligned}$$

(Note: 1 psi = 2.31 ft of water)

4. Calculate the additional blower horsepower needed:

$$\begin{aligned}\text{Blower hp} &= (\text{cfm})(\text{psi})(0.006)\\ &= (1220\text{ cfm})(7.8\text{ psi})(0.006)\\ &= 57\text{ hp}\end{aligned}$$

(Note: These calculations are strictly illustrative. See equipment curves, etc., for more precise calculations.)

ALKALINITY AND pH CONTROL.

Every time 1 mg of ammonia-nitrogen is oxidized to nitrate, 7.14 mg of alkalinity is consumed. Likewise, every time 1 mg of nitrate is converted to nitrogen gas, 3.57 mg of alkalinity is recovered.

Example 22.8: Chemical Addition for pH Control. To maintain stable operations, an effluent's alkalinity must be maintained at 80 mg/L of calcium carbonate. Suppose a 1.4 mgd wastewater treatment plant's effluent alkalinity is 120 mg/L, and it plans to nitrify 22 mg/L of ammonia. How much hydrated lime should plant staff add to nitrification effluent to maintain the desired alkalinity?

1. Calculate the amount of alkalinity required for nitrification:

   According to Table 22.2,

$$\text{Alkalinity depletion from N} = \frac{7.14\text{ mg CaCO}_3}{1\text{ mg N oxidized}}$$

   so the

$$\begin{aligned}\text{Alkalinity required} &= 22\text{ mg/L NH}_3\text{-N} \times \frac{7.14\text{ mg CaCO}_3}{1\text{ mg NH}_3\text{-N}}\\ &= 157\text{ mg/L CaCO}_3\end{aligned}$$

2. Determine how much alkalinity must be added:

$$\begin{aligned}\text{Alkalinity added} &= (\text{Alkalinity goal}) + (\text{Alkalinity required}) - (\text{Alkalinity present})\\ &= 80\text{ mg/L} + 157\text{ mg/L} - 120\text{ mg/L} = 117\text{ mg/L as CaCO}_3\end{aligned}$$

3. Estimate the amount of lime needed (assume 1.33 lb alkalinity/1 lb lime).

   a. Alkalinity added (lb/d) = (117 mg/L)(8.34)(1.4 mgd)

$$= 1366\text{ lb/d as CaCO}_3$$

b. $$\text{Lime needed} = \frac{1366 \text{ lb CaCO}_3\text{/d}}{1.33 \text{ lb alkalinity/1 lb lime}}$$

$$= 1027 \text{ lb/d}$$

DENITRIFICATION REQUIREMENTS. Facilities required to remove nitrate will need to consider whether there are suitable conditions for NO_X removal. The following calculations provided examples of how to determine if there is sufficient reactor volume and if the rate of denitrification is adequate to achieve treatment goals.

Example 22.9: Determine the Anoxic Selector Size Needed to Achieve a Specific Nitrate Limit. Suppose a 2.3-mgd wastewater treatment plant plans to convert to the MLE process. Its secondary influent has a BOD concentration of 160 mg/L. The wastewater in the 0.6-mil. gal aeration basin is about 15 °C and contains 3000 mg/L of MLSS (VSS = 2400 mg/L). The plant needs to denitrify 18 mg/L of produced nitrate. What size must the anoxic selector be to meet an effluent nitrate limit of 7 mg/L?

1. Estimate a selector size based on experience (typically 20 to 40% of the aeration basin volume). Assume that 30% of the basin will be converted to an anoxic selector:

$$V_{ax} = (0.3)(0.6 \text{ mil. gal})$$

$$= 0.18 \text{ mil. gal}$$

2. Calculate the amount of nitrate to be removed:

$$NO_x \text{ removed} = (P_{NO_x} - NO_{X2EFF})$$

$$= 18 \text{ mg/L} - 7 \text{ mg/L}$$

$$NO_x \text{ removed} = 11 \text{ mg/L}$$

$$= (11 \text{ mg/L})(8.34)(2.3 \text{ mgd})$$

$$NO_x \text{ removed} = 211 \text{ lb/d}$$

3. Determine the selector's SDNR:

$$\text{SDNR} = \frac{NO_X}{\text{lb MLVSS}}$$

$$= \frac{211 \text{ lb/d } NO_X}{(8.34)(2400 \text{ mg/L})(0.18 \text{ mil. gal})}$$

$$= \frac{211 \text{ lb/d NO}_X}{3603 \text{ lb MLVSS}}$$

$$= \frac{0.059 \text{ lb NO}_X}{1 \text{ lb/d MLVSS}}$$

4. Compare the calculated SDNR with the range of SDNRs published in Metcalf and Eddy, Inc. (2003) to confirm that too much nitrate will not be applied to the anoxic zone.

