Lecture 3

Process design concept and procedures

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Presentation Menu

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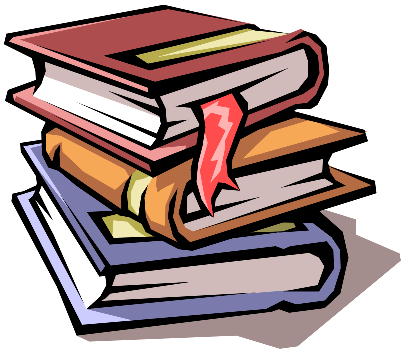
- Process variations



Introduction

Biological wastewater treatment

Processes	**Systems**
Aerobic	**Activated sludge** (suspended growth)
Facultative	Biofilm (attached growth)
Anoxic	Pond system
Anaerobic	Natural system
	Hybrid system

Terminology and Microbial Systems

Nutrients

- Chemical elements utilized for cell synthesis
- Macronutrients – C, O, H, N, P, S
- Micronutrients – Fe, Ca, Mg, K, Mo, Zn, Co
- In practice, nutrients are mainly – N & P
- N & P – contribute to eutrophication of surface waters

Terminology and microbial systems

Substrate

Group of microorganisms	Type of substrate	Examples
Photoautotrophs	Light	Green algae, bluegreen algae, colored sulfur bacteria
Photoheterotrophs	Light	Colored non-sulfur bacteria
Lithotrophs (chemoautotrophs)	Inorganics – NH^{4+} , NO_2^-, Fe^{2+}, Mn^2 , H_2S, S, $S_2O_3^{2-}$	Nitrifiers, iron bacteria, manganese bacteria, thiobacteria
Organotrophs	Organic matter	Bacteria, fungi, yeasts
Mixotrophs	Inorganic and organic compounds and occasionally light	Euglena, chlorococcal algae, Thiothrix

Terminology and Microbial Systems

Oxygen

- Functions of oxygen in bioprocess:
  - Electron acceptor
  - Nutrient
- Under anoxic and anaerobic, oxygen is nutrient
- Traditional understanding: Based on the concept of the available oxygen
- **Oxic** (or commonly aerobic) - source of oxygen is molecular, i.e. DO
- **Anoxic** - source of oxygen is chemically bound in nitrates and nitrites
- **Anaerobic** - source of oxygen is chemically bound in sulfate, carbonate, inorganics etc.

Terminology and microbial systems

Classification of conditions in regard to the electron acceptor

Processes	O_2	NO_3, NO_2	Others
Oxic	Y	-	-
Anoxic	N	Y	-
Anaerobic	N	N	Y

Y = Present and utilized
N = Not present
Not utilized, presence is not important to electron transfer

Terminology and microbial systems

Classification of cultivation conditions according to oxidation-reduction potential

ORP mV: 500, 400, 300, 200, 100, 0, -100, -200, -300, -400, -500

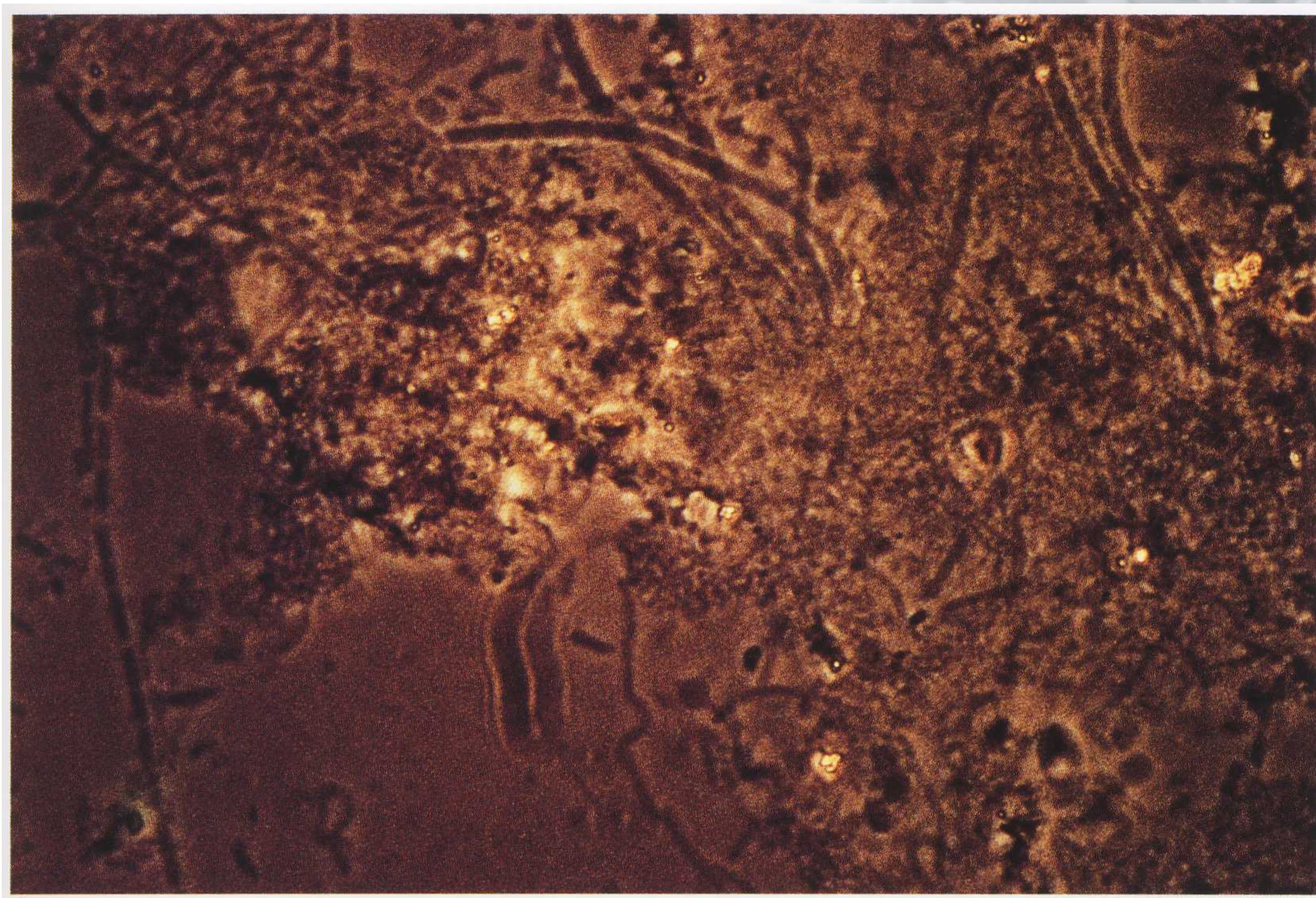
Process	Electron acceptors	Conditions
1 2 3	Oxygen	Oxic
4	NO_3-N	Anoxic
5 6 7 8	C_{org} SO_4-S	Anaerobic

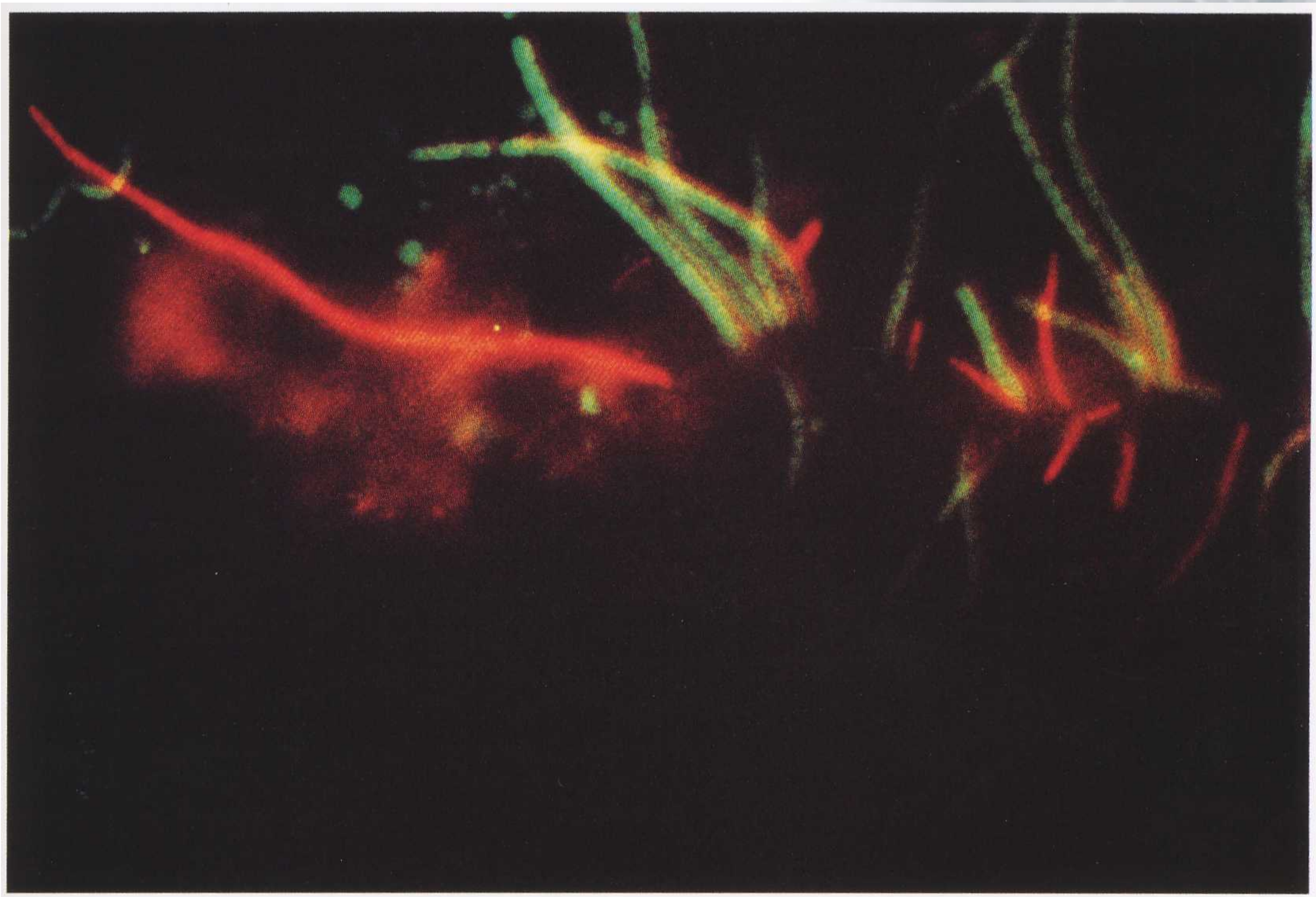
1-oxidation of organics; 2-accumulation of polyphosphates; 3-nitrification;4-denitrification; 5-depolymerization of phosphates; 6-desulfatation; 7-acido-and acetogenesis; 8-methanogenesis

