17.10 DESIGN OF ACTIVATED SLUDGE PROCESSES FOR NITROGEN AND PHOSPHORUS REMOVAL

Specialized treatment processes can be designed to provide higher removals of nitrogen and phosphorus. These processes are more complex than activated sludge systems designed to remove carbonaceous BOD. They incorporate anaerobic–anoxic–aerobic sequences that favor the growth and metabolism of organisms responsible for nitrogen removal and phosphorus uptake.

17.10.1 Enhanced Nitrogen Removal

At higher sludge ages and longer detention times a typical activated sludge process will produce a nitrified effluent. Denitrification occurs when certain microorganisms (e.g., *Pseudomonas denitrificans*) in an environment devoid of oxygen use nitrate as an electron acceptor to oxidize organic matter. Nitrate is reduced to nitrogen gas. The reactions describing nitrogen transformations in sewage treatment are as follows:

$$\text{Organic matter} + O_2 \rightarrow NH_3 + \text{microorganisms} + CO_2 \quad (17.51a)$$

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O + \text{microorganisms} \quad (17.51b)$$

$$\text{Organic matter} + NO_3^- \rightarrow N_2 + \text{microorganisms} \quad (17.51c)$$

Ammonia is produced from the decomposition of organic matter. If the sludge age is high enough and other environmental conditions are suitable, nitrifying bacteria establish themselves and convert the ammonia to nitrates (also see Section 5.9.3). Oxygen requirements for the process rise because of nitrification.

The autotrophic nitrifiers have a lower growth rate than heterotrophic bacteria responsible for the removal of carbonaceous BOD. Nitrifier growth rates are strongly dependent on temperature and other environmental variables. The interaction of carbonaceous BOD removal and ammonia production followed by conversion to nitrate is complex and various expressions and values for constants appear in the literature. The nitrifiers are more fastidious in their environmental requirements than other organisms in an activated sludge process. The USEPA (1993) discusses the theory and design approaches in detail. The minimum sludge age used to ensure nitrification at average conditions is 7 d at 10°C (USEPA, 1993). Nitrification–denitrification has been demonstrated to occur at temperatures as low as 2°C (Oleskiewicz and Berquist, 1988). Rates for nitrification and denitrification at 2°C were about one fifth and one fourth, respectively, of rates observed at 15°C.

The minimum DO concentration is 0.5 mg/L, although DO concentrations below 2.5 mg/L may limit the rate of nitrification. Nitrification consumes alkalinity, as shown in Eq. (17.51b), and sufficient buffering capacity should be present to maintain pH in the range of 6.5–8.0. There is a rather abrupt drop in rate of nitrification outside of this range.

Nitrification may be coupled with carbonaceous BOD removal in the same aeration basin or an additional basin with its own clarifier may be used for nitrification as illustrated in Fig. 17.10. Providing means for fixed film growth in CM activated sludge reactors significantly improves settling properties of the sludge and makes nitrification efficiency independent of the SRT or suspended biomass (Wanner et al., 1988).

A separate reactor is used to accomplish denitrification. When a denitrifying reactor follows a conventional reactor, the influent to the basin contains a high amount of nitrate and very little degradable carbon. Therefore, addition of organic matter is

