6 SUSPENDED-CULTURE REACTORS

6.1 Activated Sludge Unit Processes

The activated-sludge process is based upon a suspended-culture system that has been in use since the beginning of the century. The most common arrangements for nitrogen removal are the single-stage carbon oxidation and nitrification systems and the separate stage nitrification system.

The activated-sludge process can be designed with or without recycling of sludge, and may involve either a completely mixed or a plug-flow process (fig. 6.1). Other possibilities are the aerated lagoons, contact stabilization and extended aerations. Many different applications of the activated sludge process are used. Most of these are presented in Section 6.3.

The return of sludge, containing living or active organisms, is conducted to increase the available biomass and accelerate the reactions.

Most activated sludge applications are used for oxidation of organic content in the waste water, but also nitrogen conversion is to some extent possible with a suitable sludge age of 9-10 days (see Fig. 6.2). The sludge age is important because an appropriate sludge age makes possible the development of nitrifying bacteria in the flocs. These flocs will thereby be able, under suitable conditions, to convert ammonium to nitrogen gas.

The activated-sludge process is normally used for secondary treatment of large amounts of municipal wastewater, where only little nitrification can be expected.
EPA (1975) indicated that the organic loading should be below 0.16 kg BOD/ $m^3 \cdot$ day if nitrification is to be possible simultaneously with the carbon oxidation, due to the bacterial composition. The performance of nitrification in an activated sludge treatment plant, is used mostly to treat large quantities of municipal waste water.

In the activated sludge process there are two main biological activities whereby nitrogen is removed from the waste water:

1) The sludge production: only a minor fraction of nitrogen can be removed by sludge production.

2) Nitrification and denitrification depending of the oxic conditions.

The EPA (1975) manual gives the following classification between the combined carbon oxidation and nitrification process and the separate stage nitrification process. The ability of various activated sludge processes to nitrify has been correlated to the BOD_5/TKN ratio. TKN is the *total kjeldahl nitrogen,* which is the organic nitrogen plus the ammonia nitrogen. For BOD_5/TKN ratios between 1 and 3, which roughly correspond to the values encountered in separate-stage nitrification systems, the fraction of nitrifying organisms is estimated to vary from 0,21 at a BOD_5/TKN ratio of 1 to 0.083 at a ratio of 3. In most conventional activated-sludge processes, the fraction of nitrifying organisms would therefore be considered less than the 0.083 value. The EPA (1975) manual indicates that when the BOD_5/TKN ratio is greater than 5 the process can be classified as a combined carbon oxidation and nitrification process, and, when the ratio is less than 3, it can be classified as a separate-stage nitrification process (see Table 6.1).

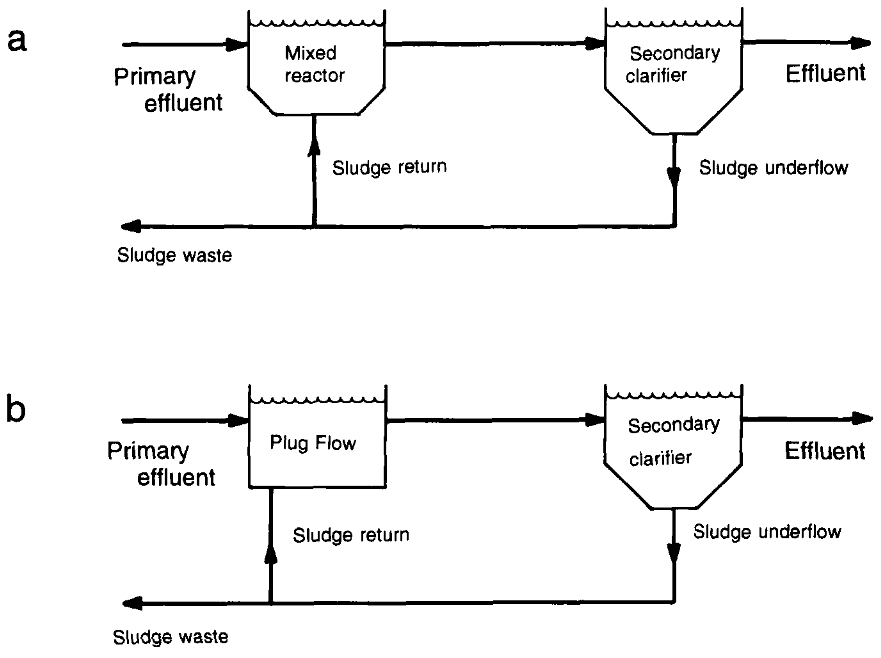


Figure 6.1 Diagram of a) completely mixed activated sludge process. b) plug-flow process.

Table 6.1 Relationship between the fraction of nitrifying organisms and the BOD_5/TKN ratio.

BOD_5/ TKN ratio	Nitrifier fraction
0,5	0,35
1	0,21
2	0,12
3	0,083
4	0,064
5	0,054
6	0,043
7	0,037
8	0,033
9	0,029

Source: EPA (1975)

6.2 Process Design

Several design variations of the completely mixed and plug-flow systems are used. Some involve minor modifications, such as application of air or waste water, or different retention times, or reactor shapes. Others involve more drastic differences, such as sorption and settling prior to the biological processes and the use of pure oxygen rather than air.

