Chapter 6  The activated sludge Process

6.1. Characteristics of Activated Sludge

- The Activated sludge Process:

1) The mostly widely used biological process for the treatment of municipal and industrial wastewaters.

2) Strictly aerobic except anoxic variation for denitrification.

3) Parts: i) aeration tank, ii) a settling tank, iii) solids recycle, and iv) a sludge wasting line

4) activated sludge: microbial aggregates (flocs) in the aeration tank

5) In 1914, E. Arden 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” -.

- The Activated sludge Process:

6) In 1917, Manchester Corporation built a 946 m³/d plant.

7) Successful application of the process occurred even though an understanding of how the process actually worked was lacking:

- 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.
• Two crucial characteristics:

1) The activated sludge contains a wide variety of microorganisms (Community of microorganisms).

- Prokaryotes: Bacteria
- Eukaryotes: Protozoa, Crustacea, Nematodes, Rotifers
- Virus: Bacteriophage

2) Most of them are held together within flocs by naturally produced organic polymers (EPS) and electrostatic forces.
### Primary consumers of organic waste: heterotrophic bacteria

(Generic parameters at 20 °C).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limiting substrate</td>
<td>( \text{BOD}_L )</td>
</tr>
<tr>
<td>( Y ) (true yield for synthesis)</td>
<td>0.45 mg VSS(_a)/mg BOD(_L)</td>
</tr>
<tr>
<td>( \dot{q} ) (substrate utilization)</td>
<td>20 mg BOD(_L)/mg VSS(_a) - d</td>
</tr>
<tr>
<td>( \mu = Y q ) (maximum specific growth rate)</td>
<td>9 d(^{-1})</td>
</tr>
</tbody>
</table>
| \( K \) (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                                       |
| \( \theta_d^{\text{min}} \) (value at which washout begins) | 0.11 d  
safety factor 100 \( \rightarrow \) 11 d  
safety factor 36 \( \rightarrow \) 4 d |
| \( S_{\text{min}} \) (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 |
Most of the other organisms are secondary consumers that feed off of materials released by the primary consumers:

- by-products of BOD degradation
- by-products 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 ($\text{NH}_4^+$, $\text{NO}_2^-$, $\text{S}^-$, and $\text{Fe}^{+2}$).
6.1.1 Microbial Ecology

• Changes in the species composition and physical characteristics take place over time:

  i) There is great competition between microorganisms for the various energy resources available in waste mixtures.

  ii) Changes to the inputs and environmental conditions (Temp, SRT, DO, pH, inhibitory chemicals, nutrient availability, fluid shear, etc.)

  iii) Death of some species caused suddenly by bacteriophage or by predation.

  iv) 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").
6.1.1 Microbial Ecology

- 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 tends to maintain consistently low substrate concentrations, while PFR tends 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 (O₂) have concentrations well above their half-saturation concentration, or K. \[ \frac{S}{(K+S)} = \sim 1 \text{ in Monod eq} \] when s is high enough.

- For example, Dissolved oxygen: K < 1 mg/L, If DO > 2 mg/L, then O₂ 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 ($\theta_x$) is commonly used to control not only i) treatment efficiency of wastewater but also ii) sludge physical and biological characteristics.

1) A longer SRT provide a greater degree of substrate removal.

$$ S = K \frac{1 + b \theta_x}{\theta_x (Y q - b) - 1} \quad [5.39] $$

2) SRT affects SMP concentration in a nonlinear manner.

$$ UAP = - \frac{(q_{UAP} X_a \theta + K_{UAP} + k_{1 ut} \theta)}{2} + \frac{\sqrt{q_{UAP} X_a \theta + K_{UAP} + k_{1 ut} \theta}^2 - 4 K_{UAP} k_{1 ut} \theta}{2} \quad (3.38) $$

$$ BAP = - \frac{(K_{BAP} + (q_{UAP} - k_2) X_a \theta)}{2} + \frac{\sqrt{(K_{BAP} + (q_{BAP} - k_2) X_a \theta)^2 + 4 K_{BAP} k_2 X_a \theta}}{2} \quad (3.39) $$
6.1.3 Impacts of Solids Retention Time

3) Altering the SRT can lead to changes in sludge physiology such as settling characteristics, EPS production, etc.

