Organic Matter Removal

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ORGANIC MATERIAL REMOVAL BY ACTIVATED SLUDGE

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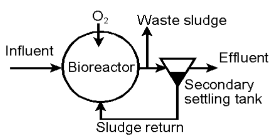
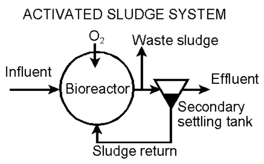
OUTLINE (1)

- (1) Activated sludge system description
- (2) Biological transformations
- (3) AS system constraints
- (4) Biological behaviour
- (5) Reactor solids concentration (VSS, TSS)
    - Unbiodegradable particulate organics
    - Active biomass
    - Endogenous residue
    - VSS and TSS
- (6) Oxygen demand



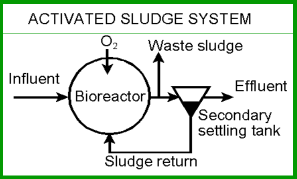
OUTLINE (2)

- (7) Effluent COD concentration
- (8) Activated sludge design model
- (9) COD balance
- (10) Reactor volume and retention time
- (11) Selecting reactor TSS concentration
- (12) Active fraction
- (13) Sludge production
- (14) Nutrient (N&P) requirements
- (15) Design procedure



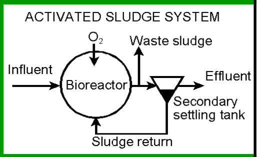
OUTLINE (2)

- (16) System control
- (17) Hydraulic control of sludge age
- (18) Selection of sludge age
- (19) Effect of sludge age on system
- (20) Effect of primary settling on system
- (21) Closure



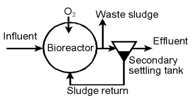
INTRODUCTION (1)

- Design and operation (control) of activated sludge (AS) requires knowledge of:
  - (1) Nature of wastewater
  - (2) Behaviour of organisms the mediate bioprocesses of importance
  - (3) Interaction between (1) and (2)
  - (4) Impact of (1) and (2) on system sizing, performance and control.
- This knowledge is codified into models (mostly mathematical) that become tools for understanding, design and operation of the system.



BASIC APPROACH

- **Level of organization:** Look at generalized, simplified concepts that describe behaviour of bacteria in WWTP
  - Organisms – collective behaviour of groups mediating a particular bio-process of importance (forest not trees).
  - Chosen interactively depending on objectives.
- Our concepts are strongly influenced by what
  - What we can measure
  - What is important to us (objectives of model).
- Models have high and low levels of complexity depending on objectives.
  - Design – steady state models – relatively simple.
  - Diurnal behaviour – dynamic simulation – complex.
  - Research (testing new refinements and extensions)



WASTEWATER COMPOSITION (1)

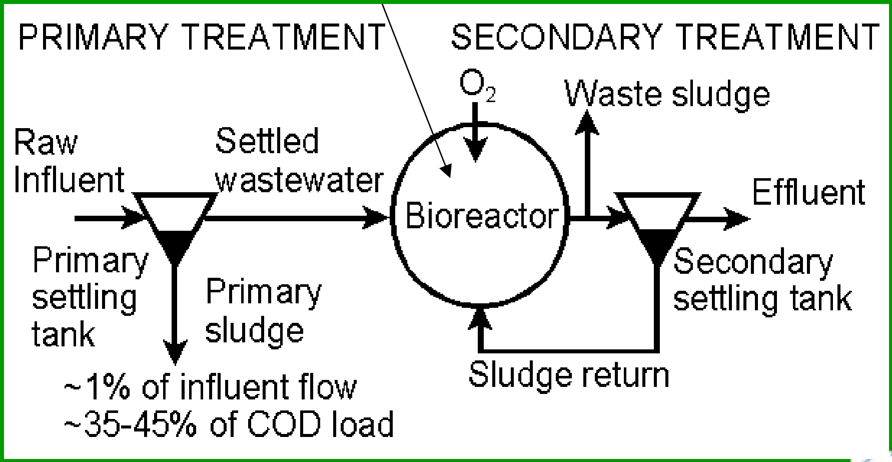
- Wastewater comprises both organic (COD, BOD) and inorganic (ISS) materials (measured in influent).
- These are removed in AS by
  - Biological oxidation (by heterotrophs)
  - Phase transformations
    (dissolved → solid, dissolved → gas↑)
    (biological and physical)
  - Solid-liquid separation (settling tanks)

WASTEWATER COMPOSITION (2)

- Wastewater organic and inorganic constituents are…...
  - (1) Settleable (settle out < 2hr)
  - (2) Non-settleable (colloidal)
  - (3) Dissolved.
- (1) can be settled out in PST (if included).
- (2) and (3) are transformed to settleable solids (biomass, if biodeg. and enmeshed if unbiodeg.) and settle out in SST.

SYSTEM DESCRIPTION

Biological & physical transformations – Dissolved and non-settleable become settleable.



PRIMARY TREATMENT

SECONDARY TREATMENT

O_2

Waste sludge

Raw Influent

Settled wastewater

Bioreactor

Effluent

Primary settling tank

Primary sludge

Secondary settling tank

Sludge return

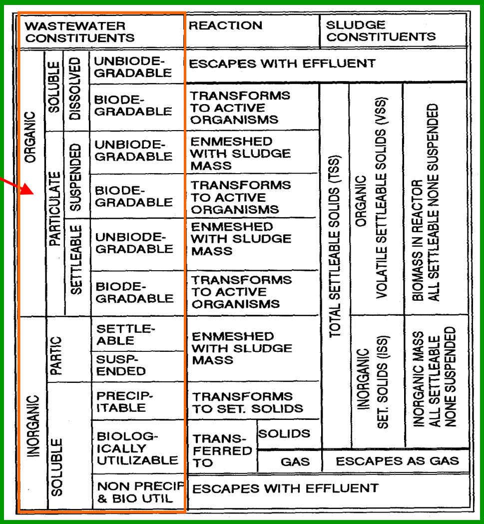
~1% of influent flow
~35-45% of COD load

REACTOR PHASE TRANSFORMATIONS

- In reactor, there are biological reactions:
  - Transforming biodegradable organics (settleable, non-settleable and dissolved) into biomass which is settleable.
- In reactor, there are physical reactions:
  - Enmeshing and entrapping biodegradable and unbiodegradable organics (settleable and non-settleable) into the sludge mass making it all settleable.

PROCESS REACTIONS

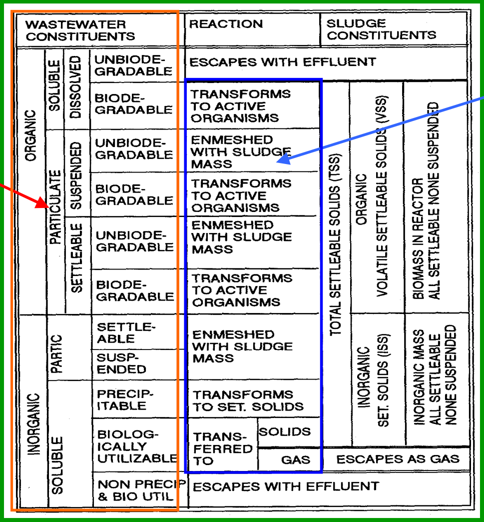
Wastewater characteristics



WASTEWATER CONSTITUENTS				REACTION		SLUDGE CONSTITUENTS		
ORGANIC	SOLUBLE	DISSOLVED	UNBIODEGRADABLE	ESCAPES WITH EFFLUENT				
			BIODEGRADABLE	TRANSFORMS TO ACTIVE ORGANISMS		TOTAL SETTLEABLE SOLIDS (TSS)	ORGANIC VOLATILE SETTLEABLE SOLIDS (VSS)	BIOMASS IN REACTOR ALL SETTLEABLE NONE SUSPENDED
	PARTICULATE	SUSPENDED	UNBIODEGRADABLE	ENMESHED WITH SLUDGE MASS				
			BIODEGRADABLE	TRANSFORMS TO ACTIVE ORGANISMS				
		SETTLEABLE	UNBIODEGRADABLE	ENMESHED WITH SLUDGE MASS				
			BIODEGRADABLE	TRANSFORMS TO ACTIVE ORGANISMS				
INORGANIC	PARTIC		SETTLEABLE	ENMESHED WITH SLUDGE MASS			INORGANIC SET. SOLIDS (ISS)	INORGANIC MASS ALL SETTLEABLE NONE SUSPENDED
			SUSPENDED					
	SOLUBLE		PRECIPITABLE	TRANSFORMS TO SET. SOLIDS				
			BIOLOGICALLY UTILIZABLE	TRANSFERRED TO	SOLIDS			
					GAS	ESCAPES AS GAS		
			NON PRECIP & BIO UTIL	ESCAPES WITH EFFLUENT				

PROCESS REACTIONS

Wastewater characteristics



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		SETTLEABLE	UNBIODEGRADABLE	ENMESHED WITH SLUDGE MASS				
			BIODEGRADABLE	TRANSFORMS TO ACTIVE ORGANISMS				
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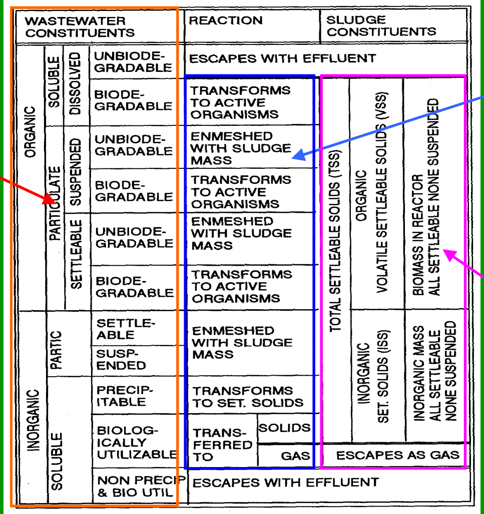
			BIOLOGICALLY UTILIZABLE	TRANSFERRED TO	SOLIDS			
					GAS	ESCAPES AS GAS		
			NON PRECIP & BIO UTIL	ESCAPES WITH EFFLUENT				

Process reactions

Organics are degraded by ordinary heterotrophic organisms (OHOs) group.

PROCESS REACTIONS



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			BIOLOGICALLY UTILIZABLE	TRANSFERRED TO	SOLIDS			
					GAS	ESCAPES AS GAS		
			NON PRECIP & BIO UTIL	ESCAPES WITH EFFLUENT				

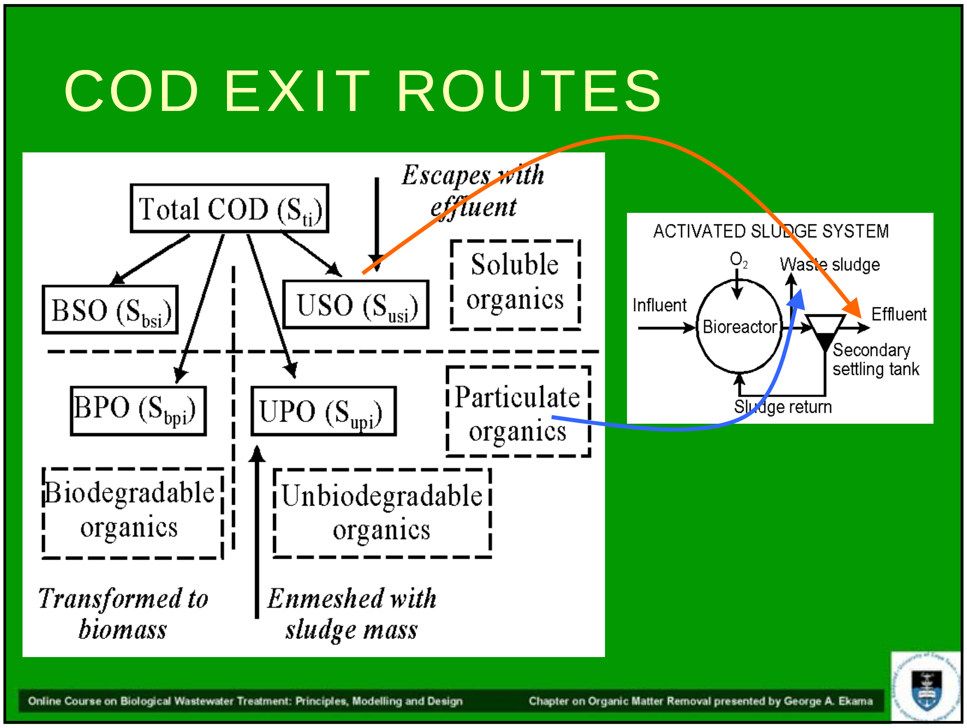
Waste-water charac-teristics

Process reactions

Reaction products

REACTOR PHASE TRANSFORMATIONS

- So irrespective of treating raw or settled WW:
  - All particulates (settleable and non-settleable) become part of the sludge mass in the reactor whether biologically degraded or not;
  - Dissolved organics that are biodegradable become settleable biomass, but those that are unbiodegradable escape with effluent.
- Some sludge mass is harvested from reactor daily to control mass in reactor.