Actual SDNRs vary widely because of wastewater characteristics, operating temperature, and the F:M ratio. Let's suppose the SDNRs in the literature range from 0.03 to 0.12. The calculated SDNR is in the lower end of this range, so the anoxic volume may be acceptable. However, to better ensure the performance of the denitrification process, plant staff could

- Enlarge the anoxic selector zone,
- Operate it at a higher MLVSS concentration, and
- Divide the anoxic selector into three or four cells to increase the F:M ratio.

OXIDATION–REDUCTION POTENTIAL. Automated control systems for the internal anoxic mixing process measure the ORP so they can detect nitrate depletion in the mixed liquor. This variable indirectly measures nitrate availability in an aqueous media, although there is no direct correlation between any specific ORP value and nitrate concentration.

Oxidation–reduction potential measures the net electron activity of all oxidation–reduction reactions occurring in wastewater. It is affected by temperature, pH, biological activity, and the system's chemical constituents, but its response pattern to changes in a solution's oxidative state is reproducible in a specific system.

In continuous-flow suspended-growth systems, the control system's ORP breakpoints must be constantly reviewed and revised. In batch systems (e.g., SBR or cyclic aeration systems), however, a characteristic "knee" (change in ORP values) indicates when the system is changing from an oxidized state to a reduced one.

RECYCLE FLOWS. For wastewater facilities with either ammonia and/or nitrate limitations, it will be necessary to adjust recycle flows (typically RAS flow and/or MLR_{Ox}) to achieve operational goals. The following are examples of calculations and that may be required.

Example 22.10: The Effect of BNR on RAS and MLR. Suppose that a 1.7-mgd activated sludge plant has a 0.4-mil. gal aeration basin, 32 mg/L of ammonia-nitrogen in its secondary influent, 1500 mg/L of MLSS, and 8000 mg/L of TSS in its RAS. To nitrify its wastewater, the plant will need to operate at an MLSS of 3000 mg/L. The plant will also be converted to the MLE process, with MLR returned to the anoxic zone for denitrification. Its new nitrous oxide standard will be 12 mg/L. With this in mind, determine the RAS flow needed to maintain 3000 mg/L of MLSS, and calculate the MLR to the anoxic zone (MLR_{Ox}).

1. Determine the Q_{RAS}:

   The mass balance around the secondary clarifier is

$$\text{Incoming solids} = \text{Outgoing solids}$$

$$(MLSS)(Q + Q_{RAS}) = (TSS_{2EFF})(Q) + (TSS_{RAS})(Q_{RAS})$$

   Because the TSS_{2EFF} is small, assume it equals zero and rearrange the equation so

$$\frac{Q}{Q_{RAS}} = \frac{TSS_{RAS}}{MLSS} - 1$$

Therefore

$$\frac{1.7\text{ mgd}}{Q_{RAS}} = \frac{8000\text{ mg/L}}{3000\text{ mg/L}} - 1 = 1.67$$

$$Q_{RAS} = 1.7/1.67$$

$$= 1.02\text{ mgd}$$

2. Calculate the MLR_{Ox} (Equations 22.15 to 22.18). First, determine how much nitrous oxide must be removed to achieve the limit (assume 1 mg/L of produced nitrous oxide for each 1 mg/L of influent ammonia):

$$Mr = \frac{P_{NO_x}}{NO_{X2EFF}} - 1 - Rr \qquad (22.20)$$

Where

Mr = MLR/Q (MLR flow ratio),
Rr = Q_{RAS}/Q (RAS flow ratio),
P_{NO_x} = Produced NO_3-N + mg/L of NO_2, and
NO_{X2EFF} = mg/L of NO_3-N + NO_2 in the effluent.