Microorganisms and their activities

Population

- The most important is bacteria population – *Acinetobacter, Arthrobacter, Achromobacter, Alcaligenes, Bacillus, Citromonas, Chromobacterium, Flavobacterium, Flexibacter, Mircococcus, Pseudomonas* and *Zooglea*
- Others – fungi, protozoa, metazoa





Identification of bacteria

- Reaction based such as MPN
- Morphology such as light microscopy
- Molecular ecology such as DNA sequencing, flouresence in-situ hybridization (FISH), denaturing gel electrophoresis (DGGE)

Microorganisms and their activities

Heterotrophic Metabolism:- Organic Substrate Utilization

- Organic substrate is the source of energy for heterotrophic bacteria.
- It may not contain all nutrients necessary to support growth of cells
- Deficient nutrients have to be identified and added in necessary amounts (frequently nitrogenous or phosphorus compounds, less frequently iron and magnesium)

Microorganisms and their activities

Energy

- Energy is permanently required by a living cell, whether it grows or not, because the biochemical reactions important to support essential life activities cannot stop.
- Growing cells utilize exogenous substrate (that located outside the cell membrane) and exogenous additional nutrients as required for growth and energy:

Substrate + Nutrients ➔ Biomass + Energy

Microorganisms and their activities

Energy

- Energy gained from substrate is transformed, utilized and dissipated as heat
- Organisms have developed a number of biomechanisms enabling them to survive rather long periods without external substrate – otherwise the bacteria will die shortly without substrate
- Several pathways and biomechanisms enabling cells to survive have been identified

Microorganisms and their activities

Pathway for and biomechanisms enabling cells to survive

- Bacteria can store products rich in both energy and nutrients
- Some of the cell materials can serve several needs:

  - cell growth (if environmental and nutritional conditions are favorable)

  - internal sources of energy (endogenous substrate) during starvation period

Microorganisms and their activities

Accumulation

- Accumulation:- uptake of small molecules.
- Rate: Accumulation > Utilization (within the cells)
- Only small amount can be accumulated, because:

  - Low molecular weight (thus high osmotic pressure)

  - Require high energy to keep them inside the cell
- Accumulation represents an immediate short-term storage that the cells utilize only under rich nutritional conditions:- mono- and dissaccharides, lower fatty acids, alcohols, amino acids

Microorganisms and their activities

Storage

- Rate: Accumulation > Storage (within the cells)
- Storage:- chemical modification and restructuring of a variety of compounds into a few types of large molecules, representing storage materials with a negligible osmotic pressure
- Can be stored for a long period without significant energetic pressure
- Typical storage compounds:

  Polysaccharides, lipids such as polyhydroxybutyric acid (PHB) and polyphosphates

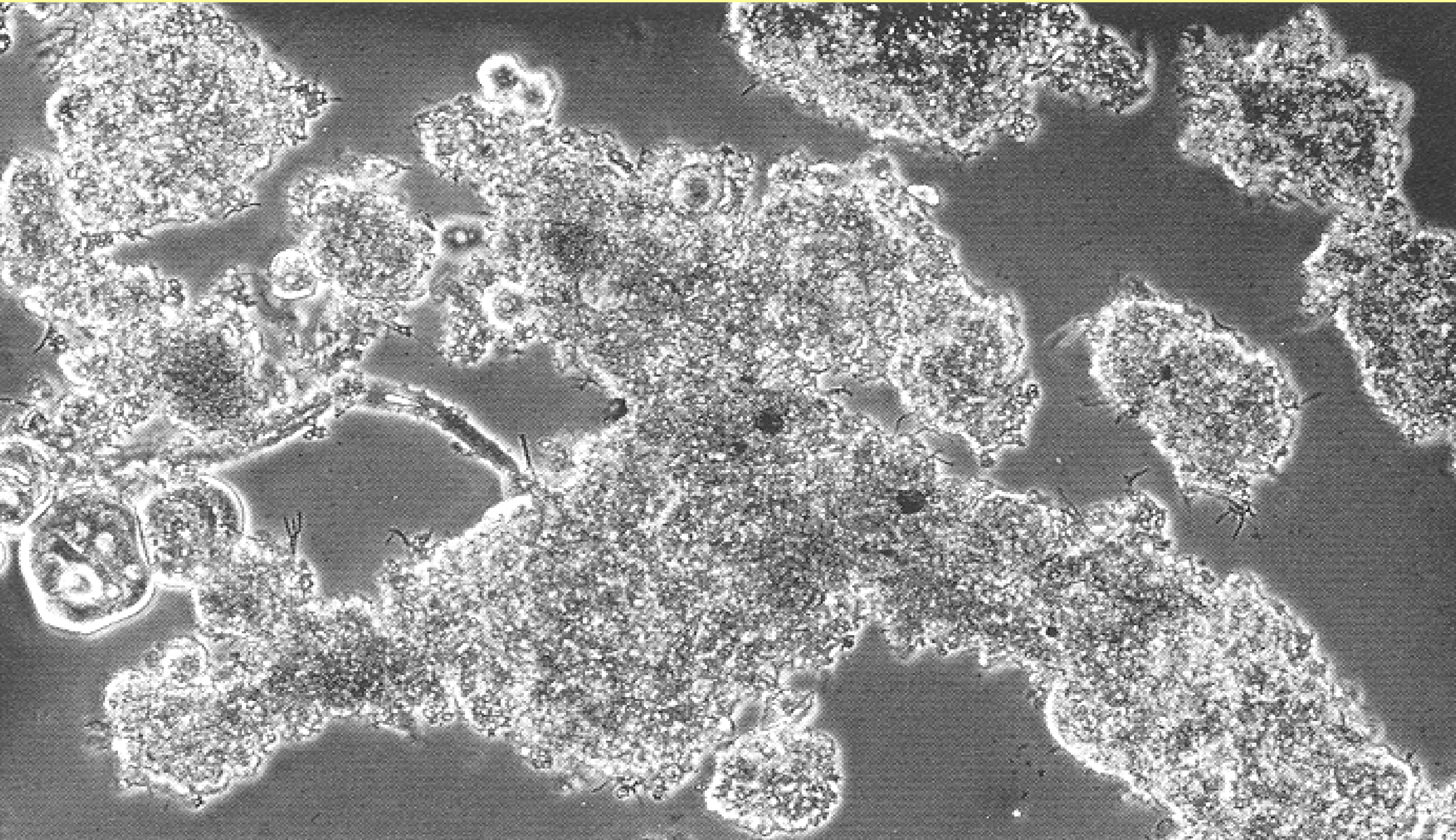
Microorganisms and their activities

Adsorption and enmeshment

- Solids in various size are available in wastewater
- Colloids adsorp on activated sludge flocs
- Larger particles are enmeshed in the spatial structure of the flocs
- Colloids and particles located on or close to the surface of bacteria:- accessible to hydrolyzing enzymes and subsequently utilized as substrate

Microorganisms and their activities

Adsorption and enmeshment



Microorganisms and their activities

Adsorption and enmeshment

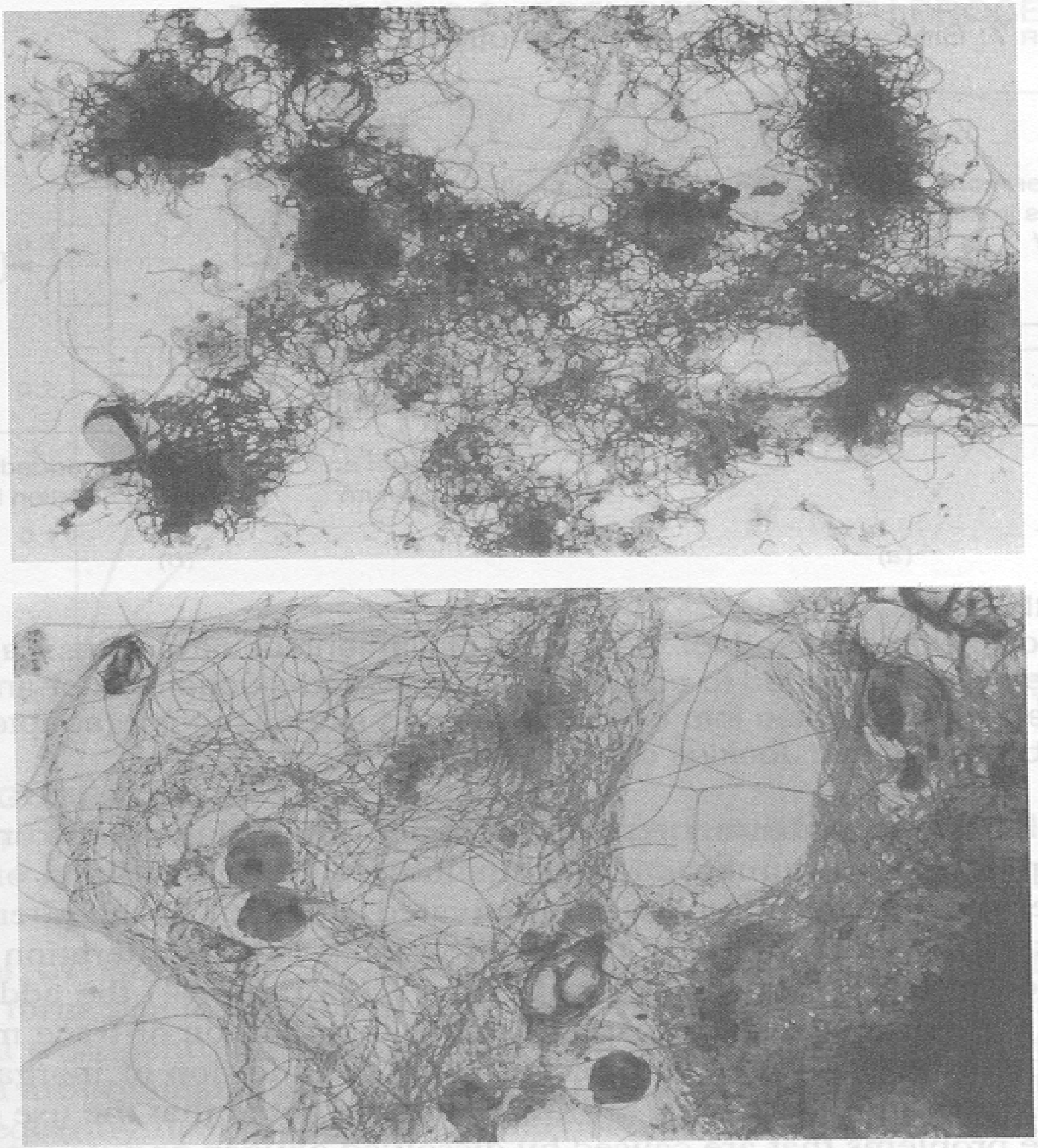


FIGURE 7-28
Typical examples of filamentous organisms that can develop in the activated-sludge process and affect the settleability of the MLSS.

