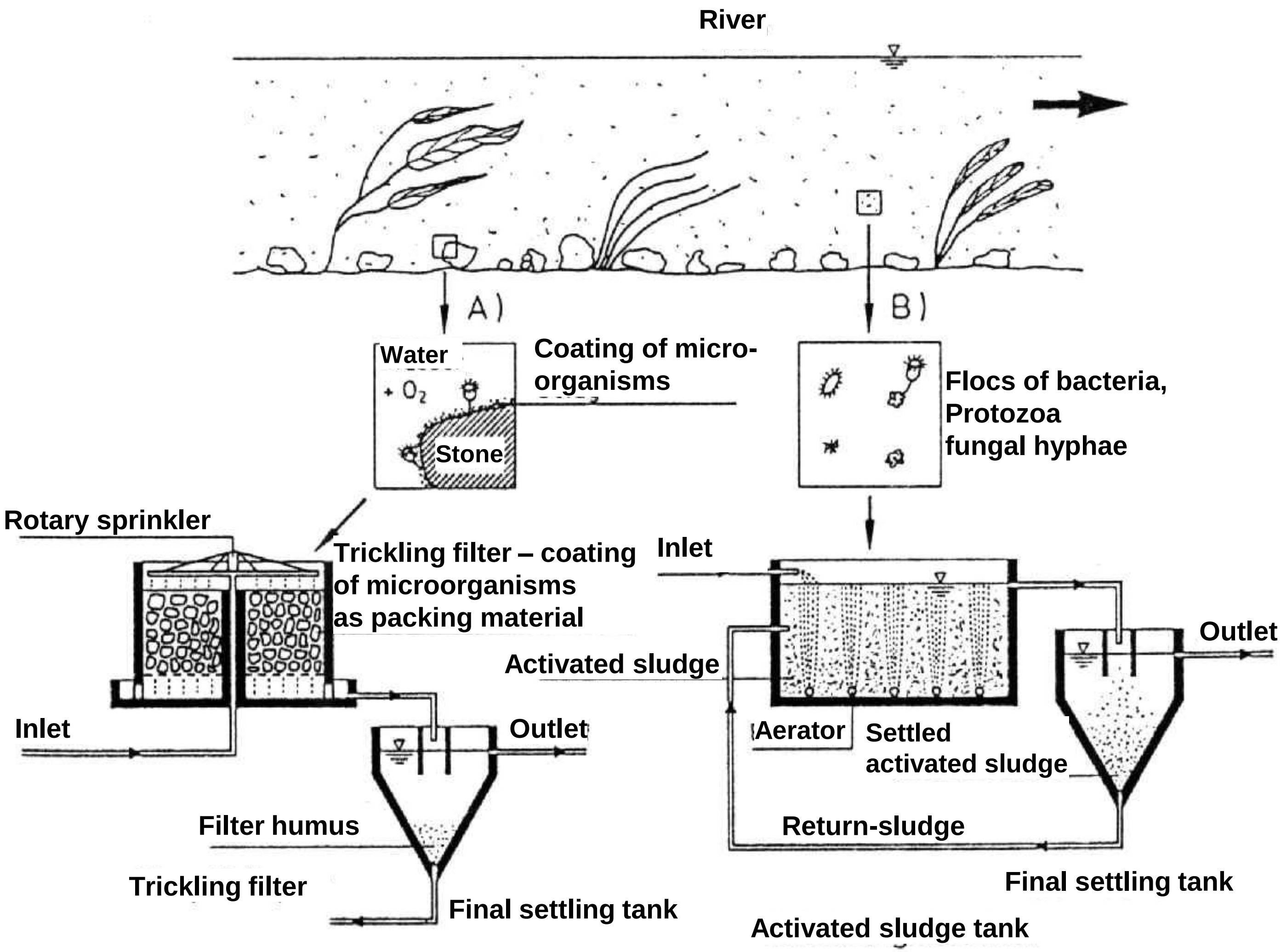
Lecture 15 and 16

Biological Treatment

Part 15:

Fundamentals of Biological Wastewater Treatment

Transfer of self-purification into technical process



River

A)

B)

Water

Stone

Coating of micro-organisms

Flocs of bacteria, Protozoa fungal hyphae

Rotary sprinkler

Trickling filter – coating of microorganisms as packing material

Inlet

Outlet

Filter humus

Trickling filter

Final settling tank

Inlet

Activated sludge

Outlet

Aerator

Settled activated sludge

Return-sludge

Final settling tank

Activated sludge tank

Aerobic processes

Biochemical microbial degradation with enough oxygen:

- **Degradation of organic substances**
  org. substances + O_2 → $CO_2 + H_2O$
- **Nitrification**
  $NH_4 + O_2 \rightarrow NO_3 + H_2O$
- **Sulfur oxidation**
  $H_2S + O_2 \rightarrow H_2SO_4 + H_2O$

Anoxic processes

Biochemical microbial degradation with bound oxygen:

- **Denitrification**
  org. substances + NO_3 → $CO_2 + N_2 + H_2O$

- **Desulfurication**
  org. substances + H_2SO_4 → $CO_2 + H_2S + H_2O$

Anaerobic processes (fermentation, digestion)

Biochemical microbial degradation by microorganisms under nitrate-reducing and sulphate-reducing conditions.

- **Acid fermentation**
  org. substances → CO_2 + org. acids
- **Methane fermentation**
  org. substances → $CH_4 + CO_2$

Requirements to increase the degradation performance of small-scale processes

1. The density of microorganisms (concentration of biomass) in the reactor has to be increased.

2. The higher demand of oxygen has to be covered.

3. The optimal contact between biomass, organics and dissolved oxygen has to be guaranteed.

4. Inhibiting substance or toxic substance have not be exceeded a certain maximum permissible concentration.

Degradability of organic substances

- Organic substances with a simple molecule structure, like e.g. sugar, starch, organic acids etc. are **easily and fast degradable.**

- Organic substances which are long-living and stable by nature e.g. because they are produced to protect living organisms, like wax or chitin are **more difficult to degrade.**

- A lot of organic substances which are produced by people and constructed to last very long, like e.g. nylon or toxins which should provide special characteristics are **not or only very slowly degradable.**

Chemical compound of bacteria

Carbon (C)	ca. 50 - 55 %
Hydrogen (H)	ca. 10 %
Oxygen (O)	ca. 20 - 25 %
Nitrogen (N)	ca. 10 - 15 %
Phosphorus (P)	ca. 2 - 6 %

The rest are sulfur and trace elements.

As a chemical empirical formula **$C_5 H_7 O_2 N$** is often used

Carbon and energy source of different bacteria types

Bacteria	**Carbon source**	**Energy source**
Heterotrophic bacteria	Organic carbon, e.g. BOD	Oxidation of organic compounds (e.g. BOD) by different oxidising agents (e.g. O_2, NO_3)
Autotrophic bacteria	Inorganic carbon, e.g. CO_2	Oxidation of inorganic compounds (e.g. NH_4) with oxygen as oxidising agent

Metabolism of bacteria

1. Basic respiration, endogenous respiration

Bacteria decompose intercalary reserves, their body-matter to gain energy.

2. Substrate respiration

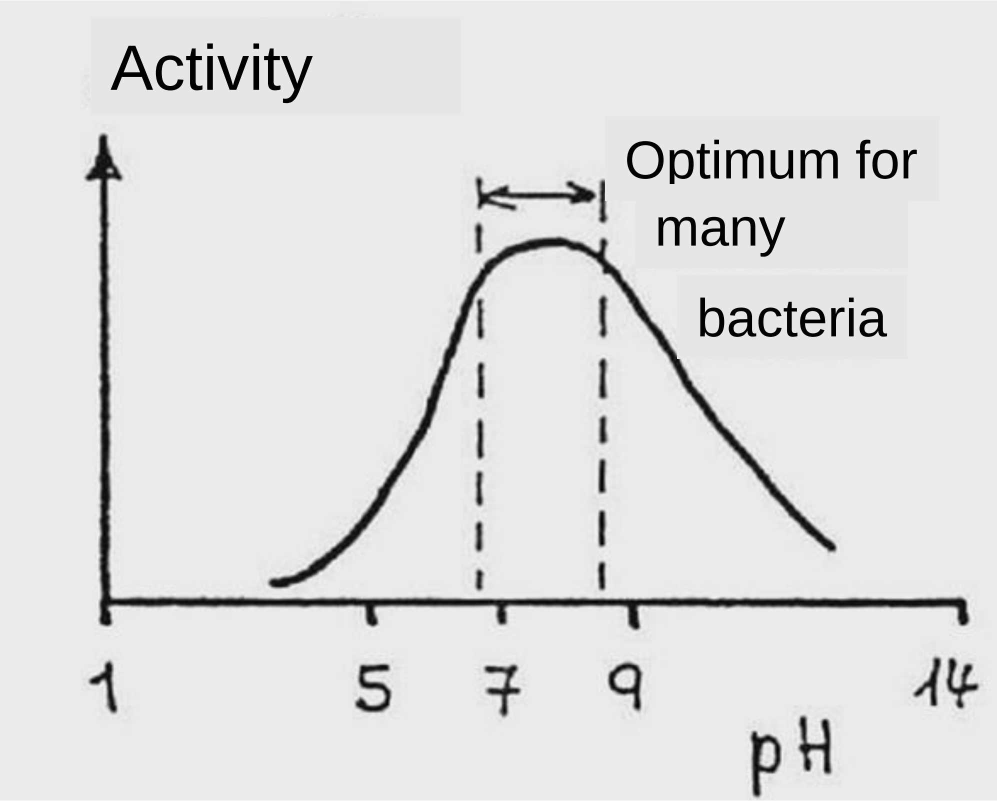
Bacteria decompose organic and inorganic contaminants to gain energy.