So

$$\mathrm{Mr} = \frac{32\ \mathrm{mg/L}}{12\ \mathrm{mg/L}} - 1 - \frac{1.02\ \mathrm{mgd}}{1.7\ \mathrm{mgd}}$$

$$\mathrm{Mr} = 1.07 = \frac{\mathrm{MLR}_{\mathrm{Ox}}}{\mathrm{Q}} = \frac{\mathrm{MLR}_{\mathrm{Ox}}}{1.7\ \mathrm{mgd}}$$

Therefore

$$\mathrm{MLR}_{\mathrm{Ox}} = (1.7\ \mathrm{mgd})(1.07)$$

$$= 1.8\ \mathrm{mgd}$$

SECONDARY CLARIFICATION. It is essential that the secondary clarifier be able to both separate biological solids from the treated effluent and also concentrate the solids without a buildup of sludge within the clarifier. Parameters of concern with clarification are the hydraulic loading rate (HLR) and the solids loading rate (SLR).

Example 22.11: Calculate Secondary Clarifier Capacity. Given the activated sludge system in Example 22.10, assume that peak flows are three times the average. Therefore, plant data are as follows:

	Present	**Future**
Flow (mgd)		
Q average	1.7	1.7
Q peak	5.1	5.1
Q_{RAS}	0.4	1.02
MLSS (mg/L)	1500	3000
RAS (mg/L)	8000	8000

Suppose the plant has two 47-ft-diameter secondary clarifiers (total clarifier area = 3470 ft^2). Calculate the current and future clarifier loading.

1. First, check the clarifier's HLR (only one calculation is shown):

$$\mathrm{HLR} = \frac{(\mathrm{Q})(1\ \mathrm{mil.\ gal/mgd})}{\mathrm{Clarifier\ area}}$$

$$\mathrm{HLR}_{1.7} = \frac{(1.7\ \mathrm{mgd})(1\ \mathrm{mil.\ gal/mgd})}{3470\ \mathrm{sq\ ft}}$$

$$= 490\ \mathrm{gpd/sq\ ft}$$

A summary of HLRs for present and future is:

Condition	Present	Future
Average flow (1.7 mgd)	490	490
Peak flow (5.1 mgd)	1470	1470

When these HLRs are compared to those typically suggested for operations, the average HLRs are within the range typically suggested for good performance (400 to 600 gpd/sq ft). Future peak HLRs, however, fall slightly above the recommended range (800 to 1200 gpd/sq ft).

2. Next, check the clarifier's SLR (only one calculation is shown):

$$\text{SLR} = \frac{(\text{Q} + \text{Q}_{\text{RAS}})(8.34)(\text{MLSS})}{\text{Clarifier area}}$$

$$\text{Present SLR}_{1.7} = \frac{(1.7 \text{ mgd} + 0.4 \text{ mgd})(8.34)(1500 \text{ mg/L})}{3470 \text{ sq ft}}$$

$$= 7.6 \text{ lb TSS/d/sq ft}$$

A summary of SLRs for present and future is:

Condition	Present	Future
Average flow (1.7 mgd)	7.6	19.6
Peak flow (5.1 mgd)	19.8	48.1

When these SLRs are compared to those typically suggested for operation, the average SLRs are below that recommended for BNR plants (20 lb TSS/d/sq ft).

Future peak SLRs are slightly above that recommended for BNR plants (35 lb TSS/d/sq ft).

So, the secondary clarifiers seem to be adequate for average loading but marginal for peak loads. Success depends on the clarifier design and configuration. Sludge settleability and characteristics will determine whether more clarifiers should be constructed.

TROUBLESHOOTING

Some of the most common operating problems at BNR facilities are foam control and bulking (nonsettling) sludge (Table 22.7, 22.8, and 22.9).

TABLE 22.7 Troubleshooting nitrification and denitrification facilities.

Observations	Solutions
BOD < 25 mg/L, NH_4-N > 3 mg/L	Ensure MCRT is sufficient for design temperature
Effluent NH_4-N varies erratically, > 3 mg/L and < 2 mg/L, in a short period of time	Waste sludge operation not stabilized, stop wasting until NH_4-N is < 2 mg/L for 3 consecutive days; restart a careful sludge-wasting operation
Effluent NH_4-N > 3 mg/L, dark brown or black MLSS	Check aeration zone DO, should be > 2 mg/L; check MLSS solids balance; MCRT may be too high
Brown clumps of sludge floating on final clarifier surface; effluent NH_4-N < 2 mg/L, BOD < 30 mg/L	Nitrogen gas bubbles being produced in stagnant sludge in clarifier; check return sludge recycle rate, increase frequency of cleaning of clarifier walls and weirs
Effluent NH_4-N > 10 mg/L, BOD > 25 mg/L	Check MCRT, check mixed liquor DO, check MLSS; if all appear satisfactory, plant may be receiving inhibitor of of nitrification from industry; check pretreatment program
Effluent NO_3-N > 7 mg/L, NH_4-N < 2 mg/L	DO in anoxic zone, should be less than 0.2 mg/L