The most commonly applied of these design variations are described in Section 6.3. The two main types are the plug-flow and the completely mixed reactors as shown in Fig. 6.1.

In the following discussion attention is focused on some of the factors affecting the activated sludge process, i.e the loading criteria, the sludge production, the air diffusion, control of filamentous organisms and the control of sludge recycling.

Loading criteria.

Many parameters have been proposed for the design and control of the activated-sludge process. The two most commonly used parameters are:

1) The food-to-microorganism ratio (F/M).

2) The mean cell-residence time ϕ_c. (sometimes called the Solids Retention time, SRT)

The food-to-microorganism ratio is defined as:

$$F/M = \frac{S_o}{\phi * X} = \frac{S_o * Q}{V * X} \tag{6.1}$$

where:

F/M = the food-to-microorganism ratio, d^{-1}.

S_0 = the influent substrate concentration in mg/l (g/m^3).

ϕ = the mean cell-residence time of the aeration tank, day.

V = the aeration tank volume.

Q = the influent waste water flow rate, m^3/d.

X = the concentration of volatile suspended solids in the aeration tank, mg/l (g/m^3).

The relationship between the food-to-microorganism ratio and the specific utilization rate U is:

$$U = (F/M) * \frac{E}{100} \tag{6.2}$$

where E = the process efficiency in %.

Substituting the first equation for the food-to-microorganism ratio and $[(S_0 - S)/S_0]$ for the efficiency yields the following term:

$$U = \frac{S_0 - S}{\phi \cdot X} \tag{6.3}$$

where S = the effluent substrate concentration in mg/l (g/m^3).

The mean cell residence time (sludge age) ϕ_c can be defined from the following relationship, defined on the aeration tank volume:

$$\phi_c = \frac{V \cdot X}{Q_{infl} \cdot X_{infl} + Q_{eff} \cdot X_{eff}} \tag{6.4}$$

If the definition is based on the total volume of the system, then the mean cell-residence time ϕ_{ct} can be expressed by the following relationship.

$$\phi_{ct} = \frac{X}{Q_{infl} \cdot X_{infl} + Q_{eff} \cdot X_{eff}} \tag{6.5}$$

where:

ϕ_c = mean cell-residence time based on the aeration tank volume, d.

ϕ_{ct} = mean cell-residence time based on the total system, d.

V = aeration tank volume.

X = concentration of volatile suspended solids in the aeration tank, mg/l.

$Q_{infl.}$ = waste sludge flowrate, m^3/d.

$X_{infl.}$ = concentration of volatile suspended solids in the waste sludge, mg/l (g/m^3)

$Q_{eff.}$ = treated effluent flow rate, m^3/d.

$X_{eff.}$ = concentration of volatile suspended solids in the treated effluent, mg/l (g/m^3)

It is recommended that the design of the reactor is based on ϕ_c, because substantially all of the substrate conversion occurs in the aeration tank.

Comparing these parameters, the specific utilization rate, U, can be considered as a measure of the rate at which substrate (nitrogen) is utilized by a unit mass of organisms, and ϕ_c can be considered as a measure of the average residence time of the organisms in the system.

The relationship between mean cell-residence time, ϕ_c, the food-to-microorganism ratio F/M, and the specific utilization rate U is:

$$\frac{1}{P_c} = Y \cdot \frac{F}{M} * \frac{E}{100} - k_d = YU - k_d \tag{6.6}$$

where:

Y = the cell yield coefficient.

E = the process efficiency, %.

k_d = the endogenous decay coefficient, time^{-1}.

It has been found that a mean cell-residence time of more than 9-10 days results in the production of a stable nitrifying sludge with good settling characteristics.

Sludge production.

It is important to know the quantity of sludge produced per day because it will affect the design of sludge-handling and disposal facilities necessary for the excess sludge.

The relationship between the mean cell-residence time (sludge age) and the nitrification efficiency in per cent, in the activated sludge is presented in Fig. 6.2.

The quantity of sludge produced daily can be estimated from the following:

$$P = Y_{obs} \cdot Q \cdot (S_o - S) \cdot (10^3 g/kg)^{-1} \tag{6.7}$$

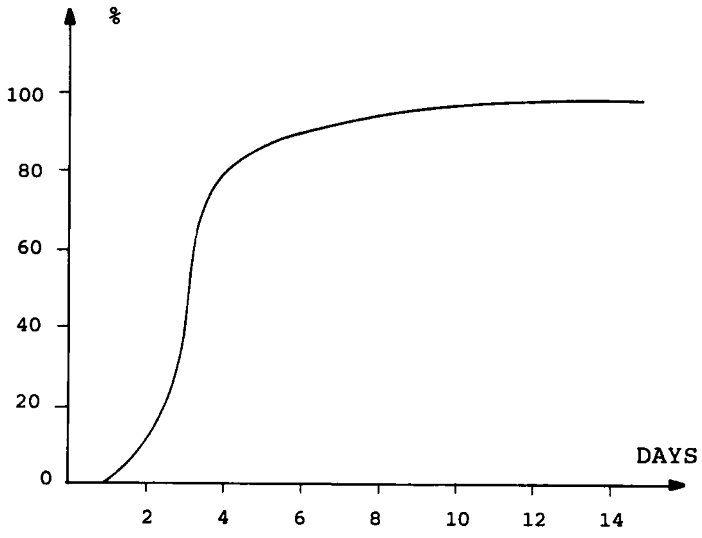


Figure 6.2 Relationship between the mean cell-recidence time (sludge age) and the nitrification efficiency in per cent, in an activated sludge (Source: Jørgensen 1989).

where:

$$Y_{obs} = \frac{Y}{1 + k_d \Phi_c} \tag{6.8}$$

P = the net waste activated sludge produced each day, measured in VSS, kg/d.

