Design & Optimisation of Aerobic Membrane Bioreactors.

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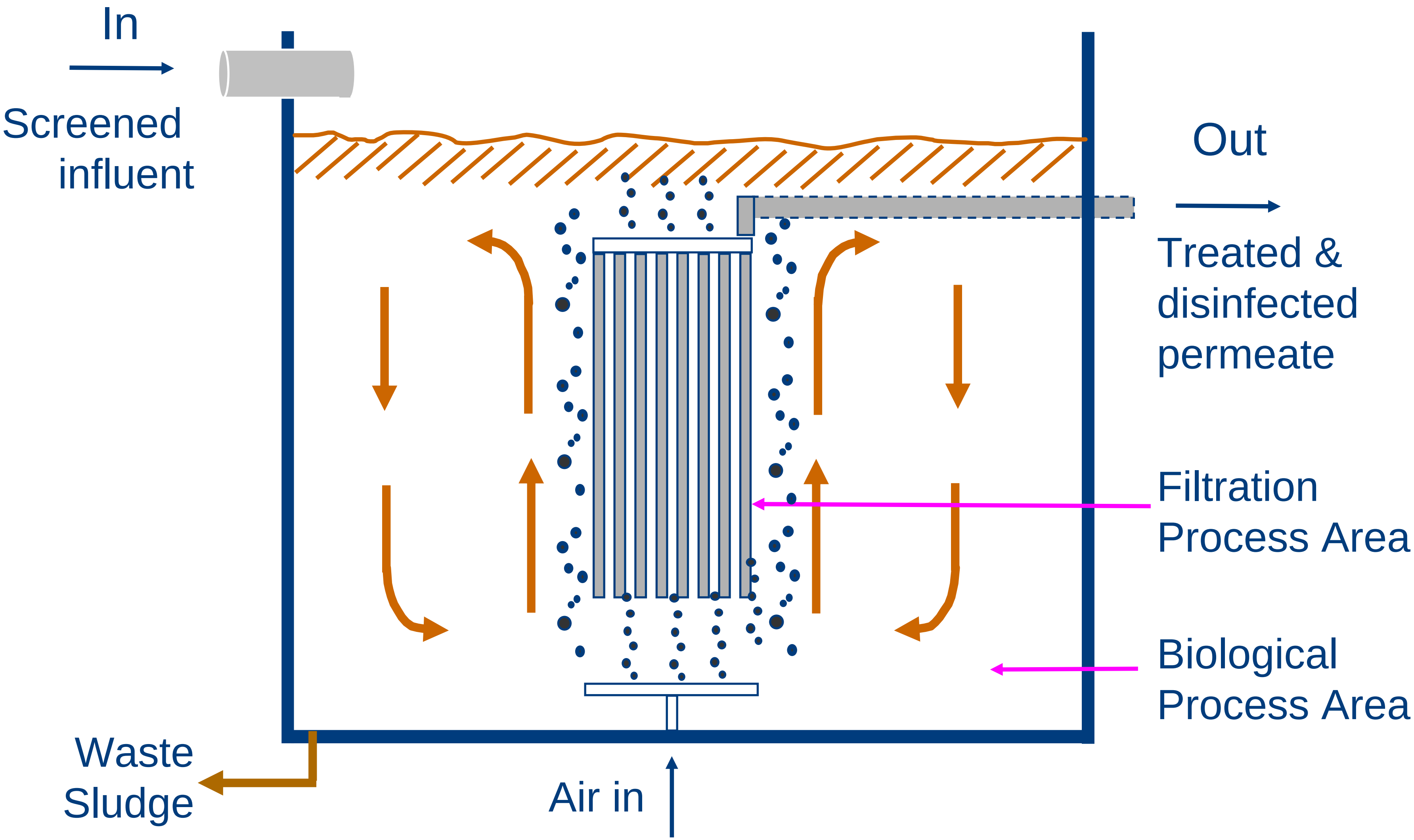
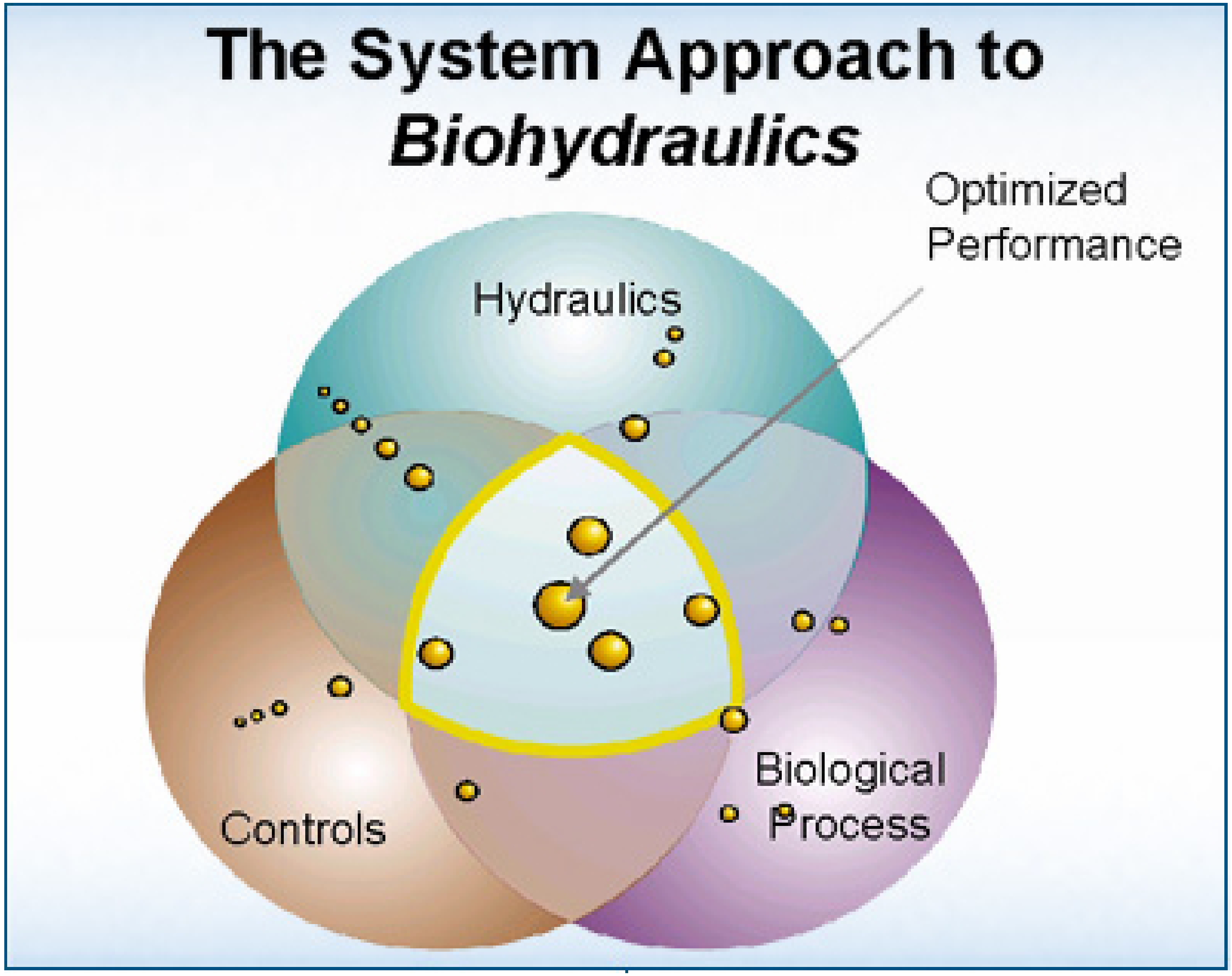
Submerged Membrane Bioreactor



MBR Optimisation Strategy



Kinetics & Stoichiometry:

Kinetics:

$$\mu = \frac{\mu_{\max} S}{\left(K_S + S\right)} - k_d$$

μ = specific growth rate – h^{-1}
μ_{max} = maximum specific growth rate – h^{-1}
K_S = overall substrate affinity constant – mg l^{-1}
k_d = overall biomass death rate – h^{-1}
S = substrate concentration in the reactor – mg l^{-1}