COD EXIT ROUTES

Total COD (S_{ti})

BSO (S_{bsi})

USO (S_{usi})

BPO (S_{bpi})

UPO (S_{upi})

Escapes with effluent

Soluble organics

Particulate organics

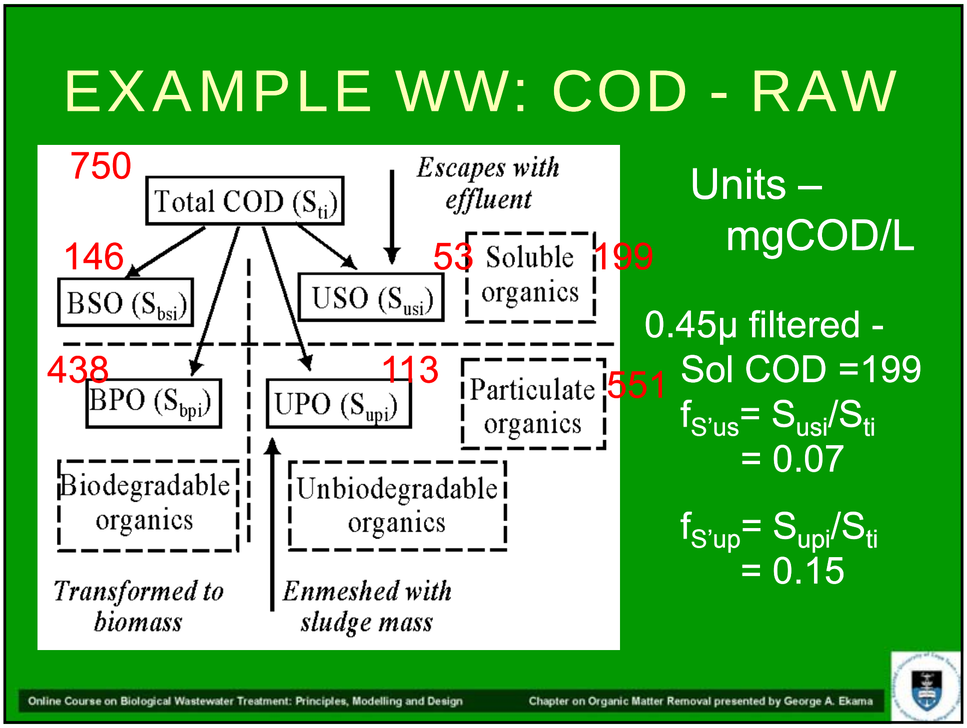
Biodegradable organics

Unbiodegradable organics

Transformed to biomass

Enmeshed with sludge mass

ACTIVATED SLUDGE SYSTEM



EXAMPLE WW: COD - RAW

750 Total COD (S_{ti})

146 BSO (S_{bsi})

53 USO (S_{usi})

438 BPO (S_{bpi})

113 UPO (S_{upi})

Escapes with effluent

Soluble organics 199

Particulate organics 551

Biodegradable organics

Unbiodegradable organics

Transformed to biomass

Enmeshed with sludge mass

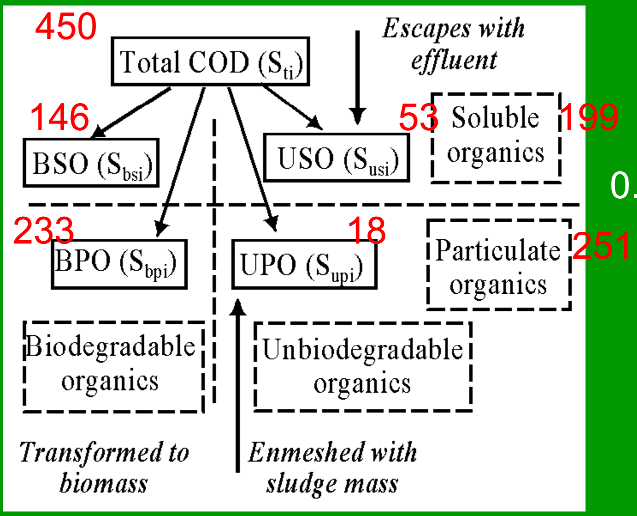
Units – mgCOD/L

0.45µ filtered - Sol COD =199

$f_{S'us} = S_{usi}/S_{ti} = 0.07$

$f_{S'up} = S_{upi}/S_{ti} = 0.15$

EXAMPLE WW: COD - SETTLED


450
Total COD (S_{ti})
Escapes with effluent
146
BSO (S_{bsi})
USO (S_{usi})
53 Soluble organics 199
233
BPO (S_{bpi})
18
UPO (S_{upi})
Particulate organics 251
Biodegradable organics
Unbiodegradable organics
Transformed to biomass
Enmeshed with sludge mass

Units – mgCOD/L

0.45μ filtered - Sol COD =199

$f_{S'us} = S_{usi}/S_{ti} = 0.113$

$f_{S'up} = S_{upi}/S_{ti} = 0.04$

MODEL REQUIREMENTS

- To model AS system, need to define two things:
  - (1) The biological processes, and
  - (2) The system constraints (or boundary conditions), i.e. the conditions imposed on the biological (and physical) processes by the reactor such as mixing conditions (plug flow or completely mixed), liquid (hydraulic) retention time and solids retention time (sludge age).

SYSTEM CONSTRAINTS

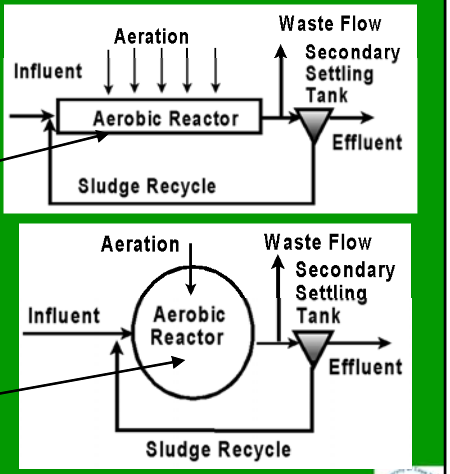
(1) Mixing regimes in reactor and reactor geometry
(2) Liquid retention time or hydraulic retention time
(3) Solids retention time or mean cell residence time, or sludge age.

(1) MIXING CONDITIONS

(1) Mixing regimes
– Two extremes

Plugflow – concentrations vary along length of reactor.

Completely mixed – concentrations same everywhere in reactor.

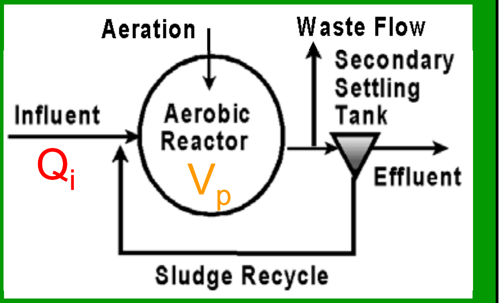


(2) RETENTION TIME (HRT)

(2) Nominal hydraulic retention time (R_{hn}) – length of time liquid stays in reactor =

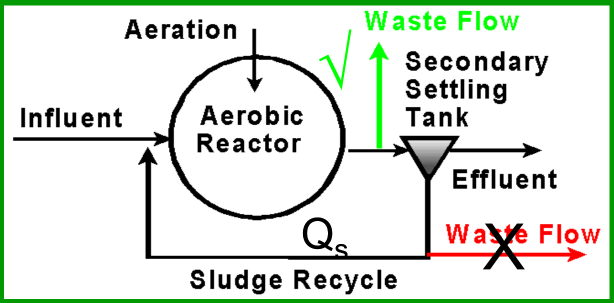
$R_{hn} = V_p/Q_i$ (day)

L/(L/d=d)



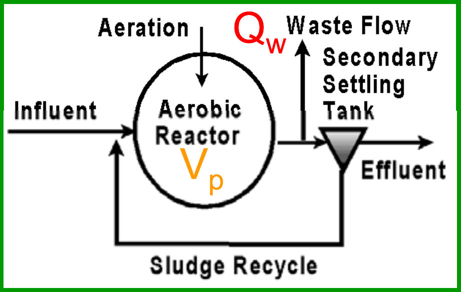
(3) SLUDGE AGE (SRT)

- If nitrification takes place, its best to control sludge age hydraulically by wasting sludge directly from the reactor rather than from the underflow - more later.



(3) SLUDGE AGE (SRT)

(3) Sludge age (R_s) – length of time solids stay in reactor (SRT)



$$R_s = \frac{\text{mass of sludge in system}}{\text{mass of sludge wasted per day}}$$

$$= (V_p\, X_t)/(Q_w\, X_t) = V_p/Q_w \quad \text{(days)}$$

So for R_s=10d, $Q_w = V_p/R_s = V_p/10$ (m^3/d).

BIOLOGICAL BEHAVIOUR

This involves two bio-processes –

(1) Organism growth – utilization of biodegradable organics for metabolism -

- Metabolism comprises 2 aspects
  - Anabolism – material for new cell mass
  - Catabolism – generation of energy to make new cell mass.

(2) Organism "Death" – loss of organism mass due to maintenance energy requirements (endogenous respiration).

BIOLOGICAL BEHAVIOUR (1)

Modelling organism growth and endogenous respiration involves two aspects:

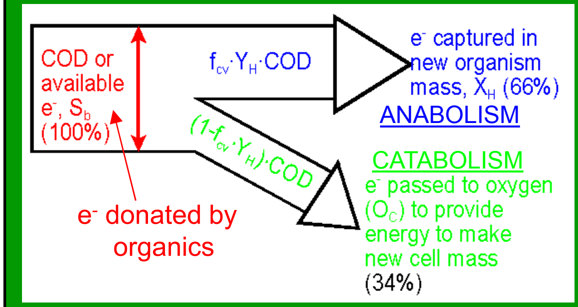
(1) Stoichiometry – quantitative relationship between bioprocess reactants (e.g. organics) and products (e.g. biomass formed, oxygen consumed).

(2) Kinetics – rate at which bioprocesses take place.

GROWTH STOICHIOMETRY

Y_{COD} = COD of biomass formed/COD utilized = 0.66

$Y_{Hv} = Y_{COD}/f_{cv} = 0.66/1.48 = 0.45$ mgVSS/mgCOD



Note: COD of biomass formed + Oxygen utilized = COD of substrate COD utilized.

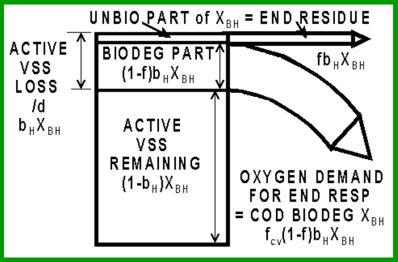
COD mass balance! – fundamental to all models

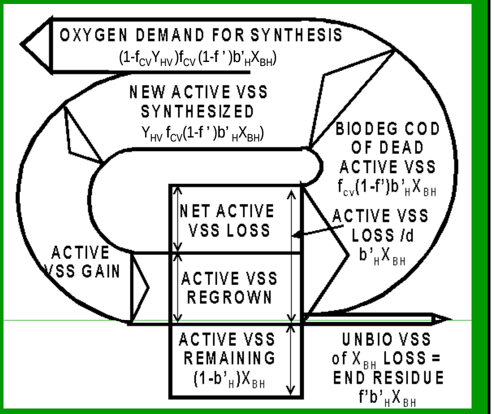
ORGANISM "DEATH" – or ENDOGENOUS RESPIRATION

- Two concepts to model this
  - (1) Death-Regeneration and
  - (2) Endogenous Respiration.
- (2) Dynamic simulation models like ASM1 include (1) but (2) is the simplest.
- So use (2) in the steady state AS model.
- Give similar results for same conditions.

ORGANISM DEATH

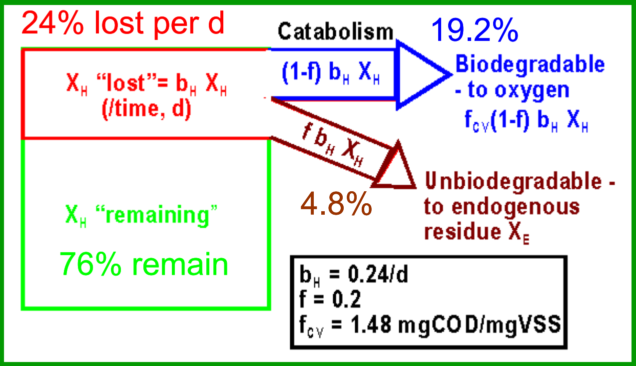
Two approaches lead to identical results!