Oxygen requirements for a nitrifying activated sludge plant.

When nitrification has to be considered, the total oxygen requirements can be found from the following equation.

$$kg\, O_2 / d = \frac{Q(S - S_o) * (10^3 g/kg)^{-1}}{f} - 1{,}42 * P + 4{,}57 * Q(N - N_o) * (10^3 g/kg)^{-1} \tag{6.9}$$

where:

N_0 = the influent total nitrogen-N in mg/l (g/m^3).
N = the effluent total nitrogen-N in mg/l (g/m^3).

For the activated-sludge process the oxygen utilization rate will always exceed the rate of natural replenishment. Thus, some artificial means of adding oxygen must be used. Oxygen is normally supplied by aerating the waste water in the biological reactor.

The oxygen utilization rate (oxygen consumed by the microorganisms) is a function of the characteristics of both the waste water and the reactor.

Treatment of ordinary municipal waste water by extended aeration usually results in an oxygen utilization rate of approximately 10 mg/l * hours. Treatment of the same waste water by a conventional activated sludge process results in an oxygen utilization rate of about 30 mg/l • hours and up to 100 mg/l • hours. The oxygen addition should be sufficient to match the oxygen utilization rate and still maintain a small excess in the waste water at all times to ensure aerobic metabolism.

Aeration techniques consist of using air diffusers to inject compressed air into the biological reactor and/or using mechanical mixers to stir the contents violently enough to entrain and distribute air through the liquid. It is common practice to use diffused air in plug-flow systems and mechanical aerators in completely mixed systems.

Control of filamentous organisms.

The growth of filamentous microorgansims is the most common operational problem in the activated sludge process. Filamentous organisms in the system result in poorly settling sludge usually termed "bulking sludge".

In the single-stage activated sludge system it is normal to see a growth of filamentous organisms because of the low-substrate levels uniformly present in the reactor.

In some plug-flow reactors, where significant back-mixing occurs, a similar phenomenon takes place.

When oxygen limits the growth of microorganisms, filamentous organisms may predominate. In practice the dissolved-oxygen concentration in the aeration tank should be maintained at about 1.5-4 mg/l in all regions of the aeration tank.

Recent research has shown that prevention and control of filamentous organisms growth can be obtained by using a separate compartment or "selector" as the initial contact zone, between microorganisms and waste water, in a biological reactor. In the selector the primary effluent and return activated sludge are combined, so that the biomass concentration is increased in the initial treatment of the waste water and therefore the reaction rate of the removal of nitrogen is increased. A selector can be used in most types of activated sludge.

Return activated-sludge control.

The purpose of the return of activated sludge is to maintain sufficient concentration of activated sludge in the aeration tank so that the required degree of treatment can be obtained in the time interval desired.

The return of activated sludge from the final clarifier to the inlet of the aeration tank is the essential feature of the process.

Sludge production

The excess activated sludge produced each day must be wasted to maintain a given food-to-microorganism ratio or mean cell residence time. The most common practice is to waste sludge from the return sludge line because it is more concentrated and requires smaller waste sludge pumps. The waste sludge is discharged to the primary tanks, to thickening tanks, or to other sludge-thickening facilities.

Operational problems.

The most common problems encountered in the operation of an activated-sludge plant are bulking sludge, rising sludge or Nocardia foam.

A bulking sludge is one that has poor settling characteristics and compactability. Two principal types of sludge-bulking problems have been identified. One is caused by the growth of filamentous organisms or organisms that can grow in a filamentous form under adverse conditions. The other is caused by bound water, in which the bacterial cells composing the floc swell through the addition of water to the extent that their density is reduced and they will not settle.

The main waste water characteristics that can affect sludge bulking includes fluctuations in flow and strength; pH, temperature, nutrient content, and the nature of the waste components (Eddy and Metcalf 1991). But some design limitations, including air supply capacity, clarifier design, return sludge-pumping capacity limitations, and poor mixing of the waste water are also factors that can affect sludge bulking.

Filamentous bulking can also be due to operational causes which include low dissolved oxygen in the aeration tank, insufficient nutrients, widely varying organic waste loading, or a low F/M ratio.

More than 20 different types of filamentous organims have been found in activated sludge plants (Eddy and Metcalf 1991).

In an emergency situation or while the factors provoking bulking are being investigated, chlorine and hydrogen peroxide may be used to provide temporary help, but chlorination of a nitrifying sludge will produce a turbid effluent due to dead nitrifying organisms.

Occasionally sludge that has a good settling characteristics will be observed to rise or float to the surface after a relatively short settling period. The cause of this phenomenon is denitrification in which the nitrites and nitrates are converted to nitrogen gas. Rising sludge can be differentiated from bulking sludge by noting the presence of small gas bubbles attached to the floating solids.