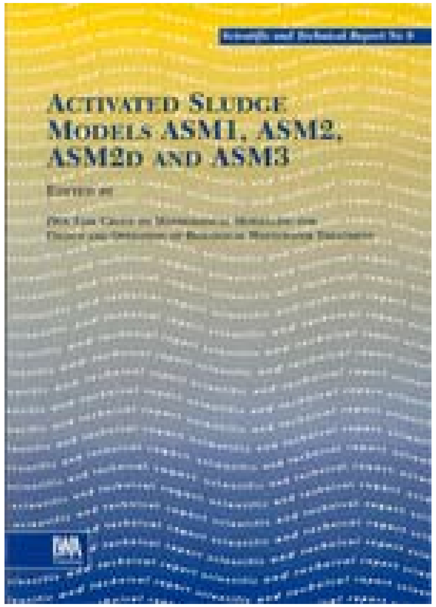
Yields:

$$Y_{(X/S)} = \frac{\Delta X}{\Delta S}$$

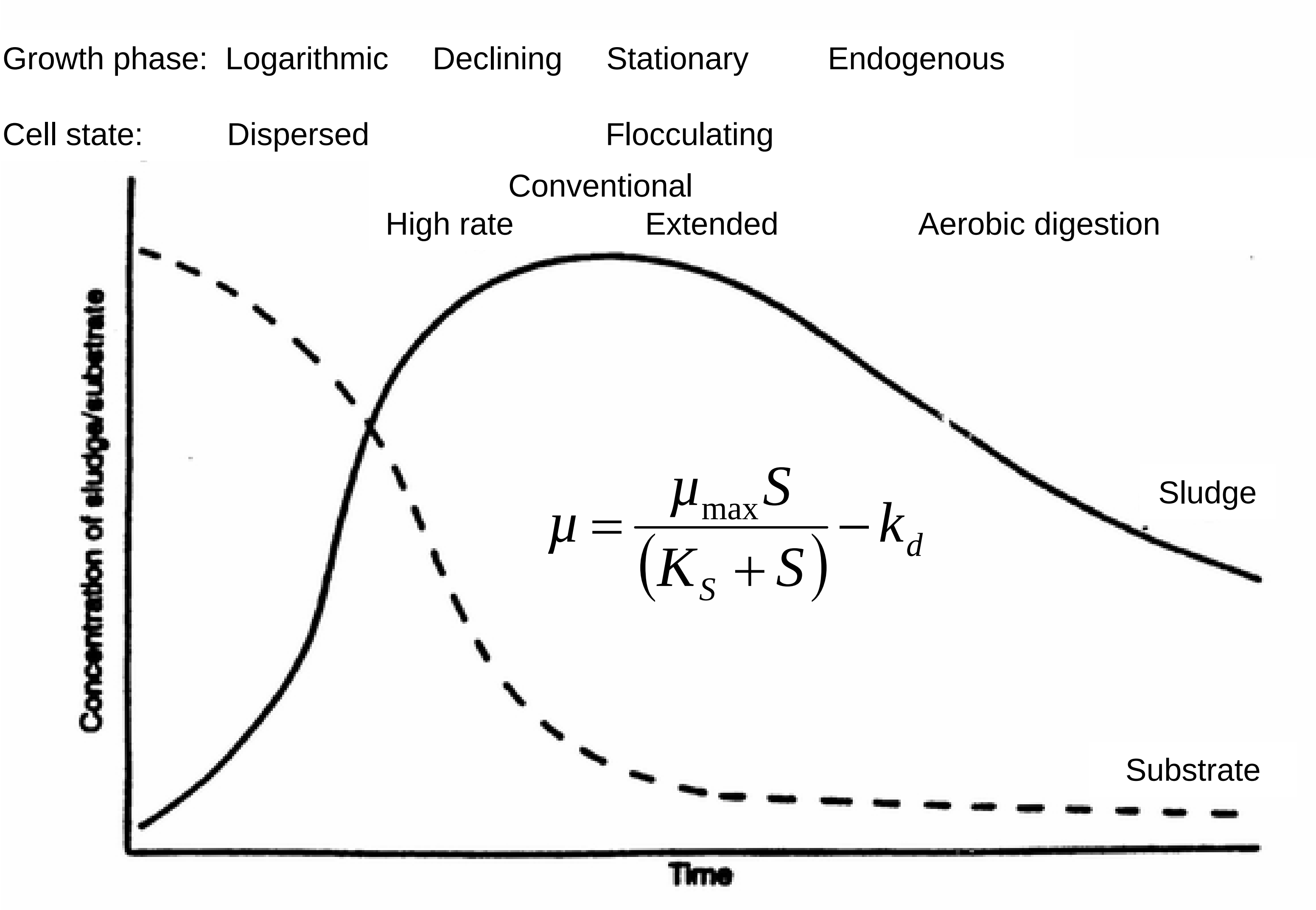
Biomass produced per substrate consumed.

$$Y_{(X/O)} = \frac{\Delta X}{\Delta O}$$

Biomass produced per oxygen consumed.



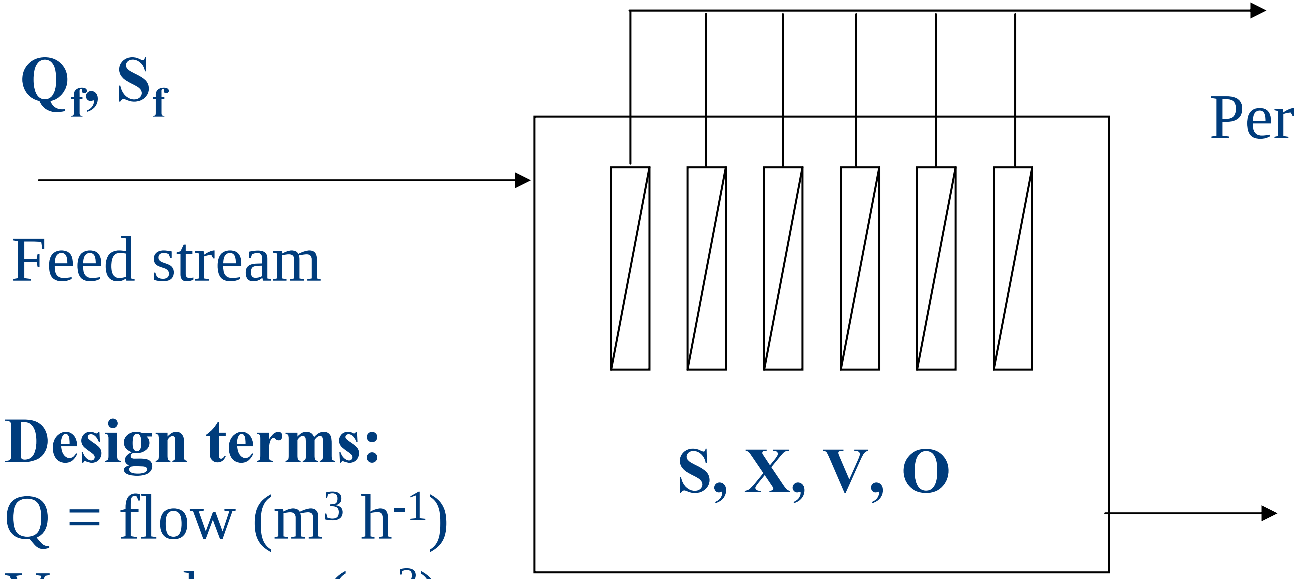
ACTIVATED SLUDGE MODELS ASM1, ASM2, ASM2D AND ASM3



$$\mu = \frac{\mu_{\max} S}{\left(K_S + S\right)} - k_d$$

Time on the x-axis can be seen as analogous to the sludge age or residence time, θ_C, in a water treatment bioreactor.

Membrane Bioreactor Modelling:



Q_f, S_f

Feed stream

Q_p, S, O

Permeate stream

S, X, V, O

Q_w, S, X_w, O

Waste stream

Design terms:
Q = flow ($m^3\ h^{-1}$)
V = volume (m^3)
Q_p/Q_w = flux ratio

Concentrations (all in mg l^{-1}):
S = substrate (BOD)
X = biomass
O = dissolved oxygen

The key unknowns for design & construction are θ, θ_C and hence **V**, and membrane flux, and hence required area, **A**.

Mass balance concept:

Mass accumulated within the system = Mass in through the system boundary - Mass out through the system boundary + Mass generated within the system - Mass consumed within the system

= 0

$$\frac{dS}{dt} = \frac{Q_f}{V} S_f - \frac{Q_p}{V} S - \frac{Q_w}{V} S - \frac{\mu X}{Y_{(X/S)}}$$

Substrate (BOD) balance:

$$\frac{dS}{dt}=\frac{Q_f}{V}S_f-\frac{Q_p}{V}S-\frac{Q_w}{V}S-\frac{\mu X}{Y_{(X/S)}}$$

but as $Q_f = Q_p + Q_w$ this becomes: $\frac{dS}{dt}=\frac{Q_f}{V}\left(S_f-S\right)-\frac{\mu X}{Y_{(X/S)}}$.

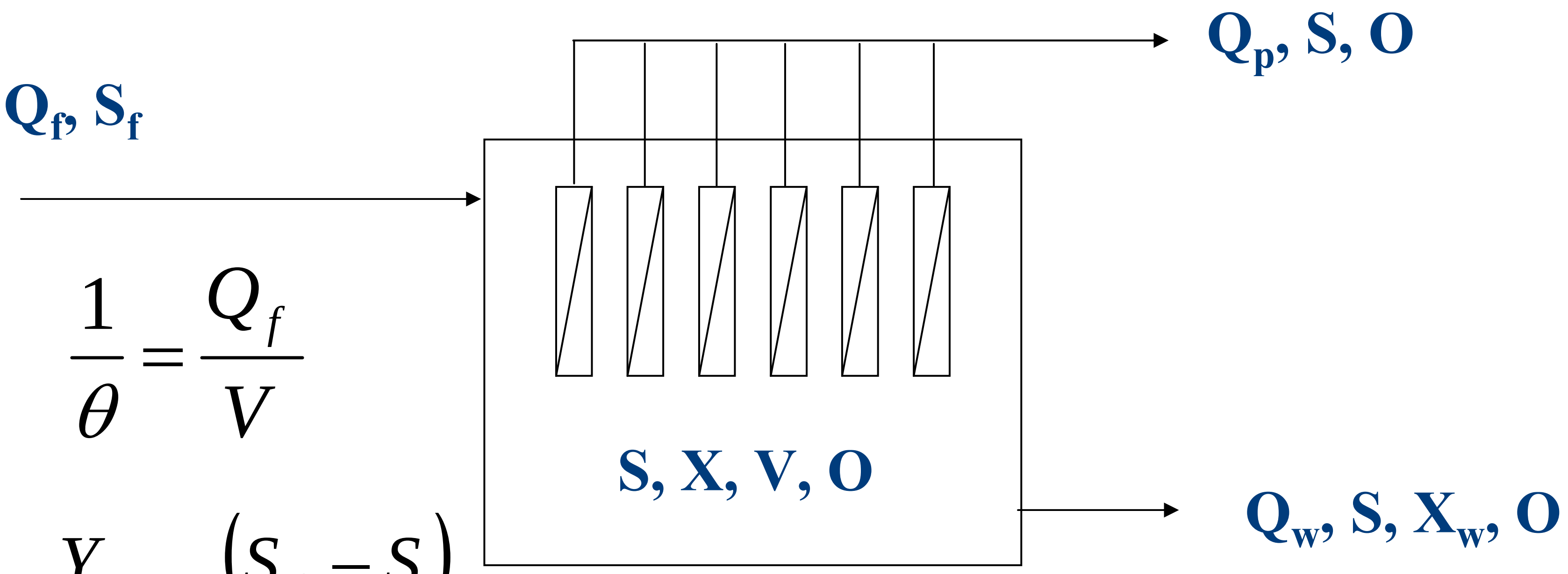
At steady state $\frac{dS}{dt}=0$, so: $\frac{Q_f}{V}\left(S_f-S\right)=\frac{\mu X}{Y_{(X/S)}}$,

