Chapter 6.
The Activated Sludge Process

All the figures and tables in this material are from the reference below unless specified otherwise.
Reference: Bruce E. Rittmann and Perry L. McCarty, "Environmental Biotechnology: Principles and Applications", McGraw-Hill, 2001.

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6.1 Characteristics of Activated Sludge

√ The Activated sludge Process:

- **The mostly widely used biological process for the treatment of municipal and industrial waste waters.**
- **Strictly aerobic except anoxic variation for denitrification.**

- **Parts: 1) Aeration tank**
  2) Settling tank
  3) Solids recycle line
  4) Sludge wasting line

- **Activated sludge : microbial aggregates (flocs) in the aeration tank**

- **In 1914, E. Ardern and W. T. Lockett discovered the activated sludge process in England.**

  - They noted aeration of sewage led to formation of flocculent suspended particles and the time to remove organic contaminants was reduced when these flocculent particles held in the system. They referred to the suspended particles as being “activated” .

Experiments on the oxidation of sewage without the aid of filters

Edward Ardern,
William T. Lockett

First published: May 30, 1914
Journal of the Society of Chemical Industry

ammonio silver nitrate in a similar manner to the others gave on analysis:—silver, 36·18 and 36·35; nitrogen, 25·65 and 25·63 per cent. Calculated for $(C(NO_2)_3NHAg)3NH_3$, Ag 35·9, N_2 25·7 per cent.

Molecular weight determination (boiling point) in acetone gave results distinctly confirmatory of the above formula, but ammonia seems to be split off from these compounds by long heating in acetone or alcohol. All these substances explode or burn rapidly when heated and are also sensitive when dry to percussion or friction.

Beyond the analyses and ebullioscopic molecular weight determination, no proof of the above formula is at present put forward.

Manchester Section.

Meeting held at the Grand Hotel on Friday, April 3rd, 1914.

MR. J. H. HOSEASON IN THE CHAIR.

EXPERIMENTS ON THE OXIDATION OF SEWAGE WITHOUT THE AID OF FILTERS.

BY EDWARD ARDERN, M.SC., AND WILLIAM T. LOCKETT, M.SC.

It has long been known that if sewage be exposed to the air for a sufficient period of time, the organic contents are gradually oxidised, with the formation of a deposit of so-called "humus" and the final production of nitrate from the ammonium salts and the nitrogenous organic matter.

This purification change of which the course of the reaction has been so carefully studied and thoroughly worked out by Adeney in his researches on behalf of the Royal Commission on Sewage Disposal, takes place, however, comparatively slowly, and even if aided by direct aeration, by no means becomes a practical method of sewage purification.

Numerous investigators have from time to time endeavoured to utilise aeration methods in the practical solution of the sewage problem, but until quite recently without any reasonable amount of success.

Among the earlier investigations may be mentioned those of Dupré and Dibdin[1] on the aeration of London Sewage, and those of the Massachusetts State Board of Health relating to the use of aeration in the filtration of sewage through gravel and sand filters. Dr. Drown,[2] chemist to this Board, concluded from the results of a series of experiments, that the oxidation of organic matter in water was not hastened by vigorous agitation with air.

Waring[3] of the United States was one of the first to apply aeration methods in the purification of sewage on a working scale.

In 1886 Hartland patented an aeration chamber for the purification of sewage or tank effluent, which Kaye Parry[4] employed in experiments undertaken in 1887, while in 1892 Lowcock conducted experiments on the aeration of filter beds by a forced air supply.

In the latter year Mason and Hine[5] published the results of a research on the aeration of mixture of sewage and water in which they concluded that aeration had but little oxidation effect on the sewage.

In 1897 Fowler[6] investigated the effect of aeration on the effluent resulting from the chemical precipitation of Manchester sewage, without any very tangible results being obtained, at any rate so far as the total amount of oxidation was concerned.

It would thus appear that the results of the earlier investigations on the subject of aeration of sewage, indicated that aeration *per se* could not be considered as a practicable adjunct in the process of sewage purification.

Recently, however, the subject has been reopened by the work of Black and Phelps, Clark, Gage and Adams, and Fowler and Mumford.

In dealing with the question of the pollution of the New York Harbour, Black and Phelps[7] studied the possibilities of the application of aeration to the treatment of sewage.

Their experiments dealt with the aeration of both fresh and partially septicised sewage, in various types of tanks and it was shown that under certain conditions it was possible by means of a reasonable amount of aeration to remove the more readily putrescible matters from the sewage and thereby to a certain extent increase its stability.

Black and Phelps were so far convinced of the practicability of such methods of treatment of sewage, as to recommend that the sewage from a certain section of the New York area should be dealt with on these lines, prior to discharge into the waters of the harbour.

In the Annual Report of the Massachusetts State Board of Health for the year 1912, published at the end of 1913, is described an investigation by Clark and De M. Gage on the possibilities of the use of aeration for preliminary treatment of sewage prior to filtration. They found that simple aeration of sewage for 24 hours reduced the free and albuminoid ammonia to some extent and that with sewage which was both aerated and seeded with green growths—*Protococcus* and *Scenedesmus*—the albuminoid ammonia was even more noticeably reduced. Later it was found that appreciable nitrification was obtained within 24 hours in the aerated sewage containing the green growths.

Subsequently Clark and Gage found that aeration for a much shorter period, in a tank containing slabs of slate about one inch apart, covered with a compact brown growth of sewage matters, was sufficient to coagulate the sewage colloids, and thus to produce a well clarified non-nitrified effluent capable of satisfactory filtration at several times the normal rate.

Later Fowler and Mumford[8] carried out experiments on the action in the presence of air, of an organism designated "M7" (isolated by Mumford from ponds receiving water discharged from a colliery) on sewage containing a certain proportion of iron salts.

This organism has the property of precipitating the iron as ferric hydroxide from solutions of iron salts.

In the paper referred to, it is stated that sewage (in presence of a certain quantity of iron salts) inoculated with this organism, can be thoroughly clarified by six hours aeration. The resultant effluent after settlement of the separated organic colloids, was quite clear and practically free from colloids. It is further stated that although the ordinary methods of analysis failed to reveal the extent of the change effected by the above treatment, the effluent after aeration was always non-putrefactive on incubation, and could be readily oxidised and nitrified by filtration at a high rate.

In quite a recent publication Clark and Adams[9] give the results obtained during 12 months operation of the specially constructed tank used in their earlier experiments previously referred to.

It is shown that a rather better coagulation of the organic colloids and purification of the sewage generally, can be obtained by means of aeration for a period of five hours, under the conditions of experiment, than is obtained by efficient chemical precipitation, and at a considerably reduced cost.

The effluent resulting from the aeration treatment was applied to trickling filters 10 feet deep, at rates varying from 8 to 10 million gallons per acre per day, with the production of a well-nitrified and thoroughly stable filtrate.

In connection with the experiments carried out by Clark and his colleagues, it should be mentioned that the sewage treated was considerably more dilute than the

[1] Report to Royal Commission on the Metropolitan Sewage Disposal, 1884, Vol. 2.
[2] Clark and Adams, Engineering Record, February 7th, 1914, p. 158.
[3] Rafter and Baker, 1894, Sewage Disposal in the United States, p. 535.
[4] Trans. Inst. C.E. Ireland, Vol. XX., 1888.
[5] Journ. Amer. Chem. Soc., Vol. 14, p. 7.
[6] Annual Report, 1897, Rivers Dept., Manchester Corporation.
[7] Mass Inst. of Technology. Contributions from the Sanitary Research Laboratory, Vol. VII., Boston, Massachusetts, 1911.
[8] Journal of Roy. San. Inst., November, 1913.
[9] Engineering Record, February 7th, 1914, p. 158.

6.1 Characteristics of Activated Sludge

- **In 1917, Manchester Corporation built a 946 m^3/d plant.**

- **The process was successfully working in spite of lack of understanding of how the process actually worked:**

  Many articles debated over whether the removal obtained was physical or biological.

  - By 1930, the evidence in favor of a biological process was sufficiently convincing.
    However, an adequate theory about factors affecting removal rates was not then available.

  - By 1950s and 1960s, a theory of operation has developed and was sufficient so that rational designs could be achieved based upon characteristics of wastewater to be treated.

  - It has still problems (like sludge bulking) or uncontrollable factors (like system ecology, “microbial population dynamics”).