4) For various reasons, a long SRT often is not beneficial, even if the substrate conc. can be driven lower.
   - $\theta_x$ is generally limited to a range between 4 to 10 days when BOD removal and economics are to be balanced.
   - high $\theta_x$ leads to poorer suspended solids capture and thus overall removals of BOD deteriorate.
a) Pin-point floc  
b) Normal floc  
c) Bulking floc (filamentous bacteria)
6.1.3 Impacts of Solids Retention Time

- 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 form 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.
• 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 Arden & Lockett first discovered it.
  - The designer can select combinations from the three different categories.

### Table 6.1 Summary of activated sludge configurations

<table>
<thead>
<tr>
<th>A. Modifications Based on Physical Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Plug Flow (Conventional)</td>
</tr>
<tr>
<td>2. Step Aeration (step feeding)</td>
</tr>
<tr>
<td>3. Completely Mixed</td>
</tr>
<tr>
<td>4. Contact Stabilization</td>
</tr>
<tr>
<td>5. Activated Sludge with Selector</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Modifications Based on Oxygen Addition or Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Conventional Aeration</td>
</tr>
<tr>
<td>2. Tapered Aeration</td>
</tr>
<tr>
<td>3. Pure Oxygen</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Modification Based on Organic (BOD) Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Conventional</td>
</tr>
<tr>
<td>2. Modified Aeration</td>
</tr>
<tr>
<td>3. High Rate</td>
</tr>
<tr>
<td>4. Extended Aeration</td>
</tr>
</tbody>
</table>
6.2.1 Physical Configurations

- **a. Plug-flow (conventional) activated sludge**
- **b. Step-aeration activated sludge**
- **c. Complete-mix 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

1) Plug-Flow

- long narrow aeration tank
- *kinetic theory*: greatest contaminant removal within a defined treatment time
- *problems*: *high conc. of contaminants* at the head end of the aeration tank (Fig. 6.2)
  i) high rates of contaminant oxidation
     → complete depletion of dissolved oxygen (anoxic condition)
     → detrimental to microorganisms (organic acid production and a drop in pH)
  ii) industrial wastes contain substances that are inhibitory to the bacteria → slowing down or stopping the process
6.2.1 Physical Configurations

1) Plug-Flow

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.
2) 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

- Effect of step aeration
  i) mixed liquor suspended solids (MLSS) is highest at the inlet end
     since the full sludge recycle mixes with only part of the influent flow.
  ii) 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.
3) 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 never are exposed to the influent conc. ($S^0$) 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
4) Contact Stabilization

- High efficiency treatment reduces significantly total reactor volume.

i) **Contact tank**: wastewater mixed with activated sludge, 
   \[ HRT = 15 \sim 60\text{min} \]
   → 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

ex) 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 $\theta_x = \frac{8,000}{1,000} = 8 \text{ d.}$

8,000 kg MLSS in one tank : 100%

2,000 kg MLSS : 25%

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

If the reactor volume is $100 \text{ m}^3$
for a conventional activated sludge system,

then, required reactor volume for contact stabilization
$= 25 + \frac{75}{4} = 43.8 \text{ m}^3$
Disadvantage of Contact Stabilization:

i) requires substantially more operational skill and attention

ii) two mixed liquors need to be monitored, and both results are necessary to compute the SRT.

iii) the small volume of the contact tank makes the effluent quality susceptible to sudden increases in loading
5) 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.)

1) 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).

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

3) Fortunately, the bacteria able to store these materials also are good at forming compact sludge floc.
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:
  1) HRT, SS, ↔ BOD$_5$ removal
  2) Organic loading, MLSS, Oxygen supply ↔ BOD$_5$ removal
  3) MLSS → MLVSS
6.3 F/M ratio

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

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

\[
F / M = \frac{Q^O S^O}{VX} \quad [6.1]
\]

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 F/M ratio

- If volatile SS are used.

\[
F / M_v = \frac{Q^o S^o}{V X_v}
\]  \[6.2\]

- For a conventional design for the activated sludge treatment of domestic sewage,