ER: b_H=0.24/d, f=0.20 D-R: b_H=0.62/d, f=0.08

ENDOGENOUS RESPIRATION



24% lost per d

X_H "lost"= $b_H X_H$ (/time, d)

X_H "remaining"

76% remain

Catabolism

$(1-f)\, b_H X_H$

19.2%

Biodegradable - to oxygen

$f_{CV}(1-f)\, b_H X_H$

$f\, b_H X_H$

4.8%

Unbiodegradable - to endogenous residue X_E

$b_H = 0.24/d$
$f = 0.2$
$f_{CV} = 1.48$ mgCOD/mgVSS

Note: COD balanced over process:

$$-f_{cv}\Delta X_H + f_{cv} f\, b_H X_H + f_{cv}(1-f)\, b_H X_H = 0$$

DEATH REGENERATION

100 mg VSS/L

Active biomass

(X_{BH})

DEATH REGENERATION

Active biomass lost: $b'_H X_{BH}$ =

62 mg VSS/L

(62 %)

X_{BH} biomass remaining: 38 %

DEATH REGENERATION

Biodegradable of X_{BH}: $(1-f')b'_H X_{BH}$ = = 57 mg VSS/L;

Active biomass lost: $b'_H X_{BH}$ =

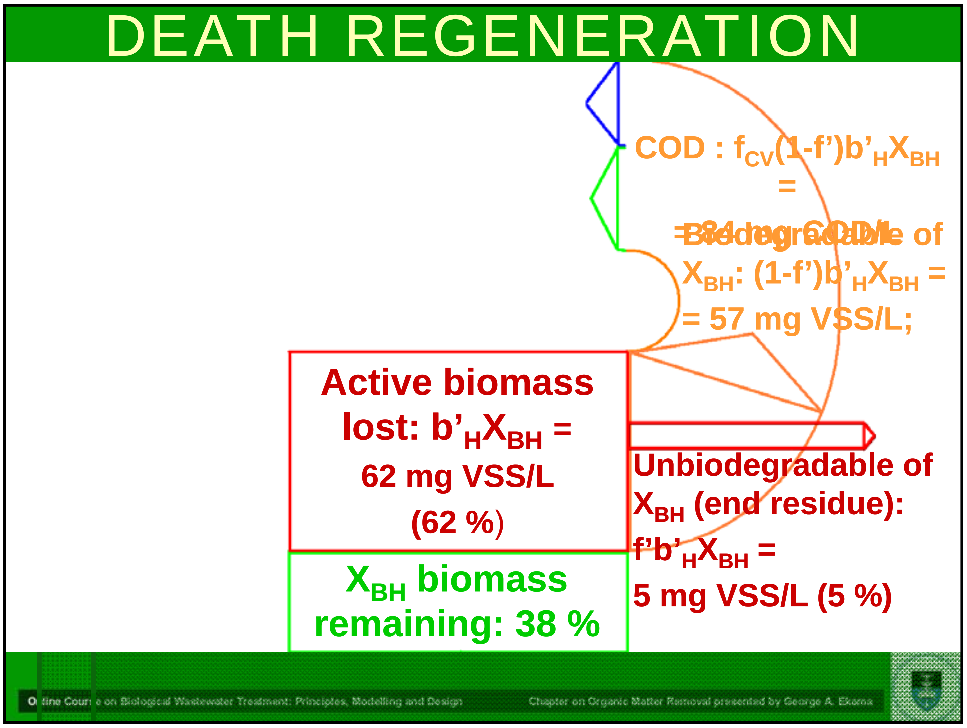
62 mg VSS/L

(62 %)

Unbiodegradable of X_{BH} (end residue): $f'b'_H X_{BH}$ =

5 mg VSS/L (5 %)

X_{BH} biomass remaining: 38 %



DEATH REGENERATION

COD : $f_{CV}(1-f')b'_H X_{BH}$ =

= 34 mg COD/L

Biodegradable of X_{BH}: $(1-f')b'_H X_{BH}$ =

= 57 mg VSS/L;

Active biomass lost: $b'_H X_{BH}$ =

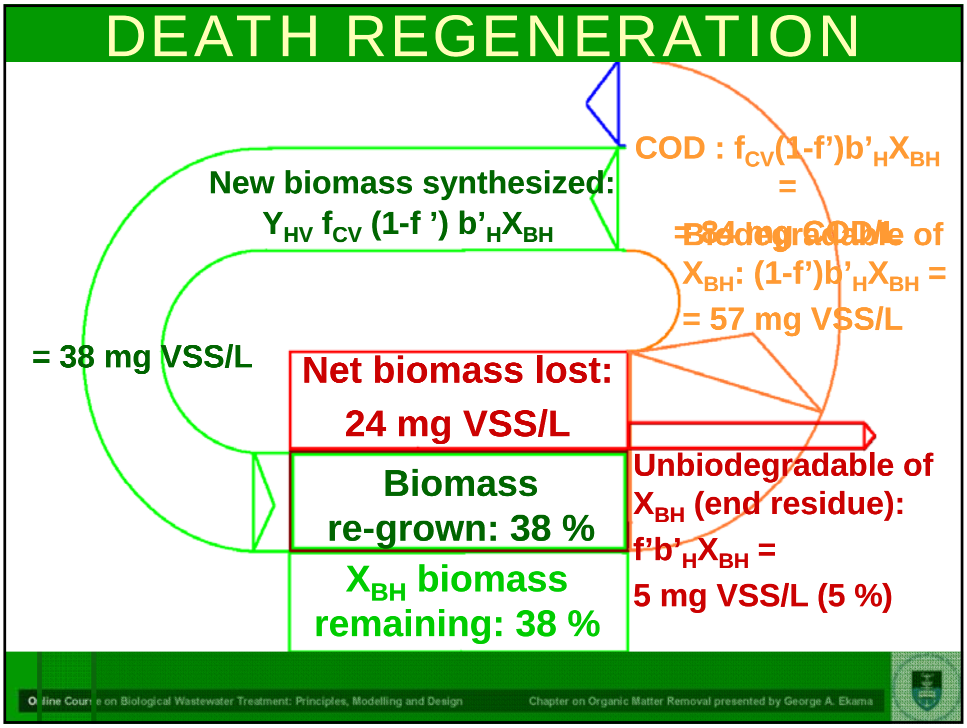
62 mg VSS/L

(62 %)

X_{BH} biomass remaining: 38 %

Unbiodegradable of X_{BH} (end residue): $f'b'_H X_{BH}$ =

5 mg VSS/L (5 %)



DEATH REGENERATION

COD : $f_{CV}(1-f')b'_H X_{BH}$ =

= 34 mg COD/L

Biodegradable of X_{BH}: $(1-f')b'_H X_{BH}$ =

= 57 mg VSS/L

New biomass synthesized: $Y_{HV}\ f_{CV}\ (1-f\ ')\ b'_H X_{BH}$

= 38 mg VSS/L

Net biomass lost:

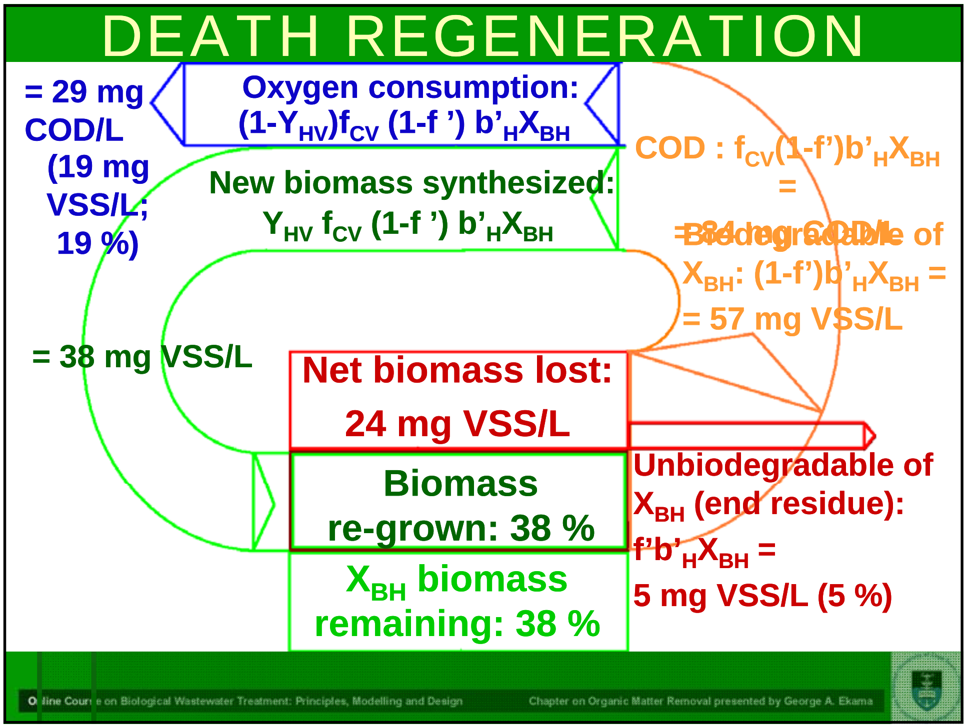
24 mg VSS/L

Biomass re-grown: 38 %

X_{BH} biomass remaining: 38 %

Unbiodegradable of X_{BH} (end residue): $f'b'_H X_{BH}$ =

5 mg VSS/L (5 %)



DEATH REGENERATION

= 29 mg COD/L (19 mg VSS/L; 19 %)

Oxygen consumption: $(1-Y_{HV})f_{CV}(1-f')b'_H X_{BH}$

New biomass synthesized: $Y_{HV} f_{CV} (1-f')b'_H X_{BH}$

= 38 mg VSS/L

COD : $f_{CV}(1-f')b'_H X_{BH}$ =

= 84 mg COD/L

Biodegradable of X_{BH}: $(1-f')b'_H X_{BH}$ =

= 57 mg VSS/L

Net biomass lost: 24 mg VSS/L

Biomass re-grown: 38 %

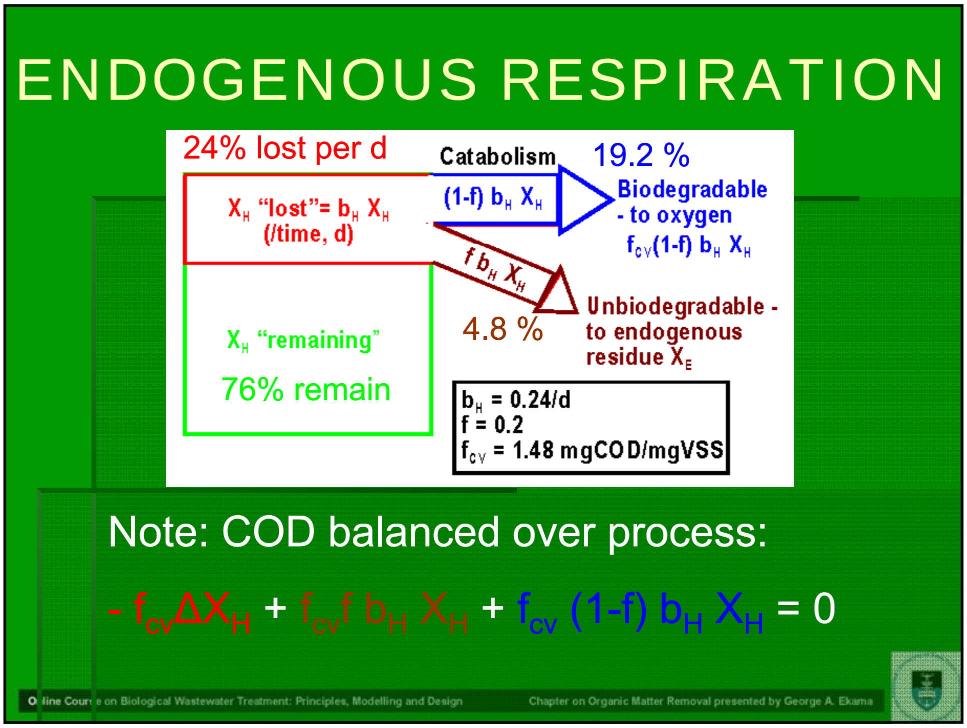
X_{BH} biomass remaining: 38 %

Unbiodegradable of X_{BH} (end residue): $f'b'_H X_{BH}$ =

5 mg VSS/L (5 %)

Online Course on Biological Wastewater Treatment: Principles, Modelling and Design

Chapter on Organic Matter Removal presented by George A. Ekama



ENDOGENOUS RESPIRATION

24% lost per d

X_H "lost"= $b_H X_H$ (/time, d)

X_H "remaining"

76% remain

Catabolism

$(1-f)\ b_H\ X_H$

19.2 %

Biodegradable - to oxygen $f_{CV}(1-f)\ b_H\ X_H$

$f\ b_H\ X_H$

4.8 %

Unbiodegradable - to endogenous residue X_E

b_H = 0.24/d
f = 0.2
f_{CV} = 1.48 mgCOD/mgVSS

Note: COD balanced over process:

$$- f_{cv}\Delta X_H + f_{cv} f\ b_H\ X_H + f_{cv}\ (1-f)\ b_H\ X_H = 0$$

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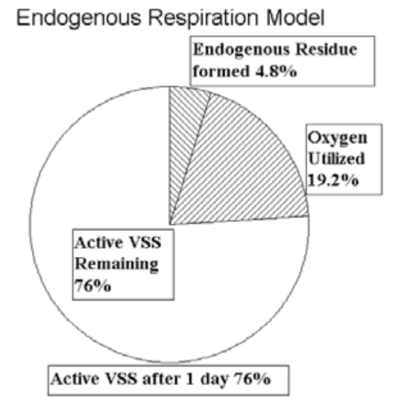
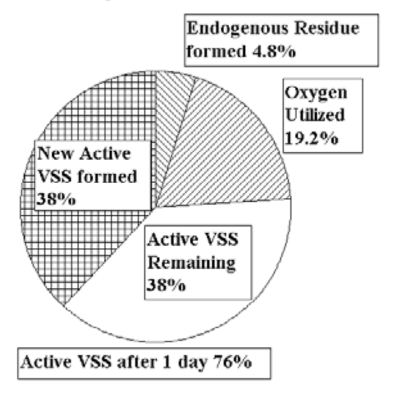
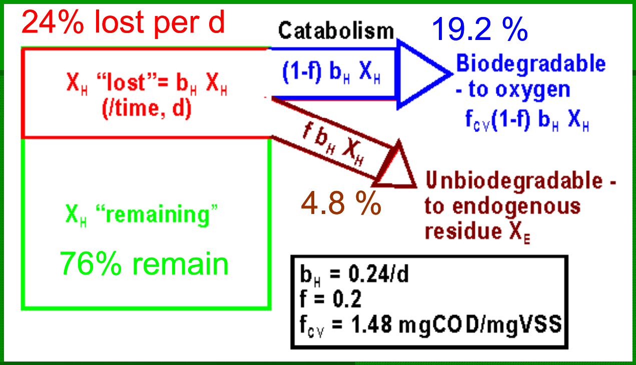
ORGANISM LOSS





Two approaches lead to identical results!