3. Growth of bacteria

The required carbon, nitrogen, phosphorus etc. is obtained by the organic pollution, the necessary energy by the operating metabolism.

Influence of the pH-value

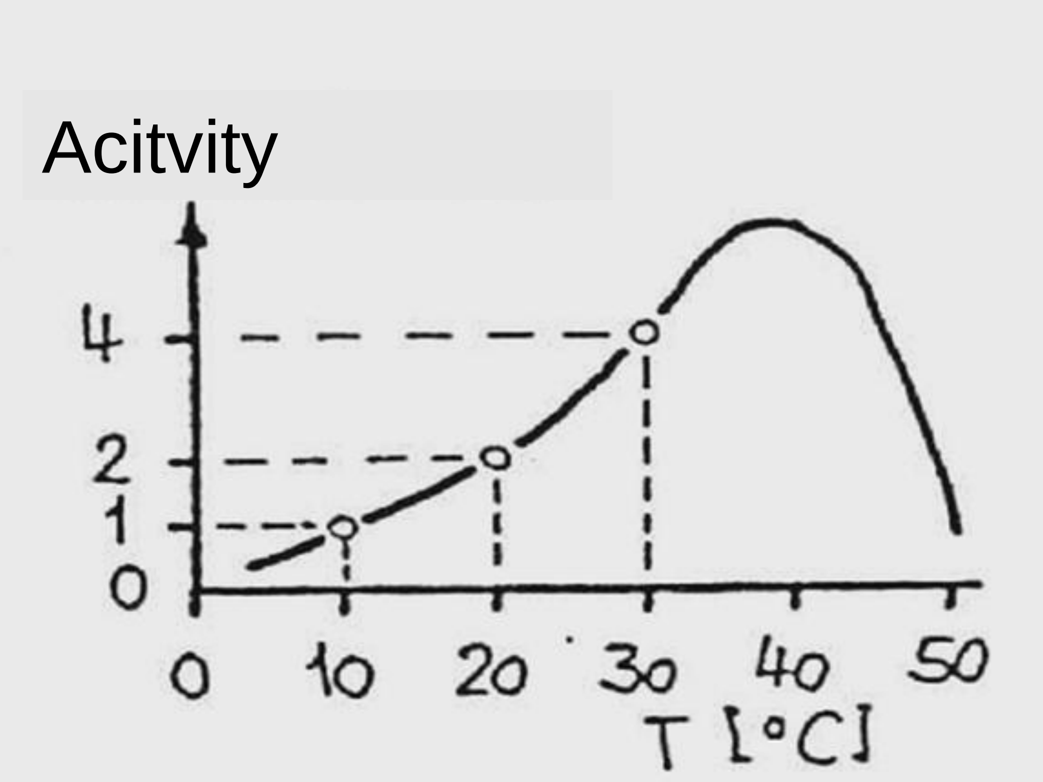
pH-value (optimum mostly between 7 and 7,5)



Source: Kayser, Kommentar zum ATV/DVWK – Regelwerk „Bemessung von Belebungs- und SBR-Anlagen“, Gesellschaft zur Förderung der Abwassertechnik e.V. (GFA), 2001

Influence of temperature T

Psychrophilic bacteria (10 - 30 ºC)
Mesophilic bacteria (20 - 50 ºC)
Thermophilic bacteria (35 - 75 ºC)



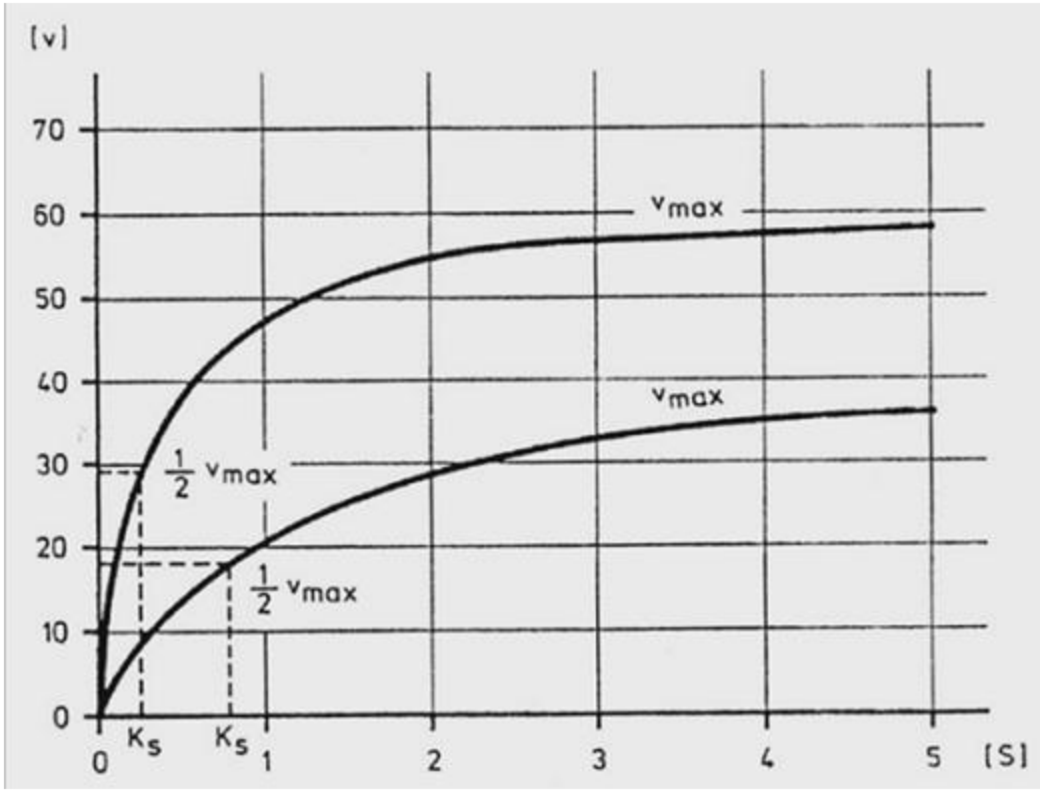
Source: Kayser, Kommentar zum ATV/DVWK – Regelwerk „Bemessung von Belebungs- und SBR-Anlagen“, Gesellschaft zur Förderung der Abwassertechnik e.V. (GFA), 2001

Influence of substrate concentration

Substrate: organic and inorganic nutrition for microorganisms in the wastewater treatment

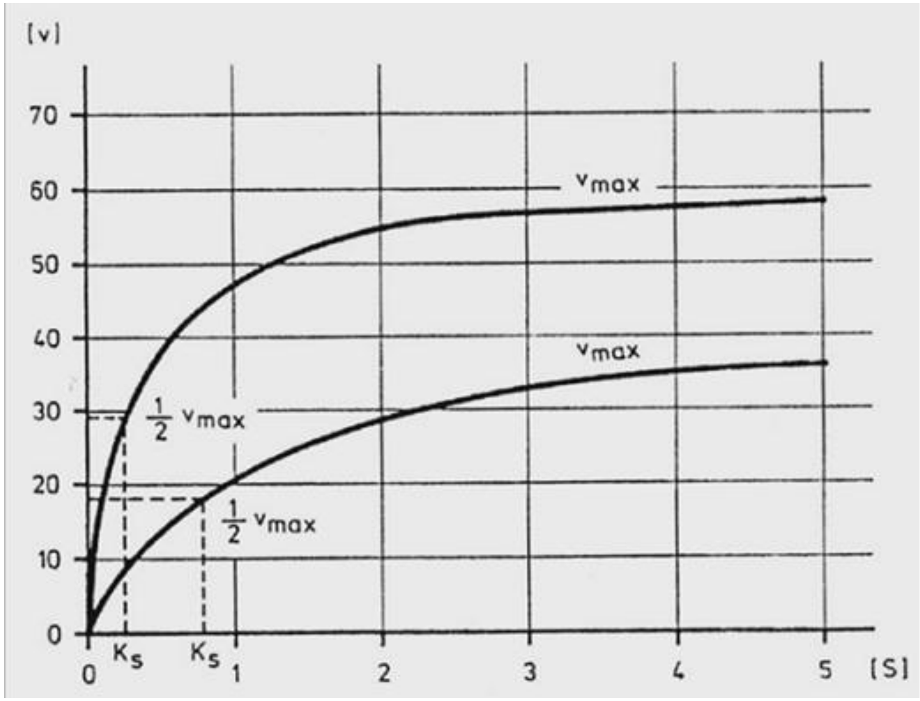
Michaelis-Menten relationship: Relationship between substrate concentration and rate of turnover

Michaelis-Menten relationship between two organism types



Michaelis-Menten relationship

$$v = v_{max} \cdot \frac{S}{K_m + S}$$



v = Reaction rate [e.g. g substrate / (g bacteria · h)]

v_{max} = maximum rate of metabolism

S = Substrate concentration [g/m³]

K_m = Substrate concentration at which the reaction rate is at half-maximum, also called auch Michaelis-Menten constant [g/m³]