Formation of flocs in activated sludge plants

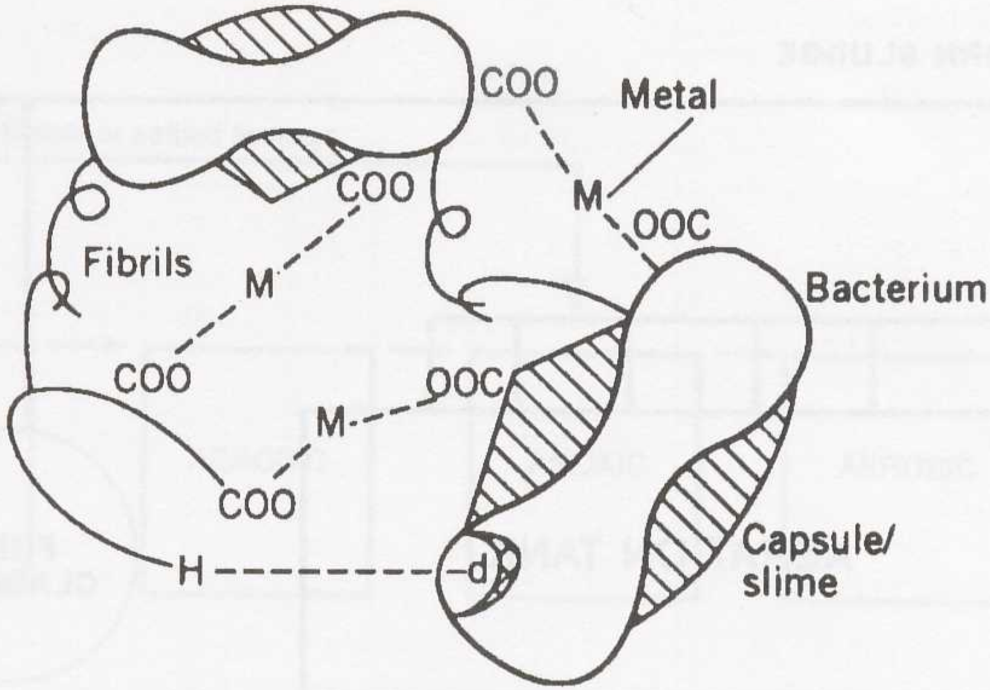


Figure 8.14 Possible structure of an activated sludge floc. From Forster and Dallas-Newton (1980). (Courtesy of the Water Environment Federation.)

Formation of flocs in activated sludge Plants

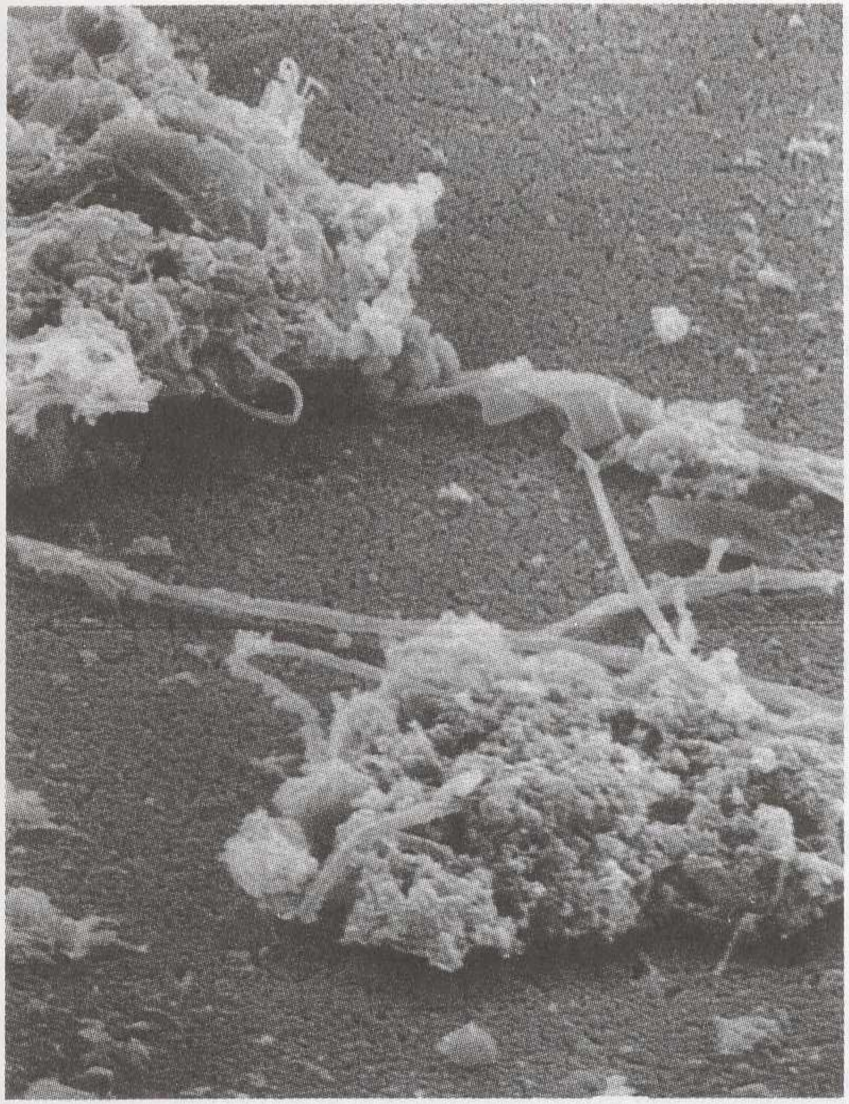


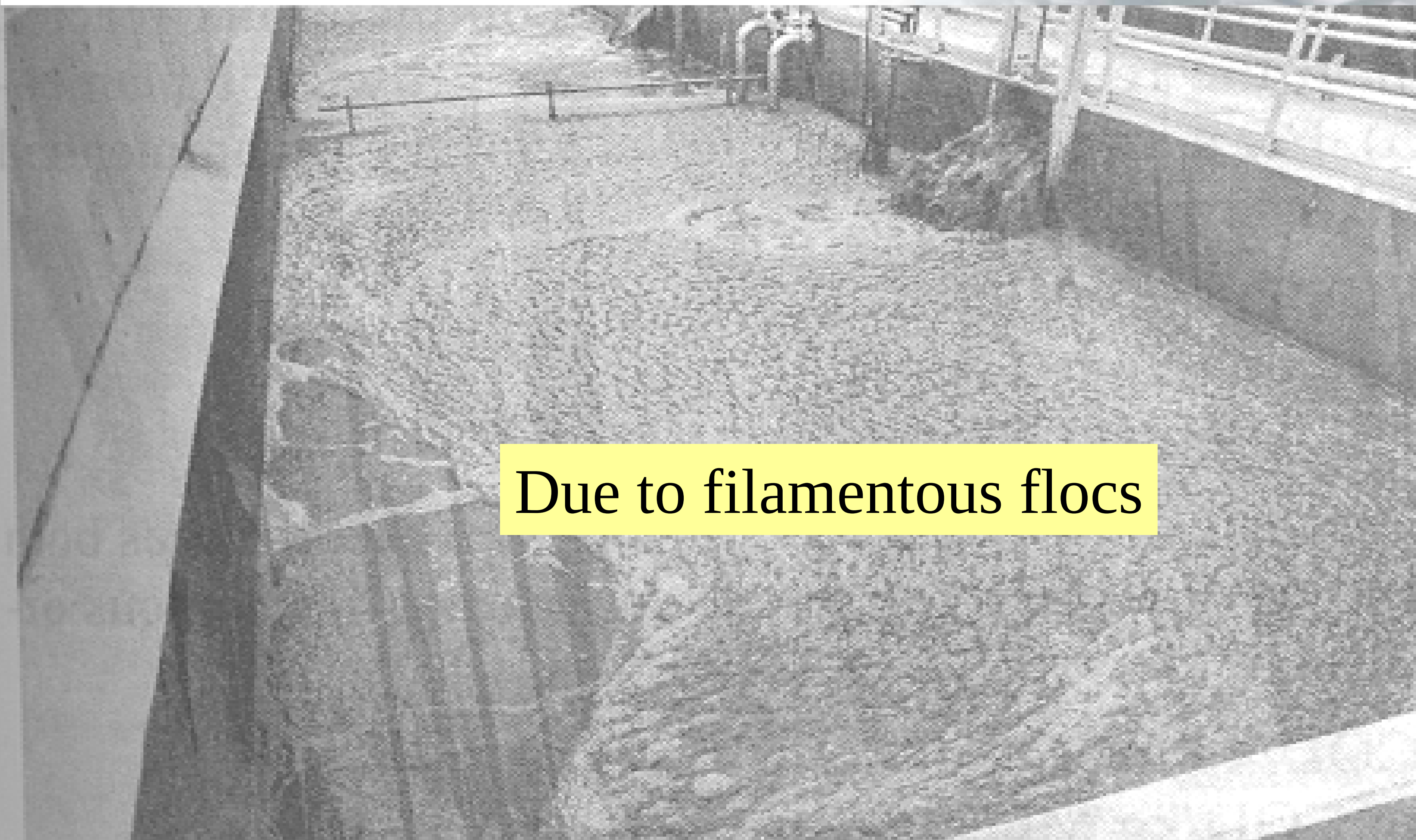
Figure 8.7 Activated sludge flocs observed by scanning electron microscopy. (Courtesy of R.J. Dutton and G. Bitton.)

Why flocs?