ENDOGENOUS RESPIRATION



24% lost per d

X_H "lost"= $b_H X_H$ (/time, d)

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76% remain

Catabolism

$(1\text{-}f)\ b_H\ X_H$

19.2 %

Biodegradable - to oxygen $f_{CV}(1\text{-}f)\ b_H\ X_H$

$f\ b_H\ X_H$

4.8 %

Unbiodegradable - to endogenous residue X_E

$b_H = 0.24/d$
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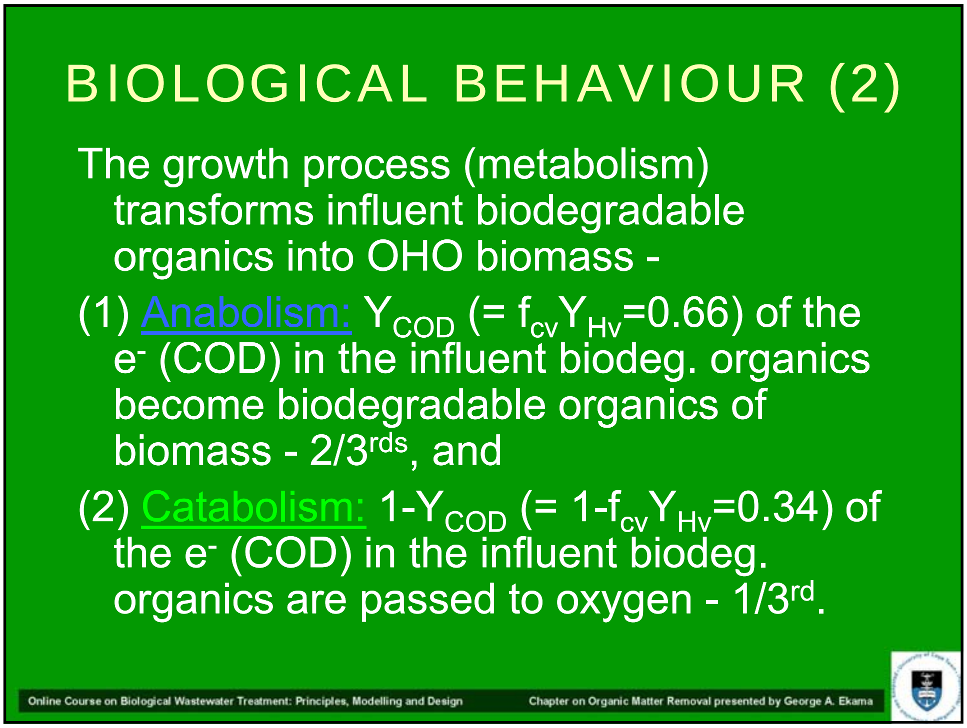
$f_{CV} = 1.48$ mgCOD/mgVSS

Note: COD balanced over process:

$$-f_{cv}\Delta X_H + f_{cv} f\ b_H\ X_H + f_{cv}\ (1\text{-}f)\ b_H\ X_H = 0$$

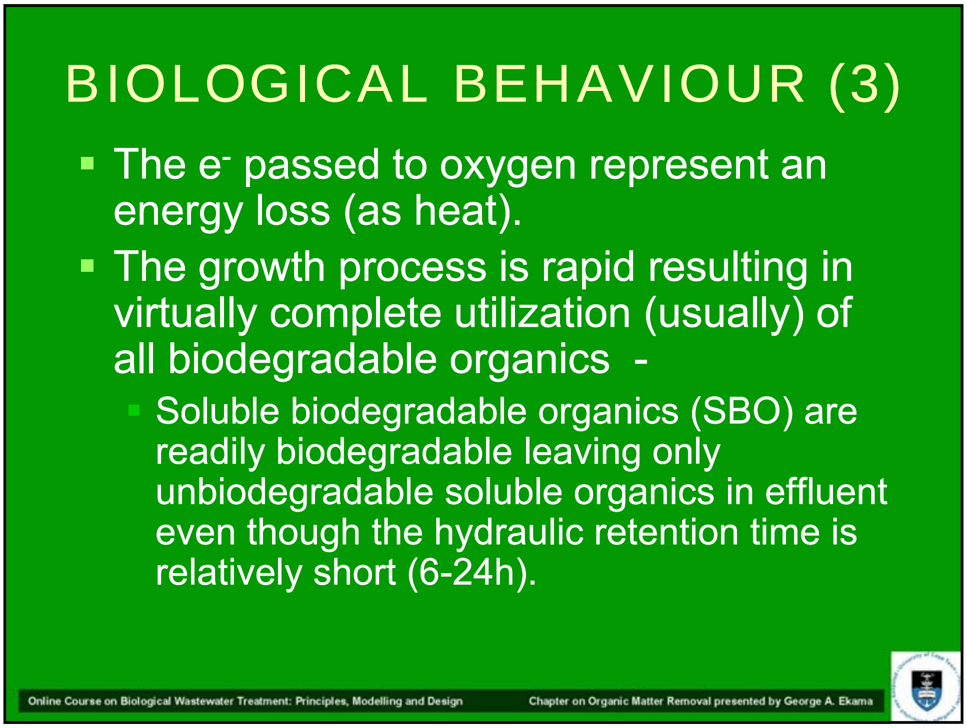


BIOLOGICAL BEHAVIOUR (2)

The growth process (metabolism) transforms influent biodegradable organics into OHO biomass -

(1) Anabolism: Y_{COD} (= $f_{cv}Y_{Hv}$=0.66) of the e^- (COD) in the influent biodeg. organics become biodegradable organics of biomass - 2/3rds, and

(2) Catabolism: 1-Y_{COD} (= 1-$f_{cv}Y_{Hv}$=0.34) of the e^- (COD) in the influent biodeg. organics are passed to oxygen - 1/3rd.



BIOLOGICAL BEHAVIOUR (3)

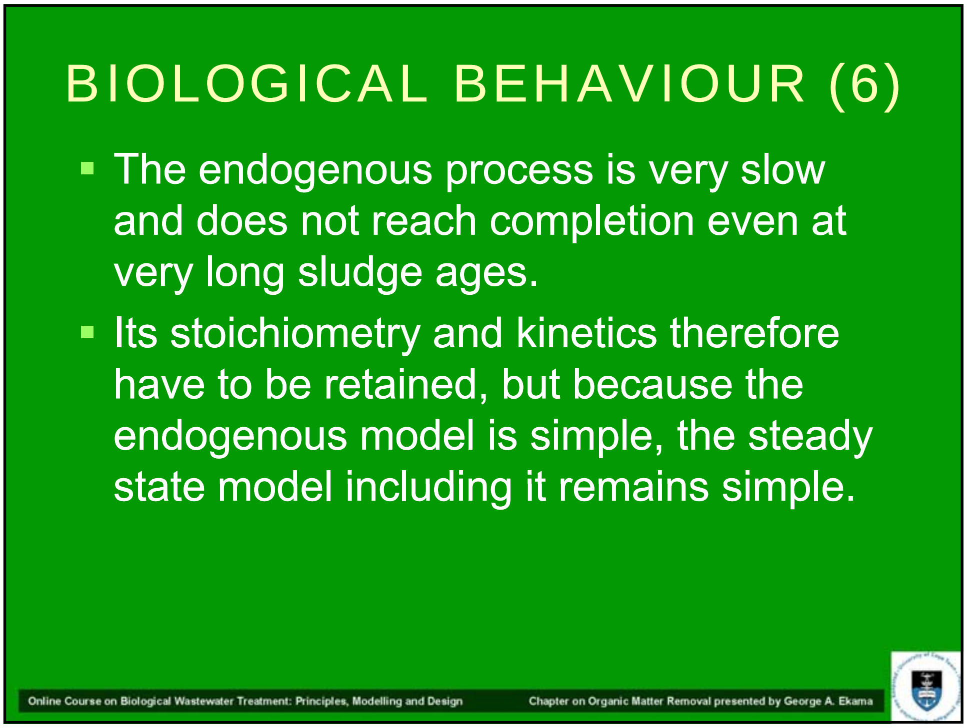
- The e^- passed to oxygen represent an energy loss (as heat).
- The growth process is rapid resulting in virtually complete utilization (usually) of all biodegradable organics -
  - Soluble biodegradable organics (SBO) are readily biodegradable leaving only unbiodegradable soluble organics in effluent even though the hydraulic retention time is relatively short (6-24h).

BIOLOGICAL BEHAVIOUR (4)

  - Particulate biodegradable organics (PBO) are slowly biodegradable, but they get enmeshed in the sludge mass and so are retained in the system by the SST and stay in the system for as long as the sludge age (>5d). This is long enough to allow near complete utilization also, leaving only the particulate unbiodegradable organics.
- So it can be assumed in the steady state AS model that all biodegradable organics are completely utilized – i.e. the growth process is complete.

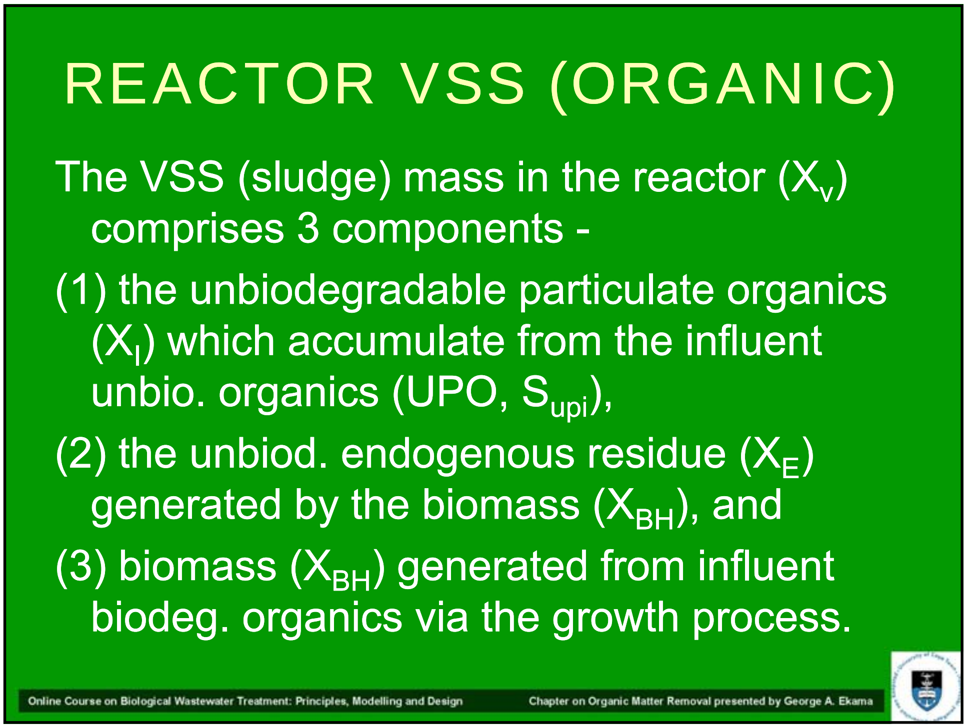
BIOLOGICAL BEHAVIOUR (5)

- With the growth process complete, it’s kinetics can be ignored !
- So in the steady state model only the stoichiometry of the growth process needs to be considered.
- The endogenous process transforms biomass biodegradable organics to (1) unbiodegradable endogenous residue, which accumulates in the reactor as VSS, and (2) additional oxygen consumption.