Monod relationship

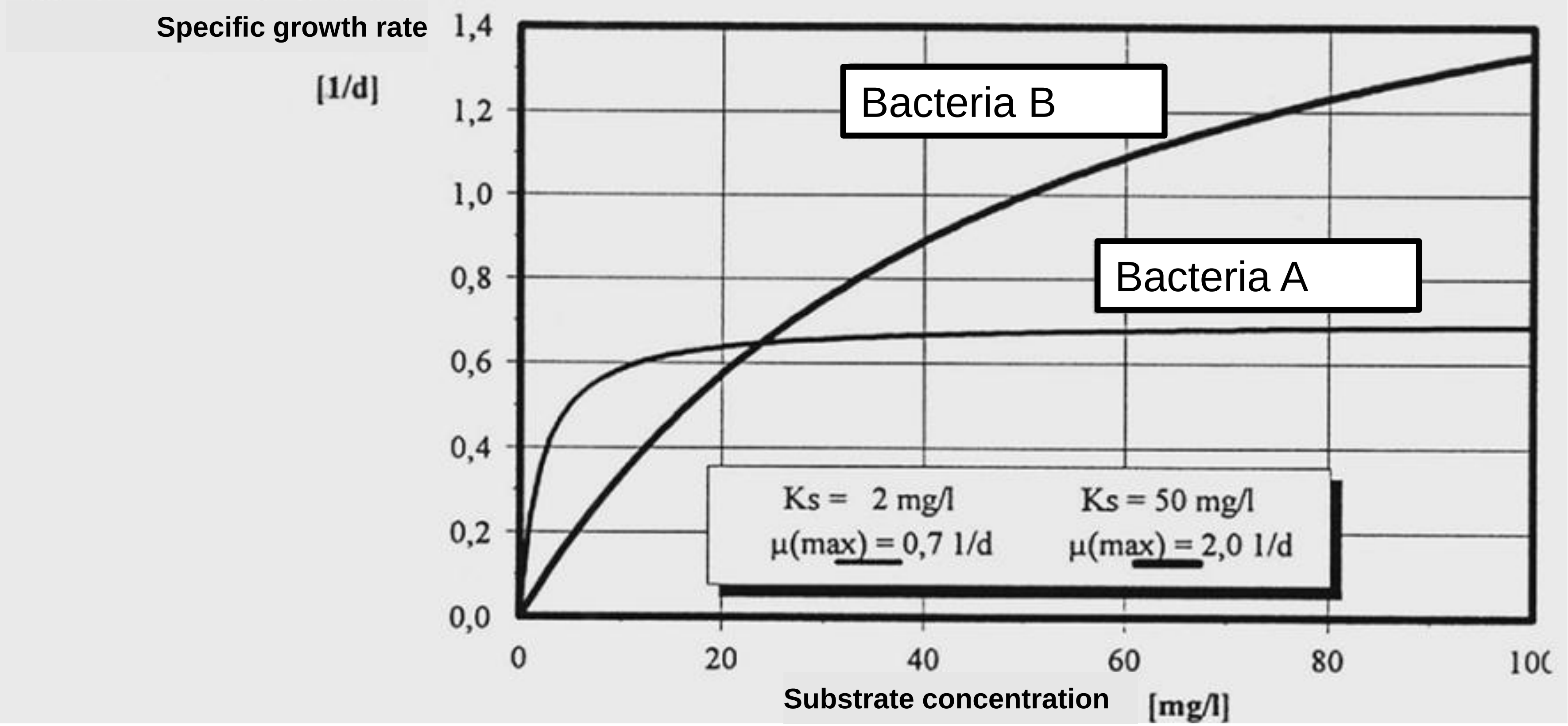
Monod relationship: Relationship between substrate concentration and specific growth rate

$$\mu = \mu_{max} \cdot \frac{S}{K_S + S}$$

μ	= Specific bacteria growth rate coefficient [1/d]
μ_{max}	= Maximum growth rate coefficient
S	= Substrate concentration [g/m³]
K_S	= Monod coefficient that corresponds to the concentration at which μ is one-half of its maximum [g/m³]

Monod relationship between two bacteria types

$$\mu = \mu_{max} \cdot \frac{S}{K_S + S}$$



Yield coefficient Y

The Yield coefficient Y declares the amount of new bacteria that is build during the degradation of 1 g of substrate.

Production of new bio-mass:

- during heterotrophic bacteria degradation of BOD:

60 g BOD/(I*d) * 0.6 = 36 g of bacteria per inhabitant and day

- nitrobacteria that oxidize ammonia into nitrites

11 g N/(I*d) * 0.16 = 1.76 g of bacteria per inhabitant and day

- ➢ Nitrobacteria are much more sensitive than heterotrophic bacteria.
- ➢ Nitrobacteria gain lower energy than heterotrophic bacteria.
- ➢ Nitrobacteria are highly temperature sensitive.
- ➢ The reproduction of nitrobacteria is very slow and in activated sludge tanks their maximum productivity is nearly reached.

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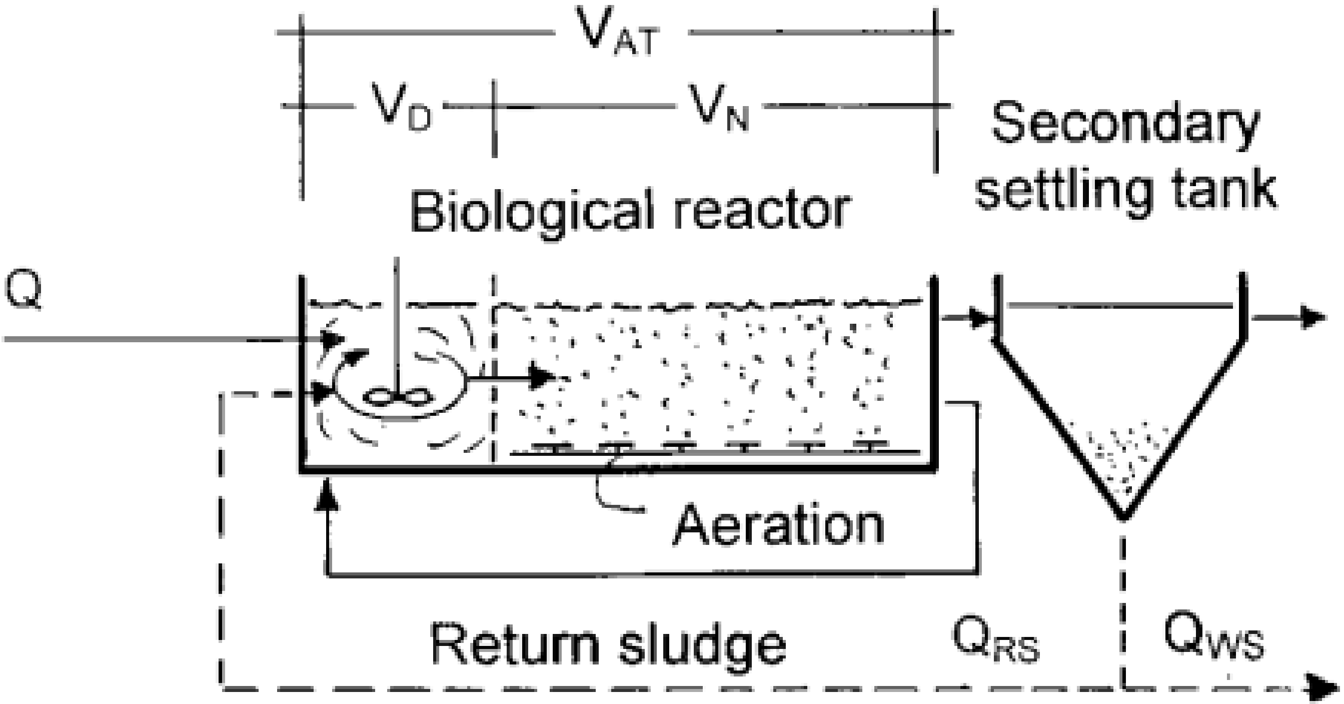
Biological Treatment

Part 16:

Activated Sludge Process and Technology

Flow diagramm of the activated sludge process



V_{AT}: Volume of the biological reactor / aeration tank [m³]
V_D: Volume of the biological reactor used for denitrification [m³]
V_N: Volume of the biological reactor used for nitrification [m³]
Q_{RS}: Return (activated) sludge flow rate [m³/h]
Q_{WS}: Waste (activated) sludge flow rate [m³/d]

ATV-A 131

Activated sludge tank

1. Activated sludge tank

- The biological degradation and modification of organic and inorganic contaminants takes place in the activated sludge tank.
- The treatment of the wastewater by the activated sludge process with regard to process technology places the following requirements on the biological reactor (aeration tank):
  - sufficient enrichment of the biomass
  - sufficient oxygen transfer to cover the oxygen uptake and its control to match the different operating and loading conditions
  - sufficiently mixing in order to prevent a permanent settling of sludge on the tank bottom

Secondary settling tank

2. Secondary settling tank

- Secondary settling tanks have the main task of separating the activated sludge from the biologically treated wastewater.
- Dimensioning, design and equipping of secondary settling tanks must be carried out that the following tasks can be met:
    - separation of the activated sludge from treated wastewater by settling;
    - thickening and removal of the settled activated sludge for recirculation to the biological reactor (aeration tank);
    - intermediate storage of activated sludge which, as a result of increased inflow rates at storm water periods, is expelled from the aeration tank.