The F/M ratio suggested is 0.25 ~ 0.5 kg BOD / kg MLSS•d

* 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 / kg MLSS•d

- High-rate treatment : 1 ~ 4 kg BOD / kg MLSS•d

Extended-aeration : 0.12 ~0.25 kg BOD / kg MLSS•d

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

X_v = volatile suspended solids concentration in aeration tank (mg/l)
6.3  \textbf{F/M ratio}

\begin{itemize}
  \item \textit{Substrate mass balance} using \textit{Monod} relationship.

  \begin{equation}
  0 = -\frac{\hat{q}S}{K+S}X_aV + Q(S^O - S)
  \end{equation}  \hspace{1cm} [3.17]

  \hat{q} = \text{maximum specific rate of substrate utilization (Ms/L}^3 \text{T)}

  K = \text{the Monod half-maximum-rate constant (Ms/L)}

  \begin{equation}
  \frac{\hat{q}S}{K+S}X_a = \frac{Q^O(S^O - S)}{V}
  \end{equation}  \hspace{1cm} [6.3]

  \begin{equation}
  \frac{Q^O S^O}{VX_a} = S \left( \frac{\hat{q}}{K+S} + \frac{Q^O}{VX_a} \right)
  \end{equation}  \hspace{1cm} [6.4]

  \item When S is small, left $>>$ right term

  \begin{align*}
  \text{F/M}_a & \quad K + S \sim K
  \end{align*}
\end{itemize}
6.3 F/M ratio

\[
\frac{Q^O S^O}{VX_a} = S \left( \frac{\hat{q}}{K + S} + \frac{Q^O}{VX_a} \right) \tag{6.4}
\]

\[
F / M_a = \frac{\hat{q}}{K} S \tag{6.5}
\]

\[
S \approx \frac{K}{\hat{q}} \cdot F / M_a \tag{6.6}
\]

- Thus, for the usual case in which we have high treatment efficiency and a low effluent BOD concentration,

\[S^e \text{ is directly related to } F / M_a\]

- However, \(M_a\) is almost impossible to measure, which breaks the connection between a measurable \(M_a\) and \(S\).
6.3 F/M ratio

- S can be estimated if we know the Ma,

\[
S \approx \frac{K}{\hat{q}} \cdot \frac{F}{M_a} \tag{6.6}
\]

\[
K = 4 \text{ mgBOD}_5 / l
\]

\[
\hat{q} = 10 \text{ kgBOD}_5 / \text{kgVSS}_a \cdot d
\]

\[
\frac{K}{\hat{q}} = 0.4 \text{ mg} \cdot d / l
\]

\[
\frac{F}{M} = 0.5 \text{kgBOD}_5 / \text{kgMLSS} \cdot d
\]

\[
F \quad M_a = 0.3 \quad M (Ma = 30\% \text{ of } \text{MLSS})
\]

\[
S = 0.4 \times 0.5 = 0.2 \text{mg} / l
\]

\[
S = 0.4 \times 1.7 = 0.67 \text{ mg} / l
\]

- The units of F/M (\( \frac{\text{kgBOD}_5}{\text{kgMLSS} \cdot d} \)) are almost the same as \( \hat{q} \) (\( \frac{\text{kgBOD}_5}{\text{kgVSS}_a \cdot d} \)).

To have a good safety factor, we must have the ratio be far less than one.

\[
\frac{F}{M} / \hat{q} < 1, \quad F / M < \hat{q}
\]
6.3.3 Solids Retention Time

**Definition**

\[
\theta_x = \frac{XV}{Q^e X^e + Q^w X^w}
\]  \[6.7\]

- \(V\) = system volume \([\text{L}^3]\),
- \(Q^e\) = effluent flow rate \([\text{L}^3\text{T}^{-1}]\)
- \(Q^w\) = waste-sludge flow rate \([\text{L}^3\text{T}^{-1}]\)
- \(X, X^e, X^w\) = the concentrations of mixed-liquor, effluent, and waste sludges in **consistent mass units**, which can be **active volatile solids**, **volatile solids**, or **suspended solids**.

*All the parameters that comprise eq 6.7 can be measured accurately and consistently.*
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 $\theta_x$.