BIOLOGICAL BEHAVIOUR (6)

- The endogenous process is very slow and does not reach completion even at very long sludge ages.
- Its stoichiometry and kinetics therefore have to be retained, but because the endogenous model is simple, the steady state model including it remains simple.



REACTOR VSS (ORGANIC)

The VSS (sludge) mass in the reactor (X_v) comprises 3 components -

(1) the unbiodegradable particulate organics (X_I) which accumulate from the influent unbio. organics (UPO, S_{upi}),

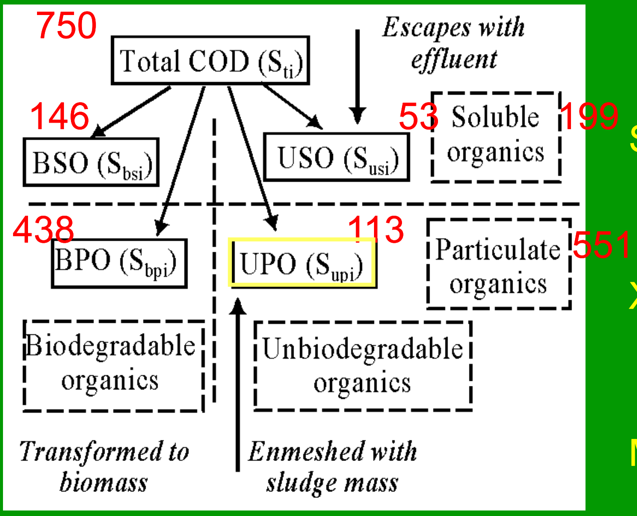
(2) the unbiod. endogenous residue (X_E) generated by the biomass (X_{BH}), and

(3) biomass (X_{BH}) generated from influent biodeg. organics via the growth process.

REACTOR VSS (ORGANIC)

- So $X_v = X_{BH} + X_{EH} + X_I$ mgVSS/l.
- The proportions of these 3 VSS components that make up the measured reactor VSS vary with sludge age (R_s).
- The VSS mass in the reactor (MX_v) is the VSS concentration (X_v) x reactor volume (V_p), i.e. $MX_v = X_v V_p$ kgVSS.
- X = Solids conc., X_v = volatile (organic) solids in mgVSS/l.

(A) UNBIODEGRADABLE PARTICULATE ORGANICS (1)

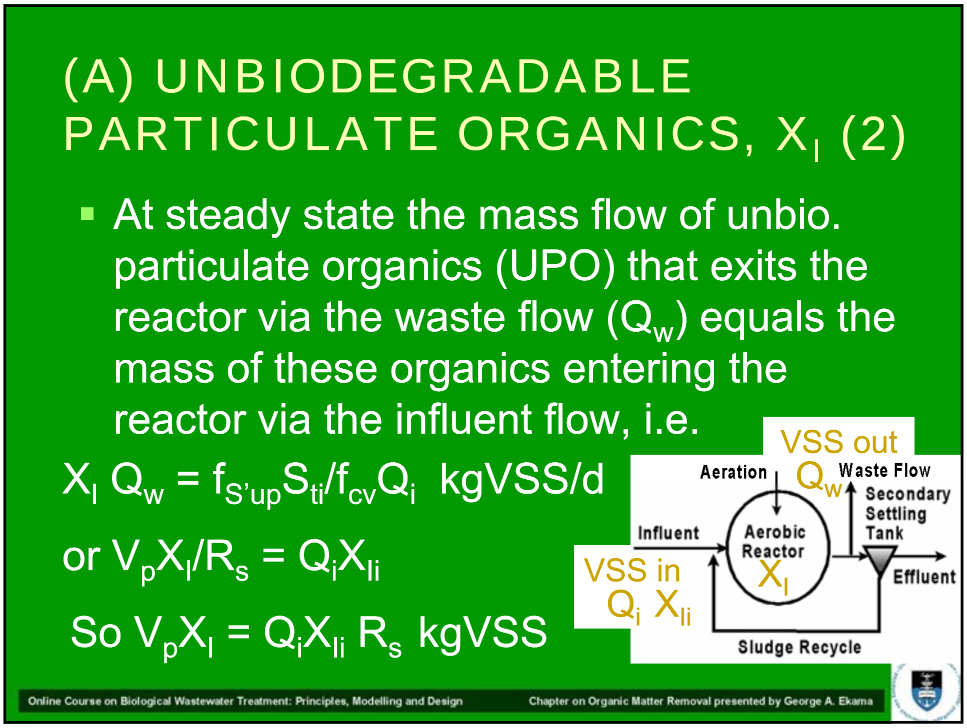


Units – mgCOD/L

$S_{upi} = f_{S'up} S_{ti}$ = 0.15x750=113 mgCOD/l

$X_{Ii} = S_{upi}/f_{cv}$ =113/1.48 =76mgVSS/l

$MX_{Ii} = Q_i X_{Ii}$ kgVSS/d



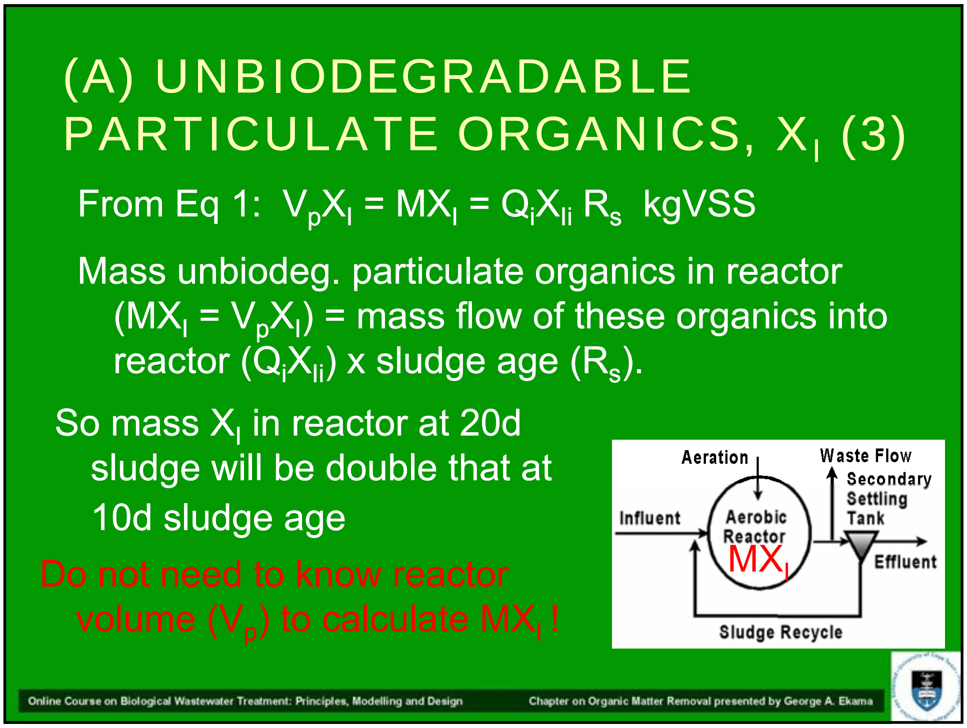
(A) UNBIODEGRADABLE PARTICULATE ORGANICS, X_I (2)

- At steady state the mass flow of unbio. particulate organics (UPO) that exits the reactor via the waste flow (Q_w) equals the mass of these organics entering the reactor via the influent flow, i.e.

$X_I\ Q_w = f_{S'up}S_{ti}/f_{cv}Q_i$ kgVSS/d

or $V_pX_I/R_s = Q_iX_{Ii}$

So $V_pX_I = Q_iX_{Ii}\ R_s$ kgVSS



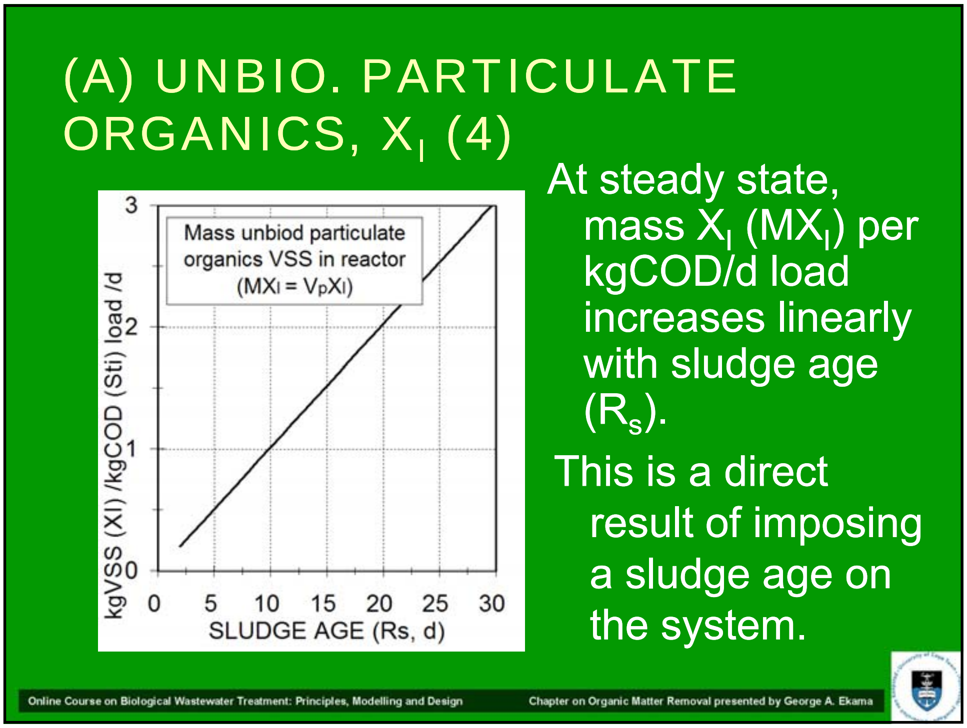
(A) UNBIODEGRADABLE PARTICULATE ORGANICS, X_I (3)

From Eq 1: $V_pX_I = MX_I = Q_iX_{Ii}\ R_s$ kgVSS

Mass unbiodeg. particulate organics in reactor ($MX_I = V_pX_I$) = mass flow of these organics into reactor (Q_iX_{Ii}) x sludge age (R_s).

So mass X_I in reactor at 20d sludge will be double that at 10d sludge age

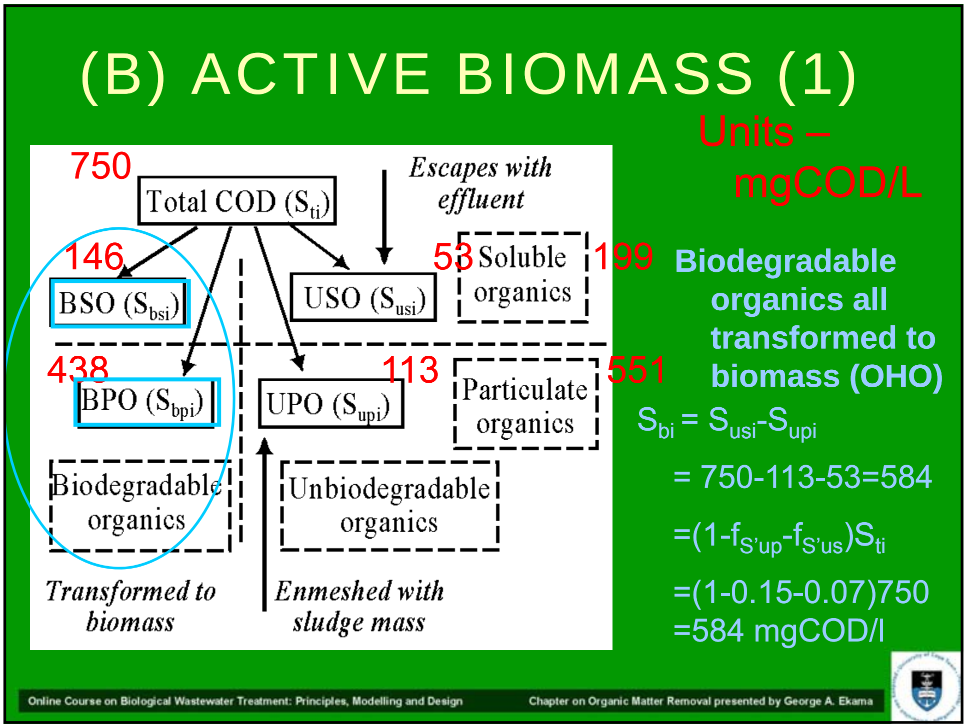
Do not need to know reactor volume (V_p) to calculate MX_I !



(A) UNBIO. PARTICULATE ORGANICS, X_I (4)

At steady state, mass X_I (MX_I) per kgCOD/d load increases linearly with sludge age (R_s).

This is a direct result of imposing a sludge age on the system.