Return sludge pipe and excess sludge

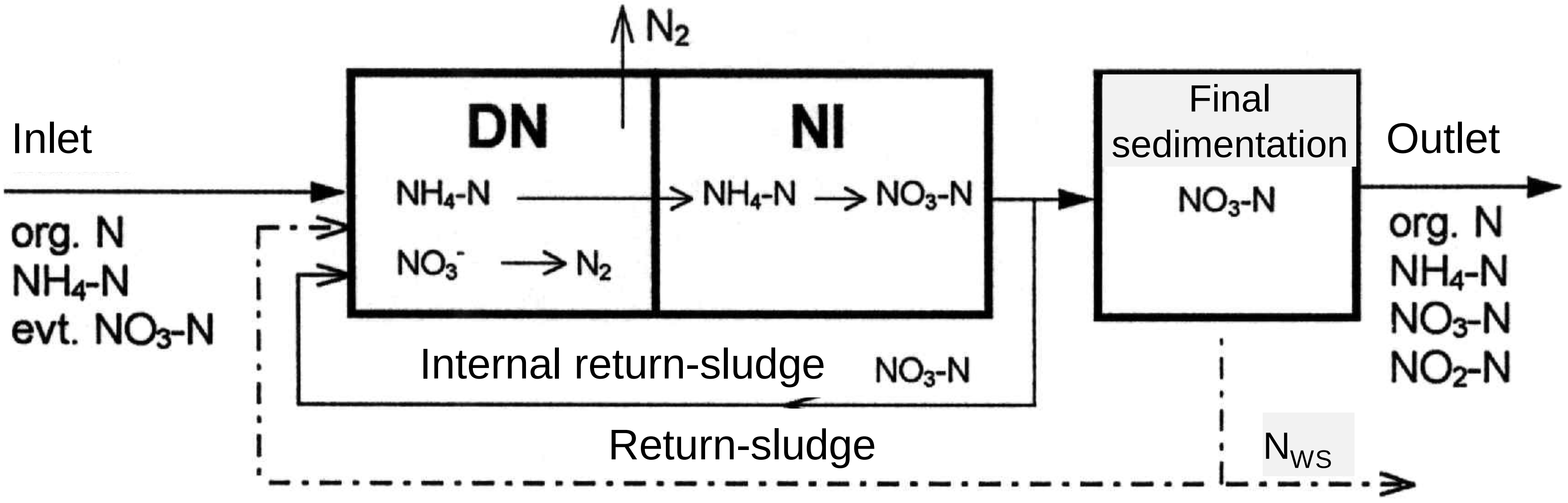
3. Return-sludge pipe

- The return-sludge pipe recycle activated sludge, which was concentrated in the secondary settling tank, into the activated sludge tank.

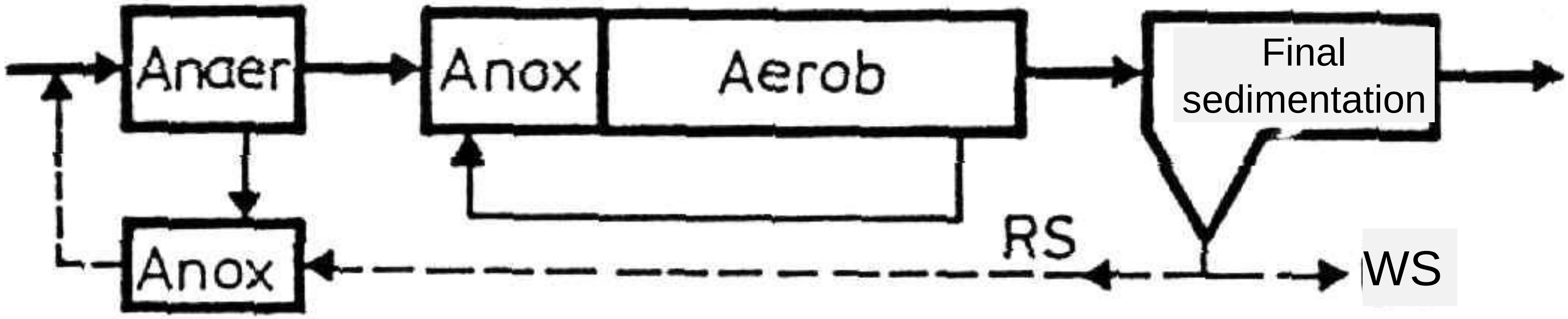
4. Excess sludge (surplus sludge, waste sludge)

- The degrading microorganisms gain energy from contaminates and by reproducing. To ensure a constant content of microorganisms in the system, it is necessary to remove new build microorganisms also called excess sludge (waste sludge or surplus sludge).

Activation plant with pre-denitrification

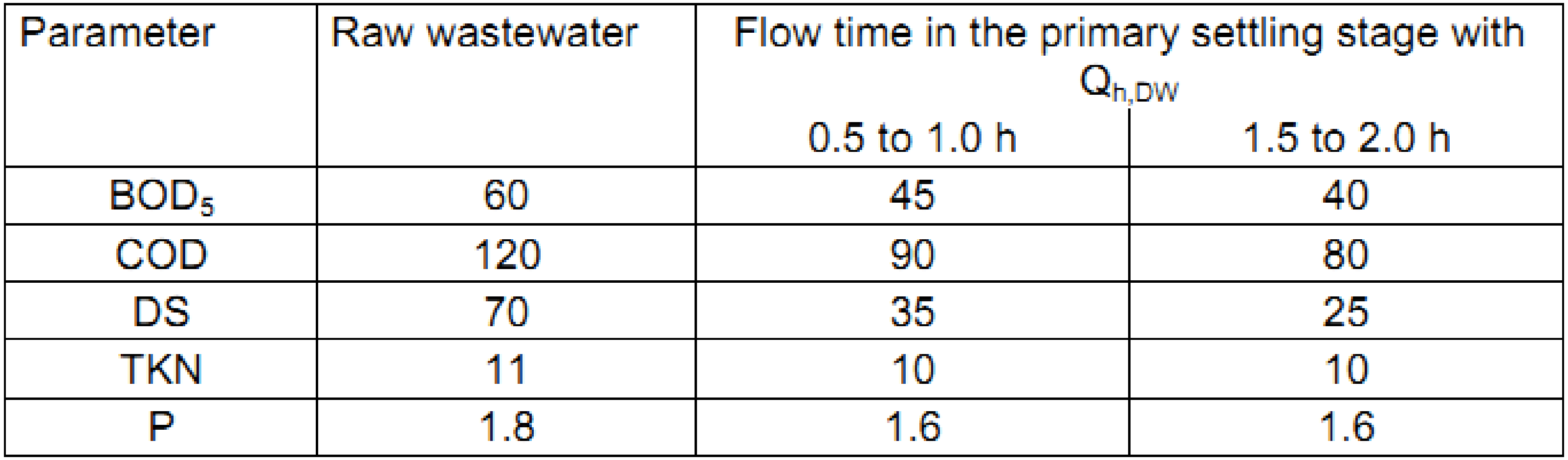


Activation plant with biological P-elimination



Inhabitant-specific loads in g/(I·d)

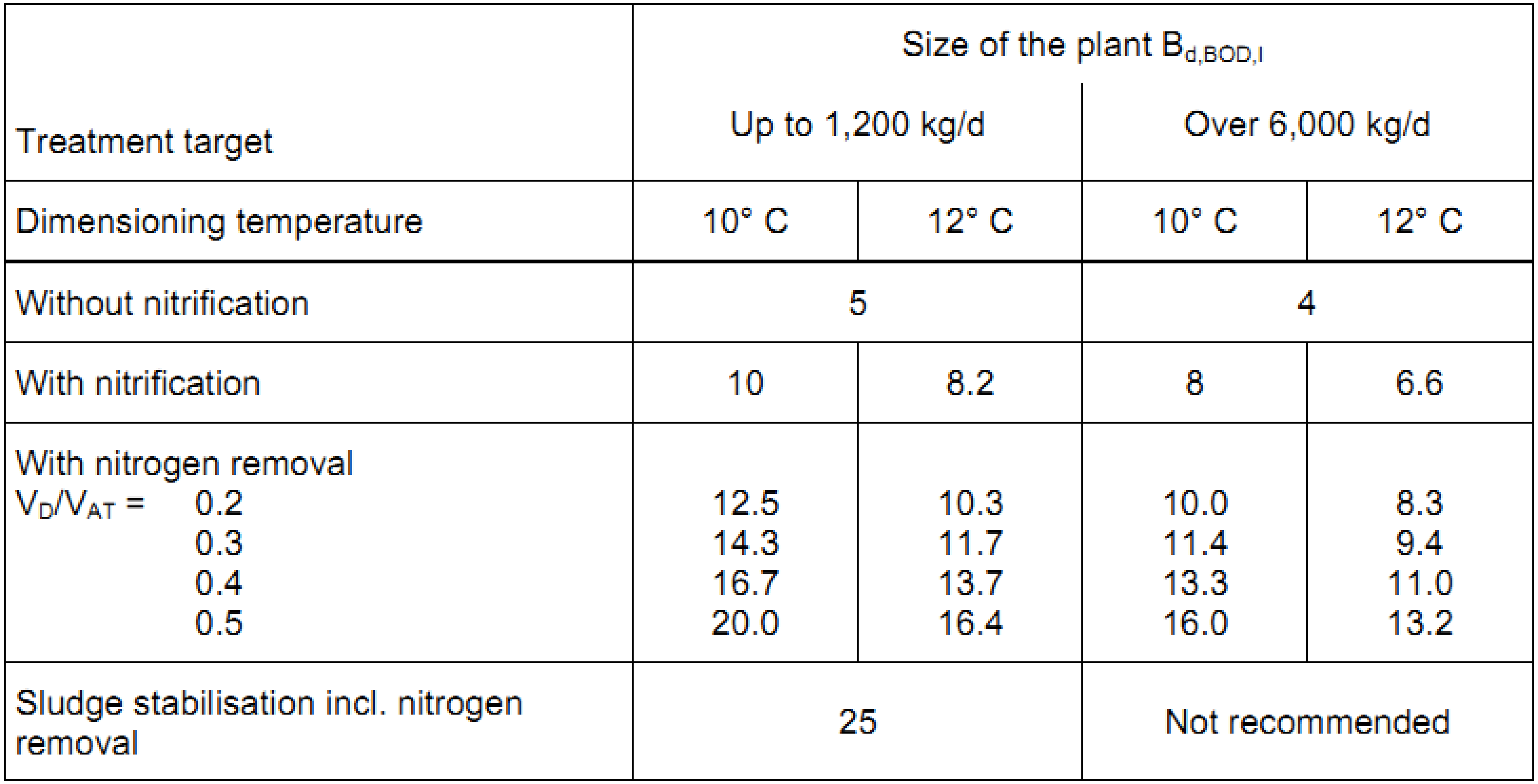
Inhabitant-specific loads in g/(I·d), which are undercut on 85 % of the days, without taking into account sludge liquor [ATV-A 131]