rearranging gives: $X=\frac{Y_{(X/S)}\left(S_f-S\right)}{\theta\,\mu}$

where $\frac{1}{\theta}=\frac{Q_f}{V}$ and θ = hydraulic residence time (h),

or $S=S_f-\frac{X\,\theta\,\mu}{Y_{(X/S)}}$

Substrate (BOD) balance summary:



Q_f, S_f

Q_p, S, O

S, X, V, O

Q_w, S, X_w, O

$$\frac{1}{\theta} = \frac{Q_f}{V}$$

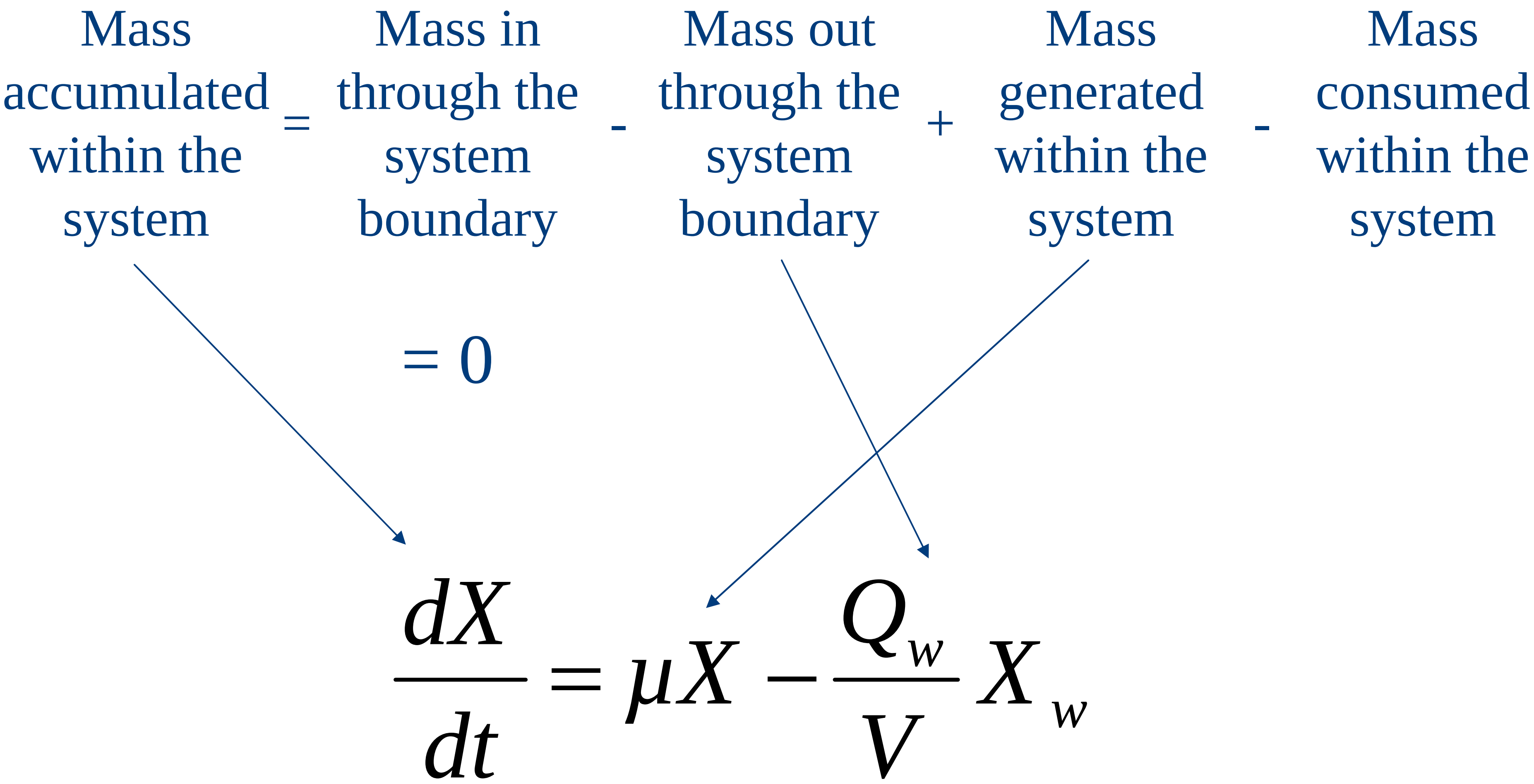
$$X = \frac{Y_{(X/S)}\left(S_f - S\right)}{\theta\,\mu}$$

or

$$S = S_f - \frac{X\,\theta\,\mu}{Y_{(X/S)}}$$

These equations link together water quality (feed & treated), biomass concentration and growth rate, stoichiometry, and reactor volume.

Mass balance concept:



Mass accumulated within the system = Mass in through the system boundary - Mass out through the system boundary + Mass generated within the system - Mass consumed within the system

= 0

$$\frac{dX}{dt} = \mu X - \frac{Q_w}{V} X_w$$

Biomass balance:

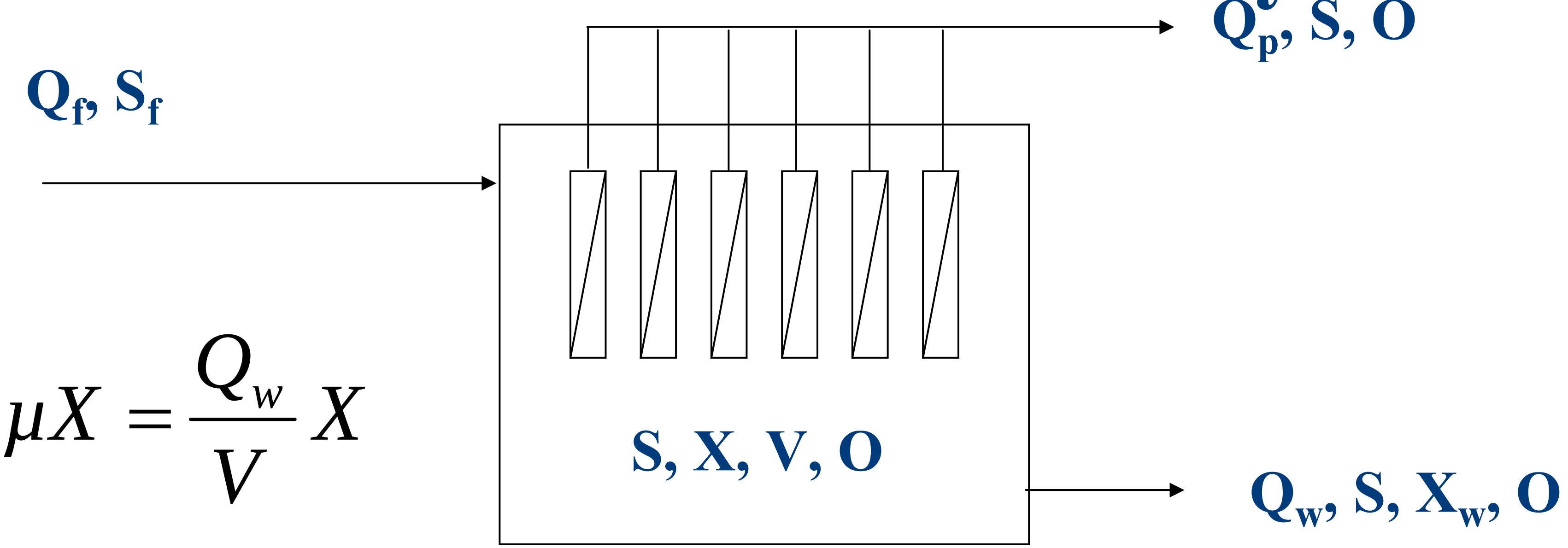
$\frac{dX}{dt} = \mu X - \frac{Q_w}{V} X_w$ (assume X_f & $X_p = 0$)

but at steady state $\frac{dX}{dt} = 0$, and $X = X_w$ if the reactor is well mixed, so:

$\mu X = \frac{Q_w}{V} X$, *ie* $\mu = \frac{Q_w}{V}$ and as $\frac{1}{\theta_C} = \frac{Q_w}{V}$, we get $\mu = \frac{1}{\theta_C}$, where

θ_C = cell (biomass, X) residence time (h).