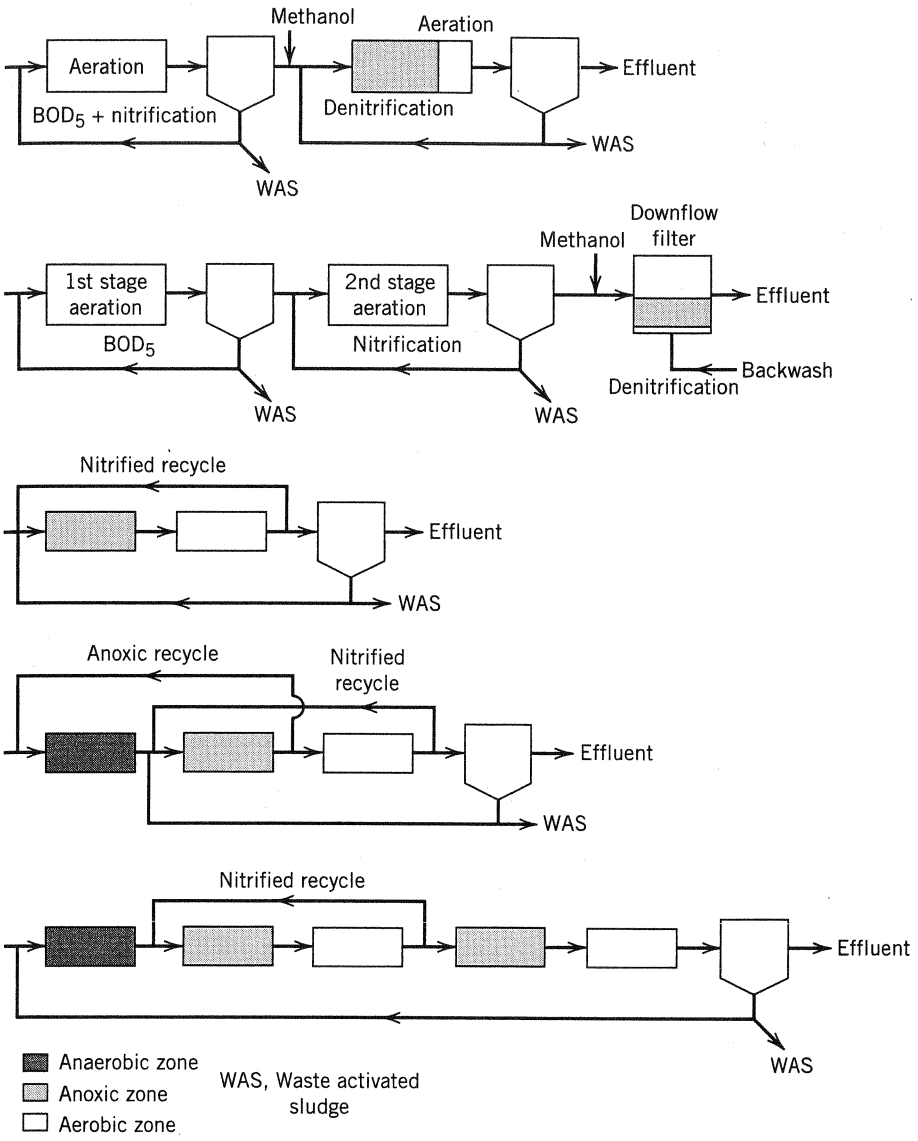


Figure 17.10 Nitrification–denitrification processes. After USEPA (1993).

required for denitrification. The organic matter is metabolized by the denitrifiers with no impairment of effluent soluble organics unless an excess is added. Any readily degradable carbon source can serve as substrate for the denitrifiers. Ease of degradation and expense are the primary considerations of supplemental carbon sources. Organics can be added by directing some influent to the denitrification basin. Methanol is a common substrate; other carbon sources that have been used are ethanol, molasses, and acetate.

The amount of carbon consumed by oxidation with nitrite or nitrate can be calculated by using half-reactions 26 and 27 in Table 1.3 and the half-reaction for the carbon source. Example 17.4 illustrates the procedure. This does not yield the total carbon required for the process, as discussed after the example, but it does provide a baseline for the amount of carbon to be added.

No oxygen is added to the reactor, which causes microorganisms to shift to metabolic pathways using nitrate as an electron acceptor. The water is in an anoxic state. If oxygen or nitrite is present in the influent to the denitrification reactor, then the

amount of carbon source must be increased to reduce these components. The carbon requirements for oxidation of these components are calculated in a manner similar to the procedure in Example 17.4 using the appropriate half-reactions.

■ **Example 17.4 Methanol Demand for Oxidation with Nitrate**

How much methanol is consumed by oxidation with 30 mg/L of NO_3^-?