Rising sludge problems may be overcome by increasing the return activated-sludge withdrawal rate from the clarifier, to reduce the detention time of the sludge in the clarifier, or by decreasing the rate of flow of the aeration tank, or by decreasing the mean cell-residence time (solids retention time) by increasing the size of the sludge-wasting tank.

The last operational problem to be discussed is the viscous brown foam, that can cover the aeration basins and secondary clarifiers. This foam has led to many problems in activated-sludge plants. The foam is associated with a slowgrowing filamentous organisms of the *Nocardia genus.*

Reducing the sludge age is the method that has been used most commonly for Nocardia control, but this prevents nitrification occurring in the plant.

Air diffusers.

Two main type of diffusers exist. Fine-bubble diffusers produce many bubbles of approximately 2,0 to 2,5 mm in diameter, while coarse-bubble diffusers inject fewer bubbles of a larger (up to 25 mm diameter) size. Both types have advantages and disadvantages. With respect to oxygen transfer, the fine-bubble diffuser is more efficient because of the larger surface area per volume of air. However, head loss through the small pores necessitates greater compression of the air and thus greater energy requirements, and compressed air must be filtered to remove all particulates that would plug the tiny diffuser openings.

Coarse-bubble diffusers offer less maintenance and lower head loss, but poorer oxygen transfer efficiencies. A compromise is to locate a mechanical turbine just above a coarse-bubble diffuser so that the shearing action of the blade at high rotational speed breaks the large bubbles into smaller ones and disperses them through the waste water.

Mechanical aerators.

Mechanical aerators produce turbulence at the air-water interface, and this turbulence entrains air into the liquid. Mechanical aerators may have high-speed impellers that add large quantities of air to relatively small quantities of water. This aerated water is then mixed with the reactor contents through velocity gradients. Large impellers driven at slow speed agitate larger quantities of water less violently.

Use of smaller, high speed units is common in extended aeration systems, while the slow-speed units are more common in conventional activated sludge systems. Brush-type aerators are used to provide both aeration and momentum to waste water in the oxidation-ditch variation of the activated sludge process.

6.3 Activated-sludge Process Configurations

Two basic activated sludge process configurations have been developed for single sludge biological nitrification and denitrification. Depending of the anoxic conditions throughout the plant, more or less denitrification is achieved. The two arrangements are:

1) The Wuhrmann configuration.

2) The Ludzack-Ettinger configuration.

Both can undergo completely mixed and plug-flow regimes for the respective reactors. These two configurations are explained in detail below.

The Wuhrmann configuration.

The single sludge nitrification-denitrification system in which endogenous energy release provides the energy source for denitrification was first proposed by Wuhrmann (1964).

It consists (Fig. 6.3) of two reactors in series, the first aerobic and the second anoxic. The influent is discharged to the first reactor where aerobic growth of both the heterotrophic and nitrifying organisms takes place. Provided the sludge age is sufficiently great and the aerobic fraction of the system is adequately large, nitrification will be complete in the first reactor. In the second anoxic reactor, the denitrification takes place. The overflow from the anoxic reactor passes through a settling tank and the underflow is recycled back to the aerobic reactor. The energy source for the denitrification process is provided by energy release by the sludge mass due to the death of organisms. However, the rate of release of energy is low, which implies the rate of denitrification is low too. Consequently, in order to obtain sufficient denitrification, the anoxic fraction of the plant must be large compared with the oxic fraction. This may cause a breakdown of the nitrification process.

It is usually not possible to remove all the nitrate, particularly if the temperatures are low, below 15°C. Furthermore, in the anoxic reactor, organic nitrogen and ammonia are released due to dead organisms, some of this combined nitrogen passes out with the effluent thereby reducing the total nitrogen removal of the system. To minimize the ammonium content of the effluent, a flash or reaeration reactor may be placed between the anoxic reactor and the settling tank. In this reactor the ammonium is then nitrified to nitrate.

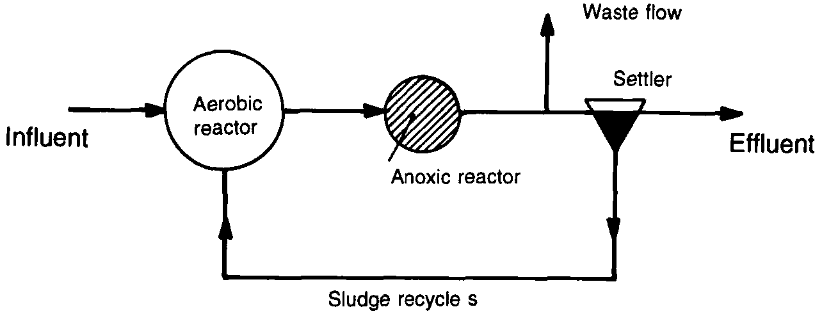


Figure 6.3 The Wuhrmann process for the removal of nitrogen.

The Ludzack-Ettinger configuration.

This configuration was first proposed in 1962 by Ludzack and Ettinger (Fig 6.4). It is a single sludge nitrification and denitrification process utilizing the biodegradable material in the influent as an energy source for the denitrification process.