Biomass balance summary:

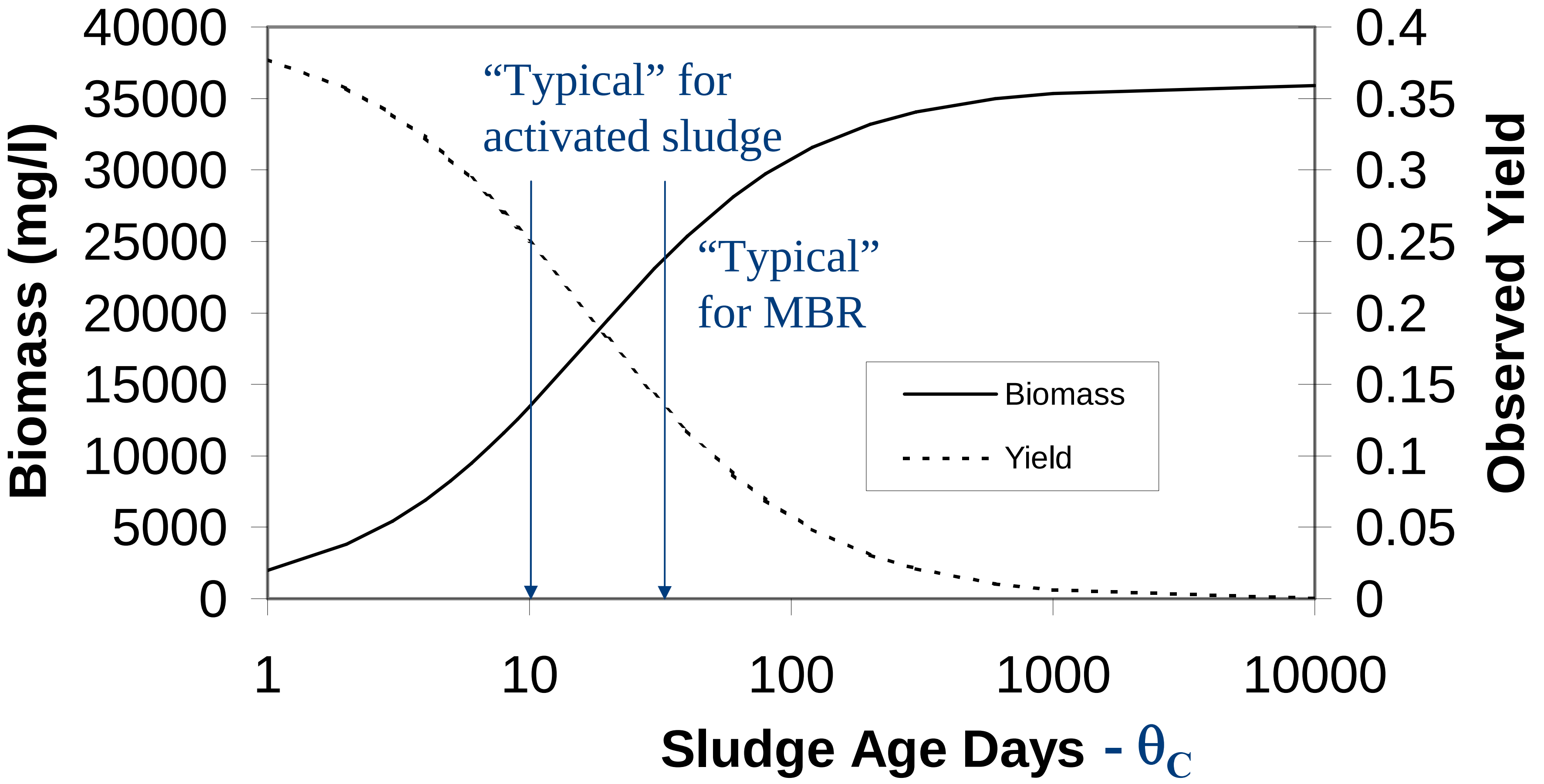


$$\mu X = \frac{Q_w}{V} X$$

$$\mu = \frac{Q_w}{V} \quad \Rightarrow \quad \frac{1}{\theta_C} = \frac{Q_w}{V} \quad \Rightarrow \quad \frac{1}{\theta_C} = \mu = \frac{\mu_{\max} S}{\left(K_S + S\right)} - k_d$$

So if we define S as a target value for water quality we can calculate μ, and hence θ_C. We can therefore use sludge wasting to control the biology and water quality.

Biomass Yields are Lower in MBRs



θ = HRT = 6 h, $Y_{(X/S)}$ = 0.4, μ_{max} = 0.35 h^{-1}, k_d = 0.0025 h^{-1}

The “Food to Micro-organism” ratio:

$$\frac{f}{m}\,\text{ratio} = \frac{S_f}{\theta\, X} = \frac{S_f}{\left(\frac{V}{Q_f}\right) X} = \frac{Q_f\, S_f}{V\, X}$$

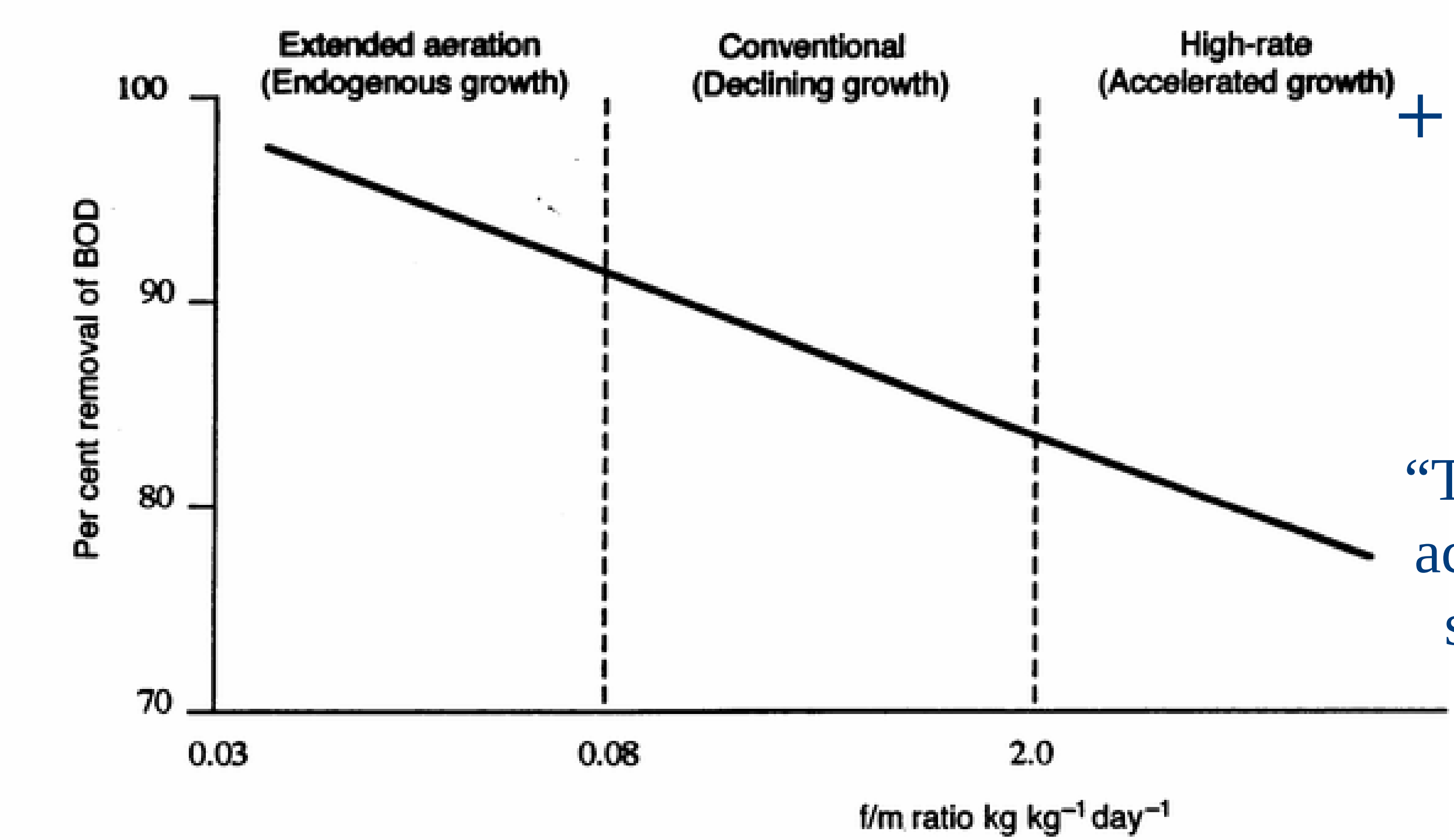
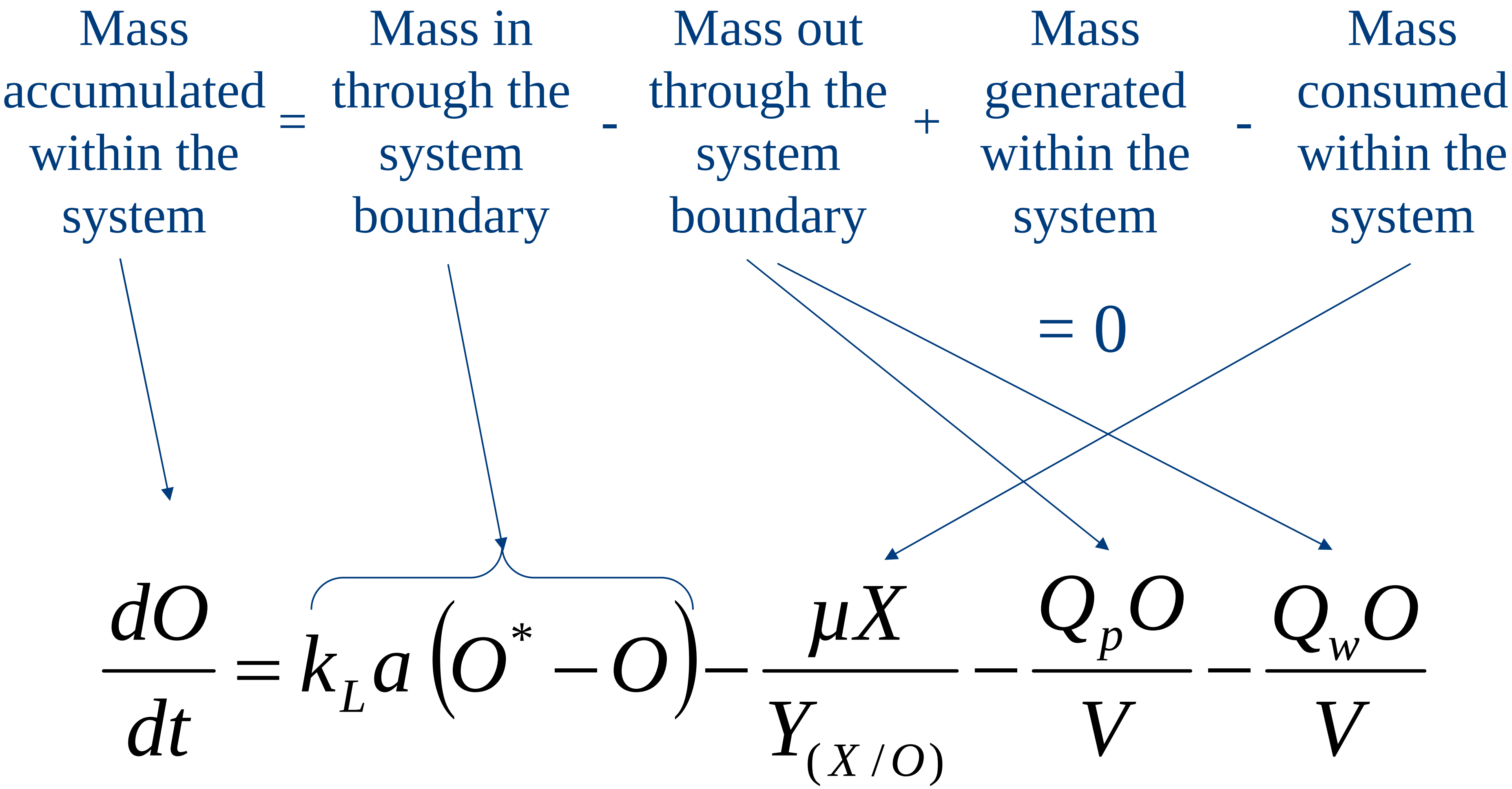