- Being able to use SS and VSS, which are simply and routinely measured, to estimate $\theta_x$ is a major practical advantage.

- Typical values of $\theta_x = 4 \sim 10$ d

- Extended aeration units generally have much longer $\theta_x$ in the range of 15 to 30 d, and sometimes longer.

- The modified aeration process has a short $\theta_x$ in the range of 0.2 to 0.5 d.
6.3.3 Solids Retention Time

- Solids Retention Time, $\theta_x$, 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.

$$\theta_x = \frac{\text{active biomass in the system}}{\text{production rate of active biomass}} = \mu^{-1} \quad [3.22]$$

$$\mu = Y \frac{q S}{K + S} - b \quad [3.9]$$
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 $\theta_x$ of 4 to 10 d originated.

- $\theta_x$ 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

- This important direct relationship between effluent SS and effluent BOD forms *one basis* upon which the typical designs leading to a $\theta_x$ of 4 to 10 d originated.

- At lower values of $\theta_x$: Bacterial flocs tend to disperse, and effluent SS concentrations are fairly high

- At longer $\theta_x$ values: Bacterial flocs also tend to break up and disperse

✓ This may be related to reduced percentage of active bacterial population,
  which through polymer production tend to hold the individual particles together in floc,
  or to the destruction of the floc through the action of predatory populations of protozoa, rotifers, and nematodes
6.3.3 Solids Retention Time

✓ Floc break up is often noted to begin with $\theta_x$ greater than 8 d at temperature of 20 °C, or at some longer times with lower temperature.

✓ Thus, the $\theta_x$ 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.
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 acids which can be a problem in low-alkalinity waters.

\[
\frac{1}{6} NH_4^+ + \frac{1}{4} O_2 = \frac{1}{6} NO_2^- + \frac{1}{3} H^+ + \frac{1}{6} H_2O \quad [9.1]
\]

\[
\frac{1}{2} NO_2^- + \frac{1}{4} O_2 = \frac{1}{2} NO_3^- \quad [9.2]
\]
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.

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 Eq. 6.7?

$$\theta_x = \frac{XV}{Q^e X^e + Q^w X^w} \quad [6.7]$$

$V =$ system volume [L$^3$],

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

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

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

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

- **What XV to use for 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 $\theta^d_x$ values for various activated sludge process modifications

<table>
<thead>
<tr>
<th>Process Modification</th>
<th>Volumetric $\text{kg BOD}_5/\text{m}^3\cdot\text{d}$</th>
<th>MLSS $\text{mg/l}$</th>
<th>$F/Mv$ $\text{kg BOD}_5/\text{kg }X_v\cdot\text{d}$</th>
<th>Typical BOD$_5$ Removal Efficiency</th>
<th>Typical $\theta^d_x$ $\text{d}$</th>
<th>Safety Factor$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended Aeration</td>
<td>0.3</td>
<td>3,000–5,000</td>
<td>0.05–0.2</td>
<td>85–95$^B$</td>
<td>&gt;14</td>
<td>&gt;70</td>
</tr>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>0.6</td>
<td>1,000–3,000</td>
<td>0.2–0.5</td>
<td>95</td>
<td>4–14</td>
<td>20–70</td>
</tr>
<tr>
<td>Tapered Aeration</td>
<td>0.6</td>
<td>1,000–3,000</td>
<td>0.2–0.5</td>
<td>95</td>
<td>4–14</td>
<td>20–70</td>
</tr>
<tr>
<td>Step Aeration</td>
<td>0.8</td>
<td>1,000–3,000</td>
<td>0.2–0.5</td>
<td>95</td>
<td>4–14</td>
<td>20–70</td>
</tr>
<tr>
<td>Contact Stabilization</td>
<td>1.0</td>
<td>A</td>
<td>0.2–0.5</td>
<td>90</td>
<td>4–15</td>
<td>20–75</td>
</tr>
<tr>
<td>Modified Aeration</td>
<td>1.5–6</td>
<td>300–600</td>
<td>0.5–3.5</td>
<td>60–85$^B$</td>
<td>0.8–4</td>
<td>4–20</td>
</tr>
<tr>
<td>High-Rate Aeration</td>
<td>1.5–3</td>
<td>5,000–8,000</td>
<td>0.2–0.5</td>
<td>95</td>
<td>4–14</td>
<td>20–70</td>
</tr>
</tbody>
</table>

* Assumed value of growth coefficients: $Y = 0.65 \text{ g cells/g BOD}_5$, $b = 0.15 \text{ d}^{-1}$.

