## 4.3.2 System configurations for denitrification

### 4.3.2.1 Denitrification with an external carbon source

Denitrification using an external source of organic matter was first implemented by Barth, Bremmer and Lewis (1969). They developed the process that is schematically represented in Fig. 4.12. The system is composed of three biological reactors in series, each one having a dedicated settler. The result is the development of a different sludge in each of the reactors, hence its name: the three sludge system. In the first reactor, which is a conventional aerobic activated sludge process operated at a short sludge age, the influent organic matter will be removed. The effluent from the first settler flows into the second reactor, also aerobic, where nitrification takes place. The sludge in this reactor is composed mainly of nitrifying bacteria. The nitrified effluent is discharged into the third reactor, operated under anoxic conditions for denitrification to take place.

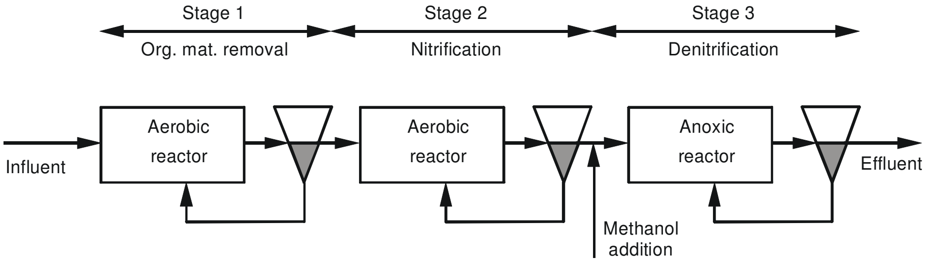

**Figure 4.12 Denitrification with an external source of carbon (three sludge system)**

As the nitrified effluent is substantially free of biodegradable organic matter, this must be added to effect the reduction of nitrate. Often methanol is used because of its relatively low price and its easy handling. Three sludge systems have been constructed and operated successfully at full scale. However, the construction and operational costs of this system is very high, not only due to the fact that three different systems must be constructed, but also because of the need to add the external electron donor. Christensen et al (1977) estimated from full-scale data a consumption of 2.2 to 2.5 mg $CH_3OH$ per mg denitrified nitrogen.

### 4.3.2.2 Denitrification with an internal carbon source

**Early designs**

In the so-called single sludge systems, the influent organic matter is used for the biological reduction of nitrate. In these systems the same sludge is placed alternately in an aerobic environment (for nitrification) and in an anoxic environment (for denitrification). The alternation can be realised by periodically interrupting the aeration in a single reactor, as for example is done in sequencing batch reactors (SBR's). Alternatively, the reactor volume can be divided into a continuously aerated reactor and a permanently anoxic reactor, with sludge recirculating between both reactors. The latter option is more practical and has found more application in large full-scale plants. SBR reactors are often used when smaller or relatively simple systems are required (due to the fact that no final settler is required).

Wurhmann (1964) operated the first single sludge system. The Wurhmann system or post-denitrification system (Fig. 4.13b) is composed of two reactors, the first one aerobic and the second anoxic. The influent enters into the first reactor, where nitrification develops, together with removal of almost all biodegradable organic material.

The nitrified mixed liquor passes to the second reactor, where the sludge is kept in suspension by moderate stirring, but no aeration is applied. In this anoxic reactor - also called the post denitrification (post-D) reactor - reduction of nitrate takes place.

The organic material available for the nitrate reduction is non-metabolised influent material and organic material released during the decay of active sludge in the anoxic reactor. The mixed liquor leaving the second reactor passes through a settler and is recirculated to the aerobic reactor.

The denitrification rate in the Wurhmann system is low, due to the low concentration of biodegradable organic material in the post-D reactor. If denitrification of a considerable nitrate concentration is required, it is necessary that a large fraction of the sludge is located in the anoxic reactor. However, the size of the anoxic sludge mass fraction is limited due to the requirement that nitrification (a prerequisite for denitrification) must be efficient (refer to Fig. 4.10).