It consists of two reactors, only partially separated, in series. The first reactor is maintained in an anoxic state by stirring without aeration. The second reactor is aerated and nitrification takes place. As there is only partial separation between the two reactors a mixing of the nitrified and anoxic waste water is induced, and the nitrate entering the anoxic reactor is reduced to nitrogen gas. With this type of configuration a varying denitrification result is obtained, probably due to the lack of control of the exchange of waste water between the two reactors.

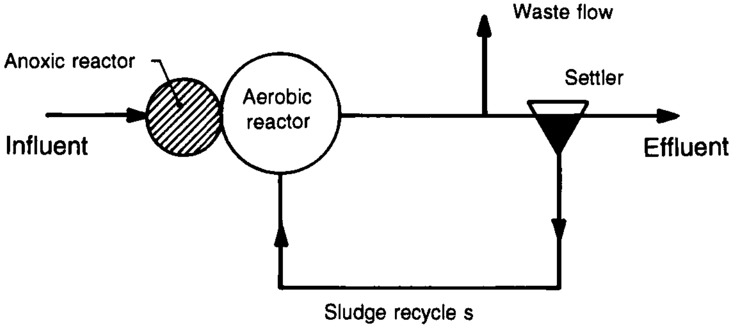


Figure 6.4 The Ludzack-Ettinger configuration for nitrogen removal.

Since the beginning of the 1960´s many improvements of the above two types of plants for nitrogen removal activated sludge have been proposed.
Some of the most popular are the modified Ludzack-Ettinger process and the Bardenpho process.

The modified Ludzack-Ettinger configuration (Fig 6.5) completely separates the anoxic and aerobic reactors, recycling the underflow from the settler to the anoxic reactor, and providing an additional recycle from the aerobic to the anoxic reactor. These modifications offer a significant improvement in control over the process performance. The high influent energy source discharged to the anoxic reactor, also called the pre-denitrification reactor or primary anoxic reactor, yields a high rate of denitrification. But complete denitrification cannot be achieved because a part of the total from the aerobic reactor is not recycled to the anoxic reactor but is discharged directly with the effluent.

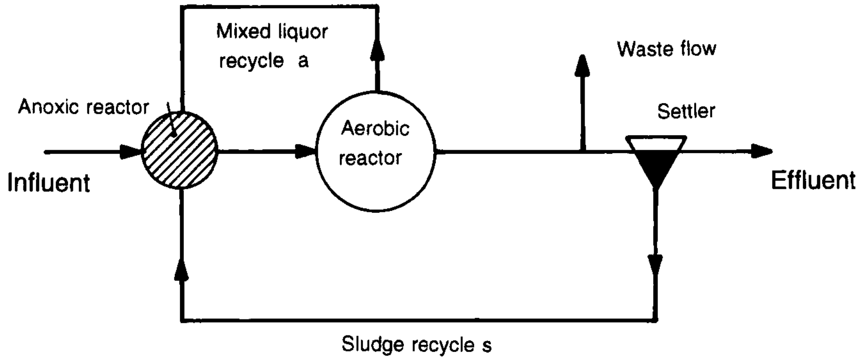


Figure 6.5 The modified Ludzack-Ettinger process.

The Bardenpho configuration (Fig. 6.6) is intended to overcome the incomplete denitrification. The low concentration of nitrate discharged from the aerobic reactor to the secondary anoxic reactor will be denitrified to produce a effluent free of nitrate. To strip the nitrogen bubbles generated in the secondary anoxic reactor attached to the sludge flocs, a flash aeration is introduced between the secondary anoxic reactor and the final settling tank.

The flash aeration is also considered necessary to nitrify the ammonia released during the sludge residence time in the secondary anoxic reactor. In order to reduce the possibility of flotation of sludge in the settler due to denitrification of residual nitrate, the sludge accumulation in the settler is kept to a minimum. This is achieved by a very high recycle rate from the settler, approximately equal to the mean influent flow.

Aerated lagoons, contact stabilization and extended aeration

These three processes cover the extremes in operation between zero and complete nitrification, by aerated lagoons and extended aeration respectively, with contact stabilization typically achieving an intermediate degree of nitrification (Gujer and Jenkins 1974). Aerated lagoons operate essentially as completely mixed, no-recycle systems, which are distinguished by the fact that their hydraulic retention time