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$_5$.


$\theta^d_x = \text{design value for } \Theta_x$

F/Mv ratio is inversely proportional to the SRT.

designed very conservatively, SRT: 25–50 d, sometimes even larger.
6.3.5 MLSS, the SVI and the Recycle Ratio

- **Choice of mixed-liquor suspended solids concentration (X)**
  - X depends upon many factors:
    1. the settling characteristics of activated sludge
    2. the rate of recycle of sludge from the settling tank back to the aeration tank
    3. the design of the settling tank

- **If a high value for X in the aeration occurs,**
  - **Advantage:**
    - lead to smaller aeration basin, which translate into lower construction cost
  - **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’)

\[ Q^i X = Q^e X^e + Q^s X^s \quad [6.10] \quad \rightarrow \quad Q^i X = Q^s X^s \quad (X^e \rightarrow 0) \quad \rightarrow \quad X^r = X^s \quad [6.11] \]

\[ Q^r = Q^s \quad (Q^w \rightarrow 0 \ll Q^r) \quad \rightarrow \quad X^r = X^s = X^w \]

- A mass balance on suspended solids around control volume ‘b’

\[ Q^i = Q^0 + Q^r \quad \rightarrow \quad R = \frac{Q^r}{Q^0} \quad \rightarrow \quad X = X^r \frac{R}{1 + R} \quad \text{or} \quad R = \frac{X}{(X^r - X)} \quad [6.12] \]

Figure 6.1  Total suspended solids flow within a complete-mix activated sludge system
6.3.5 MLSS, the SVI and the Recycle Ratio

- $X^r_m$ and SVI
  - Because of sludge settling characteristics, the recycled sludge has upper limit of the recycled sludge ($= X^r_m$)

  \[ X = X^r \frac{R}{1 + R} \quad [6.12] \quad \Rightarrow \quad X_m = X^r_m \frac{R}{1 + R} \quad [6.14] \]

  $X_m$: Maximum of $X$

  \[ X^r_m = 10,000 \sim 14,000 \text{ mg/L for typical good-settling activated sludge} \]
  \[ = 3,000 \sim 6,000 \text{ mg/L for bulking sludges} \]

  - $X^r_m$ can be approximated through simple tests:
    1) the Settled Sludge Volume Test, 2) the Sludge Volume Index (SVI), 3) 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

\[
SVI (ml / gSS) = \frac{V_{30} \cdot (1,000 \text{mg/g})}{MLSS \cdot V_t} \quad [6.15]
\]

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

FIGURE 6.1 Variation of sludge volume index with concentration of biological solids.
6.3.5 Weak points of SVI

Figure 4-41. 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

- An approximation to the maximum concentration of settled sludge

\[
X_m^r = \frac{10^6 \text{ (mg} \cdot \text{ml/g} \cdot \text{l})}{\text{SVI (ml/g)}}
\]

- **SVI and** \(X_m^r\) **with sludge type**

<table>
<thead>
<tr>
<th>sludge type</th>
<th>SVI (ml/g)</th>
<th>(X_m^r) (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical good sludge</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>Bulking sludge</td>
<td>&gt;200</td>
<td>&lt; 5,000</td>
</tr>
<tr>
<td>Highly compact and good-settling sludge</td>
<td>&lt; 50</td>
<td>&gt; 20,000</td>
</tr>
</tbody>
</table>
6.3.5 MLSS, the SVI and the Recycle Ratio