(B) ACTIVE BIOMASS (1)

Units – mgCOD/L

Biodegradable organics all transformed to biomass (OHO)

$S_{bi} = S_{usi} - S_{upi}$

$= 750-113-53=584$

$=(1-f_{S'up}-f_{S'us})S_{ti}$

$=(1-0.15-0.07)750$

$=584$ mgCOD/l

(B) ACTIVE BIOMASS (2)

- Biomass also accumulates in reactor in proportion to sludge age,

  i.e. net “entry rate” per day x sludge age.
- Its “entry rate” is via the growth process –

  $\Delta V_p X_{BH} = +Y_{Hv}\ (Q_i S_{bi})$ kgVSS/d

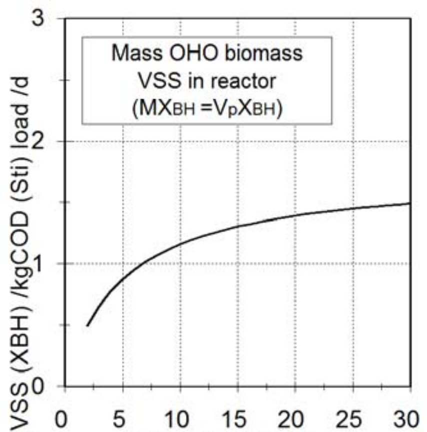
  $(Q_i S_{bi})$ = mass bio COD load /d.
- But there is also an “exit (loss) rate” via the endogenous process: $1/(1+b_H R_s)$, i.e. the longer the R_s, the greater the loss.

(B) ACTIVE BIOMASS (3)

- The net entry rate combines the entry (growth) and exit (loss) rates per day. Multiplying this net rate/d over R_s days –
- $V_p X_{BH} = \dfrac{Y_{Hv}\ (Q_i S_{bi})\ R_s}{(1+b_H R_s)}$ kgVSS

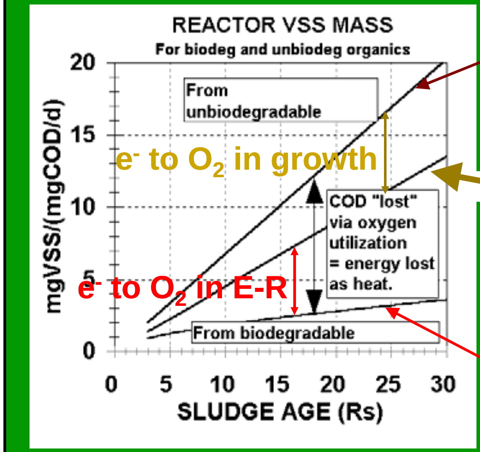
So mass of OHOs in reactor is proportional to mass of biodeg. COD load on reactor per day (all biodeg COD utilized), the net “yield” $Y_{Hv}/(1+b_H R_s)$ and R_s

(B) ACTIVE BIOMASS (4)



- Mass X_{BH} in reactor per kgCOD/d on reactor increases with sludge age (R_s) but increase gets smaller as sludge age gets longer due to longer duration of endogenous process.

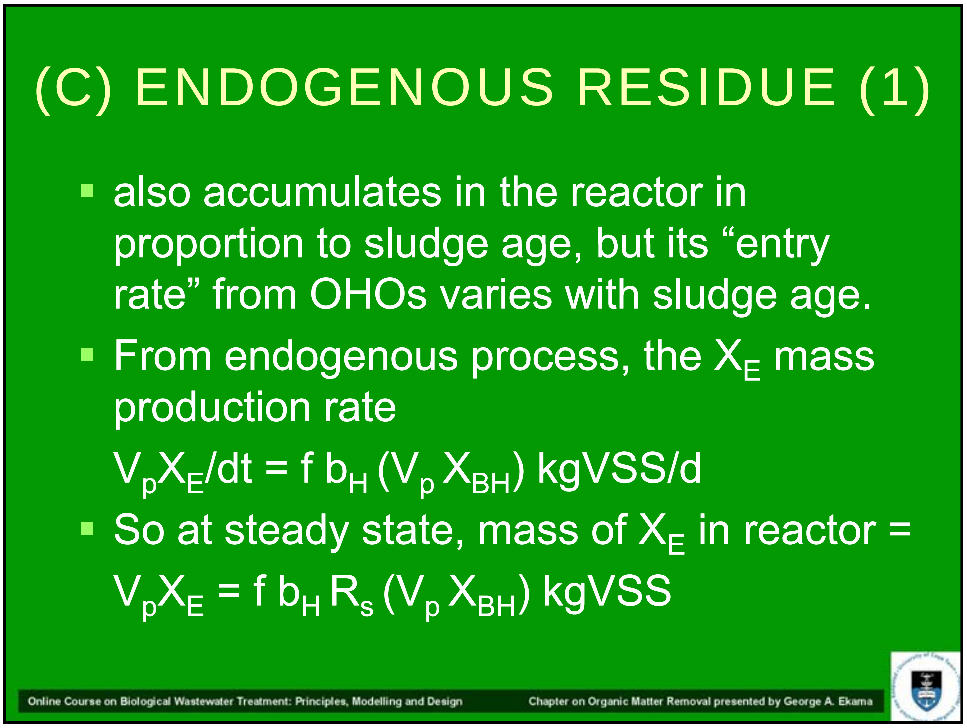
(B) ACTIVE BIOMASS (5)



From unbiodegradable particulate organics.

From biodegradable organics (Y_{Hv}=0.45) and no endogenous respiration (b_H=0).

From biodegradable organics (Y_{Hv}=0.45) and endogenous respiration (b_H=0.24/d)

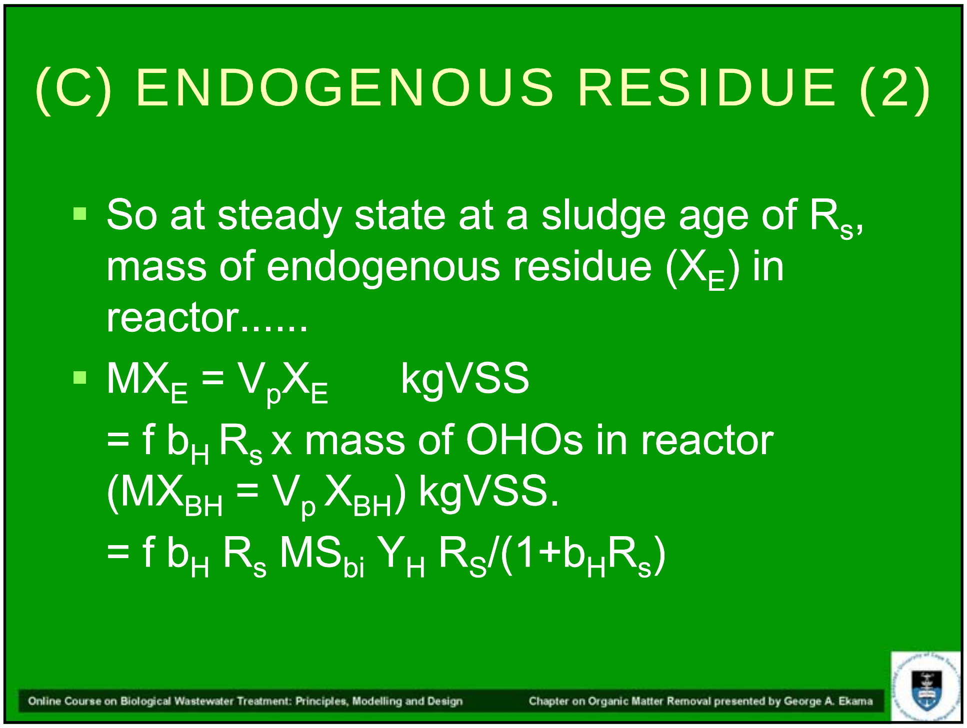


(C) ENDOGENOUS RESIDUE (1)

- also accumulates in the reactor in proportion to sludge age, but its “entry rate” from OHOs varies with sludge age.
- From endogenous process, the X_E mass production rate

  $V_pX_E/dt = f\ b_H\ (V_p\ X_{BH})$ kgVSS/d
- So at steady state, mass of X_E in reactor =

  $V_pX_E = f\ b_H\ R_s\ (V_p\ X_{BH})$ kgVSS

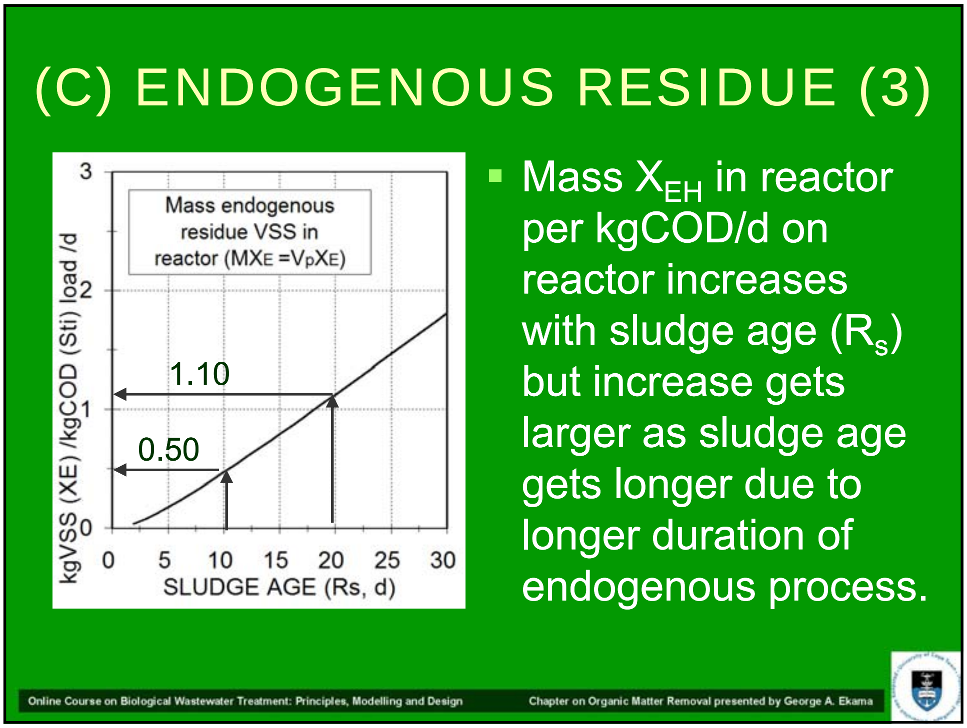


(C) ENDOGENOUS RESIDUE (2)

- So at steady state at a sludge age of R_s, mass of endogenous residue (X_E) in reactor......
- $MX_E = V_pX_E$ kgVSS

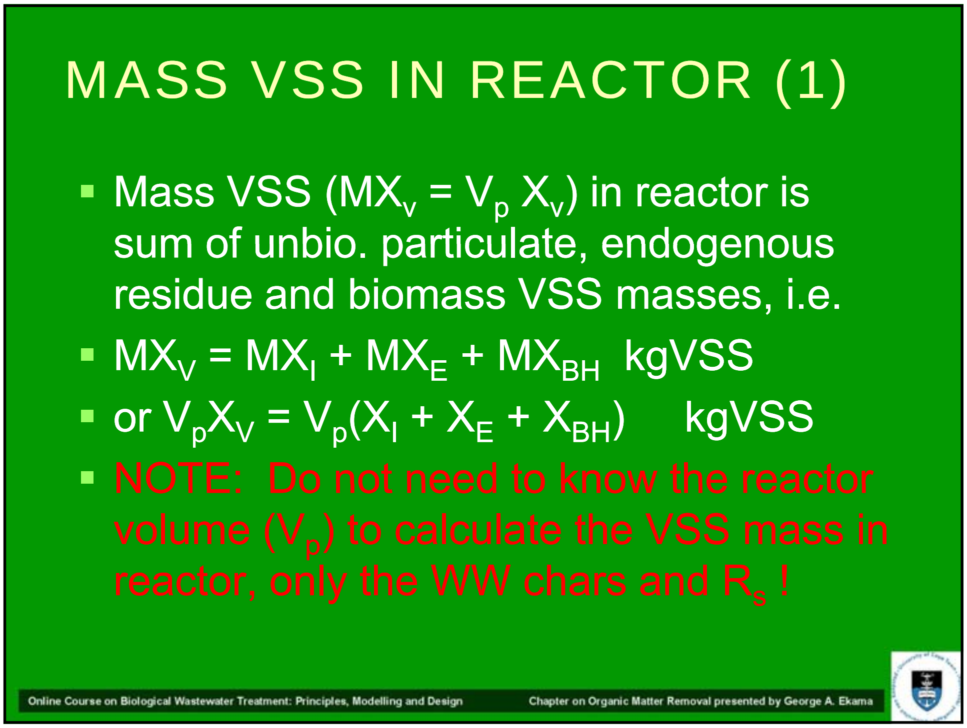
  $= f\ b_H\ R_s$ x mass of OHOs in reactor ($MX_{BH} = V_p\ X_{BH}$) kgVSS.