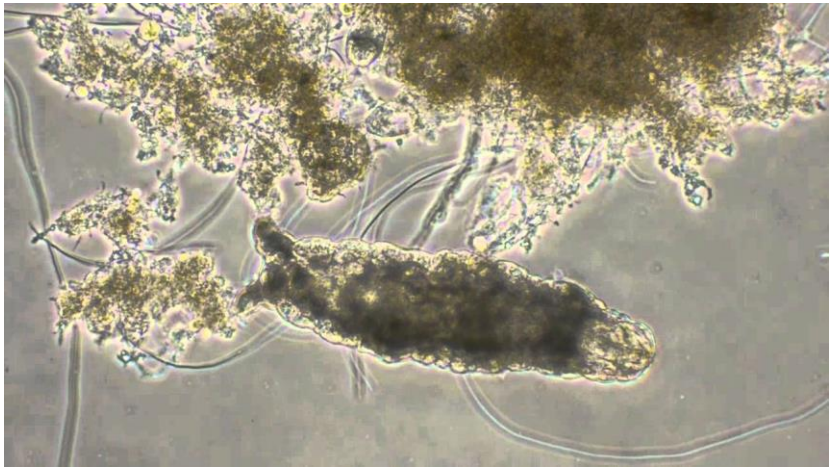
  - In late 1980s, Membrane Bioreactor (MBR) was introduced to enhance the existing conventional system**.**

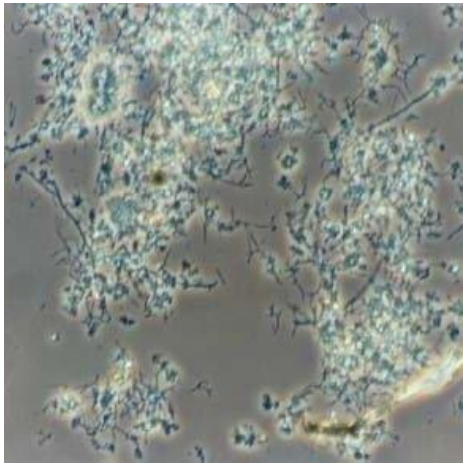
6.1.1 Microbial Ecology

√ **Two crucial characteristics :**

- **The activated sludge contains a wide variety of microorganisms (Community of microorganisms).**
  - Prokaryotes : Bacteria
  - Eukaryotes : Protozoa, Crustacea, Nematodes, Rotifers
  - Virus : Bacteriophage

- **Most of them are held together within flocs by naturally produced organic polymers (EPS) and electro static forces.**





6.1.1 Microbial Ecology

√ Other characteristics :

- **Primary consumers of organic waste are heterotrophic bacteria**
  (Generic parameters at 20℃)

Limiting substrate	BOD_L
Y (true yield for synthesis)	0.45 mg VSS_a/mg BOD_L
$\hat{q}$ (substrate utilization)	20 mg BOD_L /mg VSS_a- d
$\hat{\mu} = Y\hat{q}$ (maximum specific growth rate)	9 d^{-1}
K (conc. Giving one-half the maximum rate)	simple substrate : 1 mg BOD_L /L complex substrate : > 10 mg BOD_L /L
b (endogenous decay coefficient)	0.15 d^{-1}
f_d (biodegradable biomass fraction)	0.8
θ_x^{min} (value at which washout begins)	0.11 d safety factor 100 → 11 d safety factor 36 → 4 d
S_{min} (the minimum substrate conc. capable of supporting steady-state biomass)	simple substrate : 0.017 mg BOD_L /L complex substrate : > 0.17 mg BOD_L /L

6.1.1 Microbial Ecology

- **Most of the other organisms are secondary consumers**

  that feed off of materials released by the primary consumers :

  - byproducts of BOD degradation
  - byproducts from the death and lysis of other organisms

- **Predators**, most of which are eukaryotes feed on bacteria and bacteriophage

- **Chemolithotrophic bacteria** are sometimes present and obtain their energy from oxidation of inorganic compounds (NH_4^+, NO_2^-, S^{-2}, and Fe^{+2}).

- **Changes in the species composition and physical characteristics take place over time.**

  - There is great competition between microorganisms for the various energy resources available in waste mixtures.
  - Changes to the inputs and environmental conditions(Temp, SRT, DO, pH, inhibitory chemicals, nutrient availability, fluid shear, etc.)
  - Death of some species caused suddenly by bacteriophage or by predation
  - Changes in the floc's physical characteristics :
    1) aggregation strength
    2) settling velocity
    3) ability to compact and form a dense sludge

6.1.1 Microbial Ecology

- **The majority of the bacteria genera in activated sludge are Gram-negative.**

- However, recent studies using oligonucleotide probes show that Gram-positive bacteria are significant in activated sludge, too.

- **Many species of protozoa have been identified in activated sludge**

- Order of 50,000 cells/mL (Pike and Curds, 1971)

- They are known to be useful indicators of process performance.
  The predominance of the ciliated protozoa indicates a stable sludge.

- They tend to be highly sensitive to toxic chemicals. Hence the healthy protozoan population is indicative of a wastewater that is relatively free of toxic chemicals

- Their presence and activity are readily observed with a low-powered microscope.

6.1.1 Microbial Ecology

- **Rotifers, nematodes and other multicellular forms** often are found in activated sludge system,
  - Their roles in the process are not obvious.
  - They are generally present when the system has a long SRT.

- **The role of bacterial viruses or phages in the overall process is not well documented.**
  - Their presence can cause rapid and large shifts in dominant bacterial species.
  - If one species is decimated by a phage, another can replace it rapidly so that significant perturbations in treatment efficiency are not detected ("Redundancy").

- **Because of redundancy and the great competition for energy resources, subtle changes in the treatment process can result in major changes in the microbial composition and the floc physical characteristics.**

- **Factors that affect the microbial ecology of activated sludge:**
  1) Reactor system, 2) Dissolved oxygen level, 3) nutrient availability,
  4) temperature, 5) pH, 6) inhibitory materials, etc.

  For example, CSTR and PFR systems foster growth of quite different microorganisms, even when the input substrate and the SRT are identical. It is because CSTR tent to maintain consistently low substrate concentrations, while PFR tend to create more of a "Feast and Starve" cycle.

6.1.2 Oxygen and Nutrient Requirement

- **In most situations, the electron donor (BOD) is rate-limiting for microorganism reproduction and growth. It means that nutrients and e-acceptor (O_2) have concentrations well above their half-saturation concentration, or K .**
  → S / (K+S) = ~1 in Monod eq. when S is high enough.

- **For example, Dissolved oxygen : K << 1 mg/L, If DO > 2 mg/L, then O_2 is far from rate limiting.**

  -The literature is not definitive about just what K is for nutrients (N, P, Fe, S, Zn, Cu, Mo, and other trace constituents). But the value appears to be quite low, much less than 1 mg/L.

  -The oxygen consumption rate is proportional to the rate of donor substrate utilization and biomass endogenous decay.

  -The consumption rate of the nutrients is proportional to the net synthesis rate of biomass.

6.1.3 Impacts of Solids Retention Time

√ **SRT (θ_x) is commonly used to control not only i) treatment efficiency of wastewater but also ii) physical and biological characteristics of sludge.**

- **A longer SRT provide a greater degree of substrate removal.**

$$S = K\frac{1+b\theta_x}{\theta_x(Y\hat{q}-b)-1}$$

- **SRT affects SMP concentration in a nonlinear manner.**

$$\mathrm{UAP} = -\frac{(q_{\mathrm{UAP}}X_a\theta + K_{\mathrm{UAP}} + k_1 r_{\mathrm{ut}}\theta)}{2} + \frac{\sqrt{q_{\mathrm{UAP}}X_a\theta + K_{\mathrm{UAP}} + k_1 r_{\mathrm{ut}}\theta)^2 - 4K_{\mathrm{UAP}}k_1 r_{\mathrm{ut}}\theta}}{2}$$

$$\mathrm{BAP} = -\frac{(K_{\mathrm{BAP}} + (q_{\mathrm{UAP}} - k_2)X_a\theta)}{2} + \frac{\sqrt{(K_{\mathrm{BAP}} + (q_{\mathrm{BAP}} - k_2)X_a\theta)^2 + 4K_{\mathrm{BAP}}k_2X_a\theta}}{2}$$

6.1.3 Impacts of Solids Retention Time

- **Altering SRT can lead to changes in sludge physiology such as settling characteristics, EPS production, etc.**

- **For various reasons, a too long SRT often is not beneficial, even if the substrate concentration can be driven lower.**

  - θ_x is generally limited to a range between 4 to 10 days when BOD removal and economics are to be balanced.

  - High θ_x leads to poorer suspended solids capture and thus overall removals of BOD deteriorate.