Parameter	Raw wastewater	Flow time in the primary settling stage with $Q_{h,DW}$	
		0.5 to 1.0 h	1.5 to 2.0 h
BOD_5	60	45	40
COD	120	90	80
DS	70	35	25
TKN	11	10	10
P	1.8	1.6	1.6

Dimensioning sludge age

Dimensioning sludge age in days dependent on the treatment target and the temperature as well as the plant size (intermediate values are to be estimated)



Treatment target	Size of the plant $B_{d,BOD,I}$			
	Up to 1,200 kg/d		Over 6,000 kg/d	
Dimensioning temperature	10° C	12° C	10° C	12° C
Without nitrification	5		4	
With nitrification	10	8.2	8	6.6
With nitrogen removal V_D/V_{AT} = 0.2 0.3 0.4 0.5	 12.5 14.3 16.7 20.0	 10.3 11.7 13.7 16.4	 10.0 11.4 13.3 16.0	 8.3 9.4 11.0 13.2
Sludge stabilisation incl. nitrogen removal	25		Not recommended	

Determination of the sludge production

The sludge produced in an activated sludge plant is made up of organic matter resulting from degradation and stored solid matter as well as sludge resulting from phosphorus removal:

$$SP_d = SP_{d,C} + SP_{d,P} \qquad [\text{kg/d}]$$

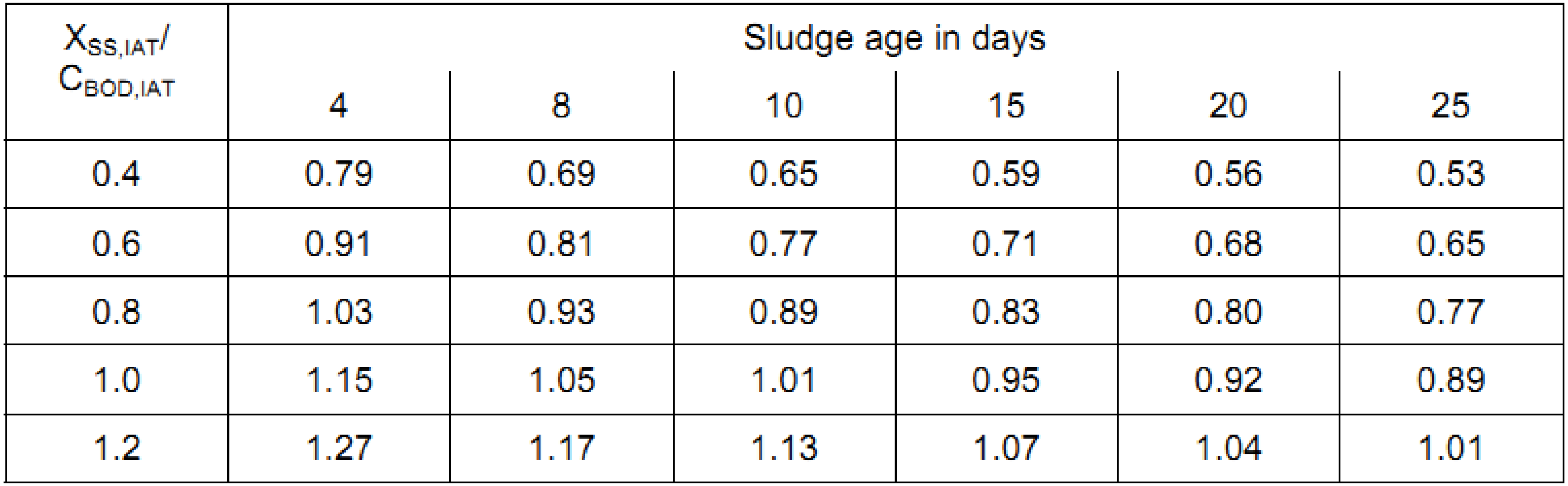
The relationship of sludge production and sludge age can be written as follows:

$$t_{SS} = \frac{M_{SS,AT}}{SP_d} = \frac{V_{AT} \cdot SS_{AT}}{SP_d} = \frac{V_{AT} \cdot SS_{AT}}{Q_{WS,d} \cdot SS_{WS} + Q_d \cdot X_{SS,EST}} \qquad [\text{d}]$$

with:

t_{SS} = Sludge age referred to V_{AT} [d]
SS_{AT} = Suspended solids concentration in the aeration reactor [kg/m³]
V_{AT} = Volume of the aeration tank [m³]
SP_d = Daily waste activated sludge production (solids) [kg/d]
$Q_{WS,d} \cdot SS_{WS}$ = Daily waste (activated) sludge
$Q_d \cdot X_{SS,EST}$ = Load of filterable matter in the effluent of the secondary settling tank

Specific sludge production $SP_{C,BOD}$ [kg SS/kg BOD_5] at 10º to 12 ºC



$X_{SS,IAT}$/ $C_{BOD,IAT}$	Sludge age in days					
	4	8	10	15	20	25
0.4	0.79	0.69	0.65	0.59	0.56	0.53
0.6	0.91	0.81	0.77	0.71	0.68	0.65
0.8	1.03	0.93	0.89	0.83	0.80	0.77
1.0	1.15	1.05	1.01	0.95	0.92	0.89
1.2	1.27	1.17	1.13	1.07	1.04	1.01

With: $X_{SS,IAT}$ = Filterable solids (0.45 µm membrane filter)

Oxygen demand

1. The oxygen demand for consumption for carbon removal (including the endogenous respiration)

   “Daily oxygen uptake for carbon removal” $OU_{d,C}$ [kg O_2/d]

2. Daily oxygen uptake for nitrification **$OU_{d,N}$ [kg O_2/d]**

3. Daily oxygen uptake for carbon removal which is covered by denitrification **$OU_{d,D}$ [kg O_2/d]**

Oxygen demand: Carbon removal

$$OU_{d,C} = B_{d,BOD} \cdot \left(0.56 + \frac{0.15 \cdot t_{SS} \cdot F_T}{1 + 0.17 \cdot t_{SS} \cdot F_T}\right) \qquad [\mathrm{kg}\ O_2/\mathrm{d}]$$

with:

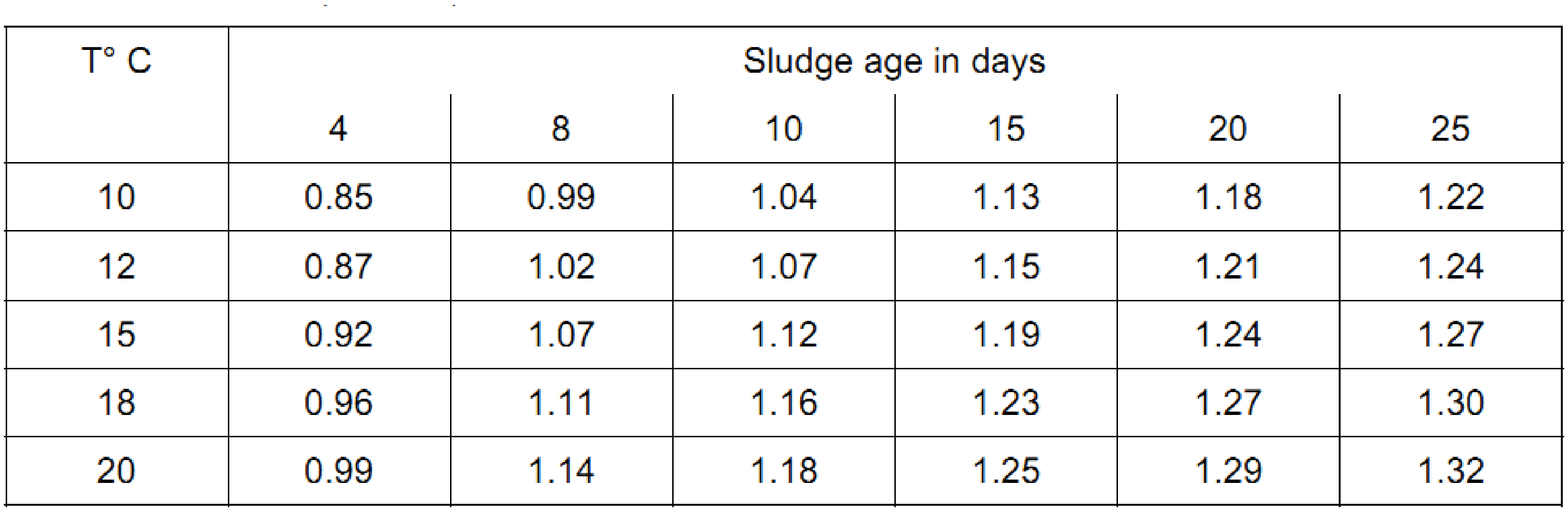
$B_{d,BOD}$ = Daily BOD_5 load [kg/d]

t_{SS} = Sludge age referred to V_{AT} [d]

F_T = Temperature factor for endogenous respiration [-]

Oxygen demand: Carbon removal

Specific oxygen consumption $OU_{C,BOD}$ [kg O_2/kg BOD_5], valid for $C_{COD,IAT}/C_{BOD,IAT} \leq 2.2$



T° C	Sludge age in days					
	4	8	10	15	20	25
10	0.85	0.99	1.04	1.13	1.18	1.22
12	0.87	1.02	1.07	1.15	1.21	1.24
15	0.92	1.07	1.12	1.19	1.24	1.27
18	0.96	1.11	1.16	1.23	1.27	1.30
20	0.99	1.14	1.18	1.25	1.29	1.32