- Heavy enough for settling or solid liquid separation in secondary clarifier
- Entrapment of substrate and other components for floc stability
- Prove “protection” for the microorganisms within the floc
- Develop aerobic and anaerobic zones in the flocs

Microorganisms and their activities

Adsorption and enmeshment



Due to filamentous flocs

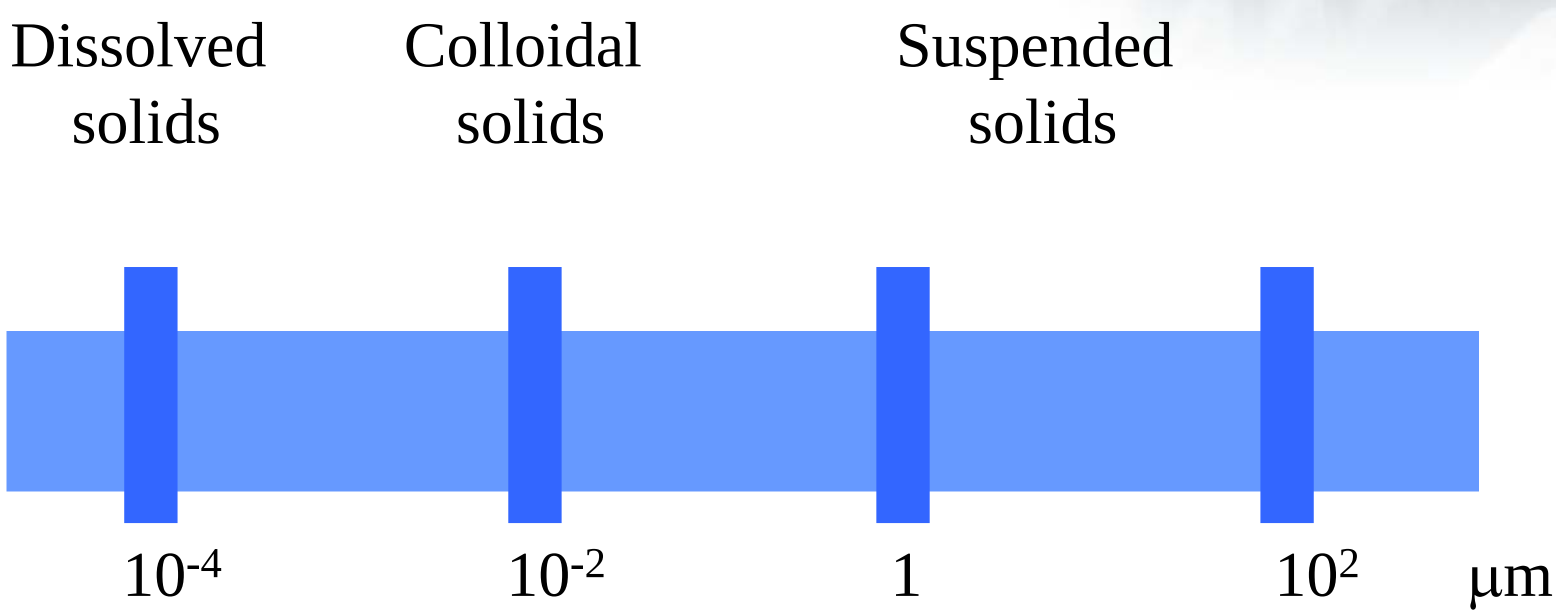
Microorganisms and their activities

Hydrolysis

- Kinetic behavior of surface-bound substrate (particle) is quite different from that of soluble substrates
- Rate: Absorption and enmeshment is very fast compared to hydrolysis
- Surface-bound substrate is slowly utilized by the cells through SRT and supplies them with soluble substrate (product of hydrolysis) at low concentrations
- This is typical for sewage: 15-30 mg/l of filterable solids in the range of 0.1-1.0 μm

Microorganisms and their activities

Hydrolysis



Microorganisms and their activities
Growth

- Definition: Synthesis of biomass indicated by increased concentration of materials, such as ATP
- Increase in weight is not a good measure for growth (because weight also include formed storage materials)
- Weight can substantially increase but with slow growth.
- In practice: weigh the biomass!!
- Concentration of biomass = mixed liquor volatile suspended solids (MLVSS)
- Primary concern: growth rate limitation

Microorganisms and their activities

Growth

$$\mu = \mu_{\max} \frac{S_n}{K_s + S_n}$$

$$\mu = \frac{dX}{Xdt}$$

μ = specific growth rate
μ_{max} = maximum specific growth rate
K_s = saturation rate constant
S_n = rate-limiting nutrient concentration
X = biomass concentration
t = time

Microorganisms and their activities

Growth for multiple substrates

$$\mu = \mu_{\max} \frac{S_{n1}}{K_{s1} + S_{s1}} \frac{S_{n2}}{K_{s2} + S_{n2}} \cdots \frac{S_{nn}}{K_{sn} + S_{nn}}$$

Index 1 to n refer to individual substrates/nutrients

Proportions between substrate utilized and biomass produced

$$S_o - S_t = Y_{obs}\left(X_t - X_o\right)$$

$$-\Delta S = Y_{obs}\Delta X$$

S = substrate concentration
X = biomass concentration
Y_{obs} = observed yield coefficient
$-\Delta S$ = substrate utilized
ΔD_x = biomass produced

- If the biomass crop is nutrient-limited, the smaller biomass increment ΔX results in lower substrate utilized, regardless of reaction time.
- Additional substrate for maintenance only
- Under nutrient-limiting, biomass concentration is limited (due to limited biomass crop due to nutrient deficiency) ➔ reduce substrate removal rate