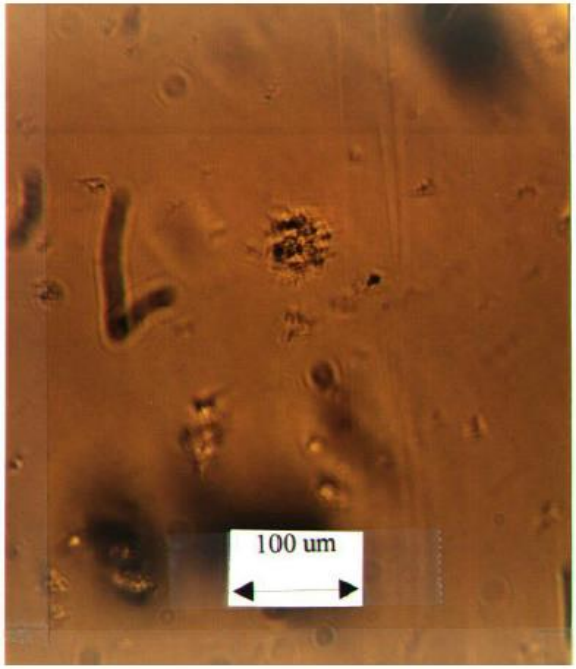
- **Operation at long SRT (> 10 days) allows for the accumulation of slower growing organisms that are washed from the system if the SRT is short.**

- **Many of the microorganisms that can cause operational problems (bulking and foaming) are relatively slow growers, compared to the bacteria that from the desirable compact floc.**

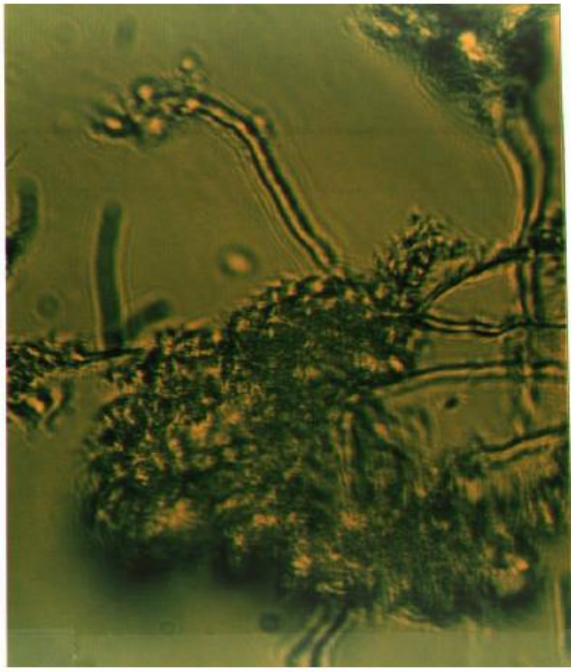
- **The chemolithotrophs, particularly the nitrifying bacteria, are slow growers that can exist in activated sludge only when the SRT is relatively long.**

6.1.3 Impacts of Solids Retention Time

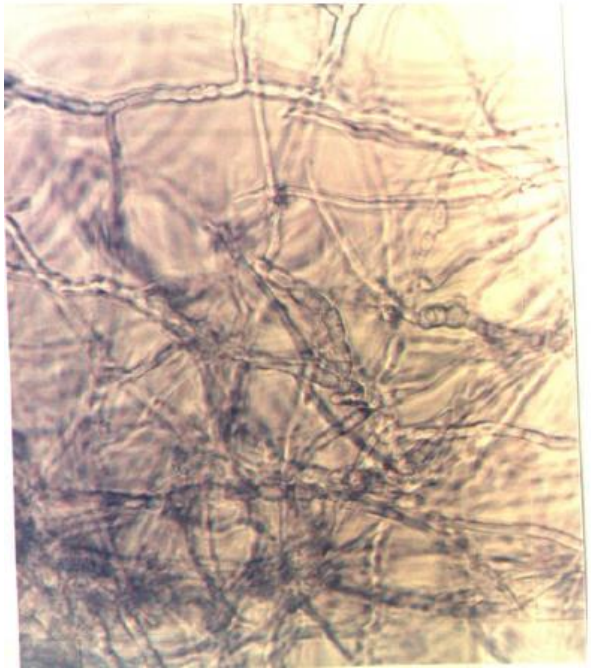
- Filamentous bacteria (causing the sludge bulking)



▲ Pin-point floc



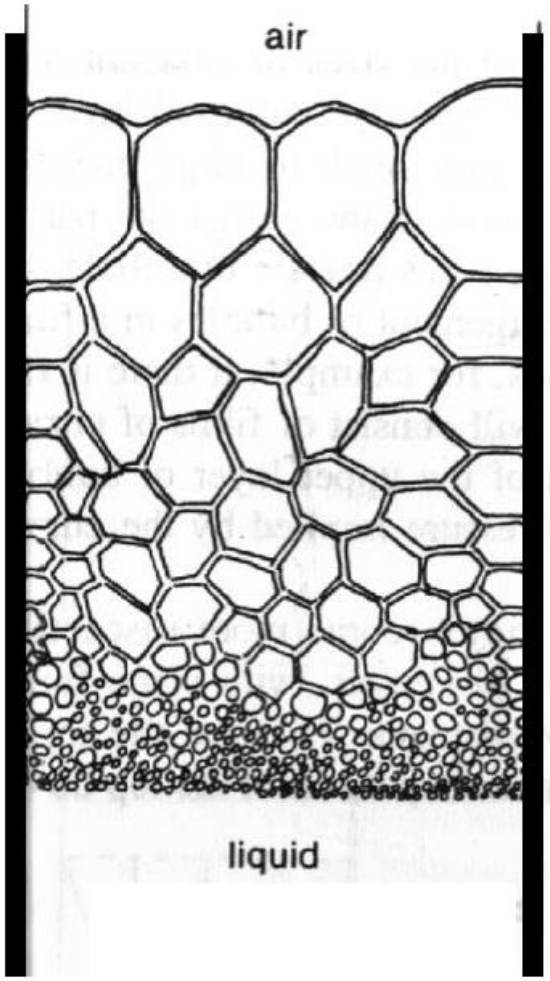
▲ Normal floc



▲ Bulking floc
(filamentous bacteria)

6.1.3 Impacts of Solids Retention Time

- **Foaming bacteria**



6.2 Process Configurations

√ Modifications of basic activated sludge process

- Trial-and-error efforts to overcome problems in activated sludge operation since 1914 when Ardern & Lockett first discovered it.
- The designer can select combinations from the three different categories.

Table 6.1 Summary of activated sludge configurations

A. Modifications Based on Physical Configuration

1. Plug Flow (Conventional)
2. Step Aeration **(=step feeding)**
3. Completely Mixed
4. Contact Stabilization
5. Activated Sludge with Selector

B. Modifications Based on Oxygen Addition or Distribution

1. Conventional Aeration
2. Tapered Aeration
3. Pure Oxygen

C. Modification Based on Organic (BOD) Loading

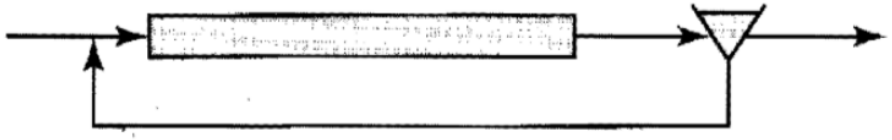
1. Conventional
2. Modified Aeration
3. High Rate
4. Extended Aeration

low BOD loading, low MLSS

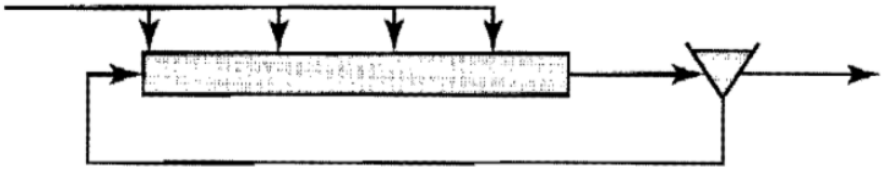
high BOD loading, high MLSS

low BOD loading, relatively high MLSS

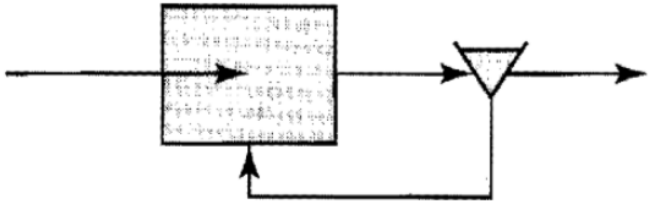
6.2.1 Physical Configurations



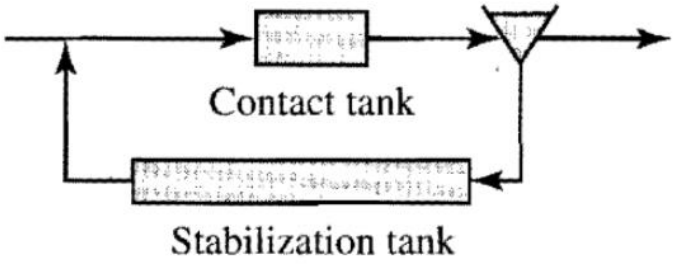
a. Plug-flow (conventional) activated sludge



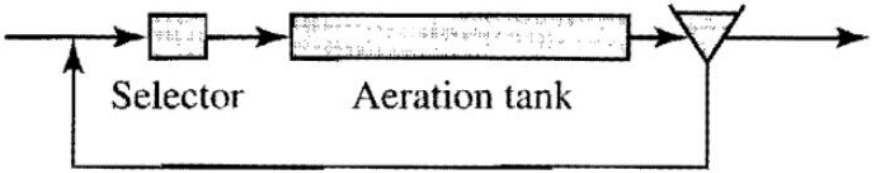
b. Step-aeration activated sludge



c. Completely mixed activated sludge



d. Contact-stabilization activated sludge



e. Activated sludge system with anoxic selector

Figure 6.1 Activated sludge configuration modifications.