Fig. 17.3 The relationship between f/m ratio and microbial growth.

\+ ← MBR

“Typical” activated sludge

Mass balance concept:



Mass accumulated within the system = Mass in through the system boundary - Mass out through the system boundary + Mass generated within the system - Mass consumed within the system

= 0

$$\frac{dO}{dt} = \overbrace{k_L a\left(O^{*} - O\right)} - \frac{\mu X}{Y_{(X/O)}} - \frac{Q_p O}{V} - \frac{Q_w O}{V}$$

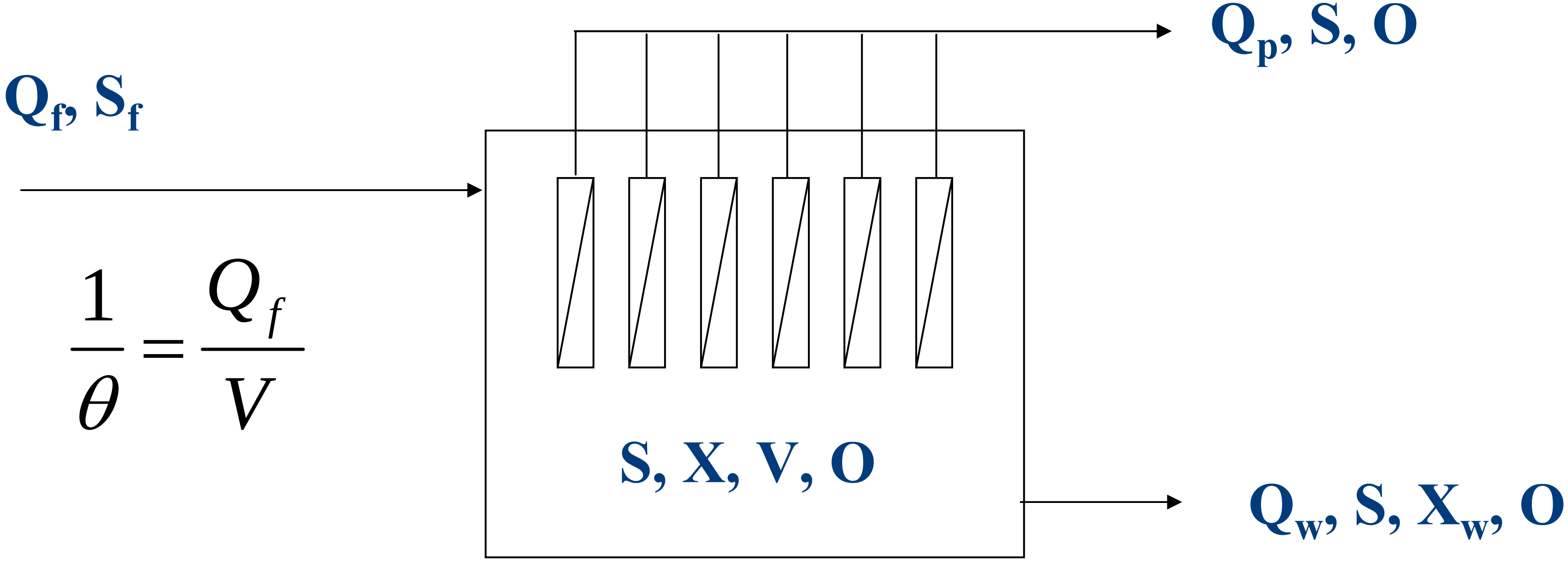
Oxygen balance: $\frac{dO}{dt} = k_L a\left(O^* - O\right) - \frac{\mu X}{Y_{(X/O)}} - \frac{Q_p O}{V} - \frac{Q_w O}{V}$,

but as $Q_f = Q_p + Q_w$ this becomes: $\frac{dO}{dt} = k_L a\left(O^* - O\right) - \frac{\mu X}{Y_{(X/O)}} - \frac{Q_f O}{V}$.

At steady state $\frac{dO}{dt} = 0$, so: $k_L a\left(O^* - O\right) = \frac{\mu X}{Y_{(X/O)}} + \frac{Q_f O}{V}$, and solving for O

gives: $O = \frac{\left(k_L a\, O^*\, Y_{(X/O)} - \mu X\right)\theta}{Y_{(X/O)}\left(k_L a\, \theta - 1\right)}$, or $k_L a = \frac{\mu\, X\, \theta - O\, Y_{(X/O)}}{Y_{(X/O)}\, \theta\left(O^* - O\right)}$.