Microorganisms and their activities

Decay

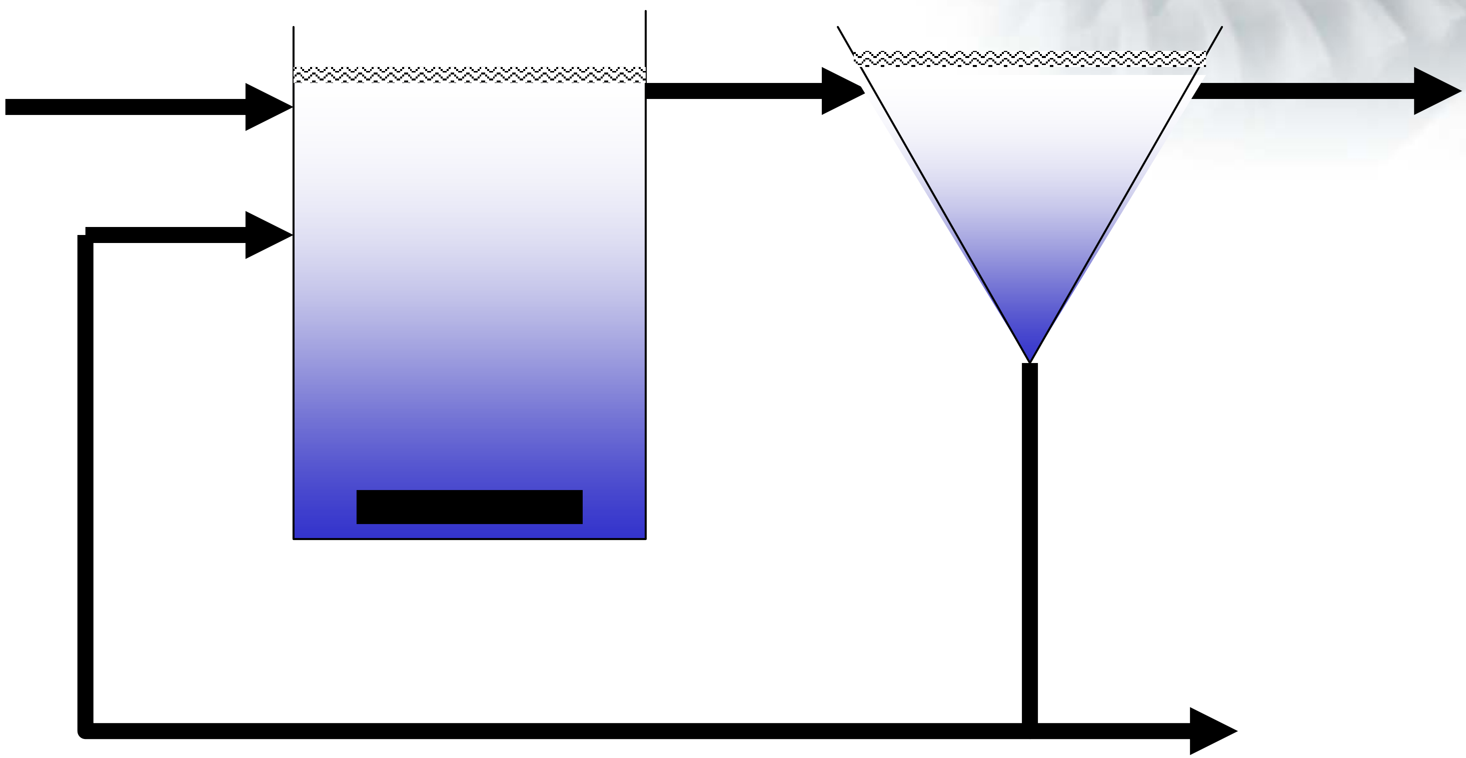
$$b = -\frac{dX}{Xdt}$$

$$\mu_{net} = \mu - b$$

b = specific decay rate
μ_{net} = total specific growth rate

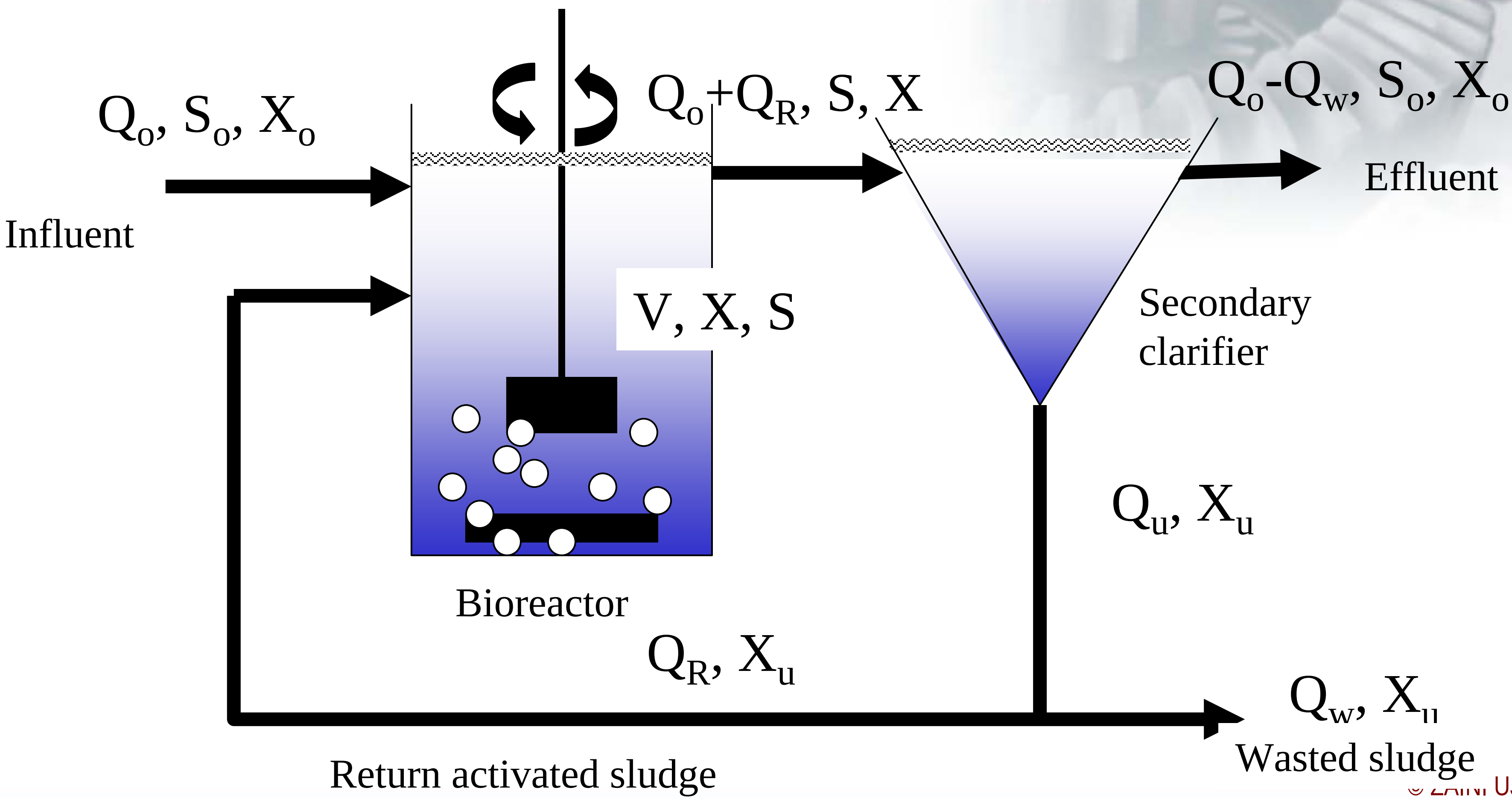
Process Theory

(i) Completely-mixed reactor
(ii) Plug-flow reactor



Process Theory

(i) Completely-Mixed Reactor



Mass Balance

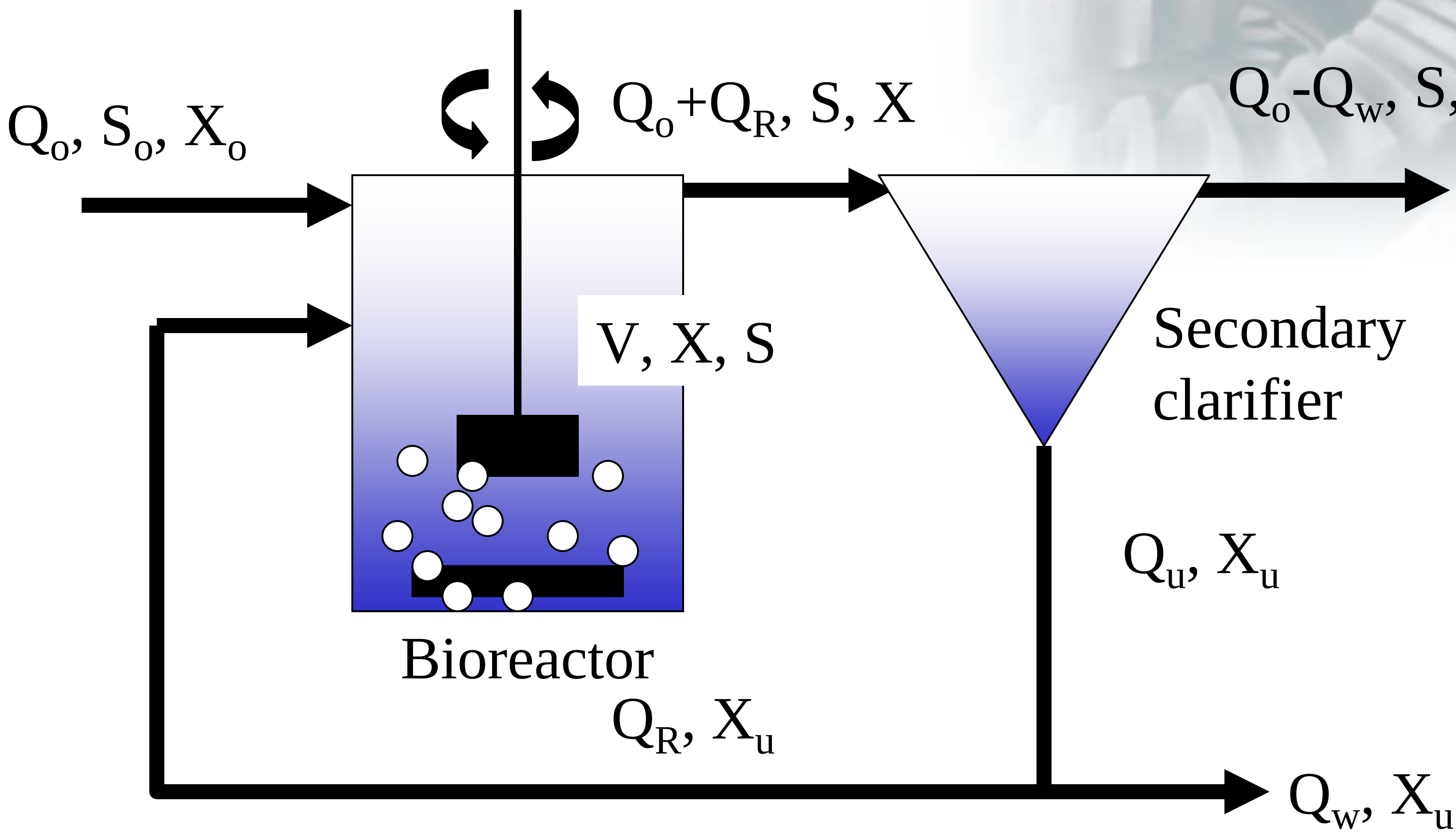
Biomass in + Biomass growth = Biomass out (effluent + wasted sludge)

Example:

100 in = 100 out

Process Theory

(i) Completely-Mixed Reactor



Mass Balance for Completely Mixed Reactor

Biomass in + Biomass growth = Biomass out

$$Q_o X_o + V\left(\frac{k_o XS}{K_s + S} - k_d X\right) = (Q_o - Q_w) X_e + Q_w X_u$$

Food in – Food consumed = Food out

$$Q_o S_o + V \frac{k_o SX}{Y(K_s + S)} = (Q_o - Q_w) S + Q_w S$$

Q_o, Q_r, Q_w = influent, return and waste-sludge flow rate, m^3/d
X_o, X, X_e, X_u = biomass concentration in influent, reactor, effluent, underflow, mg/l
S_o, S = soluble food concentration in influent and reactor, mg/l
V = volume, m^3
K_s = half saturation constant I.e. concentration of limiting food when $k = 0.5\ k_o$, mg/l
k_o = maximum growth rate constant, t^{-1}
k_d = endogenous decay rate constant, t^{-1}
Y = yield, i.e. decimal fraction of food mass converted to biomass

Assumptions

- Influent and effluent biomass X concentrations are negligible compared to biomass at other points in the system
- Influent food concentration S_o is immediately diluted to the reactor concentrations S because of the complete mix regime
- All reactions occur in the reactor, I.e. neither biomass production nor food utilization occurs in the clarifier
- Because of assumption (3) the volume represents the volume of reactor only

Mass balance

Biomass

$$Q_o X_o + V\left(\frac{k_o XS}{K_s + S} - k_d X\right) = (Q_o - Q_w) X_e + Q_w X_u$$

$$\frac{k_o S}{K_s + S} = \frac{Q_w X_u}{VX} + k_d$$

Mass balance

Food (Substrate)

$$Q_o S_o + V\frac{k_o S X}{Y(K_s + S)} = (Q_o - Q_w)S + Q_w S$$

$$\frac{k_o S}{K_s + S} = \frac{Q_o}{V}\frac{Y}{X}(S_o - S)$$

Monod terms

Mass balance

Combining biomass and food equations

$$\frac{Q_w X_u}{VX} = \frac{Q_o}{V}\frac{Y}{X}\left(S_o - S\right) - k_d$$

Solid retention time or sludge age: $\theta = \frac{V}{Q_o}$

Mass balance

Combining biomass and food equations

$$\frac{Q_w X_u}{VX} = \frac{Q_o}{V}\frac{Y}{X}(S_o - S) - k_d$$

Hydraulic retention time: $$\theta_c = \frac{VX}{Q_w X_u}$$

Mass balance

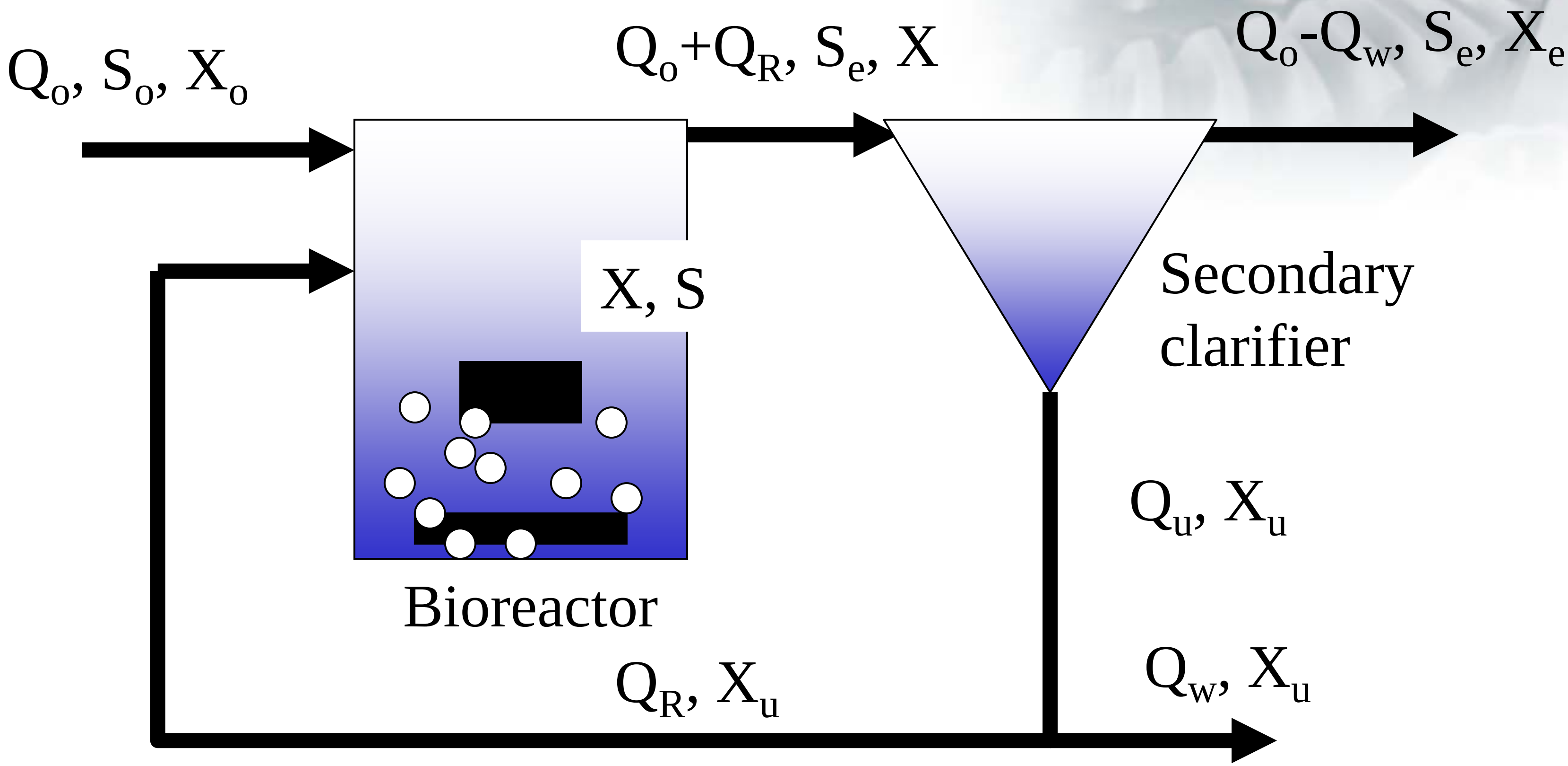
Combining biomass and food equations

$$\frac{1}{\theta_c} = \frac{Y(S_o - S)}{\theta X} - k_d$$

Mixed-liquor suspended solid: $$X = \frac{\theta_c Y(S_o - S)}{\theta(1 + k_d \theta_c)}$$

Process concept

(ii) Plug-flow reactor



Mass Balance for Plug-Flow Reactor

- Assuming complete mixing in the transverse plane but minimal mixing in the direction of flow, the mixture of wastewater and returned sludge travels as a unit through the reactor.
- Reaction kinetics for biomass production is similar to the batch process with the exception of an initially higher biomass concentration and lower food concentration because of sludge return.