## Present designs

In the pre-D system proposed by Ludzack and Ettinger (1964) and improved by Barnard (1970), the influent organic material is the main electron donor source for denitrification. In this system, there are two reactors in series, the first one anoxic and the second aerobic. The nitrate formed in the second reactor is returned to the anoxic reactor through direct recirculation of mixed liquor from the second to the first reactor and together with the return sludge flow from the final settler (refer to Fig.4.13a). This system is called a predenitrification (pre-D) system, because the anoxic reactor is placed before the aerobic reactor. Under otherwise comparable conditions, the pre-D system has a higher denitrification rate than the post-D system, because the concentration of biodegradable organic material is much higher.

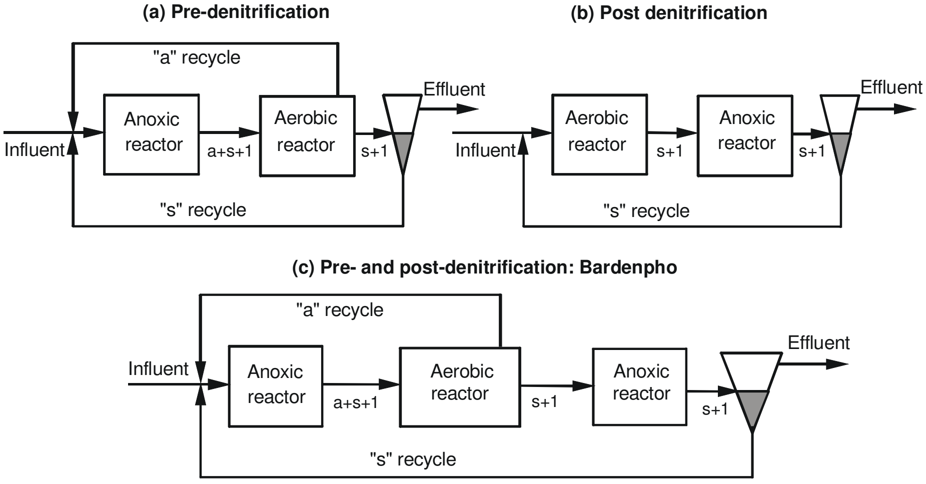

**Figure 4.13 Configuration of three widely used designs for biological nitrogen removal: pre-D (a), post-D (b) and Bardenpho (c)**

However, the pre-D system has one important disadvantage: complete nitrate removal is not possible. A fraction of the nitrate generated in the aerobic reactor is discharged directly from the settler without passing through an anoxic reactor.

The maximum nitrate removal efficiency of the pre-D system depends on the recirculation rates from the aerobic reactor and from the settler to the anoxic reactor. However, predenitrification designs are still applied, mainly when the following conditions apply:

- Complete nitrogen removal is not required;
- The COD concentration in the influent is insufficient to remove all nitrate, i.e. the ($N_{ti}/S_{ti}$) ratio is unfavourable. If so, a pre-D system can be the optimal configuration, assuming the addition of an external carbon source is not an option;
- For relatively small systems where energy consumption is not an important criterion: the recirculation flow from the aerobic reactor to the anoxic reactor can be increased to such an extent (for instance 8 to 10 times the influent flow) so that enough nitrate is returned to the pre-D reactor for denitrification in order to meet the nitrogen discharge limits.

Barnard (1973) proposed the Bardenpho system, thus combining the advantage of the post-D system (feasibility of complete denitrification) with that of the pre-D system (high-rate denitrification). Figure 4.13c shows the Bardenpho system. It is composed of four reactors, the second and the fourth being aerobic and the first and the third anoxic. Nitrification takes place in the second reactor.

In the Bardenpho process both pre- and post denitrification are applied. In the first reactor a large part of the nitrate is removed. The remaining nitrate is reduced in the third reactor and a mixed liquor, substantially free of nitrate, passes to a (optional) fourth reactor, from where it flows to the settler. The function of the fourth reactor is to provide a short period of re-aeration (the fourth reactor is much smaller than the other ones). This ensures that the sludge does not remain excessively long in an anoxic environment: without the re-aeration reactor, the sludge would be continuously in an anoxic environment from the third reactor through the settler and back to the first reactor.