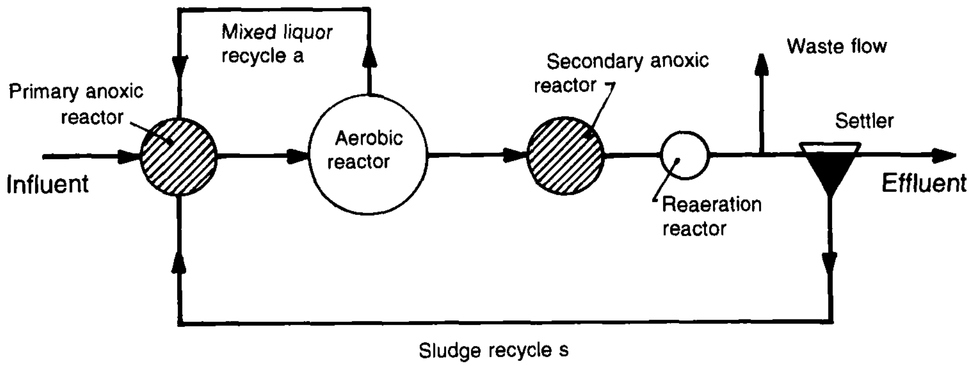
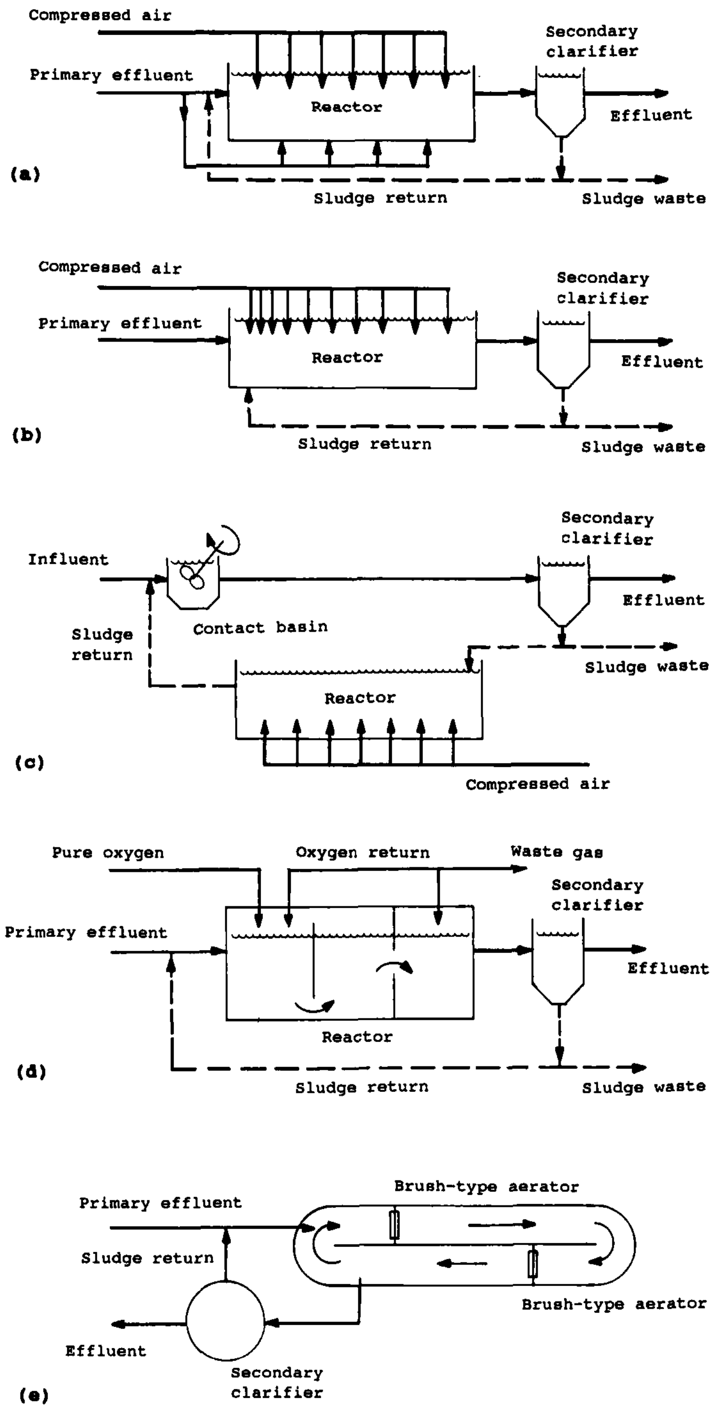


Figure 6.6 The Bardenpho process.

and mean cell residence times are equal. Such systems commonly have mean cell residence values of 1 to 5 days and may achieve nitrification at higher values under appropriate conditions, such as during summer. It is unlikely that aerated lagoons would be used where nitrification is required at low temperatures because of the large reactor volume required. One advantage of these lagoons, where they are designed to nitrify, is that their large volume serves to dilute the incoming waste water, thus reducing the impact of shock loads on nitrifier growth rate. With the exception of this reduced impact of transient loads, the design relationships developed for the complete mixed activated sludge process are directly applicable to the aerated lagoons.

Extended aeration operates at very high mean cell residence values and low organic loading rates such that nitrification is assured under all conditions. Contact stabilization differs from the flow sheet of the other processes in that it consists of two aeration stages. The first is a contact tank at short detention times of 2 to 3 hours, after which the sludge is separated from the effluent and returned to a second aeration tank (stabilization tank) with 4 to 6 hours of detention time. The short detention time in the contact tank limits the nitrification performance of this system (Gujer and Jenkins 1974).