FOAM CONTROL. Activated sludge processes typically have foam (froth) floating in the biological reactor. In a well-operated process, a 50- to 80-mm (2- to 3-in.) layer of light tan foam will cover between 10 and 25% of the reactor surface. Excessive foam, however, can degrade operations. Three types of foam typically are problematic: stiff, white foam; brown foam (either greasy and dark tan or thick, scummy, and dark brown); and very dark or black foam.

TABLE 22.8 Troubleshooting biological phosphorus removal facilities.

Observations	Solutions
Effluent SP > 1 mg/L, TP > 2 mg/L, BOD < 20 mg/L	Ensure DO in anaerobic zone is < 0.2 mg/L, NO_3-N in anaerobic zone is < 5 mg/L
Effluent SP < 1 mg/L, TP > 2 mg/L, BOD < 25 mg/L, SS > 30 mg/L	Check SS frequently, use polymer or metal salt to control SS; find reason for high SS, such as high flow rates, high return sludge recycle rate, or bulking
Effluent SP < 0.2 mg/L, TP < 1 mg/L, BOD > 30 mg/L	Plant may be organically overloaded; check F:M ratio
Effluent SP > 1 mg/L, TP > 2 mg/L, BOD < 15 mg/L	May not be enough low molecular weight acids in anaerobic zone; consider adding anaerobic digester supernatant to this zone
Thin-looking MLSS, effluent TP > 2 mg/L, BOD < 30 mg/L	Sludge may be forming a blanket in secondary clarifier, check sludge blanket depth, adjust recycle rate if necessary
Effluent TP > 2 mg/L, BOD < 25 mg/L, SS < 25 mg/L	Start or increase dose of metal salt to assist in precipitating TP

TABLE 22.9 Troubleshooting facilities that remove both nitrogen and phosphorus.

Observations	Solutions
Effluent TP < 2 mg/L, NH_4-N < 2 mg/L, NO_3-N > 7 mg/L	Check recirculation rate between aerobic zone and anoxic zone, increase rate if necessary; check DO in anoxic zone, should be < 0.2 mg/L
Effluent TP < 2 mg/L, NH_4-N < 2 mg/L, NO_3-N < 2 mg/L, BOD > 30 mg/L	Check feed rate of optional chemical dosing pump for adding organics to second anoxic zone
Effluent TP < 2 mg/L, NH_4-N > 3 mg/L, NO_3-N < 5 mg/L, BOD < 25 mg/L	Check DO in aerobic zone, should be > 2 mg/L

Stiff, White Foam. If stiff, white foam builds up and the wind can blow it onto walkways and other structures, where it looks unsightly and makes working conditions hazardous. This foam also can be odorous and transport pathogens. If it overflows to the secondary clarifiers, this foam tends to collect behind the influent baffles, creating more cleaning problems, and can plug the scum-removal system.

This type of foam indicates a “young” sludge (low MCRT); it is typically found in new or underloaded plants when the MLSS concentration is too low and the F:M ratio is too high. The foam may consist of detergents or proteins that cannot be converted to food by the type of bacteria that are predominant in the mixed liquor. Such foam may occur when

- Activated sludge is not returned to the biological reactor;
- MLSS is low because the process is being started up;
- MLSS is low because of excessive sludge wasting or a high organic load from an industry (typically occurs after low-load periods, such as weekends and early mornings);
- Operations conditions are unfavorable (toxic or inhibiting materials are present, pH is less than 6.5 or more than 9.0, dissolved oxygen or nutrient concentrations are too low, or seasonal temperature changes have reduced microorganism activity and growth);
- Secondary clarifier effluent loses biomass unintentionally because of excessive (shock) hydraulic loads or biological upset;
- A high sludge blanket in the secondary clarifier because of leaking seals or open dewatering valves; or
- Wastewater or RAS is improperly distributed among multiple biological reactors.

Excessive Brown Foam. Brown foam occurs in plants operating at low loading ranges. Nitrification plants operating in nitrifying mode, for example, typically have low to moderate amounts of chocolate brown foam. If *Nocardia* (a filamentous organism) is present, the foam will be strong (not easily collapsed), greasy, and dark tan. It also will overflow onto the clarifier surface. Filamentous organisms containing scum should be wasted from the system rather than returned to the biological reactors in order not to concentrate foam-causing organisms.