  $= f\ b_H\ R_s\ MS_{bi}\ Y_H\ R_S/(1+b_HR_s)$



(C) ENDOGENOUS RESIDUE (3)

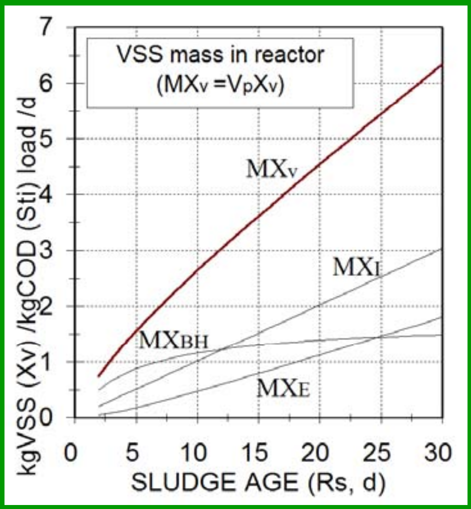
- Mass X_{EH} in reactor per kgCOD/d on reactor increases with sludge age (R_s) but increase gets larger as sludge age gets longer due to longer duration of endogenous process.



MASS VSS IN REACTOR (1)

- Mass VSS ($MX_v = V_p X_v$) in reactor is sum of unbio. particulate, endogenous residue and biomass VSS masses, i.e.
- $MX_V = MX_I + MX_E + MX_{BH}$ kgVSS
- or $V_pX_V = V_p(X_I + X_E + X_{BH})$ kgVSS
- NOTE: Do not need to know the reactor volume (V_p) to calculate the VSS mass in reactor, only the WW chars and R_s !

MASS VSS IN REACTOR (2)



- For raw WW:
- At 10d sludge age, VSS mass in reactor is ~2.7 kgVSS per kgCOD load in reactor,
- At 20d, ~4.5 kgVSS/kgCOD load per day.

TSS MASS IN REACTOR (1)

- VSS is organic part of suspended solids in reactor.
- TSS is total and includes inorganic suspended solids (ISS).
- Reactor ISS arises from two sources
  - (1) Influent ISS accumulation
  - (2) Biomass OHO “ISS” – intracellular dissolved solids which precipitate as ISS in the drying step of TSS procedure.

TSS MASS IN REACTOR (2)

(1) influent ISS accumulates in reactor linearly with sludge age just like unbiodeg. particulate organics, i.e.

$V_p X_{Io} = Q_i X_{Ioi} R_s$ kgISS

$Q_i X_{Ioi}$ = influent ISS load = kgISS/d.

(2) biomass (OHOs) adds about 0.15 (f_{iOHO}) times their mass to measured ISS.

So mass ISS in reactor (V_pX_{Io})

$V_pX_{Io} = Q_i X_{Ioi} R_s + f_{iOHO} MX_{BH}$ kgISS

TSS MASS IN REACTOR (3)

- If influent ISS is not known, can choose a VSS/TSS ratio (f_i) for the AS, e.g.

  f_i = 0.75- 0.85 for raw wastewater

  f_i = 0.80- 0.88 for settled wastewater.

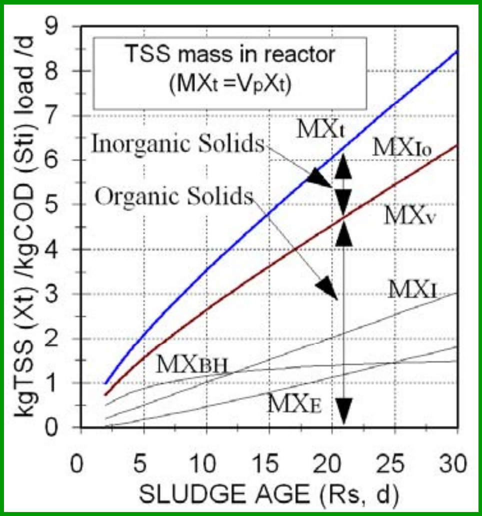
  f_i does not vary much with sludge age.

Select from similar wastewater, catchment characteristics and population behaviour.

So reactor TSS (MX_t) = MX_v/f_i kgTSS and

$MX_{Io} = MX_t - MX_v$ kgISS

TSS MASS IN REACTOR (4)



- For raw WW:
- At 10d sludge age, TSS mass in reactor is ~3.5 kgTSS per kgCOD load in reactor,
- At 20d, ~6.0 kgTSS/kgCOD load per day.

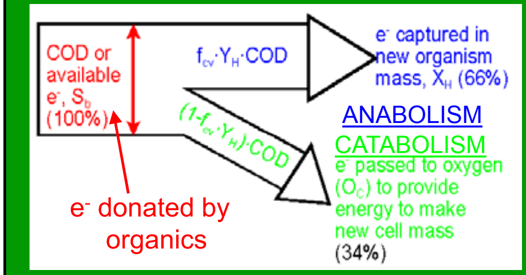
OXYGEN DEMAND, OD (1)

- Recall that oxygen is required for two bio-processes:

(1) Growth and

(2) Endogenous Respiration

OXYGEN FOR GROWTH



Organics e^- through catabolism passed to oxygen.

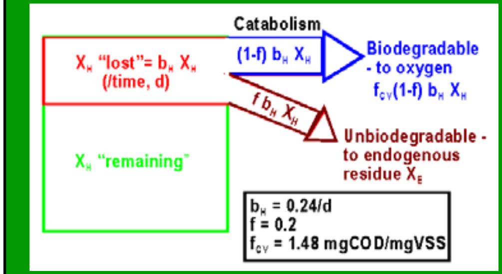
So OD for growth $O_s = (1-f_{cv}Y_{Hv})$xCOD utilized.

COD utilized = biodeg. COD load = $Q_i\ S_{bi}$ kgO/d

So $MO_s = V_pO_s = (1-f_{cv}Y_{Hv})\ Q_i\ S_{bi}$ kgO/d

MO_s = Oxygen for synthesis of cell mass (growth) kgO/d

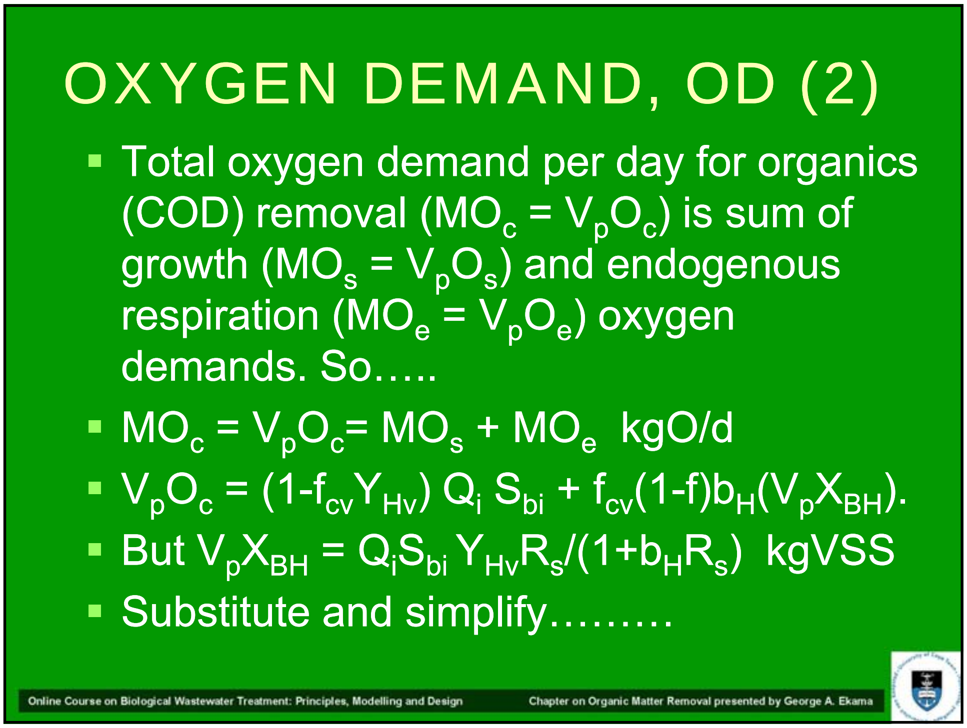
OXYGEN DEMAND FOR ENDOGENOUS RESPIRATION



e^- of biomass (X_{BH}) biodeg. organics "lost" passed to oxygen – catabolic energy generation.

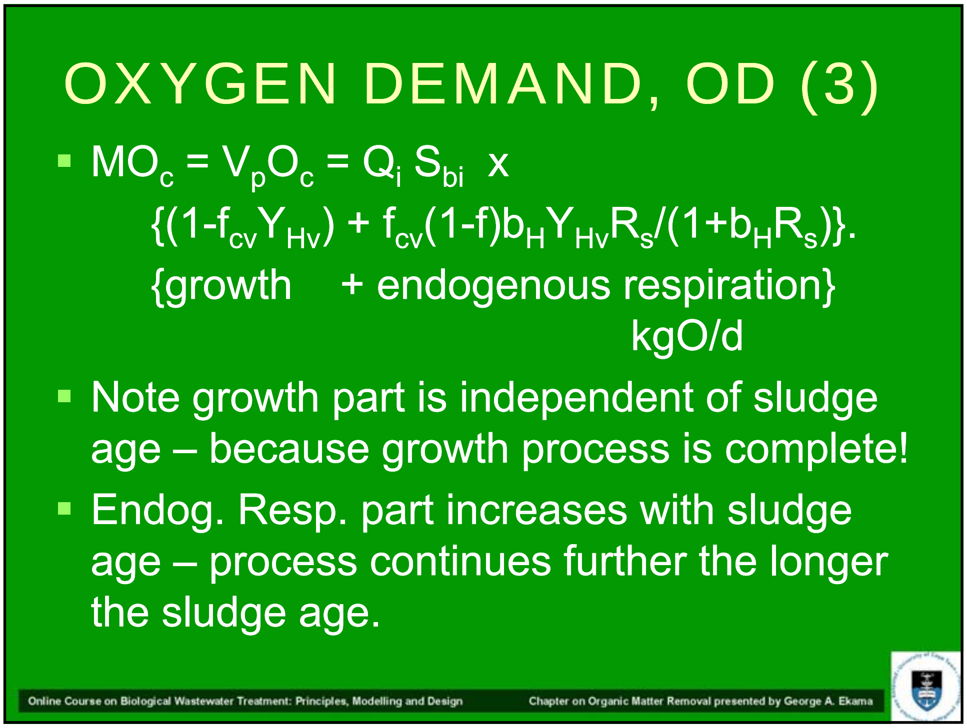
So OD/d for End Resp = COD of biomass biodeg organics lost per day

$MO_e = V_pO_e = f_{cv}\ (1-f)\ b_H\ (V_p\ X_{BH})$ kgO/d



OXYGEN DEMAND, OD (2)

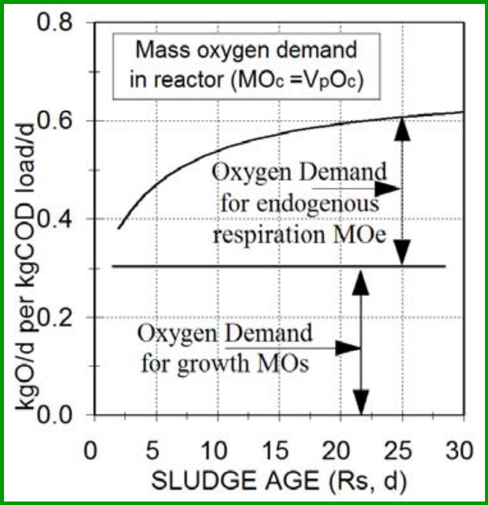
- Total oxygen demand per day for organics (COD) removal ($MO_c = V_pO_c$) is sum of growth ($MO_s = V_pO_s$) and endogenous respiration ($MO_e = V_pO_e$) oxygen demands. So…..
- $MO_c = V_pO_c = MO_s + MO_e$ kgO/d
- $V_pO_c = (1\text{-}f_{cv}Y_{Hv})\ Q_i\ S_{bi} + f_{cv}(1\text{-}f)b_H(V_pX_{BH})$.
- But $V_pX_{BH} = Q_iS_{bi}\ Y_{Hv}R_s/(1+b_HR_s)$ kgVSS
- Substitute and simplify………



OXYGEN DEMAND, OD (3)

- $MO_c = V_pO_c = Q_i\ S_{bi}$ x
  $\{(1\text{-}f_{cv}Y_{Hv}) + f_{cv}(1\text{-}f)b_HY_{Hv}R_s/(1+b_HR_s)\}$.
  {growth + endogenous respiration}
  kgO/d
- Note growth part is independent of sludge age – because growth process is complete!
- Endog. Resp. part increases with sludge age – process continues further the longer the sludge age.

OXYGEN DEMAND, OD (4)



- Note: Oxygen demand for organics removal increases as sludge age increases because endogenous process continues further the longer the sludge age.

EFFLUENT COD

- Because….

  (1) the biodeg. organics are all utilized – the soluble organics rapidly well within the hydraulic retention time, and the particulate organics well within the sludge age, and

  (2) the particulate unbiodeg. organics get enmeshed with the sludge mass,

……the effluent COD is mainly the unbiodeg. soluble organics: $S_{te} = S_{use} = S_{usi}$.