From the principles in Section 1.5, the half-reaction for methanol can be formulated as

$$\tfrac{1}{6}CO_2 + H^+ + e^- = \tfrac{1}{6}CH_3OH + \tfrac{1}{6}H_2O$$

which is combined with half-reaction 27 from Table 1.3 to find the overall reaction as

$$\tfrac{1}{6}CH_3OH + \tfrac{1}{5}NO_3^- + \tfrac{1}{5}H^+ \rightarrow \tfrac{1}{10}N_2 + \tfrac{1}{6}CO_2 + \tfrac{13}{30}H_2O$$

The molecular weight of nitrate is 48 and the molecular weight of methanol is 32. Therefore, 5.33 mg of CH_3OH are required for 9.60 mg of NO_3^-. The amount of methanol consumed is

$$M = \left(\frac{5.33}{9.60}\right) 30 \text{ mg/L} = 16.7 \text{ mg/L}$$

In addition to the carbon consumed by microbial oxidation with nitrate, nitrite, or oxygen, carbon must be supplied for growth of the microorganisms; i.e., a portion of the carbon source is oxidized to provide energy for the microorganisms to incorporate the remainder of the carbon source into new cells. The commonly accepted overall stoichiometries of reactions for methanol involving the three oxidation agents are as follows (McCarty et al., 1969):

$$1.08CH_3OH + NO_2^- + 0.24H_2CO_3 \rightarrow 0.056C_5H_7NO_2 + 0.47N_2 + HCO_3^- + 1.68H_2O \quad (17.52a)$$

$$0.67CH_3OH + NO_3^- + 0.53H_2CO_3 \rightarrow 0.04C_5H_7NO_2 + 0.48N_2 + HCO_3^- + 1.23H_2O \quad (17.52b)$$

$$0.93CH_3OH + O_2 + 0.056NO_3^- \rightarrow 0.056C_5H_7NO_2 + 0.48N_2 + 0.59H_2CO_3 + 1.04H_2O \quad (17.52c)$$

The overall amount of methanol required (M) can be calculated from Eqs. (17.52a–c) as

$$M = 2.47(NO_3^-\text{-}N) + 1.53(NO_2^-\text{-}N) + 0.87O_2 \quad (17.53)$$

For carbon sources other than methanol, the amount of carbon source required can be estimated by multiplying the amount of methanol by the ratio of the COD of the carbon source to the COD of methanol.

The redox reaction for denitrification with methanol can be rearranged to

$$\tfrac{5}{6}CH_3OH + NO_3^- + \tfrac{1}{6}H_2CO_3 \rightarrow \tfrac{1}{2}N_2 + HCO_3^- + \tfrac{4}{3}H_2O$$

which clearly illustrates that alkalinity is produced. Most of the carbon source will be consumed by denitrification as opposed to biomass synthesis. Denitrification in general results in a net production of alkalinity. The optimal pH range for denitrification is 6.0–8.0 (USEPA, 1993).

A 2 to 3-h retention time is typical in a suspended growth denitrification reactor. The sludge age in a denitrifying reactor must be beyond the minimum age of 1–2.5 d required to produce a flocculating sludge (USEPA, 1993). An alternative to a suspended growth process is the proprietary downflow packed-bed filter reactor of Tetra Technologies. The filter is similar to a gravity filter and contains coarse, round, high-density medium to which denitrifying bacteria attach and grow. The medium also filters out solids and eliminates the need for a secondary clarifier. The filter is backwashed for a few seconds every 4–8 h to remove accumulated nitrogen gas. The filter is backwashed for a longer period of time every 1–5 d to remove solids and excess biomass growth without totally cleaning the media.

Loading rates to the filter are generally in the range of 58–117 $m^3/m^2/d$ (1 400–2 900 $gal/ft^2/d$), with an empty bed contact time of 30 min or greater (USEPA, 1993). The fixed medium retains biomass well in excess of minimum sludge ages required for denitrification.