- The effect of the recycle ratio on $X_m$ for various of $X_m$ of

1. **<Good sludge>**

   $X_m^r = 10,000\,\text{mg/l}$ and $X = 2,000\,\text{mg/l}$
   
   $R = 0.25$

2. **<Bulking sludge>**

   $X_m^r = 2,500\,\text{mg/l}$ and $X = 2,000\,\text{mg/l}$

   $R = 4$

3. **<Good sludge>**

   $R = 0.7$ and $X = 4,000\,\text{mg/l}$

   $X_m^r = 10,000\,\text{mg/l}$

4. **<Bulking sludge>**

   $X_m^r = 5,000\,\text{mg/l}$ and $X = 4,000\,\text{mg/l}$

   $R = 4$
## 6.5 Bulking and Other Sludge Settling Problems

### Table 6.3: Biosolids separation problems encountered in activated sludge operation

<table>
<thead>
<tr>
<th>Biosolids Separation Problem</th>
<th>Cause of Problem</th>
<th>Effect of Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulking</td>
<td>Filamentous organisms extend from flocs into the bulk solution and interfere with compaction and settling</td>
<td>High sludge volume index with clear supernatant. Overflow of sludge blanket can occur. Solids handling processes become hydraulically overloaded</td>
</tr>
<tr>
<td>Viscous bulking or nonfilamentous bulking</td>
<td>Microorganisms present in large amounts of exocellular slime. In severe cases, the slime imparts a jelly-like consistency</td>
<td>Reduced settling and compaction rates. Can result in overflow of sludge blanket from secondary clarifier or formation of a viscous foam</td>
</tr>
<tr>
<td>Dispersed growth</td>
<td>Microorganisms do not form flocs, but are dispersed, forming only small clumps or single cells</td>
<td>Turbid effluent. No zone settling of sludge</td>
</tr>
<tr>
<td>Pin floc or pinpoint floc</td>
<td>Small, compact, weak, roughly spherical flocs. Larger aggregates settle rapidly, smaller ones slowly</td>
<td>Low sludge volume index and cloudy turbid effluent</td>
</tr>
<tr>
<td>Foaming/Scum formation</td>
<td>Caused by (i) nondegradable surfactants, or (ii) the presence of <em>Norcardia</em> sp. and/or <em>Microthrix parvicella</em></td>
<td>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</td>
</tr>
<tr>
<td>Blanket rising</td>
<td>Denitrification in settler releases poorly soluble N₂ gas, which attaches to activated sludge flocs and floats them to the clarifier surface</td>
<td>&quot;Chunks&quot; of activated sludge collect on the surface of the settler and may result in turbid effluent</td>
</tr>
</tbody>
</table>

**Jenkins (1992)**: different solids separation problems

---

6.5.1 Bulking Sludge

- Bulking sludge

**Bulking**: 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

**Difficult in fast removal of the sludge**

- Sludge blanket rising

**Activated sludge solids in the effluent**

- Massive loss of biomass
- Decrease the SRT in uncontrolled manner
- Destroying effluent SS and BOD quality

**Total failure of the activated sludge process**
6.5.1 Bulking Sludge

- Formation of Sludge bulking
  
  Floc microstructure with backbone of filamentous bacteria for strong and compact macrostructure

  Too many filamentous bacteria outside the compact floc extended filaments create bridge 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 $\gg 500$ mg/L
  - Rising sludge blanket and a low concentration of suspended solids in the settler underflow
6.5.1 Bulking Sludge

- **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 $K$) and a low endogenous decay rate (low $b$).

  - **Reduced–sulfur bulking** by filamentous bacteria (sulfur-oxidizing species, *Thiothrix*) that gain a competitive advantage from the chemolithothrophic electron donor (reduced sulfur compounds).
6.5.1 Bulking Sludge

- **Low-F/M bulking**
  - Long SRT such as extended aeration
  - *Microthris parvicella*, 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 H₂O₂ x 4 = 136g
32g/ M S⁻ x 1 = 32g
→ 4.25 g H₂O₂ 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 NO₃⁻) concentration is needed to prevent sulfate reduction
Formation of foam or scum on the surface of aeration tanks

Problem - Excessive suspended solids in the effluent
- 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
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 $\rightarrow$ No $N_2$ gas by denitrification)

- reduce SRT and wash out the slow-growing nitrifiers

- promote denitrification as part of the activated sludge process
  $\rightarrow$ 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: 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.

Thus the community becomes less and less enriched in the good floc formers that are needed if polymer addition is to be stopped.