Compressed air
Primary effluent
Reactor
Secondary clarifier
Effluent
Sludge return
Sludge waste
(a)
Compressed air
Primary effluent
Reactor
Secondary clarifier
Effluent
Sludge return
Sludge waste
(b)
Influent
Contact basin
Sludge return
Secondary clarifier
Effluent
Sludge waste
Reactor
Compressed air
(c)
Pure oxygen
Oxygen return
Waste gas
Primary effluent
Secondary clarifier
Effluent
Reactor
Sludge return
Sludge waste
(d)
Primary effluent
Brush-type aerator
Sludge return
Brush-type aerator
Effluent
Secondary clarifier
(e)

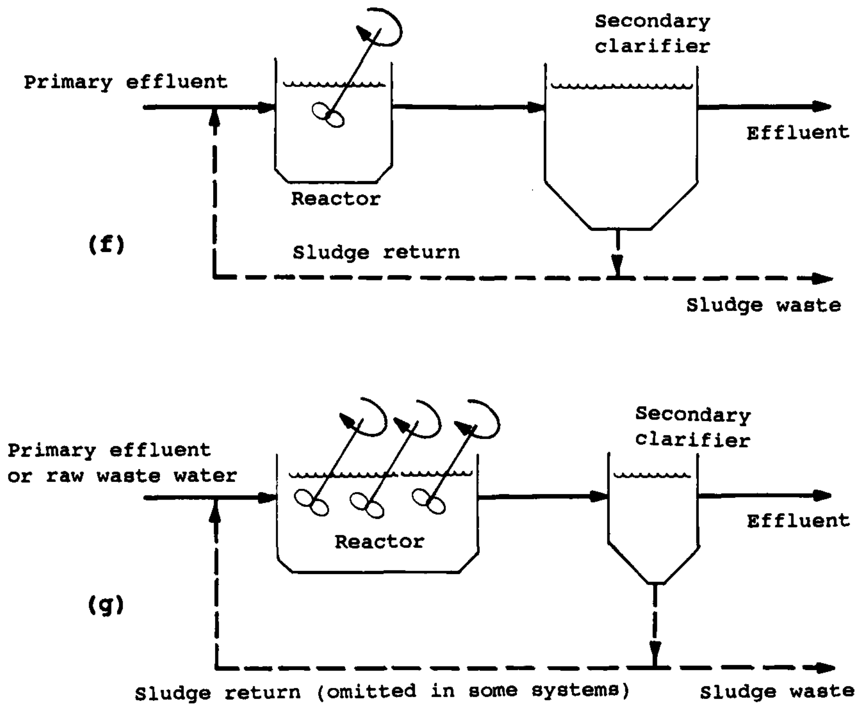


Figure 6.7. Overview of common applications of the activated-sludge process. (a) step aeration; influent addition: influent addition at intermidate points provides more uniform removal throughout the tank. (b) Tapered aeration: air added in proportion to nutrient exerted. (c) Contact stabilization: biomass adsorbs organics in contact basin and settles out in secondary clarifier; the thickened sludge is aerated before being returned to the contact basin. (d) Pure-oxygen activated sludge: oxygen added under presurre keeps dissolved oxygen level high. (e) Oxidation ditch, plan view. (f) High rate: short detention time and high food/mass ratio in aerator to maintain culture in log-growth phase. (g) Extended aeration: long detention time and low food/mass ratio to maintain culture in endogeneos phase.

This limited efficiency makes contact stabilization less attractive as a design alternative for nitrification.

6.4 The Kinetics of the Activated Sludge Process

The kinetics of the nitrification process are well-defined for the suspended-growth systems. From experience, it has been found that the following factors have a significant effect on the kinetics of the nitrification process.

1) Ammonia and nitrite concentration, 2) COD/total N ratio, 3) Dissolved-oxygen concentration, 4) Temperature and 5) pH.

The impact of these variables on the nitrification and denitrification processes and the approach developed to account for them are reported in Chapters 3 and 4. Table 6.2 shows typical kinetic coefficients for the activated-sludge nitrification process. The kinetic expression used for analysis of suspended-growth nitrification and denitrification are summarized in Table 6.3.

6.5 Modification of Activated Sludge Plants for Biological Nitrogen Removal

Today´s high standards for nitrogen removal from waste water often demand modification of existing plants. The approache necessary to convert an existing waste water treatment plant to a biological nitrogen removal plant is dependent on the site conditions and on the level of treatment required.

For existing systems that accomplish only removal of organic material, a higher solid retention time will have to be provided for nitrification to occur. This can be done by increasing the size of the aeration tank and/or the sludge concentration. This will need a greater quantity of oxygen.

If the system is already designed for nitrification, additional volume may be required to provide anoxic zones for denitrification. The anoxic volume in an activated sludge nitrification-denitrification system may account for 20 to 40% of the total tank volume. If denitrification is required the oxygen supply must be reduced.

A number of activated-sludge designs have been developed for the combined removal of nitrogen and phosphorus. Some of these processes were developed originally for phosphorus removal and later developed into combined phosphorus and nitrogen removal systems.

Table 6.2 Typical coefficient for the different parameters in the nitrifying activated sludge process.

Coefficient	*Unit*	*Value*	
		Range	*Typical*
		Reported at 20 ° C	
Nitrosomonas			
μm	d^{-1}	0,3 - 2,0	0,7
K_s	NH_4^+-N mg/l	0,2 - 2,0	0,6
Nitrobacter			
μ_{max}	d^{-1}	0,4 - 3,0	1,0
K_s	NN_4^--N mg/l	0,2 - 5,0	1,4
Overall			
μ_{max}	d^{-1}	0,3 - 3,0	1,0
K_s	NH_4^+-N mg/l	0,2 - 5,0	1,4
Y	NH_4^+-N mg VSS/mg	0,1 - 0,3	0,2
K_d	d^-	0,03 - 0,06	0,05

After: Schroeder (1976); EPA (1975) and Eddy and Metcalf (1991).