Treatment plants that re-aerate sludge typically have heavy, greasy, dark brown foam in their aeration stage. A thick, scummy, dark brown foam indicates an old sludge (long MCRT). This foam can build up behind influent baffles in the clarifier, creating a scum disposal problem.

Overall, brown foam is likely to occur when

- The F : M ratio is low because of nitrification and denitrification;
- The MLSS concentration is high because of insufficient sludge wasting (can happen unintentionally when seasonal temperature changes increase microorganism activity and, therefore, sludge production);
- Sludge is re-aerated (especially if the F : M ratio is low); or
- The wasting controls are insufficient.

Very Dark or Black Foam. Very dark or black foam occurs when aeration is insufficient (anaerobic conditions) or industrial wastes, such as dyes and inks, are present. To correct this problem, operators should

- Increase aeration;
- Investigate industrial waste sources for dyes or inks; and
- Reduce the MLSS concentration.

BULKING SLUDGE. If the supernatant above poorly settling sludge is clear, filamentous microorganisms are hindering settling. To correct this problem, operators should

- Add nutrients, such as nitrogen, phosphorus, and iron;
- Raise the dissolved oxygen concentration in the biological reactor; or
- Correct the pH (either raise or stabilize it).

If the supernatant above poorly settling sludge is cloudy, the problem is dispersed-growth bulking caused by improper organic loading, overaeration, or toxics.

REFERENCES

Daigger, G. D.; Sedlak, R.; Eckenfelder, W.; Jenkins, D.; Stensel, D.; Banard, J. (1988) Principles and Practice of Nutrient Removal from Municipal Wastewater. Presented seminars sponsored by The Soap and Detergent Association, New York.

Harrison, J. R. (1999) Coupling TFs or RBCs with Activated Sludge. Paper presented at the 4th Annual Central States Water Environment Educational Seminar, Madison, Wisconsin,

Metcalf and Eddy, Inc. (2003) *Wastewater Engineering*, 4th ed.; McGraw-Hill, Inc.: New York.

Randall, C. W. (1992) *Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal*, Vol. 5; Technomic Publishing Company: Lancaster, Pennsylvania.

Stensel, H. D. (2001) Biological Nutrient Removal: Merging Engineering Innovation and Science. *Proceedings of the 74th Annual Water Environment Federation Technical Exposition and Conference* [CD-ROM]; Atlanta, Georgia, Oct. 13–17; Water Environment Federation: Alexandria, Virginia.

Stensel, H. D.; Coleman (2000) *Technology Assessments: Nitrogen Removal Using Oxidation Ditches*; Project 96-CTS-1; Water Environment Research Foundation: Alexandria, Virginia.

U.S. Environmental Protection Agency (1993) *Nitrogen Control Manual;* EPA-625/R-93-010; Washington, DC.

Water Environment Federation (1996) *Developing Source Control Programs for Commercial and Industrial Wastewater;* 2nd ed.; Manual of Practice No. OM-4; Water Environment Federation: Alexandria, Virginia.

Water Environment Federation (1998a) *Biological and Chemical Systems for Nutrient Removal*; Special Publication; Water Environment Federation: Alexandria, Virginia.

Water Environment Federation (1998b) *Design of Municipal Wastewater Treatment Plants*, 4th ed.; Manual of Practice No. 8, Water Environment Federation: Alexandria, Virginia.

Water Environment Federation (2000) *Aerobic Fixed-Growth Reactors*; Special Publication; Water Environment Federation: Alexandria, Virginia.

Water Environment Federation (2001) *Natural Systems for Wastewater Treatment*, 2nd ed.; Manual of Practice No. FD-16; Water Environment Federation: Alexandria, Virginia.

Water Environment Federation (2005) *Biological Nutrient Removal (BNR) Operation in Wastewater Treatment Plants;* Manual of Practice No. 29; Water Environment Federation: Alexandria, Virginia.

Water Environment Research Foundation (2000a) *Membrane Technology: An Innovative Alternative in Wastewater Treatment;* Project 97-CTS-10; Water Environment Research Foundation: Alexandria, Virginia.

Water Environment Research Foundation (2000b) *Investigation of Hybrid Systems for Enhanced Nutrient Control;* Project 96-CTS-4; Water Environment Research Foundation: Alexandria, Virginia.