Oxygen balance summary:



Q_f, S_f

Q_p, S, O

S, X, V, O

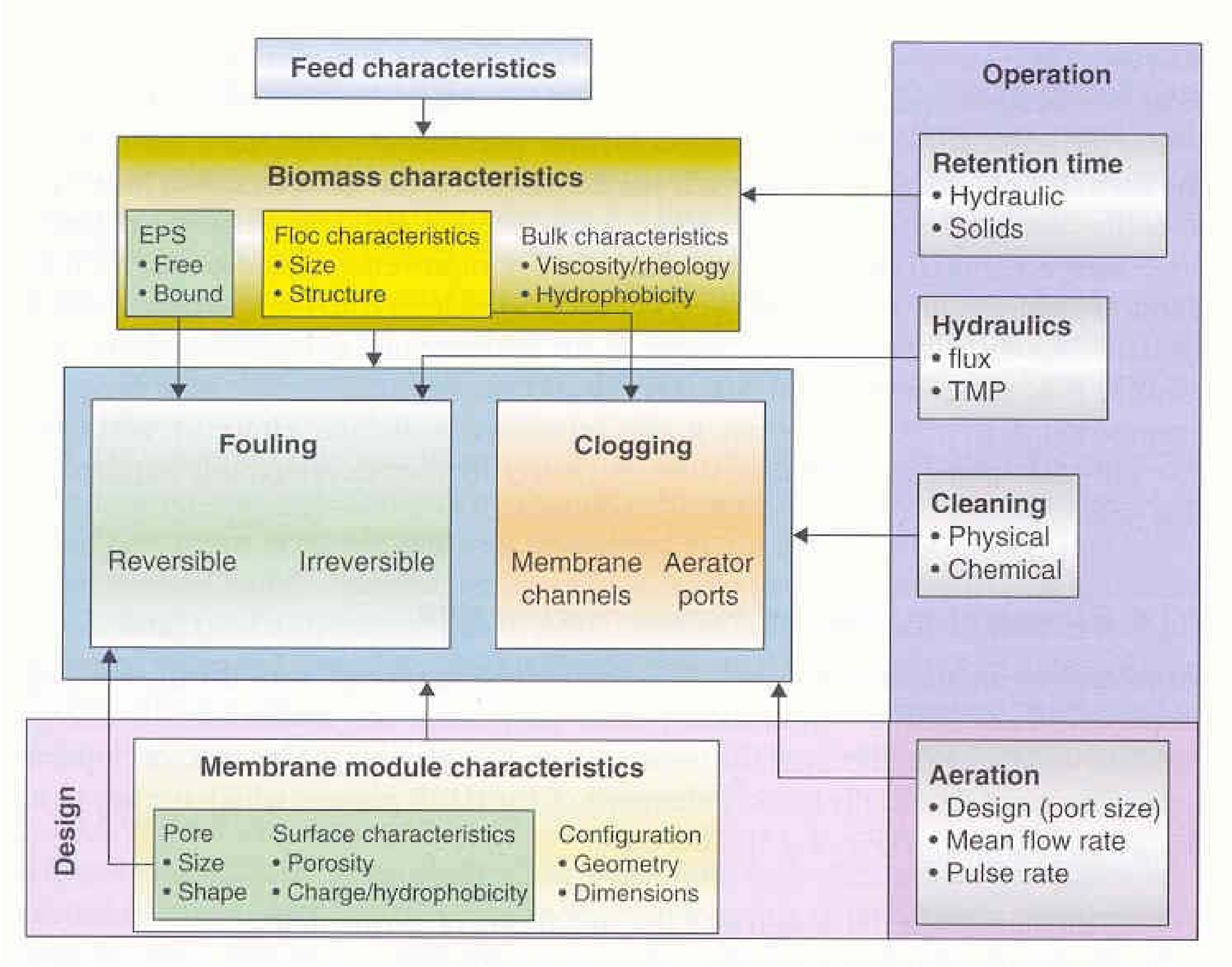
Q_w, S, X_w, O

$$\frac{1}{\theta} = \frac{Q_f}{V}$$

$$O = \frac{\left(k_L a\, O^* \, Y_{(X/O)} - \mu X\right)\theta}{Y_{(X/O)}\left(k_L a\, \theta - 1\right)}$$

or

$$k_L a = \frac{\mu\, X\, \theta - O\, Y_{(X/O)}}{Y_{(X/O)}\, \theta\left(O^* - O\right)}$$



Feed characteristics

Biomass characteristics

EPS
- Free
- Bound

Floc characteristics
- Size
- Structure

Bulk characteristics
- Viscosity/rheology
- Hydrophobicity

Operation

Retention time
- Hydraulic
- Solids

Hydraulics
- flux
- TMP

Cleaning
- Physical
- Chemical

Fouling

Reversible

Irreversible

Clogging

Membrane channels

Aerator ports

Design

Membrane module characteristics

Pore
- Size
- Shape

Surface characteristics
- Porosity
- Charge/hydrophobicity

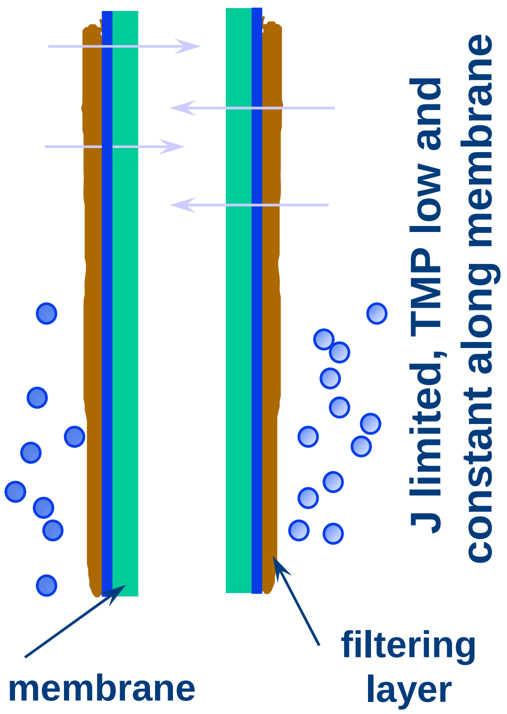
Configuration
- Geometry
- Dimensions

Aeration
- Design (port size)
- Mean flow rate
- Pulse rate

Fouling Control with Immersed Membranes

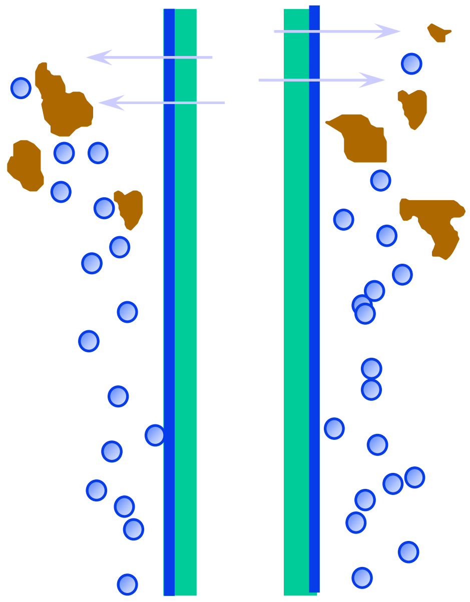
Filtration

Transfer enhanced by three-phase flow



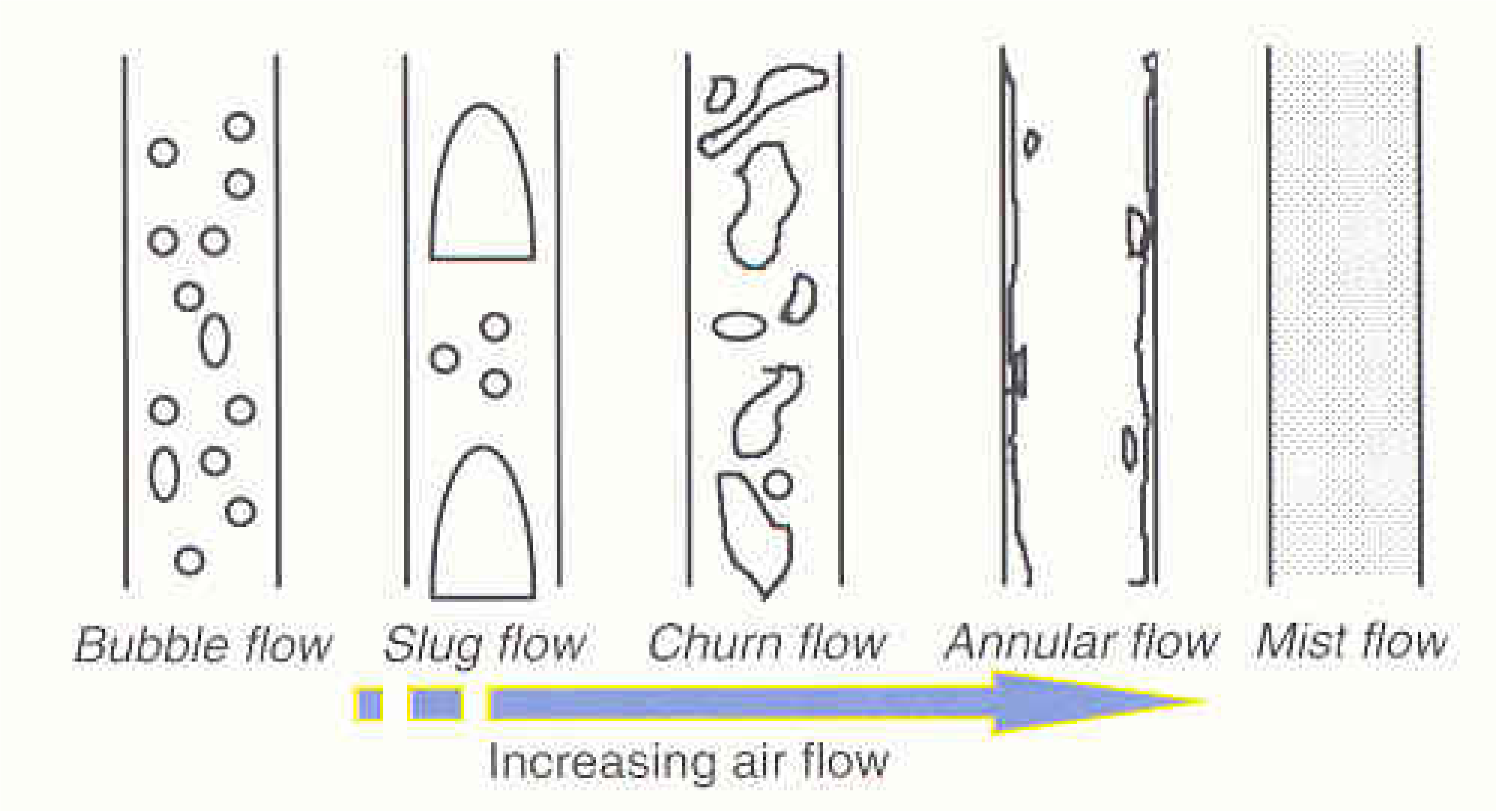
Backwashing

Periodic backwashing gives cake destabilization



- Use of membranes with a lower cost, under conditions of low trans-membrane (TMP) pressure and limited flux.
- Use three-phase (gas / liquid / biomass) flow, permeate backwash, & flux relaxation, to control fouling.