The most commonly used processes for combined nitrogen and phosphorus removal are: 1) the A^2/O process (Hong *et al.*1984), 2) the five-stage Bardenpho process, 3) the UCT process and 4) the VIP process. They are all described in Metcalf and Eddy (1991). Stensel *et al.* showed in Table 6.4 the nitrification rate obtained, based on both total MLVSS and on calculated *Nitrosomonas* biomass for the biological nutrient removal (BNR) and the conventional activated sludge process.

Table 6.3 Summary of kinetic expressions used for the analysis of activated-sludge nitrification and denitrification. See also Chapters 3 and 4.

Equation	*Definition of terms*
$\mu = \mu_{max} \frac{S}{K_S + S}$	μ = specific growth rate, time^{-1}
$\frac{ds}{dt} = - \frac{\mu_{max} X \cdot S}{Y (K_s + S)}$	ds/dt = substrate utilzation rate, mass/unit volume.
	S = concentration of growth limiting substrate in solution, mass/unit volume.
	Y = maximum yield coefficient, mass of cell formed per mass of substrate consumed.
	K_s = maximum rate of substrate utilization.
$k = \frac{\mu_{max}}{Y}$	k = maximum rate of substrate utilizaion.
$\frac{1}{\phi_2} = YU - kd$	ϕ = hydraulic detention time, time.
	ϕ_c = design mean cell-residence time, time.
	U = substrate utilization rate, time^{-1}.
$\frac{1}{\phi_c^m} = Yk - kd$	ϕ_c^m = minimum mean cell-residence time.
$SF = \frac{\phi_c}{\phi_c^m}$	SF = safety factor
$U = \frac{S_o - S}{\phi \cdot X}$	S_o = influent substrate concentration mass/unit volume.
	X = conc. of microorganisms.

Table 6.4 Summary of specific Nitrification Rates and Ammonia Oxidation Rates in tbe biological nutrient removal process (BNR) and the conventional activated sludge process.

System	SRT d	Aerobic SRT d	T °C	Total NH_3-N Oxidized mg/l	Aerobic MLVSS mg/l	Specific Nitrification Rate mgN/gMLVSS/h	Nitrosomonas VSS mg/l	Ammonia Oxidation rate mgN/mg Nitrosomonas, d
BNR	15	8.3	20	18.8	2636	1.783	122	0.834
	5	2.7	20	23.2	1014	5.720	74	1.729
	2.7	1.5	20	21.6	749	7.210	42	2.695
	1.5	0.9	20	12.3	446	6.895	14	4.382
Conventional	15	15	20	21.2	1348	1.986	101	0.631
	15	15	15	26.6	2177	1.527	143	0.560
	5	5	20	26.5	1284	2.580	72	1.107
	2.7	2.7	20	27.1	658	5.148	47	1.716

Source: Stensel *et al.* (1992)

6.6 Modelling the Activated Sludge Process

A mathematical model, Activated Sludge Model No. 1, for the removal of carbonaceous biodegradable material, nitrification and denitrification was developed by the IAWPRC Task Group (Henze *et al.* 1987) and modified by Wentzel *et al.* (1991) and Dold (1991).

A total of ten dissolved and seven particulate components are used to characterize the wastewater and the activated sludge. These include:

1) Dissolved oxygen, bicarbonate alkalinity, and soluble phosphorus.

2) Three forms of biomass (Heterotrophs and two types of autotrophs, all represented in terms of COD)

3) Five forms of nitrogen (particulate and soluble biodegradable organic nitrogen, ammonia, nitrite and nitrate).

4) Six forms of COD (inert soluble and particulate in feed, two forms of biodegradable soluble, enmeshed slowly degradable particulate, and inert particulate COD from endogenous decay).

For a detailed overwiev of the formula matrix the authors recommend consulting the Activated Sludge Model No 1. (Henze *et al.* 1987), because the most recent attempts at modelling the activated sludge have been made with this model.

6.7 Advantages and Disadvantages of the Separate and Combined Activated Sludge Process

The following gives an overview of some of the advantages and disadvantages of the activated sludge process, both as A) a separate stage process and B) as a combined stage process.

A) Separate stage activated sludge process for nitrification.

Advantages:

1) Good protection against most toxicants.

2) Stable operation.

3) Low effluent ammonia concentration possible.

Disadvantages:

1) Sludge inventory requires careful control when BOD_5/TKN ratio is low.

2) Stability of operation linked to operation of secondary clarifier for biomass return.

3) Greater number of unit processes required than for the combined oxidation and nitrification unit.

B) Combined carbon oxidation and nitrification activated sludge process for nitrification.

Advantages:

1) Combined treatment of carbon and ammonia in a single stage.

2) Low effluent ammonia is possible.

3) Inventory control of mixed-liquor sample due to high BOD_5/TKN ratio.

Disadvantages:

1) No protection against toxicants.

2) Only moderate stability of operation.

3) Stability linked to operation of secondary clarifier for biomass return.

4) Large reactors required in cold weather.