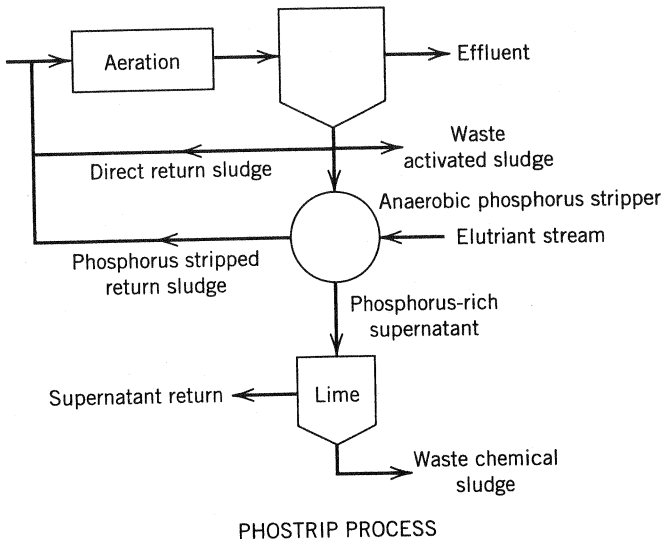
Effluent from a separate suspended growth denitrification reactor is usually freshened by aeration for a short period of time from 20 to 60 min (USEPA, 1993). Aeration promotes removal of excess carbon source added for denitrification and improves settleability of the sludge by stripping nitrogen gas.

Oxygen does not repress denitrifying enzymes in activated sludge processes (Simpkin and Boyle, 1988). The versatility of microorganisms is illustrated by *Nitrobacter* species, which are capable of growing effectively in the absence of oxygen, and some strains are able to use nitrate as an electron acceptor and soluble organic substances as a carbon source provided that nitrite concentrations remain below 23 mg/L (Bock et al., 1988). Therefore, single sludge nitrification–denitrification systems are another alternative (see the last three processes in Fig. 17.10). In these systems nitrified effluent from a later stage in the process is recycled to an anoxic stage near the beginning of the process. Carbonaceous BOD in the influent serves as the carbon source for denitrification in the reactor. There are a variety of single sludge systems in addition to those shown in Fig. 17.10. The design and operation of these systems relies on the principles just given. The USEPA (1993) gives a thorough discussion of these systems. SBR systems can also be operated to produce nitrification–denitrification.

17.10.2 Enhanced Phosphorus Uptake

There are bacteria with the ability to accumulate phosphorus in the form of polyphosphates well in excess of the phosphorus requirements for growth of microorganisms. Conventional activated sludge biomass typically contains 1–2% phosphorus on a dry weight basis, whereas biomass in an enhanced phosphate removal process is capable of accumulating phosphorus in excess of 3%; in some cases phosphorus contents up to 18% have been obtained with artificial, tailored substrates (Appeldoorn et al., 1992). The highest phosphorus concentration found in the biomass with domestic sewage as a substrate is near 7%. The microbiological and chemical processes that lead to enhanced phosphorus uptake are not clear (Bark et al., 1992) but the operational features of an enhanced phosphorus uptake process are known.

The essential features of the process are an anaerobic phase followed by an aerobic phase. It is generally thought that microorganisms are responsible for the phenomenon (bio-P microorganisms) but chemical precipitation of phosphorus may be a significant factor (Bark et al., 1992). The most commonly implicated species are from the genus *Acinetobacter* but other related species may be involved. Operation of the process with anaerobic–aerobic sequencing provides favorable conditions for enrichment of



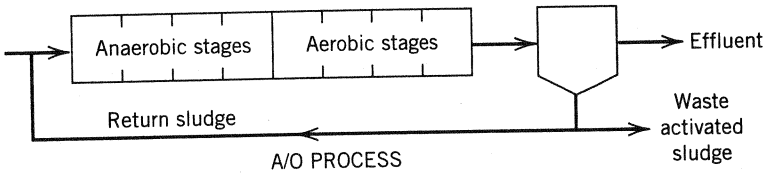


Figure 17.11 Enhanced phosphorus removal processes. After USEPA (1987).

the sludge with bio-P microorganisms. It is hypothesized that in the presence of short chain fatty acids under aerobic conditions the bio-P microorganisms are able to store polyphosphates as a phosphorus source and for energy generation. The initial anaerobic phase is required to produce short chain acids. Phosphorus is released from the sludge during the anaerobic phase but the released phosphorus is taken up later in the process. These acids are able to be utilized by the bio-P microorganisms with concomitant phosphorus removal in a subsequent aerobic reactor. The phosphorus-rich sludge formed is settled and removed from the wastewater.