Re-aeration also removes nitrogen bubbles formed in the post-D reactor, which might otherwise cause problems in the settler due to aggregation to sludge flocs, resulting in flotation of the sludge blanket. As an alternative for the fourth aerobic reactor, a cascade can be placed between the post-D reactor and the secondary clarifier, if the hydraulic profile permits this. The feasibility to produce an effluent with a very low total dissolved nitrogen concentration has made the Bardenpho configuration a very popular design. When the single sludge system (and particularly the Bardenpho system) is compared to the three sludge system several important advantages of the former become apparent:

- In the single sludge system there is no cost for the addition of organic material. In contrast, the costs of adding organic material to the three sludge system are considerable as the following evaluation shows. For an assumed per capita contribution of nitrogen in the sewage of 10 g $N.hab^{-1}.d^{-1}$ and an estimated requirement for sludge production of 2 g $N.hab^{-1}.d^{-1}$ (i.e. twenty percent of the influent TKN), the nitrification potential is 8 g $N.hab^{-1}.d^{-1}$. If the consumption of external organic material is 2.5 g $CH_3OH.g\ N^{-1}$ (Christensen et al, 1977), the daily per capita methanol consumption for denitrification is $2.5 \cdot 8 = 20$ g. This quantity amounts to about 10 $litre.hab^{-1}.year^{-1}$ with a cost comparable to that of aeration: US$ 3 to 5 per capita and per annum;
- In the single sludge system part of the oxygen used for nitrification can be recovered as “equivalent” oxygen for the oxidation of organic material. In Section 4.1.3, it was shown that the use of nitrate for the oxidation of organic material reduces oxygen consumption by some twenty percent. For complete denitrification, the nitrate mass to be denitrified equals 8 g $N.hab^{-1}.d^{-1}$.

Knowing that 1 mg N is equivalent to 2.86 mg $O_2$, it can be calculated that denitrification reduces the oxygen demand by $8 \cdot 2.86 = 23$ g $O_2$.hab$^{-1}$.d$^{-1}$. If it is further assumed that the energy consumption of the aerators is 1 Wh.g$^{-1}$$O_2$, the application of denitrification reduces the required power by 23 Wh.hab$^{-1}$.d$^{-1}$ or 23/24 = 1 W.hab$^{-1}$.

- The reduction of 1 W.hab$^{-1}$ in power consumption is very significant in economic terms, because aeration is the largest item of the operational costs for waste water treatment plants. On an annual basis the reduction of energy consumption amounts to 8.7 kW.hab$^{-1}$, which at an assumed price of 0.10 US\$.kWh$^{-1}$ results in a cost reduction of almost US\$ 1 per capita.year$^{-1}$;
- In the single sludge system, the alkalinity produced during denitrification can be used in the process. In Section 4.1.3, it was demonstrated that in the activated sludge process there is an alkalinity consumption of 7.14 ppm $CaCO_3$.mg N$^{-1}$ in the nitrification process and a production of 3.57 ppm $CaCO_3$.mg N$^{-1}$ during the denitrification process. Hence in single sludge systems half of the alkalinity consumed during nitrification can be recovered when denitrification is complete.

  In the three-sludge system, nitrification and denitrification develop sequentially in the second and the third part of the system respectively. Thus, the recovery of alkalinity by denitrification in the last part of the system cannot be used to balance the consumption of alkalinity due to nitrification in the second part. For this reason, in the three-sludge system there is usually a need for alkalinity addition (e.g. lime), whereas the alkalinity of most municipal waste waters is high enough to operate a nitrogen removing single sludge system without alkalinity addition;
- In the three-sludge process, it is very difficult to exactly match the dosage of organic material with the nitrate concentration so that neither organic material nor nitrate are present in the final effluent. In practice it will be required that a small aerobic reactor is added after the third reactor, where excess organic material is removed biologically, thereby complicating even more the already complex configuration of the three sludge system;
- For the biological excess removal of phosphorus it is necessary to create a truly anaerobic zone, characterised by the absence of both dissolved oxygen and nitrate. Such an anaerobic reactor is only feasible in a single sludge system with a pre-D reactor. Thus in the three sludge system biological phosphorus removal is not possible, which reduces its applicability in practice.

There is one advantage that the three-sludge process may have compared with the single sludge system: in a single sludge system nitrification occurs in the aerobic part of the system. In a system with a large anoxic sludge fraction (which in practice will usually be required), the sludge age needs to be relatively high and hence a large treatment system is required. Thus it is possible that the reactor volume of the single sludge process is larger than the volume of the three reactors of the three sludge system together. However, this possible advantage will certainly not compensate for the very serious disadvantages inherent to the three sludge system as discussed above. For that reason, only the single sludge system will be considered further.