6.2.1 Physical Configurations

√ Plug-Flow

- **Long narrow aeration tank**
- **Kinetic theory: greatest contaminant removal within a defined treatment time (or a defined treatment volume)**
- **Problems : high conc. of contaminants at the head end of the aeration tank (Fig. 6.2)**

- High rates of contaminant oxidation
  → complete depletion of dissolved oxygen (anoxic condition)
  → detrimental to microorganisms (organic acid production and a drop in pH)

- Industrial wastes contain substances that are inhibitory to the bacteria → slowing down or stopping the process

6.2.1 Physical Configurations

√ Step Aeration (= Step Feeding)

- **Distributing the influent along the length of the reactor in steps**

- **The concentration of influent contaminant is diluted much more and the oxygen-uptake rate is spread out (Fig. 6.2)**

  → overcome the two problems associated with plug-flow

- **Effects of step aeration**

  - Mixed liquor suspended solids (MLSS) is highest at the inlet since the full sludge recycle mixes with only part of the influent flow.

  - This feature can be exploited to increase the average MLSS concentration in plug flow, which increases the SRT for the same reactor and the same sludge wasting rate.

6.2.1 Physical Configurations

√ Completely-Mixed (CSTR with settling and recycle)

- Evolved in the 1950s when reactor modeling begins.
  "The simplest system for reactor modeling for biological processes"
- Ultimate approach for spreading the wastewater uniformly throughout the treatment system.
- The microorganisms are not exposed to the influent concentration (S^0) as long as the substrate is biodegradable.
- Contaminant concentration and oxygen demand do not vary over the reactor length (Fig. 6.2).
- Most favorable with wastewaters containing nonbiodegradable materials (phenols, petroleum aromatic hydrocarbons, chlorinated aromatics, etc.) that also are toxic to microorganisms at the modest concentration.
- Disadvantages: removal efficiency for an individual organic compound is not as high as in a well operating plug-flow system

6.2.1 Physical Configurations

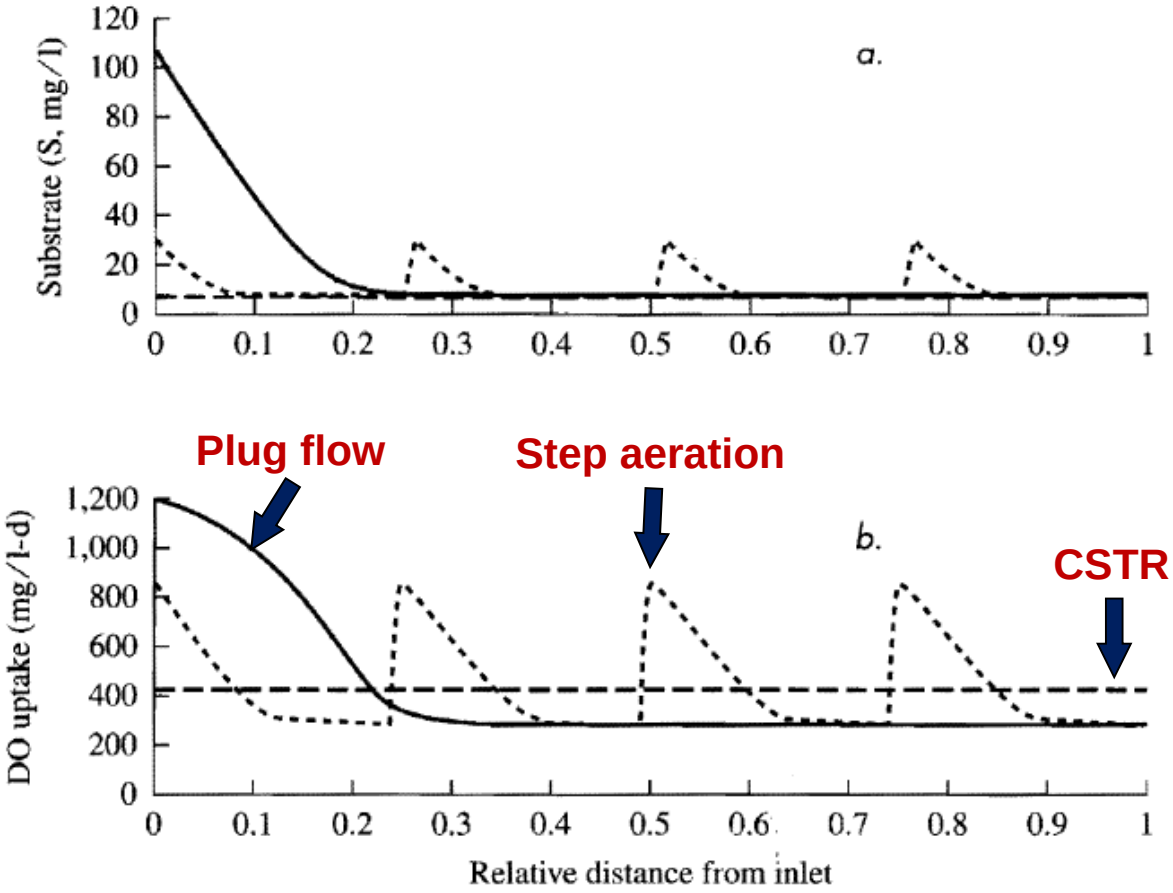
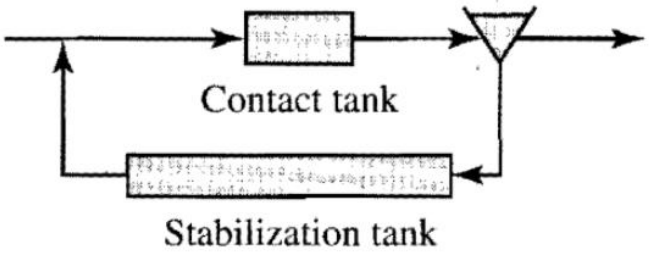


Figure 6.2 Changes in contaminant (substrate) concentration and oxygen (DO) uptake rate along the reactor length for plug flow (PF, solid lines), step aeration (SA, small-dash lines), and continuous-stirred tank (CSTR, large-dash lines) reactors for a typical loading with a dilute wastewater.

6.2.1 Physical Configurations

√ Contact stabilization



- **High efficiency treatment significantly reduces total reactor volume.**

i) **Contact tank**: wastewater mixed with activated sludge,

HRT= 15 ~ 60 min

→ Most of readily biodegradable organic contaminants are oxidized or stored inside the cells, and the particulate matter is adsorbed to the activated sludge flocs.

ii) **Settling tank**: Activated sludge and the treated wastewater are separated

iii) **Stabilization tank**: Settled and concentrated activated sludge is sent to the stabilization tank → adsorbed organic particles, stored substrates, and biomass are oxidized.

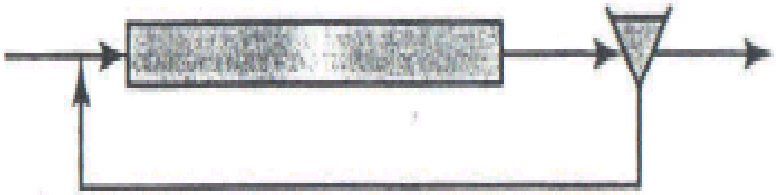
6.2.1 Physical Configurations

√ Advantage of contact stabilization

: reduction in overall reactor volume

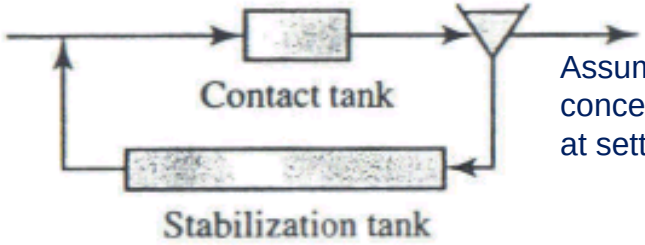
e.g., If sludge production is 1,000 kg MLSS/day,
MLSS in contact tank is 2,000 kg, MLSS in stabilization tank is 6,000 kg,
four fold concentration at settling tank. Then θ_x = 8,000/1,000 = 8 d.