Oxygen consumption for nitrification

Nitrification: $NH_4^+ + 2\,O_2 \rightarrow NO_3^- + H_2O + 2\,H^+$ - 425 kJ/mol

For nitrification the oxygen consumption is assumed to be 4.3 kg O_2 per kg oxidised nitrogen taking into account the metabolism of the nitrificants:

$$OU_{d,N} = Q_d \cdot 4.3 \cdot (S_{NO3,D} - S_{NO3,IAT} + S_{NO3,EST})/1000 \qquad [\text{kg } O_2/\text{d}]$$

with:
$S_{NO3,D}$ = Concentration of nitrate nitrogen to be denitrified [mg/l]
$S_{NO3,iAT}$ = Influent nitrate nitrogen concentration [mg/l]
$S_{NO3,EST}$ = Effluent nitrate nitrogen concentration of the secondary settling tank [mg/l]

Oxygen consumption for denitrification

Denitrification: $2\ NO_3^- + 2\ H^+ \rightarrow N_2(\uparrow) + H_2O + 2{,}5\ O_2$

For denitrification one reckons for carbon removal with 2.9 kg O_2 per kg denitrified nitrate nitrogen:

$$OU_{d,D} = Q_d \cdot 2.9 \cdot S_{NO3,D} / 1000 \qquad [kg\ O_2/d]$$

Total oxygen demand: **4.3 – 2.9 = 1.4 [g O_2/g N]**

oxygen uptake rate for the daily peak

Carbon shock loading and mean nitrogen loading
or
mean carbon loading and **nitrogen shock loading**

$$OU_h = \frac{f_C \cdot (OU_{d,C} - OU_{d,D}) + f_N \cdot OU_{d,N}}{24} \qquad [\mathrm{kg}\ O_2/\mathrm{h}]$$

Peak factor f_C = Ratio of the oxygen uptake rate for carbon removal in the peak hour to the average daily oxygen uptake rate

Peak factor f_N = Ratio of the TKN load in the 2 h peak to the 24 h average load

Peak factors for the oxygen uptake rate

Peak factors for the oxygen uptake rate (to cover the 2 h peaks compared with the 24 h average, if no measurements are available)

	Sludge age in d					
	4	6	8	10	15	25
f_C	1.3	1.25	1.2	1.2	1.15	1.1
f_N for $B_{d,BOD,I} \leq 1200$ kg/d	-	-	-	2.5	2.0	1.5
f_N for $B_{d,BOD,I} > 6000$ kg/d			2.0	1.8	1.5	-

The necessary oxygen transfer for aerated tanks

$$req.\ \alpha OC = \frac{C_S}{C_S - C_X} \cdot OV_h \qquad [\mathrm{kg}\ O_2/h]$$

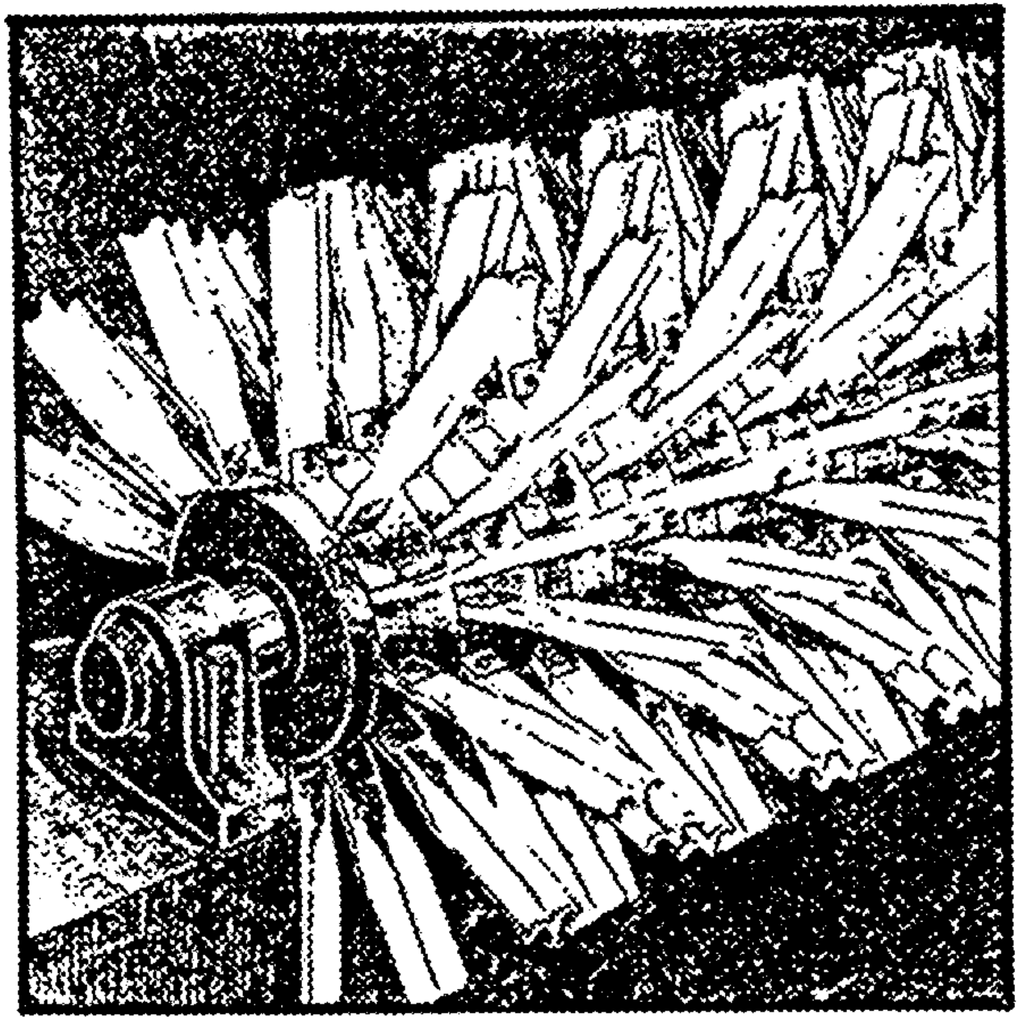
With:

C_S = Dissolved oxygen saturation concentration dependent on the temperature and partial pressure [mgO_2/l]

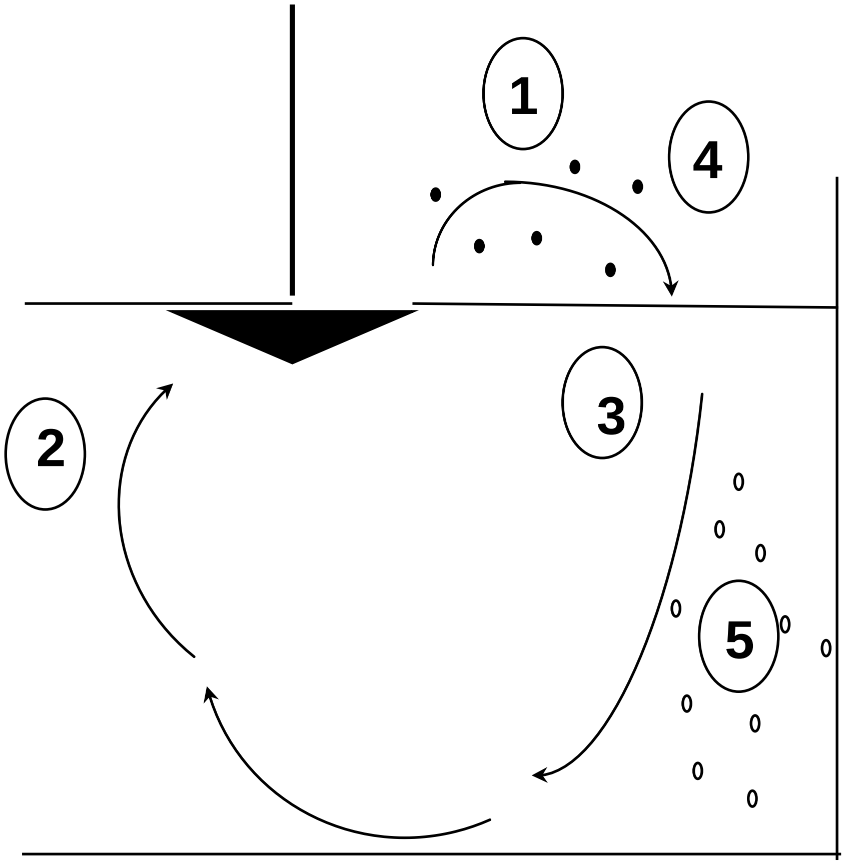
C_x = Dissolved oxygen concentration in aeration tanks (DO) [mgO_2/l]

$$OC_{operation} = \frac{24 * erf.\ \alpha\ OC}{\alpha} \qquad [\mathrm{kg}\ O_2/h]$$