Effects of gassing rate on flow:



Increasing energy consumption →

Membrane modelling / sizing:

$$\frac{dJ}{dt} = -k_J \left(J - J^*\right) J^{(2-n)}, \quad J = \frac{Q_p}{A}$$ (A = membrane area – m^2)

n = fouling mechanism index (0, 1, 1.5, 2 - *after Hermia*) – a function of TMP, particle size, flux, back flush frequency, flux relaxation, and gassing rate.

J^* = critical flux – a function of TMP, back flush frequency, flux relaxation, particle size, biomass concentration (X), and gassing rate.

k_J = fouling rate – a function of TMP, flux, flux relaxation, back flush frequency, particle size, biomass concentration (X), and gassing rate.

Membrane fouling mechanisms

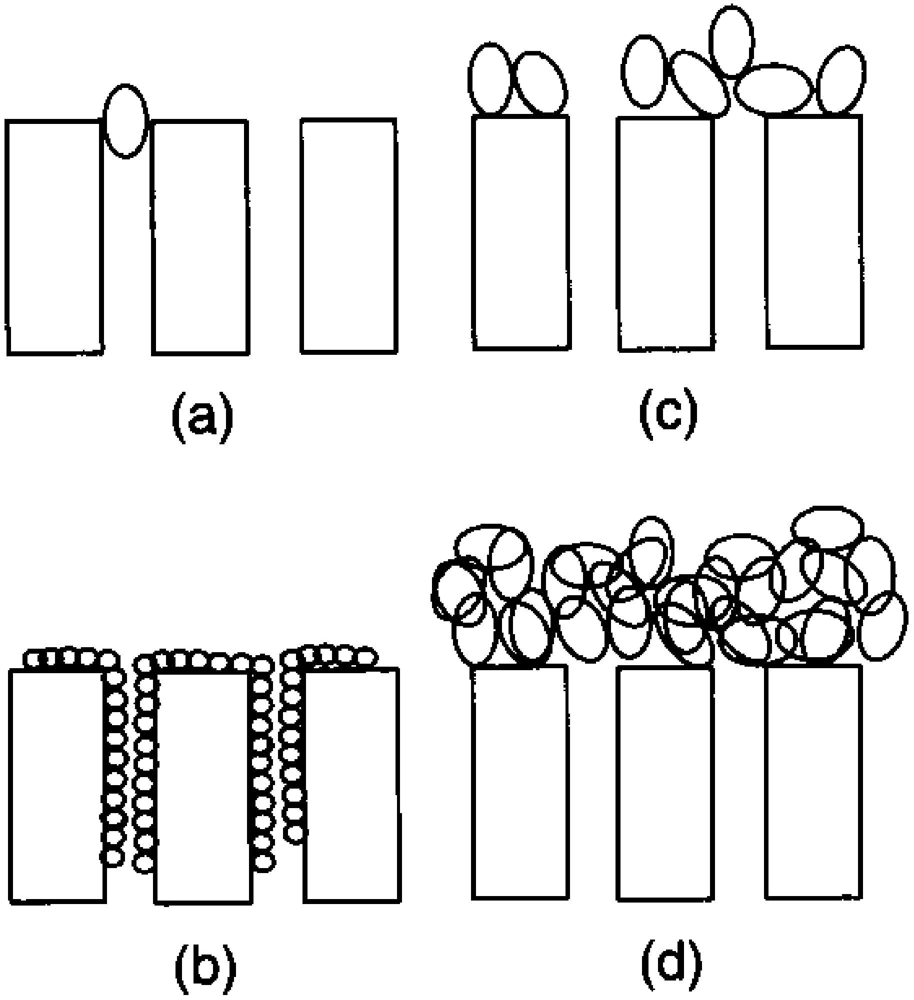
From Hermia’s analysis the value of n varies with different membrane fouling mechanisms:

(a) n = 2.0 for “complete” blocking,

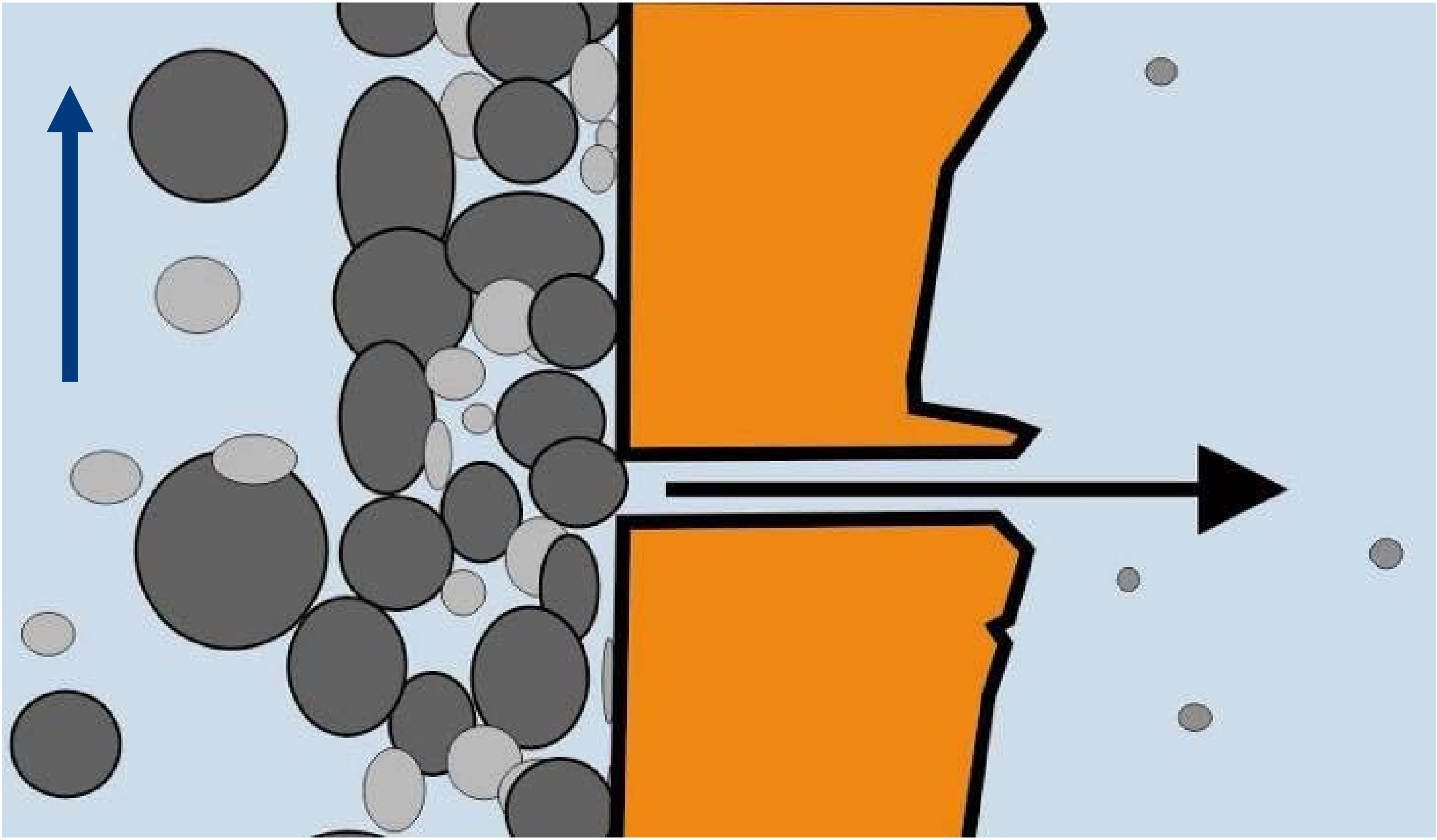
(b) n = 1.5 for standard blocking,

(c) n = 1.0 for incomplete pore blocking (intermediate fouling),

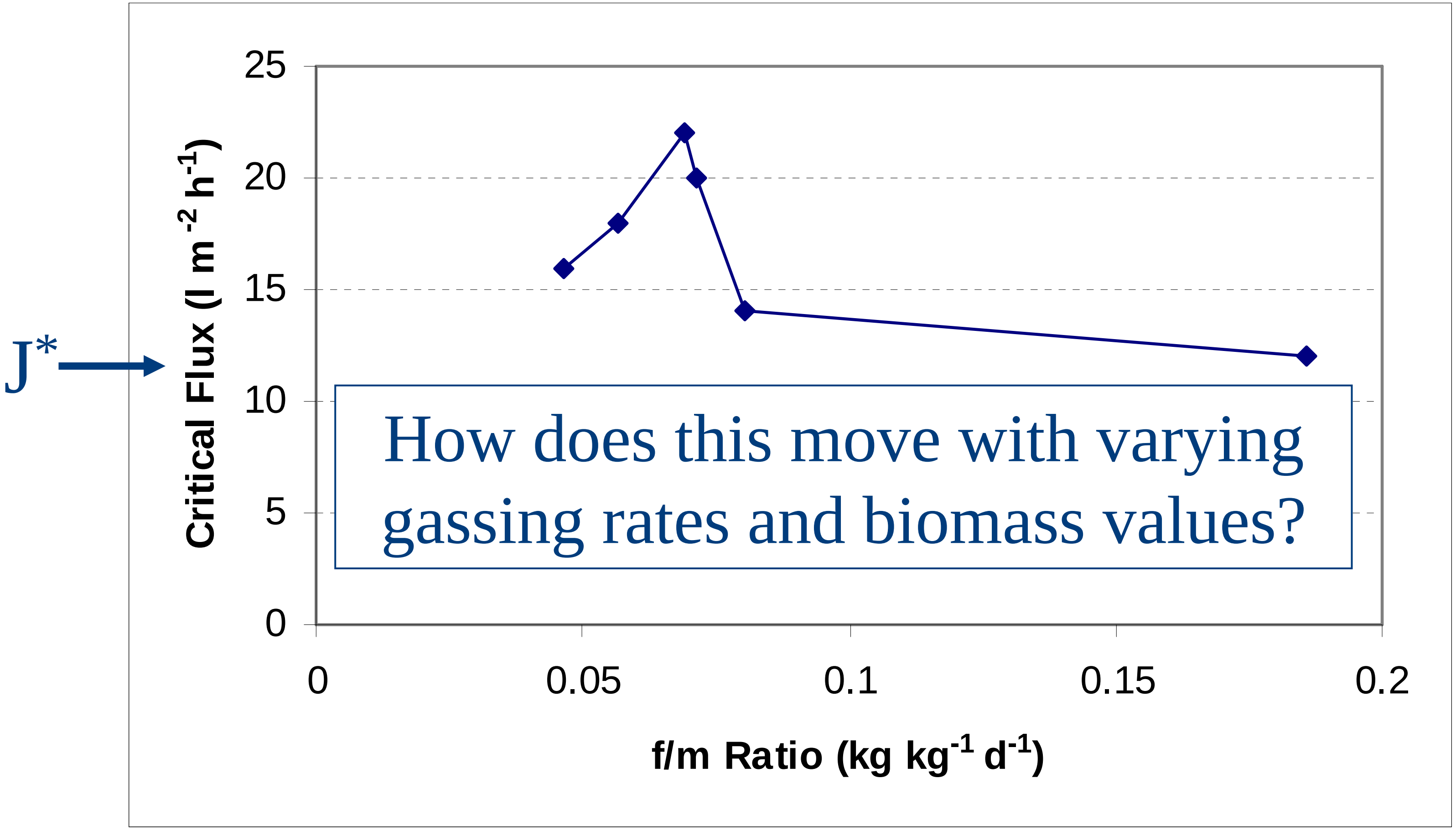
(d) n = 0 for cake filtration.



However it is not always so simple!

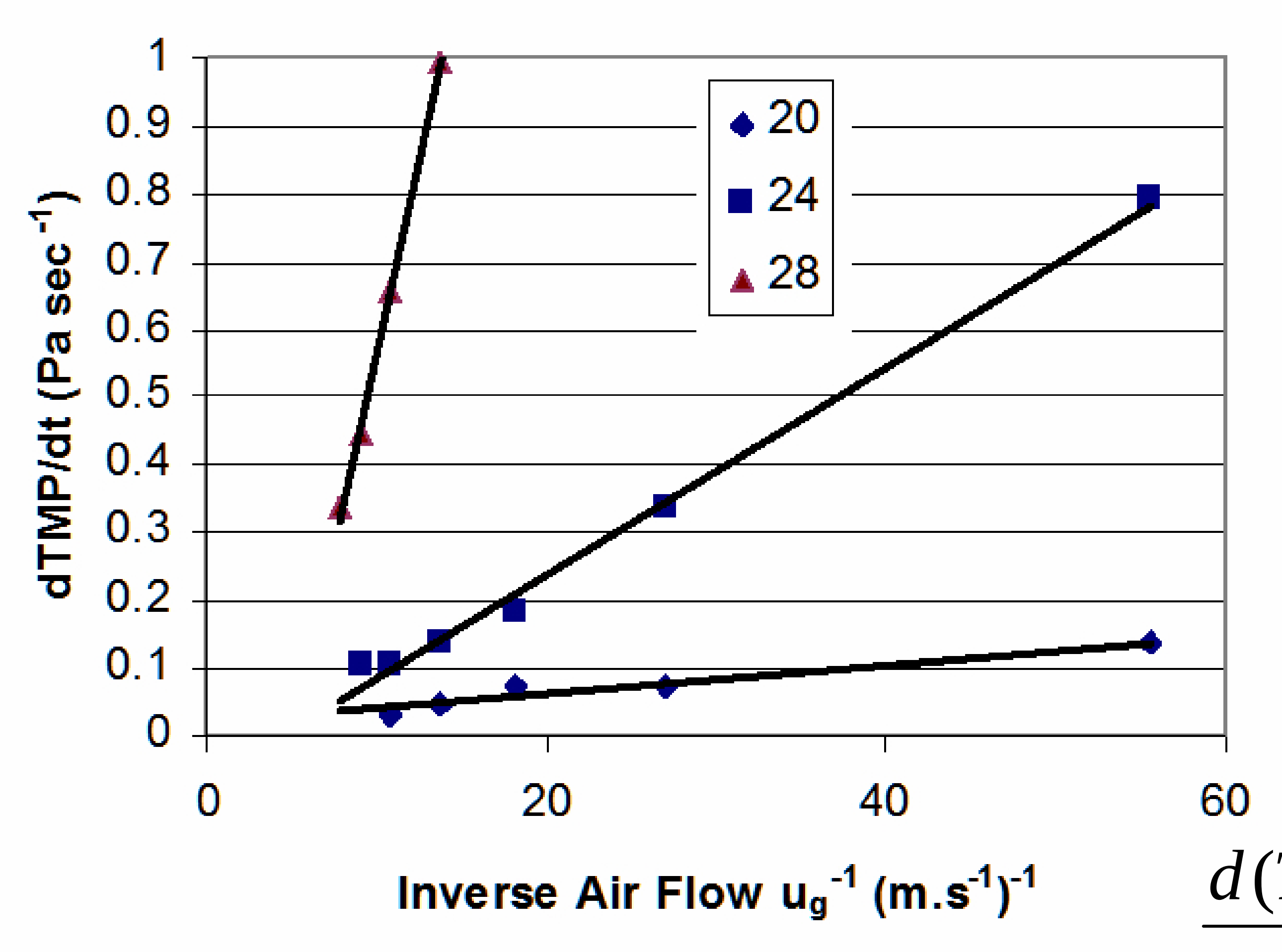


Critical membrane flux versus f/m ratio



How does this move with varying gassing rates and biomass values?

Gassing rate, $\mathbf{u_g}$ = 88 mm s^{-1}; biomass, **X** = 17,420 mg l^{-1}



Residual membrane fouling rate (**k$_J$**) versus inverse gassing rate (**u$_g$**) for various fluxes (**J** = 20, 24 & 28 l m^{-2} h^{-1}), and a fixed biomass (**X** = 17,420 mg l^{-1}).

Increased aeration can be used to achieve higher fluxes for less TMP at the same biomass concentration.

We can link fouling rate to flux and gassing rate:

$$\frac{d(TMP)}{dt} = \frac{0.684}{u_g} e^{0.3893J}$$

How generic?

Design - steady state summary:

$$\mu = \frac{\mu_{\max} S}{(K_S + S)} - k_d \qquad \frac{1}{\theta_C} = \mu = \frac{Q_w}{V} \qquad \frac{1}{\theta} = \frac{Q_f}{V} \qquad X = \frac{Y_{(X/S)}(S_f - S)}{\theta\,\mu}$$

$$A = \frac{Q_p}{J^*} = \frac{Q_f - Q_w}{J^*} \qquad O = \frac{\left(k_L a\, O^* \, Y_{(X/O)} - \mu X\right)\theta}{Y_{(X/O)}\left(k_L a\,\theta - 1\right)}$$

$\mathbf{Q_f}$ and $\mathbf{S_f}$ are characteristics of the feed stream, and hence known.

$\mathbf{k_L a}$ is a function of aeration – this may be designed for.

$\boldsymbol{\mu_{max}}$, $\mathbf{K_S}$ and $\mathbf{k_d}$ depend on kinetics, $\mathbf{Y_{(X/S)}}$ and $\mathbf{Y_{(X/O)}}$ from stoichiometry.

S is a target for the treated water quality – select an appropriate value.

The key unknowns for design & construction are therefore θ, θ_C, **V** and **A** (*i.e.* $\mathbf{J^*}$).

MBRs are optimised on the basis of cost:

Capital costs (usually amortised at 6% over 20 years):

- Treatment tank volume
- Membrane installation and pumps
- Aeration (blowers / compressors)
- Off gas treatment (filtering, scrubbing *etc*)

Operating costs:

- Aeration (blower / compressor operation)
- Off gas treatment (not always necessary)
- Sludge disposal (increasingly important)
- Membrane replacement (becoming less important)

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  - UK EPSRC, 2000-2003.
  - UK MOD, 2003-2005.
  - EU PURATREAT Project, 2006-2009, www.puratreat.com.