8,000 kg MLSS in one tank : 100%



If the reactor volume is 100m^3 for a conventional activated sludge system,

2,000 kg MLSS : 25%



Assume 4-fold concentration at settling tank

6,000 kg MLSS : 75%
(4-fold concentrated sludge)

then, required reactor volume for contact stabilization
: 25 + 75/4 = 43.8m^3

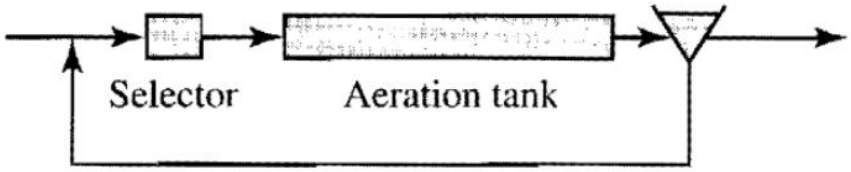
6.2.1 Physical Configurations

√ Disadvantage of Contact Stabilization:

- requires substantially more operational skill and attention
- two mixed liquors need to be monitored, and both results are necessary to compute the SRT.
- the small volume of the contact tank makes the effluent quality susceptible to sudden increases in loading

6.2.1 Physical Configurations

√ **Activated sludge with a selector**



- **To solve the failure of activated sludge system: sludge bulking (= poor settleability)**

- **Selector tank: to change the ecology of the activated sludge system towards organisms with good settling characteristics.**
  (The filaments do not form storage material, while some floc formers do.)

- Return activated sludge is contacted with the waste stream for only 10 ~ 30 min where complete BOD reduction is impossible. Fermentation reactions then converts carbohydrates and some proteinaceous materials to fatty acids, which cannot be oxidized but stored by microorganisms in the form of glycogen or polybetahydroxybutyric acid (PHB).

- The storage materials provide an ecological advantage to the bacteria when they enter the oligotrophic environment of the normal aeration tank.

- Fortunately, the bacteria able to store these materials also are good at forming compact sludge floc.

6.3 Design and Operating Criteria

6.3.1 Historical Background

6.3.2 Food-To- Microorganism Ratio (F/M ratio)

6.3.3 Solids Retention Time

6.3.4 Comparison of Loading Factors

6.3.5 MLSS, the SVI and the Recycle Ratio (& weak points of SVI)

6.3.1. Historical Background

- Criteria used for the design and operation of activated sludge range from those totally empirical to those soundly based in fundamentals.

- When the activated sludge process was first invented in 1914, there was no understanding of kinetics of biological growth and substrate removal. → designs were based on empiricism.

- Empiricism :
  - HRT, SS, ↔ BOD_5 removal
  - Organic loading, MLSS, Oxygen supply ↔ BOD_5 removal
  - MLSS → MLVSS

6.3.2 F/M Ratio

√ **F/M ratio:**

Food-to-microorganism ratio was developed in the 1950s and 1960s and still widely used because of its simplicity.

$$F/M = \frac{Q^{O} S^{O}}{VX}$$

F/M = food-to-microorganism ratio, kg BOD or COD applied per day per kg of total suspended solids in the aeration tank

Q^{O} = influent wastewater stream flow rate (m^3/d)

S^{O} = influent wastewater concentration (BOD or COD in mg/l)

V = aeration-tank volume (m^3)

X = total suspended solids concentration in aeration tank (mg/l)

6.3.2 F/M Ratio

- **If volatile SS are used.**

$$F / Mv = \frac{Q^o S^o}{VXv}$$

F/M_v = food-to-microorganism ratio **on volatile solids basis**, kg BOD or COD per day per kg of volatile suspended solids in aeration tank

X_v = volatile suspended solids concentration in aeration tank (mg/l)

- **For a conventional design for the activated sludge treatment of domestic sewage, the F/M ratio suggested is 0.25 ~ 0.5 kg BOD_5 per day per kg MLSS**

***6 h detention time (V/Q^o), S^o=200 mg/l, X_v = 1,600 mg/l, then F/M_v = 0.5 kg BOD_5 / {(kg MLSS)•(day)}**

- **High-rate treatment : 1 ~ 4 kg BOD_5 / {(kg MLSS)•(day)}**
  Extended-aeration : 0.12 ~0.25 kg BOD_5 / {(kg MLSS)•(day)}

6.3.2 F/M Ratio

- **Substrate mass balance using Monod relationship.**

$$0 = -\frac{\hat{q}S}{K+S}X_a V + Q(S^O - S)$$

$\hat{q}$ = maximum specific rate of substrate utilization (Ms / L^3 T)
K = the Monod half-maximum-rate constant (Ms/L)

$$\frac{\hat{q}S}{K+S}X_a = \frac{Q^O(S^O - S)}{V}$$

$$\frac{Q^O S^O}{VX_a} = S\left(\frac{\hat{q}}{K+S} + \frac{Q^O}{VX_a}\right)$$

When S is small, left >> right term
K + S ≈ K

F/M_a

6.3.2 F/M Ratio

$$F / M_a = \frac{\hat{q}}{K} S$$

$$S \approx \frac{K}{\hat{q}} \cdot F / M_a$$

- **Thus, for the usual case in which we have high treatment efficiency and a low effluent BOD concentration, "S^e is directly related to F / M_a"**

- **However, M_a is almost impossible to measure, which breaks the connection between a measurable M_a and S.**

6.3.2 F/M Ratio

- **S can be estimated if we know the M_a,**

$$S \approx \frac{K}{\hat{q}} \cdot F/M_a$$

$$K = 4\ mgBOD_5 / l$$

$$\hat{q} = 10\ kgBOD_5 / kgVSS_a \cdot d$$

$$\frac{K}{\hat{q}} = 0.4\ mg \cdot d / l$$

$$\frac{F}{M} = 0.5 kgBOD_5 / kgMLSS \cdot d$$

$$S = 0.4 \times 0.5 = 0.2 mg / l$$

$$M_a = 0.3\ M\ (Ma = 30\%\ of\ \ MLSS)$$

$$\frac{F}{M_a} = 1.7$$

$$S = 0.4 \times 1.7 = 0.67\ \ mg / l$$

- **The units of F/M ($kgBOD_5$ / kgMLSS•d) are almost the same as $\hat{q}$ ($kgBOD_5$ /$kgVSS_a$•d)**
  To have a good safety factor, we must have the ratio far less than one.

$$F / M \Big/ \hat{q} < 1, \quad F / M < \hat{q}$$

6.3.3 Solids Retention Time

√ **SRT**

$$\theta_x = \frac{XV}{Q^e X^e + Q^w X^w}$$

V = system volume [L^3],

Q^e = effluent flow rate [L^3T^{-1}]

Q^w= waste-sludge flow rate [L^3T^{-1}]

X, X^e, X^w = the concentrations of mixed-liquor, effluent, and waste sludges in consistent mass units, which can be active volatile solids, volatile solids, or suspended solids.

- As long as active biomass is not an input, any of the three solids measurements can be used for the X values in Eq.6.7 and give the same correct value of θ_x.
- Being able to use SS and VSS, which are simply and routinely measured, to estimate θ_x is a major practical advantage.
- Typical values of θ_x = 4 ~ 10 d
- Extended aeration units generally have much longer θ_x in the range of 15 to 30 d, and sometimes longer.
- The modified aeration process has a short θ_x in the range of 0.2 to 0.5 d.

6.3.3 Solids Retention Time

- **Solids Retention Time, θ_x is the master variable for the design and operation of the AS process,**
  - because it is fundamentally related to the growth rate of the active microorganisms,
  - which in turn controls the concentration of the growth-rate-limiting substrate in the reactor.

$$\theta_x = \frac{\text{active biomass in the system}}{\text{production rate of active biomass}} = \mu^{-1}$$

$$\mu = Y \frac{\hat{q}\, S}{K + S} - b$$

6.3.3 Solids Retention Time

- This important direct relationship between effluent SS and effluent BOD forms **one basis** upon which the typical designs leading to a θ_x of 4 to 10 d originated.
  - At lower values of θ_x : Bacterial flocs tend to disperse, and effluent SS concentrations are fairly high
  - At longer θ_x values : Bacterial flocs also tent to break up and disperse.

- θ_x values have evolved from **empirical practice** over the years

- Effluent BOD = BOD of **effluent SS** + SMP + residual substrate

- If good solids **separation is not achieved**, the oxygen demand from decay of active cells can overwhelm the soluble components.