Detention times of 0.5–2 h under anaerobic conditions are typical. The aerobic stage is designed conventionally. Two commercial processes designed for BOD removal and enhanced phosphorus uptake are shown in Fig. 17.11. In the A/O (anaerobic/oxic) process the reactor is compartmentalized into a number of equal sized anaerobic and aerobic stages. Each compartment is CM but compartmentalization promotes PF. The A/O process directly applies the principle of an anaerobic phase followed by an aerobic phase.

The A/O process can be modified for denitrification by incorporating an anoxic stage into the middle of the process and recycling effluent from the end of the aerobic (nitrification) stage to the anoxic stage. The anoxic stage is also divided into equal sized compartments.

The Phostrip process incorporates both biological and chemical removal of phosphorus. In the anaerobic stripper, sludge thickening occurs under anaerobic conditions. Phosphorus release occurs in this tank. The underflow from the stripper may be recycled to the influent to the stripper or an elutriation stream may be passed through the stripper. The elutriation stream may be primary effluent, secondary effluent, or supernatant from the lime precipitation reactor. The supernatant from the stripper is sent to a lime precipitation clarifier, where a chemical sludge is formed. A portion of

the phosphorus is removed in the waste activated sludge and the remainder is removed in the sludge from the lime clarifier. Biological removal occurs through an anaerobic–aerobic sequence.

The modified Bardenpho process (the last process pictured in Fig. 17.10) is another process that accomplishes both enhanced phosphorus uptake and nitrification–denitrification. Volatile acids are produced in the initial anaerobic reactor. Some BOD removal and denitrification occurs in the second reactor. Phosphorus uptake occurs in the third reactor along with BOD removal and nitrification. In the second anoxic reactor additional denitrification occurs through endogenous decay of the biomass with nitrate as an electron acceptor. The final aerobic stage strips nitrogen gas and supplies oxygen to the biomass to minimize losses of phosphorus in the clarifier.

Operating conditions for the three enhanced phosphorus removal processes are given in Table 17.4. SBR systems can be operated to achieve enhanced phosphorus uptake.

As noted above, activated sludge that has aerobically accumulated phosphorus in an enhanced phosphorus uptake system will begin to release phosphate when an oxygen deficiency occurs (Schön et al., 1993). Under anaerobic conditions Rasmussen et al. (1994) found that most of the release was accomplished in the short time of 4 h. Designing clarifiers to minimize residence time of the sludge within them is essential to proper operation of an enhanced phosphorus removal process.

TABLE 17.4 Typical Operating Conditions for Enhanced Bio-P Processes[a]

	Process			
Parameter	Phostrip	A/O	A/O with nitrification	Modified Bardenpho
F:M, kg TBOD[b]/kg MLVSS/d	[c]	0.2–0.7	0.15–0.25	0.1–0.2
SRT,[d] d	[c]	2–6	4–8	10–30
MLSS, mg/L	600–5 000	2 000–4 000	3 000–5 000	2 000–4 000
HRT,[e] h	1–10			
Anaerobic		0.5–1.5	0.5–1.5	1–2
Anoxic 1		[f]	0.5–1.0	2–4
Aerobic 1		1–3	3.5–6.0	4–12
Anoxic 2		[f]	[f]	2–4
Aerobic 2		[f]	[f]	0.5–1.0
Return sludge flow, % of influent		25–40	20–50	100
Internal recycle, % of influent			100–300	400
HRT in stripper, h	5–20			
Elutriation flow, % of stripper feed	50–100			
Stripper feed, % of influent	20–30			
Stripper underflow, % of influent	10–20			
Lime clarifier loading, $m^3/m^2/d$	48			
(gal/ft²/d)	(1 180)			
Lime dosage in lime clarifier, mg/L	100–300			

[a]From USEPA (1987).
[b]TBOD is total (particulate + soluble) BOD.
[c]Based on activated sludge system design.
[d]Average mass of solids in the system divided by average solids waste rate.
[e]HRT is based on volume divided by influent flow rate.
[f]Not present.