Rotor aerator in a mammoth rotor



Feed mechanism in a surface aerator



① "Drop"-effect

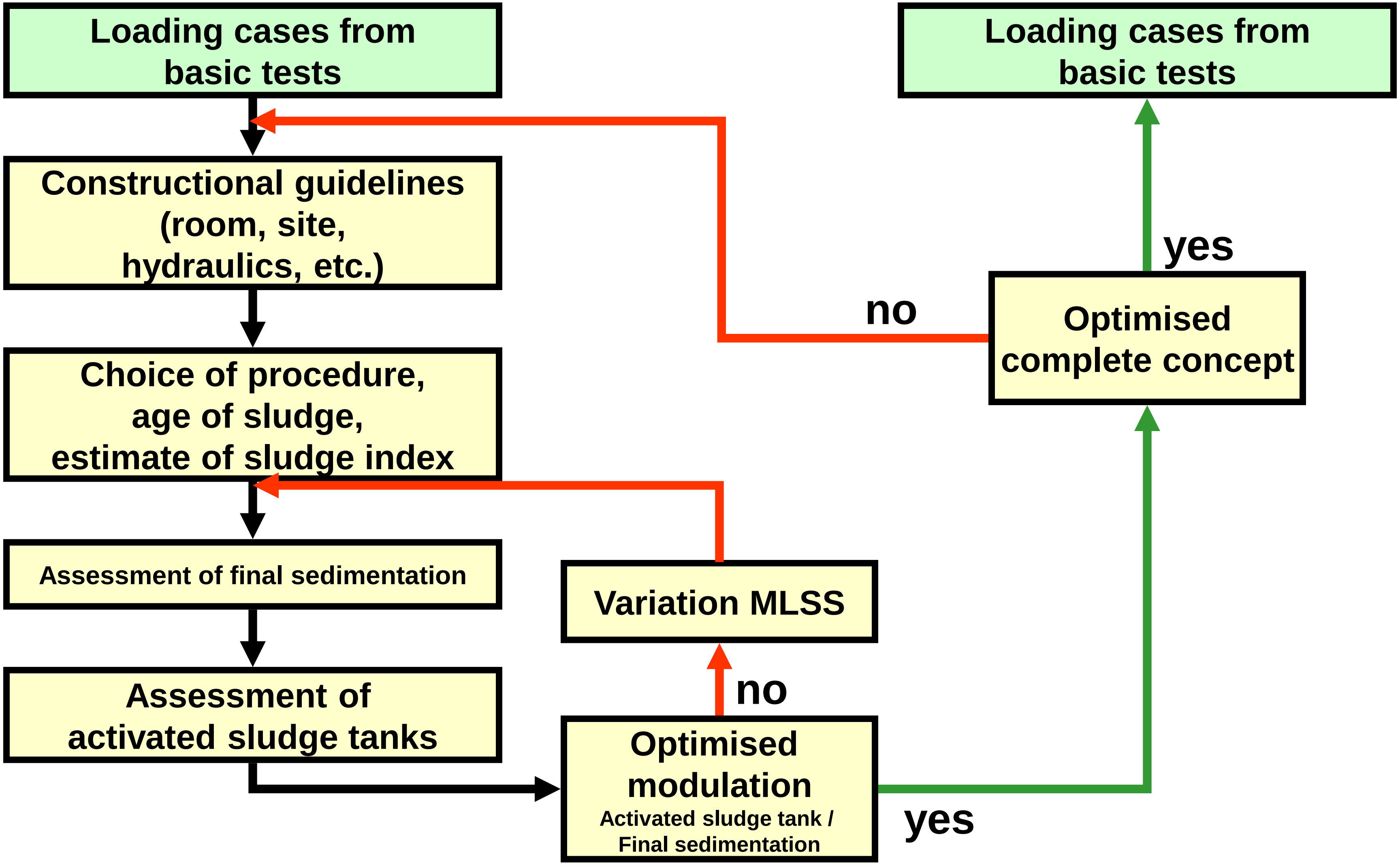
② Air inlet ?

③ "Jet"-aeration

④ Surface aeration

⑤ Bubble aeration

Operation of planning and assessment



Loading cases from basic tests

Constructional guidelines (room, site, hydraulics, etc.)

Choice of procedure, age of sludge, estimate of sludge index

Assessment of final sedimentation

Assessment of activated sludge tanks

Optimised modulation

Activated sludge tank / Final sedimentation

no

Variation MLSS

yes

Optimised complete concept

no

yes

Loading cases from basic tests

Assessment of the final sedimentation

The following characteristics have to be determined for the sizing of the **final settling tank**:

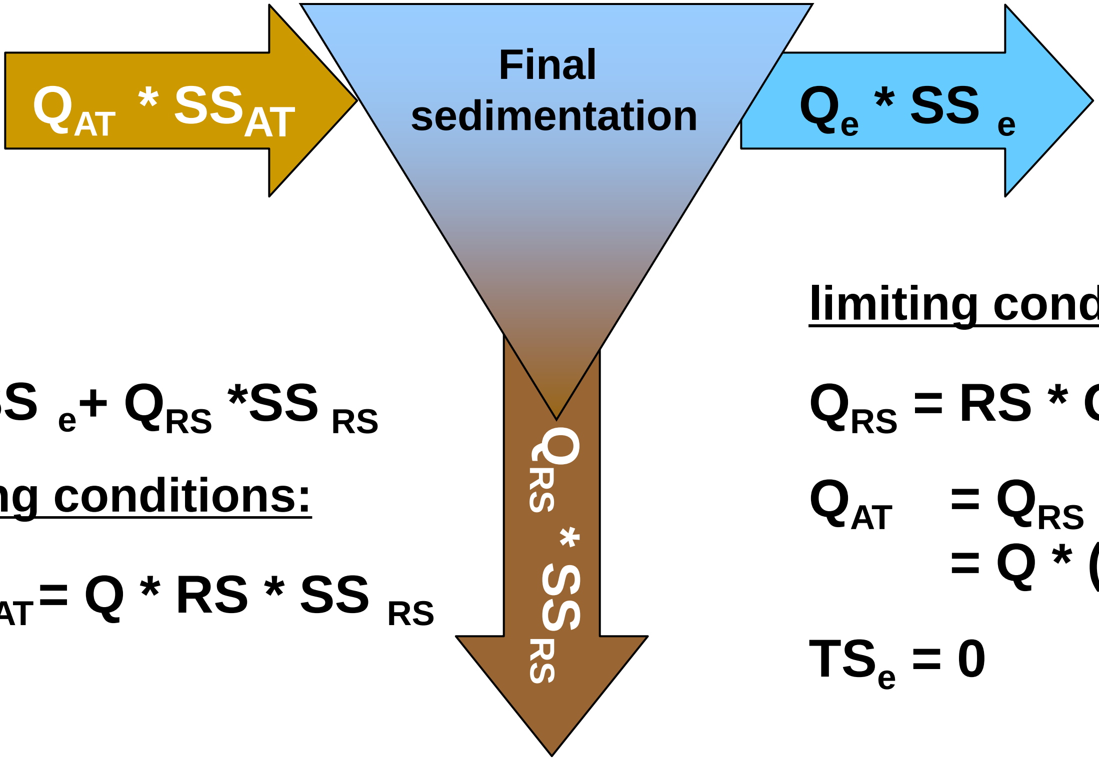
- Form and dimension of the final sedimentation tank
- Tolerable time of sludge storage and concentration
- Return-sludge flow and regulation
- Kind and operating mode of the cleaning devices
- Arrangement and construction of the in and outlets

Design rules

Design rules apply to:

- Final settling tanks with a length/diameter up to 60 m
- Sludge index 50 l/kg $\leq$ SVI $\leq$ 200 l/kg
- Parallel sludge volume PSV $\leq$ 600 l/m^3
- Return-sludge flow
  $Q_{RS} \leq 0.75 * Q_m$ (horizontal flow) or
  $Q_{RS} \leq 1.0\ Q_m$ (vertical flow)
- Content of dry substances in the inflow of the final settling tank SS_{AT} (MLSS) $>$ 1.0 kg/m^3

Solid material balance (Final sedimentaion)



Q_{AT} * SS_{AT}

Final sedimentation

Q_e * SS_e

Q_{RS} * SS_{RS}

Balance equation:

$Q_{AT} * SS_{AT} = Q_e * SS_e + Q_{RS} * SS_{RS}$

Together with limiting conditions:

$Q_0 * (1 + RS) * SS_{AT} = Q * RS * SS_{RS}$

$$SS_{AT} = \frac{RS \cdot SS_{RS}}{1+RR}$$

limiting conditions:

$Q_{RS} = RS * Q_0$

$Q_{AT} = Q_{RS} + Q_0$

$= Q * (1 + RS)$

$TS_e = 0$

Reflux ratio and content of dry substance in the sludge in the inflow of the final sedimentation

Return sludge ratio:

$$RS = Q_{RS}/Q$$

The equilibrium state follows from the solid material balance among the dereliction of $X_{SS,AN}$:

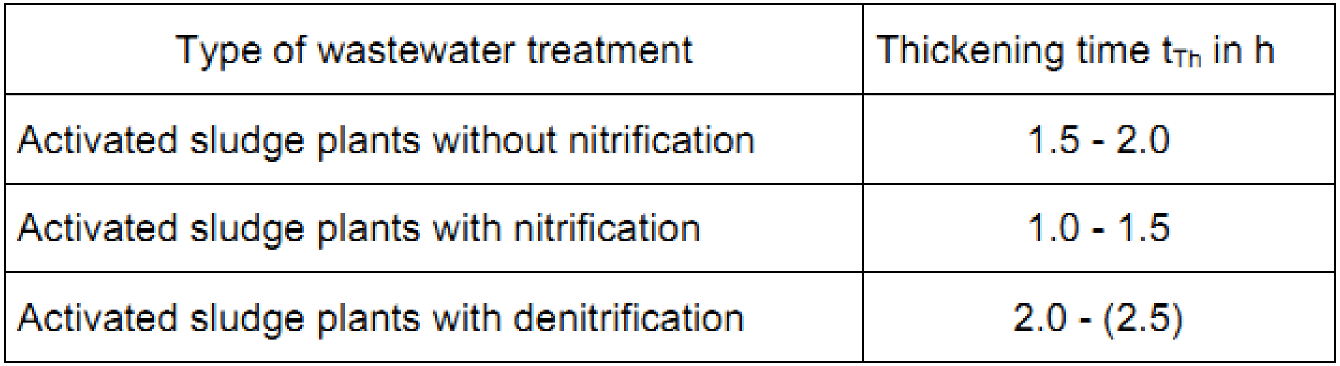
$$\text{MLSS or } SS_{AT} = \frac{RS \cdot SS_{RS}}{1 + RS} \quad [\text{kg/m}^3]$$

Sludge Volume Index and Permitted Thickening Time

- The sludge volume index together with the thickening time (t_{Th}) in the secondary settling tank determines the suspended solids concentration in the bottom sludge (SS_{BS}).