- Where high BOD removal efficiencies are desired, the effluent SS must be very low concentrations.

- Thus, **the settling ability** of the activated sludge and the efficiency of the final clarifier take on **paramount importance**.

6.3.3 Solids Retention Time

- Floc break up is often noted to begin with θ_x greater than 8 d at temperature of 20℃, or at some longer times with lower temperature.

- Thus, the θ_x range of 4 ~ 10 d represents a zone where biological flocculation and clear effluents appears to be optimal.

- It is the preferred range for design of well-operating and efficient activated sludge treatment systems.

6.3.3 Solids Retention Time

- **Second basis** for the conventional range of 4~10 days: Higher SRTs allow the growth and accumulation of slow growing microorganisms that are not desired.

1) Nitrifying bacteria

When the oxidation of ammonia is not a treatment goal, having nitrifier is undesirable for three reasons.

i) ammonium oxidation creates a very large oxygen demand

ii) the nitrifiers release a significant amount of SMPs

iii) the nitrifiers generates a significant amount of acid which can be a problem in low-alkalinity waters.

$$\frac{1}{6}NH_4^+ + \frac{1}{4}O_2 = \frac{1}{6}NO_2^- + \frac{1}{3}H^+ + \frac{1}{6}H_2O$$

$$\frac{1}{2}NO_2^- + \frac{1}{4}O_2 = \frac{1}{2}NO_3^-$$

2) Filamentous bacteria

- Causes bulking
- A second group of undesired slow growers

6.3.3 Solids Retention Time

- **What volume to use for V in the equation below?**

$$\theta_x = \frac{XV}{Q^e X^e + Q^w X^w}$$

V = system volume [L^3],

Q^e = effluent flow rate [L^3T^{-1}]

Q^w= waste-sludge flow rate [L^3T^{-1}]

- Ought to include biomass in the settler as well as in the aeration tank

- **What XV to use for the settler?**

  - Assume the average sludge concentration in the settler is equal to that in the aeration basin

$$XV = X\,(V_{aer} + V_{set});$$

V_{aer} = Volume of aeration basin

V_{set} = Volume of the settler

6.3.4 Comparison of Loading Factors

Table 6.2 Typical process loading factors and θ_x^d values for various activated sludge process modifications

Process Modification	Normal Ranges for Various Factors: Volumetric kg BOD_5/m^3-d	MLSS mg/l	F/M_v kg BOD_5/ kg X_v-d	Typical BOD_5 Removal Efficiency	Typical θ_x^d d	Safety Factor*
Extended Aeration	0.3	3,000–5,000	0.05–0.2	85–95[B]	>14	>70
Conventional						
Conventional	0.6	1,000–3,000	0.2–0.5	95	4–14	20–70
Tapered Aeration	0.6	1,000–3,000	0.2–0.5	95	4–14	20–70
Step Aeration	0.8	1,000–3,000	0.2–0.5	95	4–14	20–70
Contact Stabilization	1.0	A	0.2–0.5	90	4–15	20–75
Modified Aeration	1.5–6	300–600	0.5–3.5	60–85[B]	0.8–4	4–20
High-Rate Aeration	1.5–3	5,000–8,000	0.2–0.5	95	4–14	20–70

designed very conservatively, SRT: 25-50 d, sometimes even larger.

*Assumed value of growth coefficients: $Y = 0.65$ g cells/g BOD_5, $b = 0.15$ d^{-1}.
A: Contact tank typically has 1,000–3,000 mg/l; stabilization tank typically has 5,000–10,000 mg/l.
B: Higher efficiency is based upon soluble effluent BOD_5.
SOURCE: Lawrence and McCarty (1970).

θ_x^d= design value for θ_x

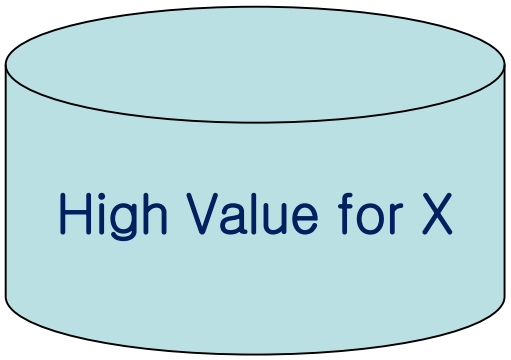
- **F/M_v ratio is inversely proportional to the SRT**

6.3.5 MLSS, the SVI and the Recycle Ratio

√ Choice of mixed-liquor suspended solids (MLSS) concentration, X

- X depends upon many factors :
  - i) the settling characteristics of activated sludge
  - ii) the rate of recycle of sludge from the settling tank back to the aeration tank
  - iii) the design of the settling tank

- If a high value for X in the aeration occurs,



Aeration tank

1) Advantage:
   - lead to smaller aeration basin, which translate into lower construction cost

2) Disadvantage:
   - increase in the settling tank size
   - increase in the cost of aeration system
   - increasing X requires the recycle sludge of a faster rate.
   - high X leads to high effluent SS and BOD

Clearly, an arbitrary choice for MLSS is very risky.

6.3.5 MLSS, the SVI and the Recycle Ratio

- The relationship between X and the return sludge flow rate Q^r

  - A mass balance on suspended solids around settling tank (control volume 'a')

$$Q^i X = \cancel{Q^e X^e}^{\,0} + Q^s X^s \quad \Rightarrow \quad Q^i X = Q^s X^s (X^e \to 0),\ Q^r = Q^s\ (Q^w \to 0 \ll Q^r) \quad \Rightarrow \quad X^r = X^s\ (X^r = X^s = X^w)$$

$Q^i X = Q^r X^r$

  - A mass balance on suspended solids around control volume 'b'

$$Q^i = Q^0 + Q^r \qquad R = \frac{Q_r}{Q^0} \quad \Rightarrow \quad X = X^r \frac{R}{1+R} \quad or \quad R = \frac{X}{(X^r - X)}$$

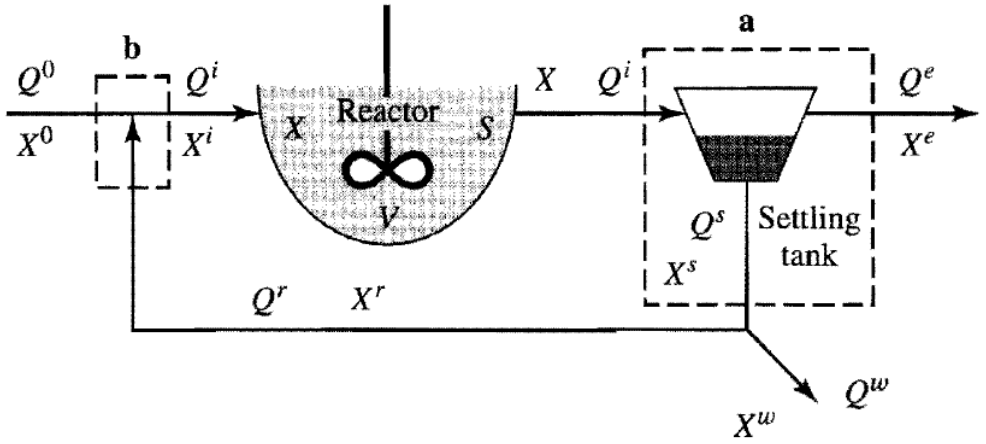


Figure 6.4
Total suspended solids flow within a complete-mix activated sludge system.