Mass Balance for Plug-Flow Reactor

Average MLSS:

$$\bar{X} = \frac{\theta_c Y(S_o - S)}{\theta(1 + k_d \theta_c)}$$

Food utilization:

$$r_s = -\frac{k_o}{Y}\frac{S\,\bar{X}}{K_s + S}$$

$\bar{X}$ = average biomass concentration in the reactor.

Both equations are applicable only when $\theta_c/\theta \geq 5$

Mass Balance for Plug-Flow Reactor

Integrating the food utilization equation over detention time in the reactor and substituting the appropriate boundary conditions and recycle factor yields:

$$\frac{1}{\theta_c} = \frac{k_o(S_o - S)}{(S_o - S) + (1-\alpha)(K_s \ln S_i / S)} - k_d$$

Where α = recycle factor, Q/Q_r

S_i = concentration of substrate after mixing with recycled sludge, mg/l

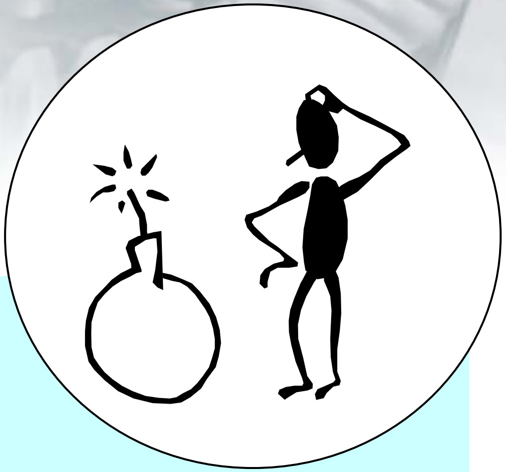
$$S_i = \frac{S_o + \alpha S}{1+\alpha}$$

Design considerations

- **Internal factors:**
  - Process variations
  - Reactors types
  - Technology know-how
- **External factors:**
  - Construction costs
  - Operation and maintenance difficulties and costs
  - Space limitations

Major Design Parameters

Activated sludge system



- Solid retention time (SRT)
- Organic loading rate (OLR)
- Food-to-Microorganism ratio (F/M)

Retention time

Activated sludge system

- Solid retention time (SRT)
- Hydraulic retention time (HRT)

SRT = ratio of the amount of biomass in inventory within the system to the growth rate of new microorganisms (R_g):

$$SRT = \frac{M}{R_g} days$$

HRT = the residence time for the liquid fraction in the bioreactor

$$HRT = \frac{Volume}{Flowrate}$$

Solid retention time

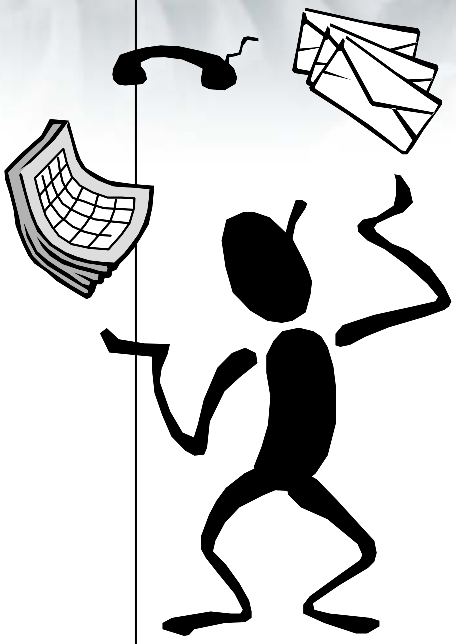
Within the limits, a longer SRT results in:

- **More efficient biodegradation**
- **Smaller reactor size**
- **Lower cost**

If SRT drops below the cell regeneration time, biomass will wash out faster than it forms new cells.

Rule-of-thumb (without experimental data):
SRT = 20-30 days with X < 5000 mg/L

Higher SRT » clarifier failure



Mass balance

Combining biomass and food equations

$$\frac{1}{\theta_c} = \frac{Y(S_o - S)}{\theta X} - k_d$$

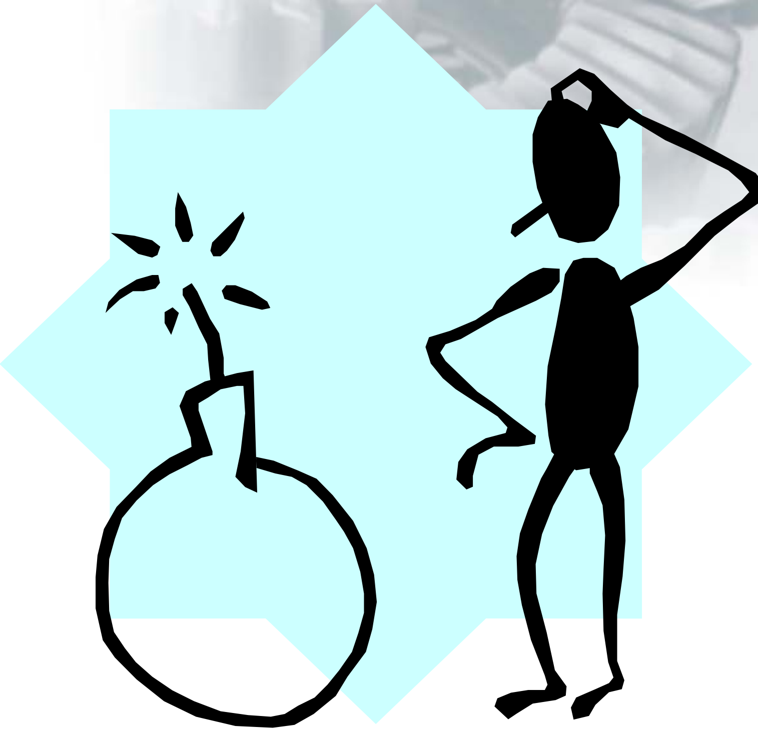
Mixed-liquor suspended solid: $$X = \frac{\theta_c Y(S_o - S)}{\theta(1 + k_d\theta_c)}$$

Biological waste treatment

- OLR = mass of BOD per day per unit volume
- OLR = kg BOD/d.m^3

F/M = amount of BOD applied per day per unit of biomass in the reaction basins

$$F/M = \frac{kgBOD/d}{kgM}$$

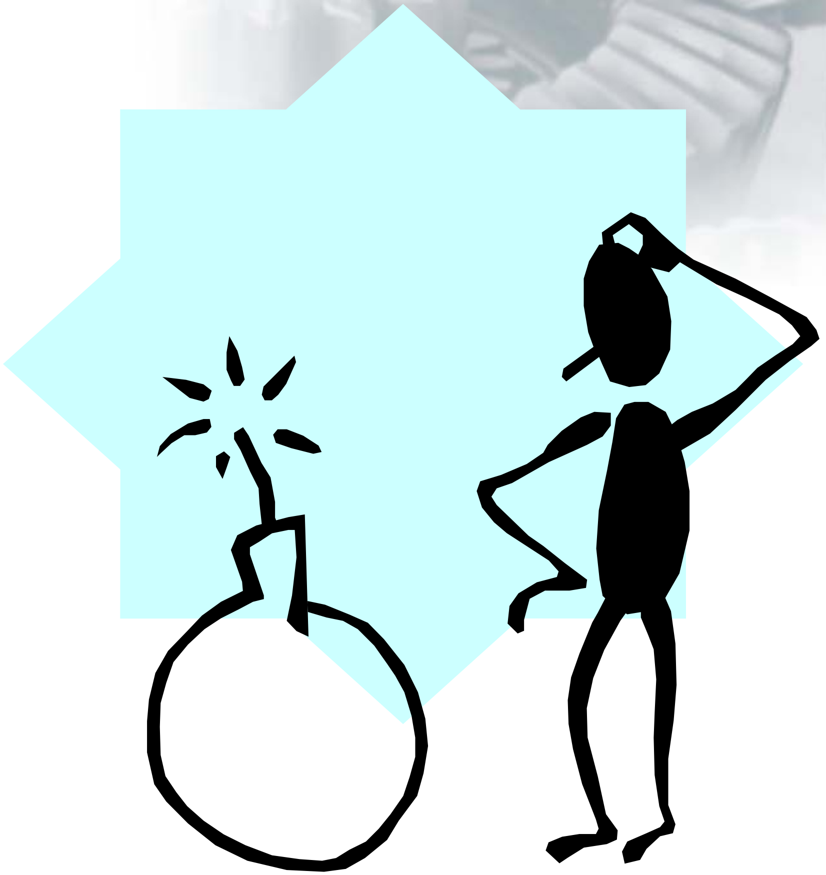


OLR = organic loading rate
F/M = food / microorganism

Engineering factor

Activated sludge system

- Electron acceptor
- Moisture
- Temperature
- pH
- Total dissolved solid
- Nutrients