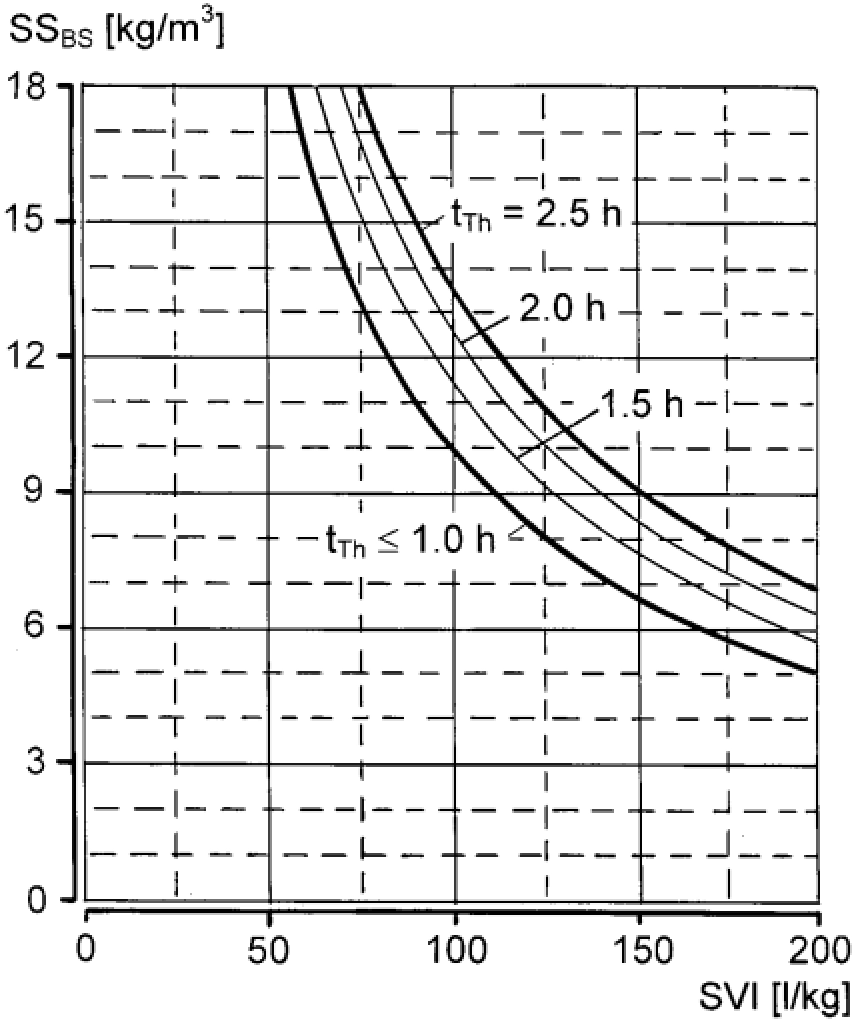
- To prevent redissolution (of phosphate) and the formation of floating sludge as a result of unwanted denitrification in the secondary settling tank, the retention time of the settled sludge in the thickening and sludge removal zone must be kept as short as possible.

Recommended thickening time in dependence on the degree of wastewater treatment



Type of wastewater treatment	Thickening time t_{Th} in h
Activated sludge plants without nitrification	1.5 - 2.0
Activated sludge plants with nitrification	1.0 - 1.5
Activated sludge plants with denitrification	2.0 - (2.5)

Suspended Solids Concentration in the Return Sludge



$$SS_{BS} = \frac{1000}{SVI} \cdot \sqrt[3]{t_{Th}} \qquad [kg/m^3]$$

with: SVI = Sludge volume index [l/kg]
t_{Th} = Thickening time [h]
SS_{BS} = Bottom sludge [kg/m³]

with scraper facilities $SS_{RS} \sim 0.7 \cdot SS_{BS}$

with suction facilities $SS_{RS} \sim 0.5$ to $0.7 \cdot SS_{BS}$

Surface Overflow Rate and Sludge Volume Surface Loading Rate

The surface overflow rate q_A is calculated from the permitted sludge volume loading rate q_{SV} and the diluted sludge volume DSV as:

$$q_A = \frac{q_{SV}}{DSV} = \frac{q_{SV}}{SS_{EAT} \cdot SVI} \qquad [\mathrm{m/h}]$$

In order to keep the concentration of suspended solids $X_{SS,EST}$ and the resulting COD and phosphorus concentration in the effluent of horizontal flow secondary settling tanks low, the following sludge volume loading rate q_{SV} shall not be exceeded:

$q_{SV} \leq 500\ \mathrm{l/(m^2 \cdot h)}$ for $X_{SS,EST} \leq 20\ \mathrm{mg/l}$

For mainly vertical flow secondary settling tanks, the following applies with the formation of a closed sludge blanket or with an easily flocculating activated sludge:

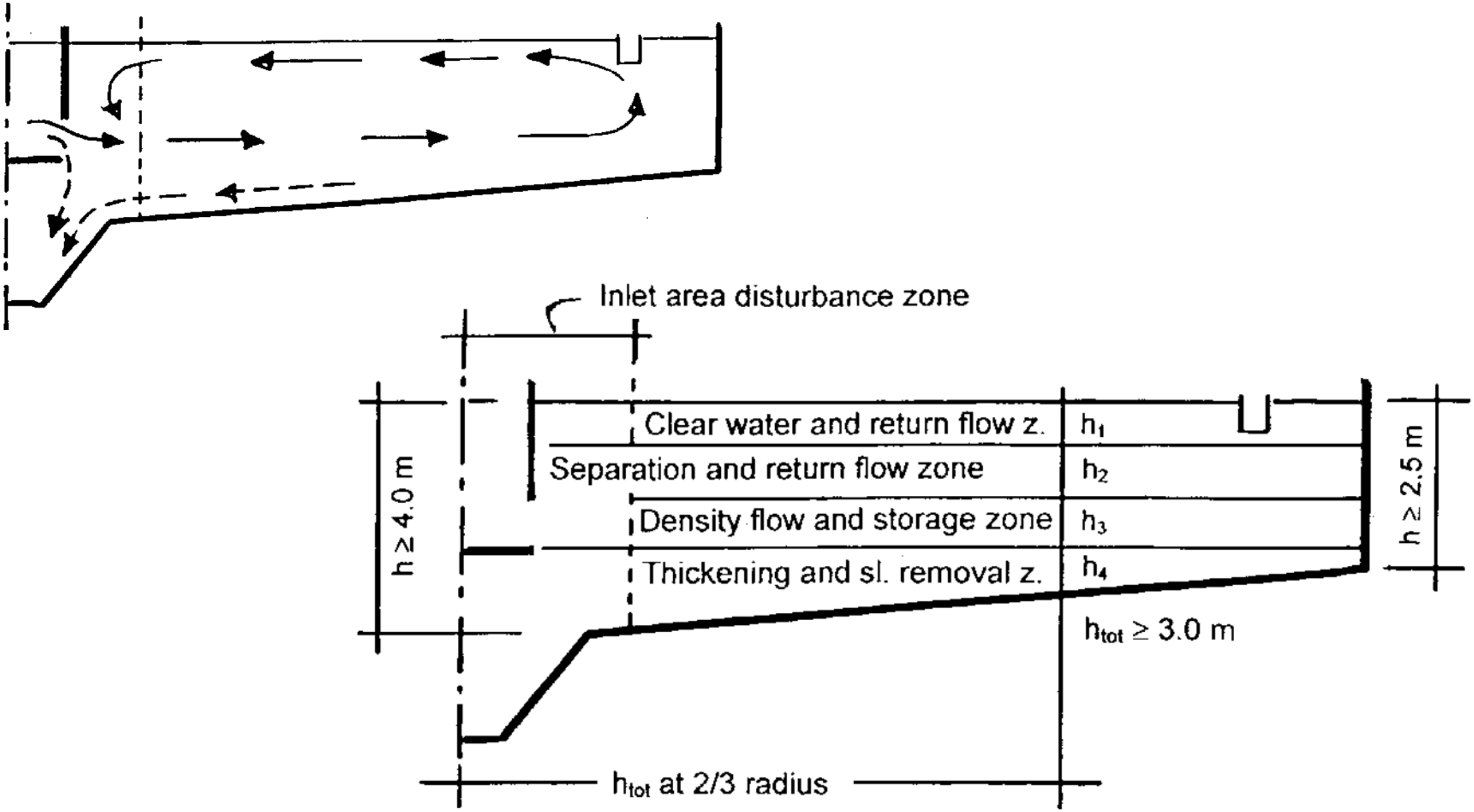
$q_{SV} \leq 650\ \mathrm{l/(m^2 \cdot h)}$ for $X_{SS,EST} \leq 20\ \mathrm{mg/l}$

Settling Tank Surface Area

The required surface area of the secondary settling tank results as follows:

$$A_{ST} = \frac{Q_{WW,h}}{q_A} \qquad [m^2]$$

Main directions of flow and functional tank zones of horizontal flow circular secondary settling tanks



Minimum depths of the functional zones of secondary settling tanks

- **Clean water zone** $h_1 = 0.50$ m

- **Separation/return flow zone** $h_2 = \dfrac{0.5 \cdot q_A \cdot (1 + RS)}{1 - DSV / 1000}$ [m]

- **Density flow and storage zone** $h_3 = \dfrac{1.5 \cdot 0.3 \cdot q_{SV} \cdot (1 + RS)}{500}$ [m]

- **Thickening and sludge removal zone** $h_4 = \dfrac{SS_{EAT} \cdot q_A \cdot (1 + RS) \cdot t_{Th}}{SS_{BS}}$ [m]

Functional zones and depths of vertical flow (inverse cone) tanks