6.3.5 MLSS, the SVI and the Recycle Ratio

√ X_m^r and SVI

- Because of sludge settling characteristics, the recycled sludge has upper limit (= X_m^r)

$$X = X^r \frac{R}{1+R} \quad \Rightarrow \quad X_m = X_m^r \frac{R}{1+R}$$

X_m = Maximum of X

X_m^r = 10,000 ~ 14,000 mg/L for typical good-settling activated sludge
= 3,000 ~ 6,000 mg/L for bulking sludges

- X_m^r can be approximated through simple tests:
  - i) the Settled Sludge Volume Test
  - ii) the Sludge Volume Index (SVI)
  - iii) the Zone Settling Rate Test

6.3.5 MLSS, the SVI and the Recycle Ratio

- **SVI** is defined as the volume in milliliters occupied by 1g of the suspended solids after settling

$$SVI\,(ml/gSS) = \frac{V_{30} \cdot (1{,}000\,mg/g)}{MLSS \cdot V_t}$$

  - V_{30} : the volume of the settled sludge after 30 min (unit : ml)
  - V_t : the total volume of cylinder (unit : l)

- **An approximation to the maximum concentration of settled sludge**

$$X_m^r = \frac{10^6 \;\; (mg \cdot ml/g \cdot l)}{SVI \;\; (ml/g)}$$

SVI and X_m^r with sludge type

	SVI (ml/g)	X_m^r (mg/l)
Typical good sludge	100	10,000
Bulking sludge	>200	< 5,000
Highly compact and good-settling sludge	< 50	> 20,000

6.3.5 MLSS, the SVI and the Recycle Ratio

√ Weak points of SVI

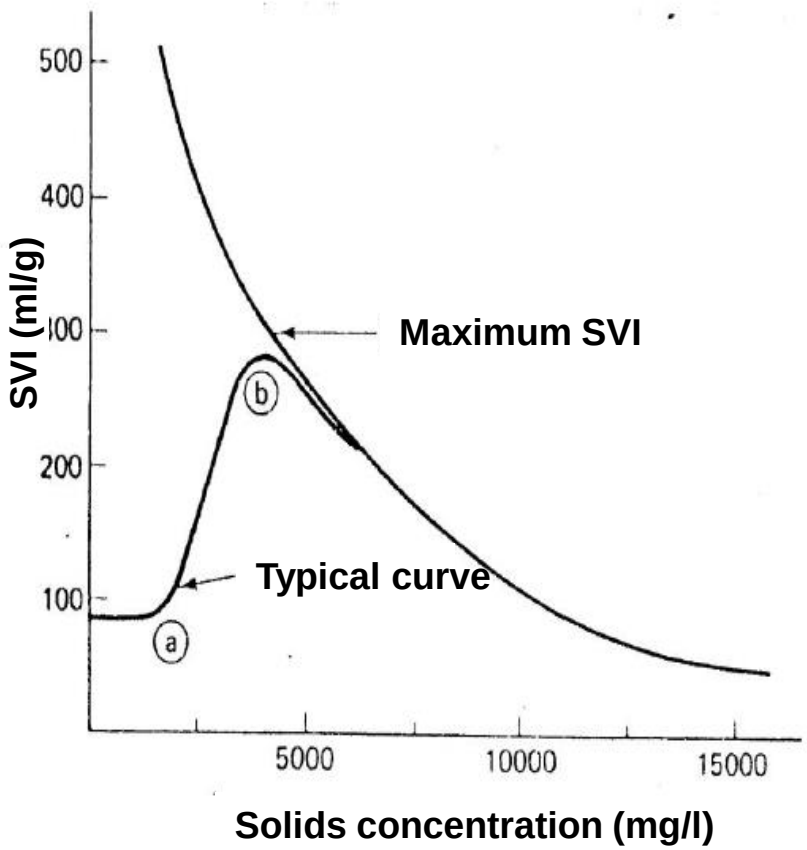


Figure. Variation of sludge volume index with concentration of biological solids

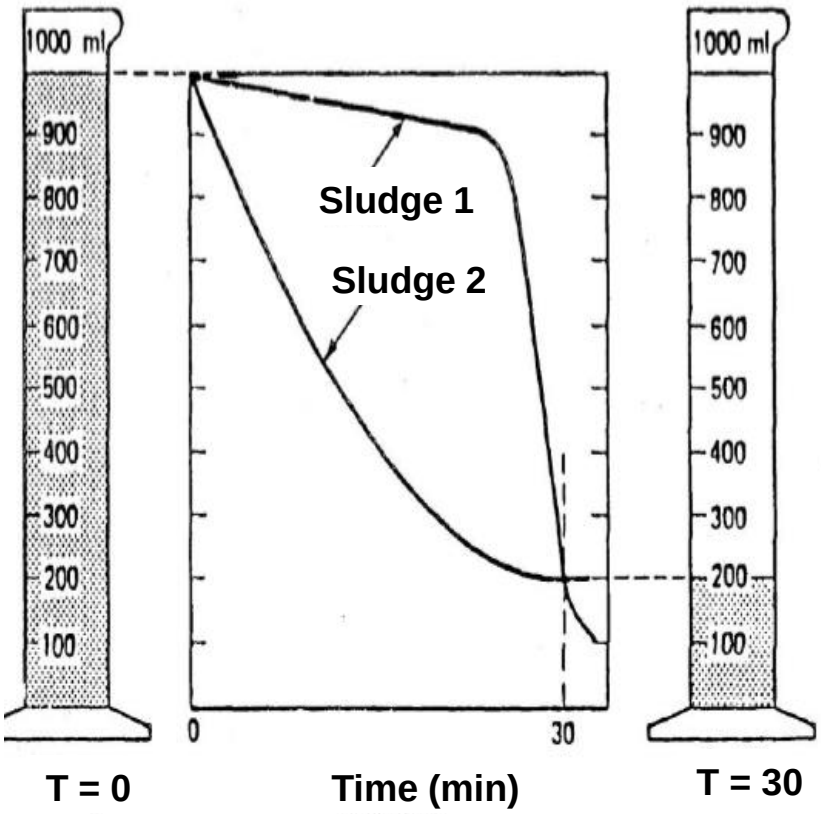


Figure. The sludge volume index can be equal for two sludges having very different settling characteristics (After Vesilind, 1974.)

6.3.5 MLSS, the SVI and the Recycle Ratio

- **The effect of the recycle ratio on X_m for various of X_m^r**

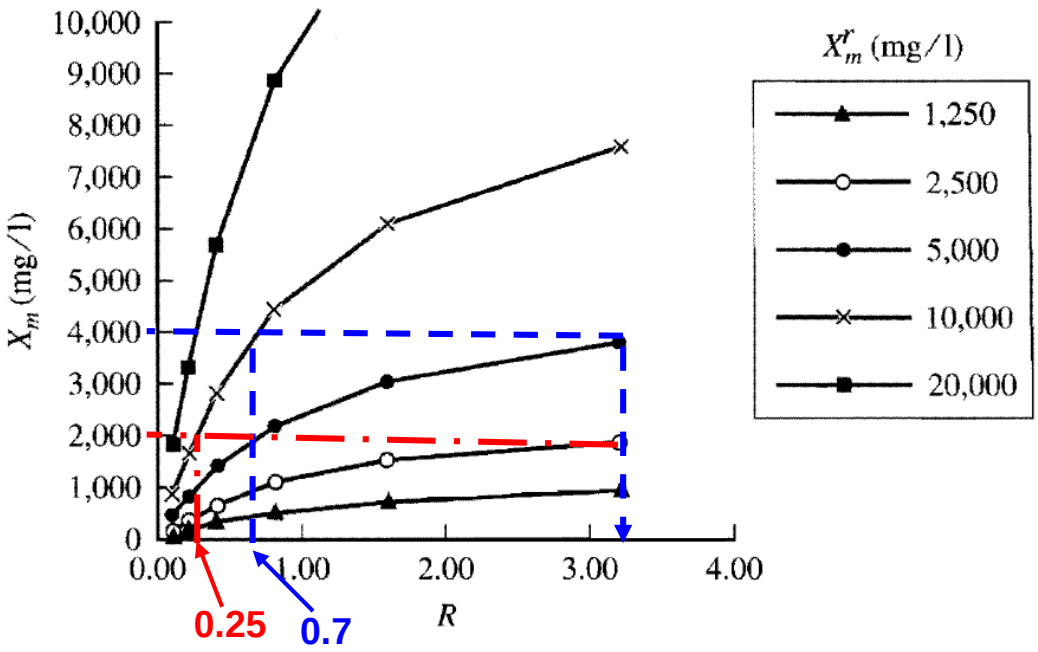


Figure 6.5 Effect of recycle ratio (R) on the maximum mixed-liquor suspended solids concentration in the aeration tank (X_m) for various maximum concentrations of sludge compaction in the settling tank (X_m^r).