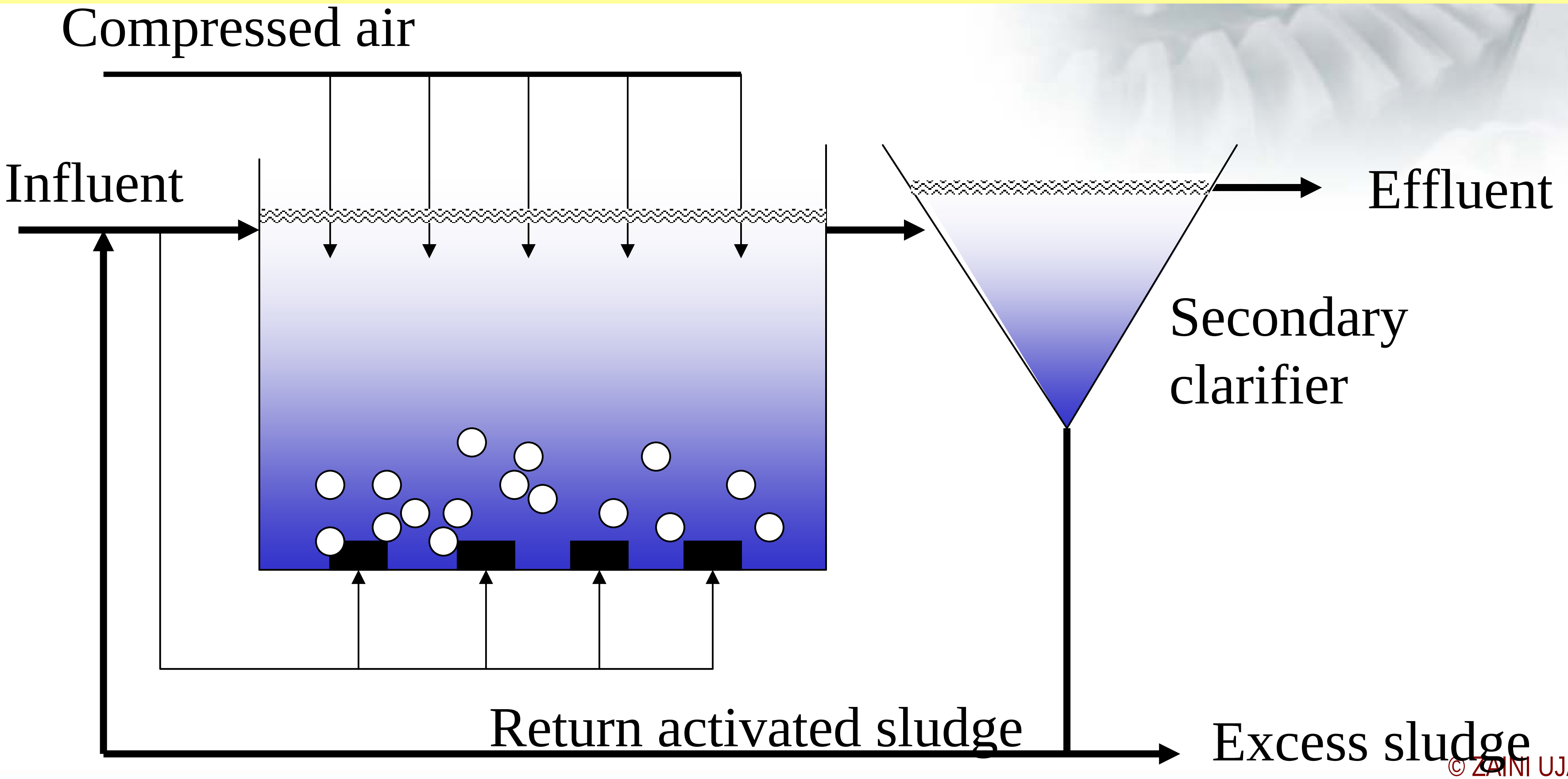
Common Variations of Activated Sludge Process

- Step aeration
- Tapered aeration
- Contact stabilization
- Pure-oxygen activated sludge
- Oxidation ditch
- High rate
- Extended aeration
- Sequencing batch reactors
- Membrane bioreactors

Common Variations of Activated Sludge Process

STEP AERATION

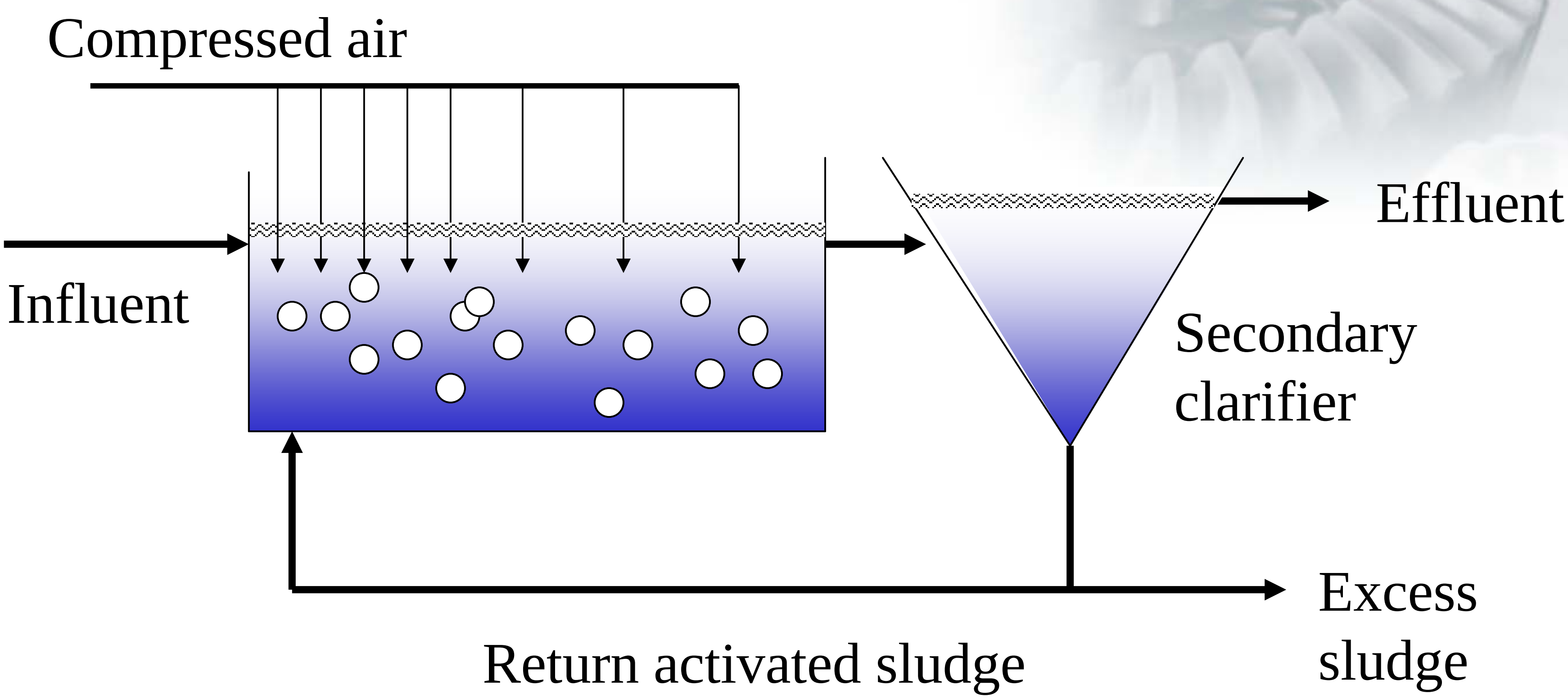
Influent addition at intermediate points provides more uniform organic removal throughout tank



Common Variations of Activated Sludge Process

TAPERED AERATION:

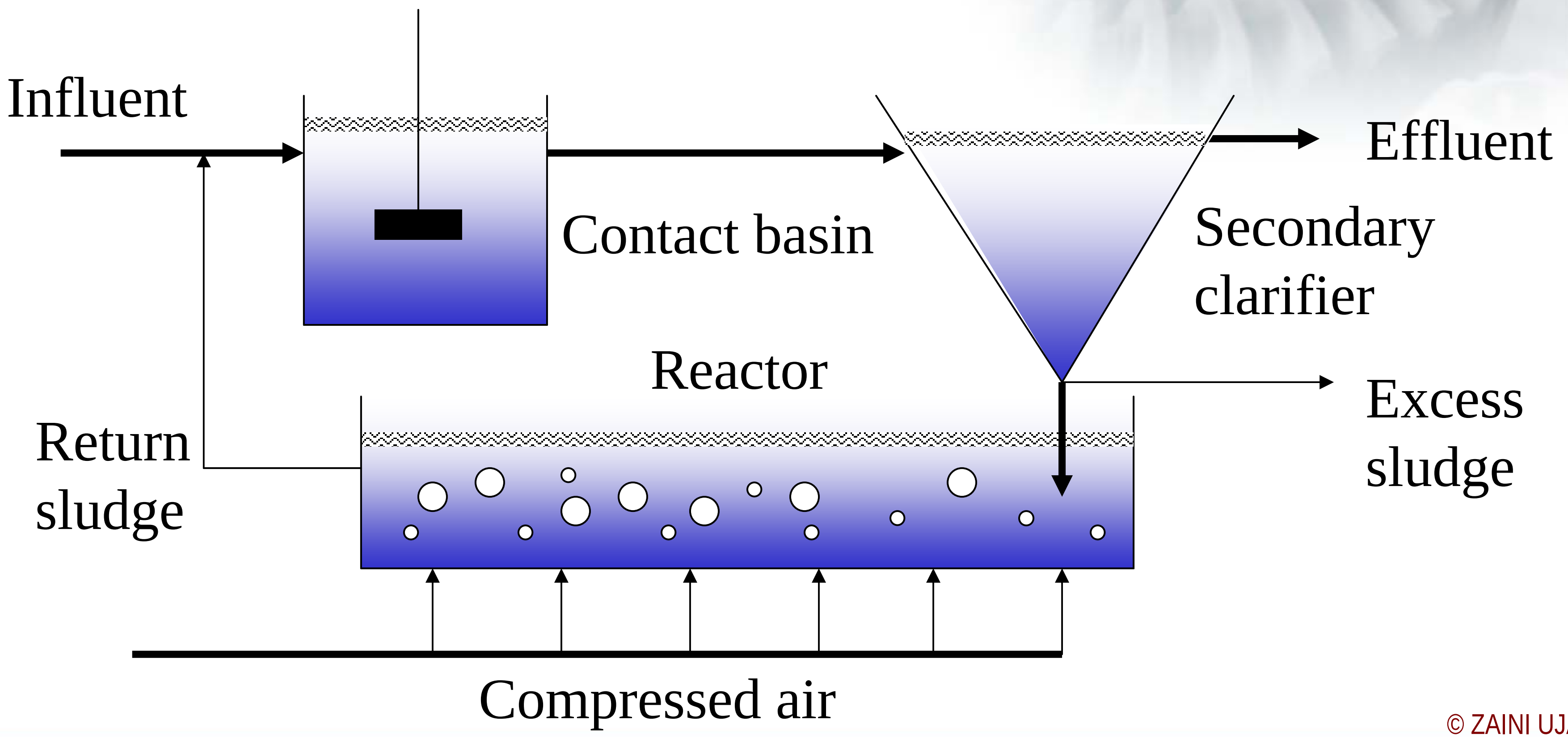
Air is added in proportion to BOD exerted