(1) <Good sludge>

X_m^r = 10,000 mg/l and X_m= 2,000 mg/l

➡ **R = 0. 25**

<Bulking sludge>

X_m^r = 2,500 mg/l and X_m= 2,000 mg/l

➡ **R = 3.2**

(2) <Good sludge>

R = 0.7 and X_m= 4,000 mg/l

➡ **X_m^r = 10,000 mg/l**

<Bulking sludge>

X_m^r = 5,000 mg/l and X_m= 4,000 mg/l

➡ **R = 3.2**

6.5 Bulking and Other Sludge Settling Problems

Table 6.3 Biosolids separation problems encountered in activated sludge operation

Biosolids Separation Problem	Cause of Problem	Effect of Problem
Bulking	Filamentous organisms extend from flocs into the bulk solution and interfere with compaction and settling	High sludge volume index with clear supernatant. Overflow of sludge blanket can occur. Solids handling processes become hydraulically overloaded
Viscous bulking or nonfilamentous bulking	Microorganisms present in large amounts of exocellular slime. In severe cases, the slime imparts a jelly-like consistency	Reduced settling and compaction rates. Can result in overflow of sludge blanket from secondary clarifier or formation of a viscous foam
Dispersed growth	Microorganisms do not form flocs, but are dispersed, forming only small clumps or single cells	Turbid effluent. No zone settling of sludge
Pin floc or pinpoint floc	Small, compact, weak, roughly spherical flocs. Larger aggregates settle rapidly, smaller ones slowly	Low sludge volume index and cloudy turbid effluent
Foaming/Scum formation	Caused by (i) nondegradable surfactants, or (ii) the presence of *Norcardia* sp. and/or *Microthrix parvicella*	Foams float large amounts of biosolids to surface of treatment units. Microorganism-caused foams are persistent and difficult to break. Causes solids overflow into secondary effluent and onto walkways. Anaerobic digestion foaming can also result
Blanket rising	Denitrification in settler releases poorly soluble N_2 gas, which attaches to activated sludge flocs and floats them to the clarifier surface	"Chunks" of activated sludge collect on the surface of the settler and may result in turbid effluent

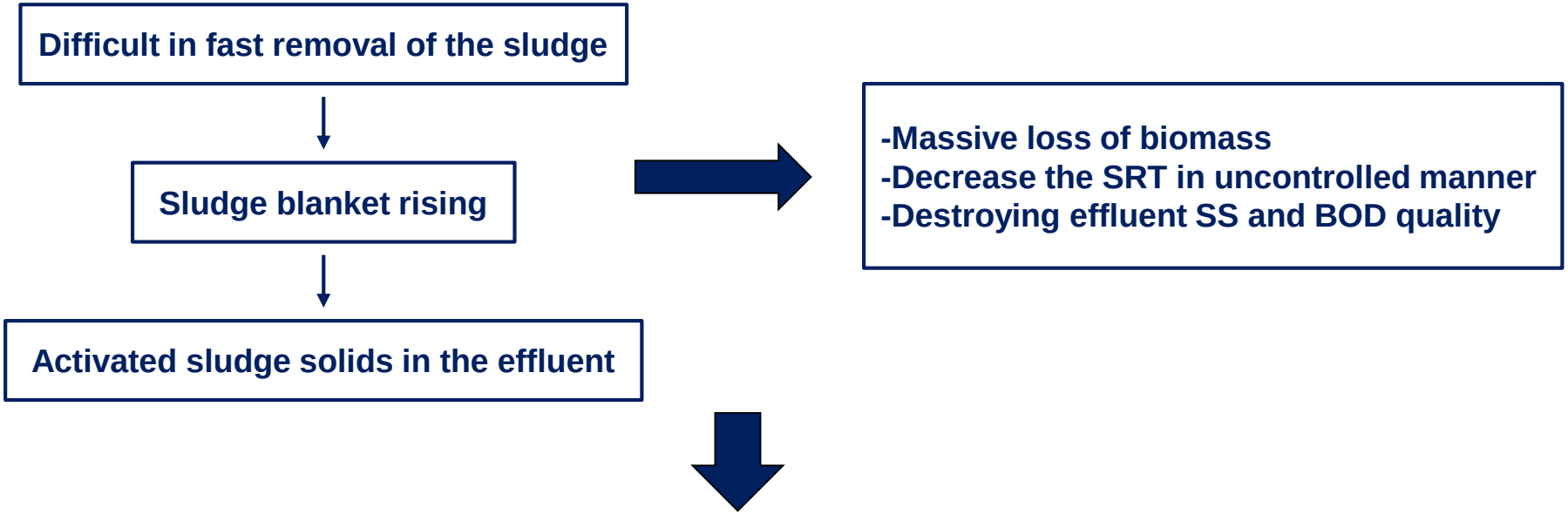
SOURCE: After Jenkins (1992).

Jenkins (1992)
: different solids
-separation problems

6.5.1 Bulking Sludge

√ Bulking sludge

- **Sludge bulking** is the formation of activated sludge floc that settles slowly and compacts poorly
- Difficult removal of the sludge from the settling tank for return to the aeration basin



6.5.1 Bulking Sludge

Floc microstructure with backbone of filamentous bacteria → strong and compact macrostructure

Too many filamentous bacteria → extension of filaments outside the compact floc → bridging between flocs

- Effects of extended filaments' bridges causing sludge bulking
  - prevent the flocs from coming close together or compacting
  - trap water within and between the flocs
  - prevent movement of the water upward

6.5.1 Bulking Sludge

√ Onset of sludge bulking

- Microscopic examination
  - Identification through steady trend of more extended filaments by a trained technician
- Sludge volume index
  - serious bulking : SVI >200 mg/L
  - very bad bulking : SVI ≫500 mg/L
- Rising sludge blanket and a low concentration of suspended solids in the settler underflow

High SVI → Low X_m^r

√ Cause of sludge bulking

- Low–DO bulking by filamentous bacteria (Sphaerotilus natans) that have good affinity for dissolved oxygen (a low K for O_2). They begin to predominate when the DO is not enough to allow good oxygen penetration into the floc.
- Low–F/M bulking by filamentous bacteria (Microthrix parvicellar) that have a high affinity for organic substrates (a low K for S) and a low endogenous decay rate (low b). They begin to predominate when the SRT is long.
- Reduced–sulfur bulking by filamentous bacteria (sulfur-oxidizing species, Thiothrix) that gain a competitive advantage from the chemolithotrophic electron donor (reduced sulfur compounds). They occur when reduced sulfur compounds enter the reactor.

6.5.1 Bulking Sludge

- **Low-F/M bulking**
  - Long SRT such as extended aeration
  - *Microthrisparvicella*, Type0041, Type0092, Type0581, *Haliscomenbacter hydrosis*
  - Situation with extended aeration in low-F/M bulking
    - Oligotrophs having a high affinity for organic substrate
    - Low endogenous decay rate

6.5.1 Bulking Sludge

- **Reduced-sulfur bulking**

  - Reduced sulfur compounds (sulfides) entered the activated sludge unit
  - Sulfur-oxidizing species : *Thiothrix*, 021N
  - Eliminating reduced-sulfur bulking is to eliminate all inputs of reduced sulfur

$$4H_2O_2 + HS^- \rightarrow SO_4^{2-} + 4H_2O + H^+$$

34g/ M H_2O_2 x 4 = 136g
32g/ M S^- x 1 = 32g
$\rightarrow$ 4.25 g H_2O_2 is needed to oxidize one g S

  - Formation of sulfides in a reactor from sulfate in feed) within the sludge floc due to D.O. depletion. Increased D.O.(or NO_3^-) concentration is needed to prevent sulfate reduction

6.5.2 Foaming and Scum Control

√ Formation of foam or scum on the surface of aeration tanks

- **Problems**
  - Excessive suspended solids in the effluent
  - Unsightly and dangerous conditions (e.g., slippery walkways around them)
  - Great difficulties in making a sludge inventory

- **Cause**
  - Long SRT and high wastewater temperatures
  - Causative organisms: Nocardia and Microthrix

- **Solution**
  - Reducing SRT to 6 d or less
  - Chlorination of return activated sludge

6.5.3 Rising Sludge

√ Rising Sludge in the settling tank with nitrification

- **Denitrification in the sludge blanket of the settler**
  - Gas bubbles (N_2) attach to the settled sludge particles
  - Chunks of sludge become buoyant and rise to the surface of the settler
  - These pieces of sludge blanket can increase in effluent suspended solids

- **Solution**
  - Stop nitrification in the activated sludge
    (No nitrate formed by nitrification → No N_2 gas by denitrification)
  - Reduce SRT and wash out the slow-growing nitrifiers
  - Promote denitrification as part of the activated sludge process
    →removal of the nitrate before the mixed liquor enters the settler

6.5.5 Viscous Bulking

√ Viscous Bulking

- Form of nonfilamentous bulking
- Excess of extra-cellular polymer produced by floc-forming bacteria

Moderate amounts of polymer : causing bacteria flocculation for good floc formation

Excess amounts of polymer : detrimental to the settling of the bacterial flocs

- Foaming and scum formation by voluminous character by sludge flocs (jelly-like)
- Poor settling caused by the high water content of the polymeric material

6.5.6 Addition of Polymers

- **Quick fix solution**
  - Addition of organic polymers (cationic polyelectrolytes) to the mixed liquor between the aeration basin and the settling tank to enhance flocculation, settling and compaction

- **Advantages**
  - Effective for relief from a rising sludge blanket, dispersed growth, or pinpoint floc
  - Prevention of the loss of suspended solids

- **Disadvantages**
  - Loss of the effectiveness : polymers are biodegraded by the microbial community, which adapts to it over time.→ rising the required dosage over time
    → increase of the polymer cost
  - Normal selection process for natural floc formers is short-circuited.
    → the microbial community becomes less and less enriched in the good floc formers.