Common Variations of Activated Sludge Process

CONTACT STABILIZATION

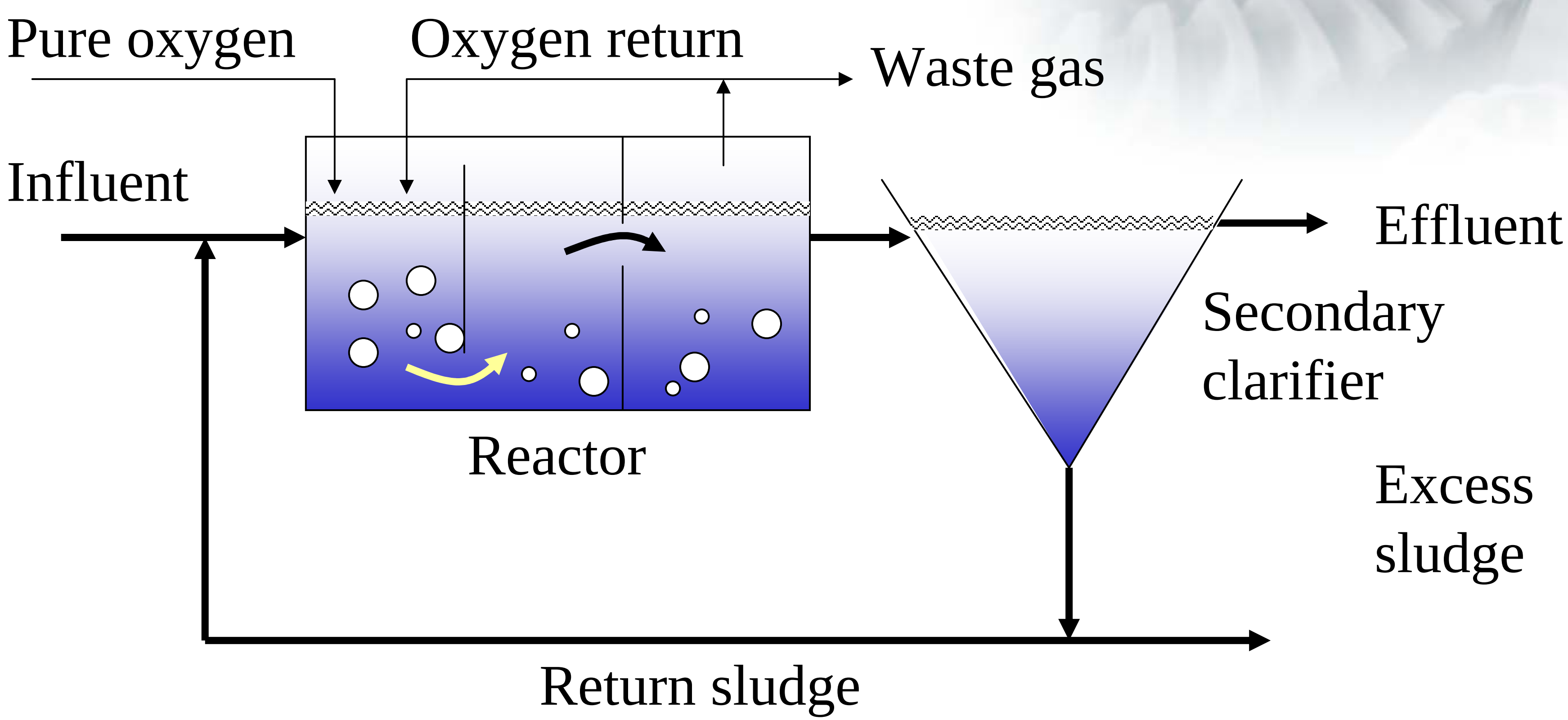
Biomass adsorbs organics in contact basin and settles out in secondary clarifier; the thickened sludge is aerated before being return to the contact basin



Common Variations of Activated Sludge Process

PURE OXYGEN ACTIVATED SLUDGE

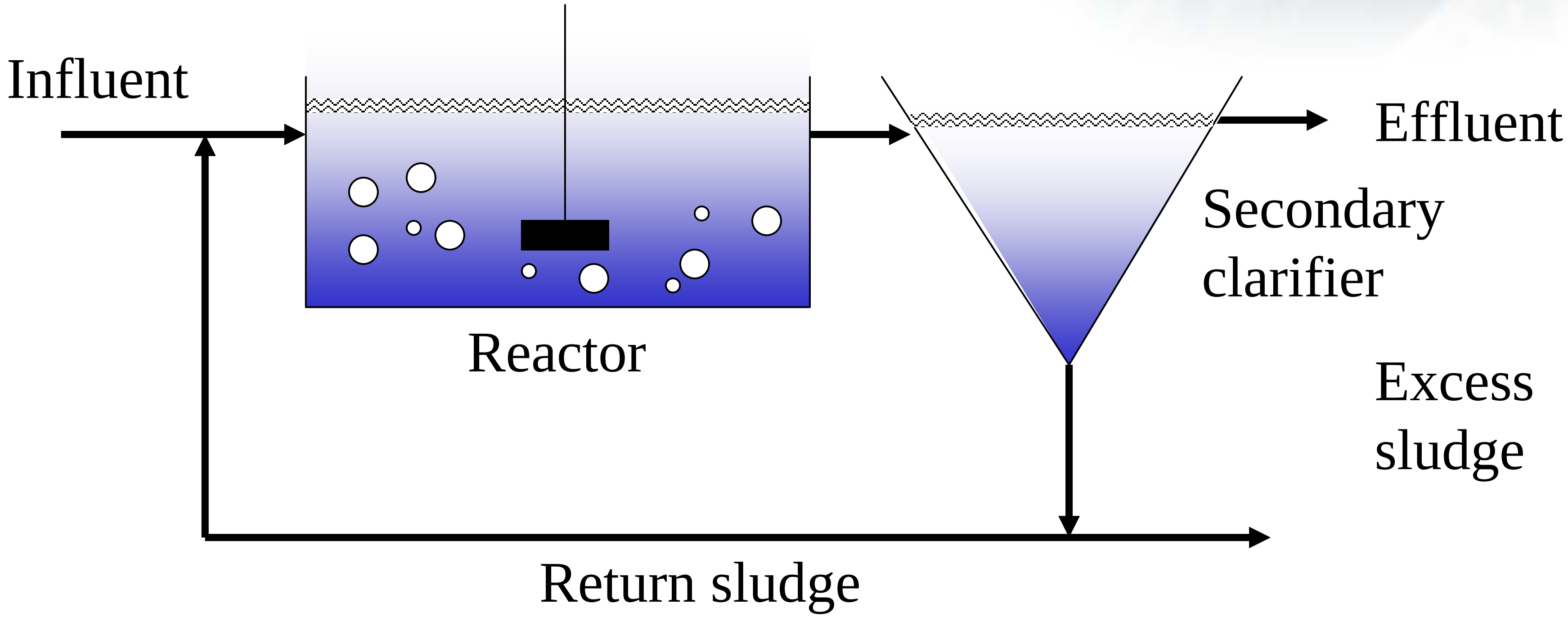
Oxygen added under pressure keeps dissolved oxygen level high



Common Variations of Activated Sludge Process

HIGH RATE

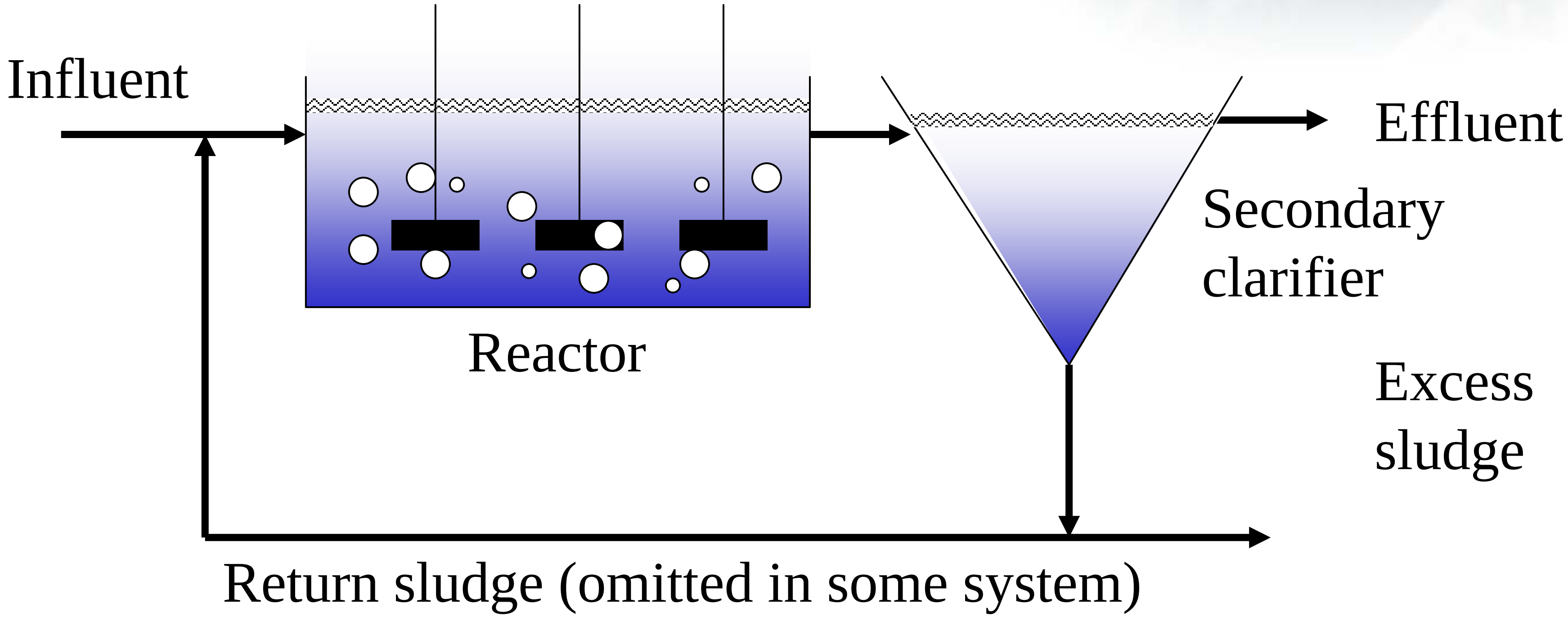
Short detention time and high F/M ratio in aerator to maintain culture in log-growth phase



Common Variations of Activated Sludge Process

EXTENDED AERATION

Long detention time and low F/M ratio in aerator to maintain culture in endogenous phase



Common Variations of Activated Sludge Process

OXIDATION DITCH

Similar to extended aeration, except the aeration is done by brush-type aerators, thus reducing electricity