(Symbol S denotes COD, mgCOD/l)

AS DESIGN MODEL (1)

- From the basic equations, mass VSS (MX_v), TSS (MX_t) and oxygen demand (MO_c) and effluent COD conc (S_{te}) are all functions of ….

(1) WW characteristics [$f_{S'up}$, $f_{S'us}$, X_{Ioi}/S_{ti}],

(2) WW COD load [$MS_{ti} = Q_i\ S_{ti}$ kgCOD/d]

(3) System sludge age [R_s, d]

(4) OHO stoichiometric constants [Y_{Hv}, f_{cv}, f]

(5) OHO kinetic constant [b_H]

AS DESIGN MODEL (2)

- Values for stoichiometric and kinetic constants remain unchanged for different WWs. So VSS, TSS, OD and effluent COD conc. are functions of WW characteristics [$f_{S'up}$, $f_{S'us}$, X_{Ioi}/S_{ti}] and COD load [$Q_i\ S_{ti}$] and selected system sludge age [R_s, d].
- So WW characteristics and COD load need to be well defined and sludge age carefully selected!.

VALUES OF CONSTANTS

- Stoichiometric –
  Y_{Hv} = OHO yield = 0.45 mgVSS/mgCOD
  f_{cv} = COD/VSS = 1.48 mgCOD/mgVSS
  f = OHO unbiodegradable fraction = 0.20
- Kinetic – only the endogenous rate
  $b_{HT} = b_{H20}(1.029)^{(T-20)}$ /d ; b_{H20}=0.24/d
  (valid between 12 and 30°C)

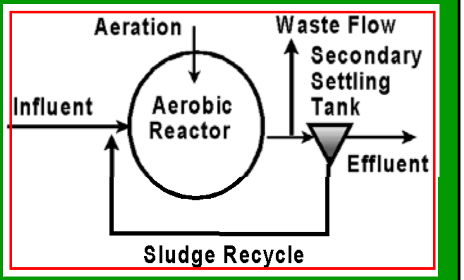
THE COD (e^-) BALANCE (1)

- Electrons (e^-) cannot be created or destroyed so the e^- mass (COD) of the influent must go somewhere!

System boundary

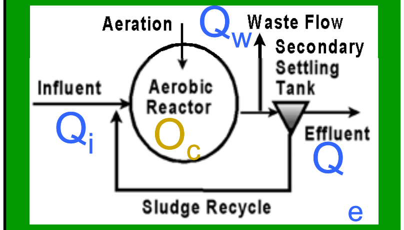
- Exit routes for e^-…..

(1) Effluent COD
(2) COD of waste sludge
(3) Oxygen utilized
$4e^- + 4H^+ + O_2 \rightarrow 2H_2O$



Think e^-, not O!

THE COD (e^-) BALANCE (2)



Water balance

$$Q_w + Q_e = Q_i$$

$$\begin{bmatrix}\text{Mass of COD } (e^-) \\ \text{output per day}\end{bmatrix} = \begin{bmatrix}\text{Mass of COD } (e^-) \\ \text{input per day}\end{bmatrix}$$

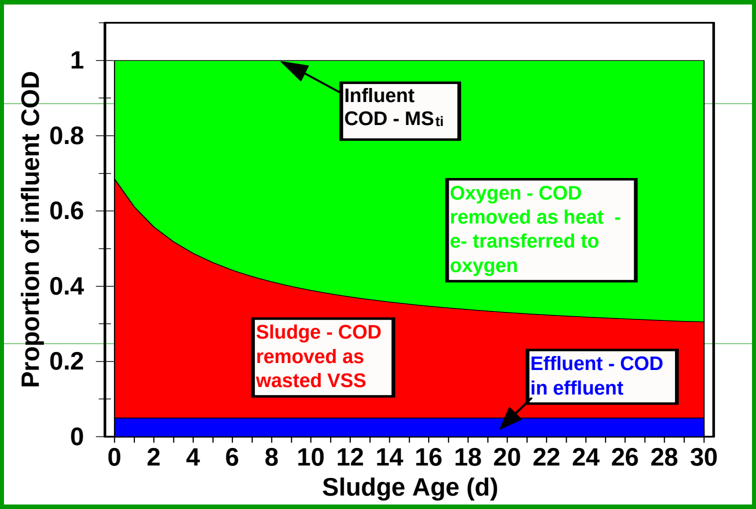
$$\begin{bmatrix}\text{Mass of} \\ \text{soluble} \\ \text{COD in} \\ \text{effluent} \\ \text{per day}\end{bmatrix} + \begin{bmatrix}\text{Mass of} \\ \text{soluble} \\ \text{COD in} \\ \text{waste flow} \\ \text{per day}\end{bmatrix} + \begin{bmatrix}\text{Mass of} \\ \text{particulate} \\ \text{COD in} \\ \text{waste flow} \\ \text{per day}\end{bmatrix}$$

$$+ \begin{bmatrix}\text{Mass of oxygen utilized} \\ \text{by OHOs for COD} \\ \text{breakdown per day}\end{bmatrix} = \begin{bmatrix}\text{Mass of} \\ \text{COD input} \\ \text{per day}\end{bmatrix}$$

$$\boxed{Q_e} S_{te} + \boxed{Q_w} S_{te} + \boxed{Q_w} X_v f_{cv} + V_p \boxed{O_c} = Q_i S_{ti}$$

$$MS_{te} + f_{cv} MX_v / R_s + MO_c = MS_{ti}$$

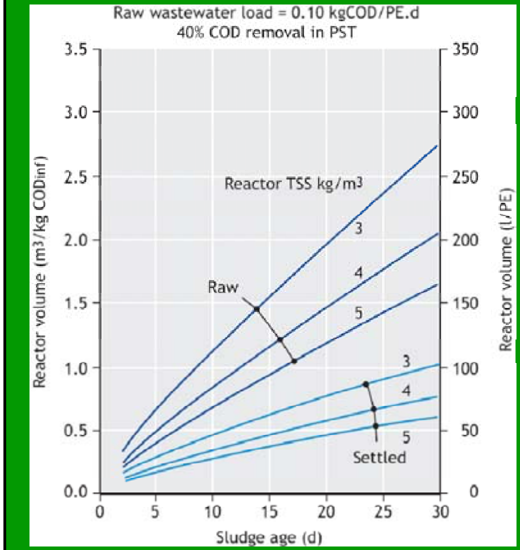
THE COD (e^-) BALANCE (3)



THE COD (e^-) BALANCE (4)

- So the longer the sludge age, the greater the mass of VSS (TSS) in the reactor, but the lower the VSS (TSS) mass wasted per day from the reactor.
- The longer the sludge age, the longer the sludge stays in the reactor giving the endogenous process longer time to continue, which causes the oxygen demand to increase and the VSS mass wasted per day to decrease.

REACTOR VOLUME



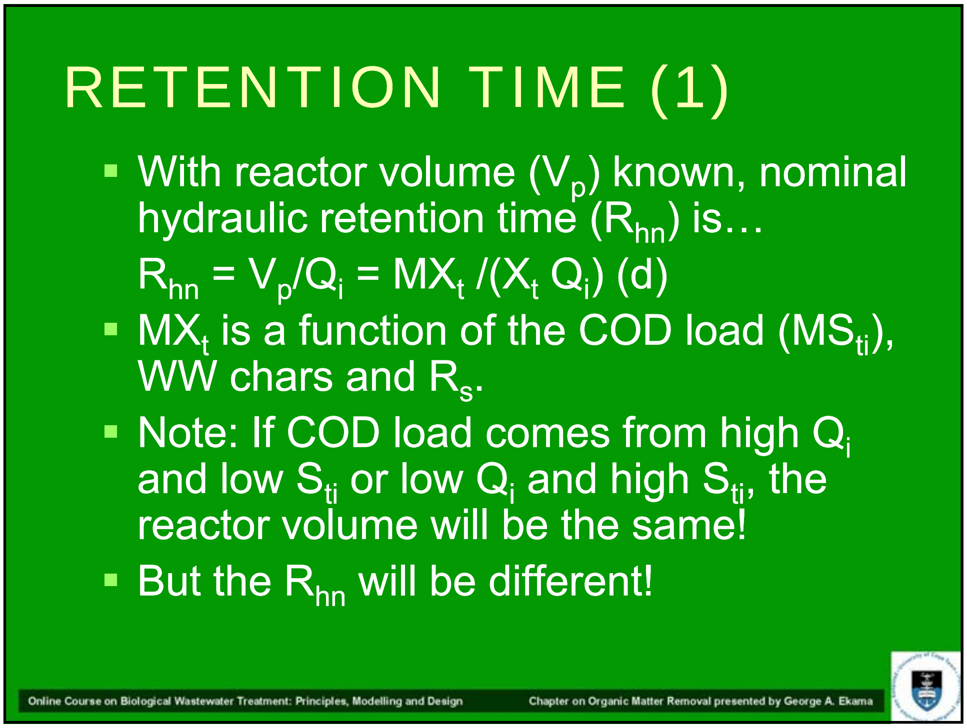
- Knowing MX_t, the reactor volume V_p is calculated from a selected reactor concentration (X_t)...

  $V_p = MX_t / X_t$ m^3

Note: As SRT↑, V_p ↑

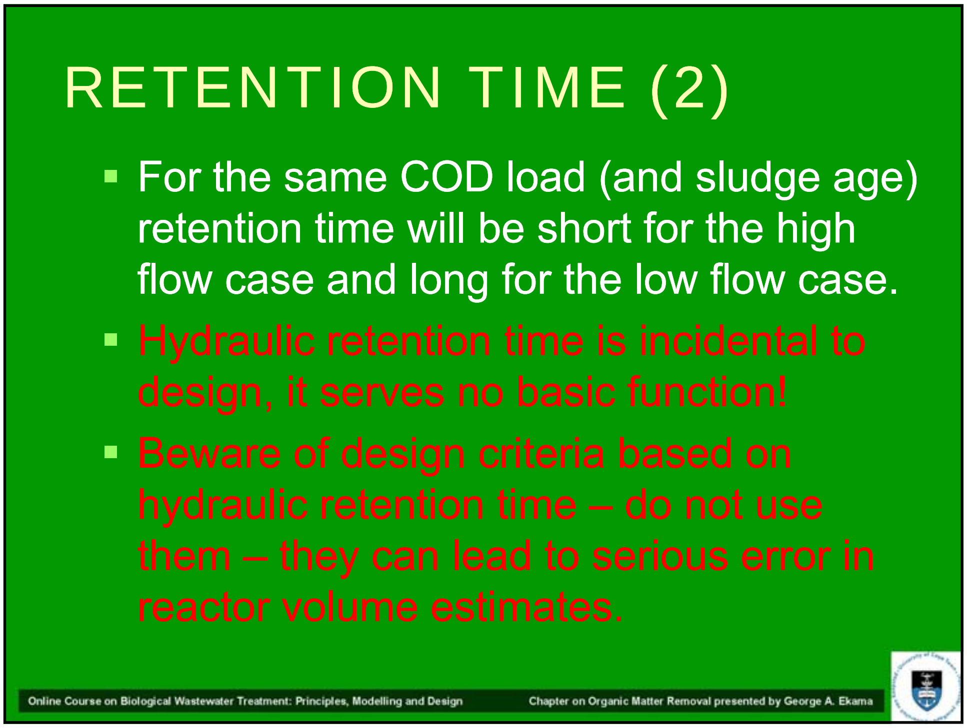
As X_t ↓, V_p ↑

V_p Raw > V_p Settled



RETENTION TIME (1)

- With reactor volume (V_p) known, nominal hydraulic retention time (R_{hn}) is…
  $R_{hn} = V_p/Q_i = MX_t /(X_t\ Q_i)$ (d)
- MX_t is a function of the COD load (MS_{ti}), WW chars and R_s.
- Note: If COD load comes from high Q_i and low S_{ti} or low Q_i and high S_{ti}, the reactor volume will be the same!
- But the R_{hn} will be different!



RETENTION TIME (2)

- For the same COD load (and sludge age) retention time will be short for the high flow case and long for the low flow case.
- Hydraulic retention time is incidental to design, it serves no basic function!
- Beware of design criteria based on hydraulic retention time – do not use them – they can lead to serious error in reactor volume estimates.

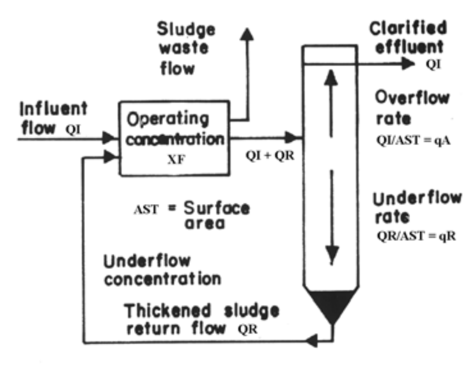
SELECTING REACTOR X_t (1)

- Done with a reactor volume (V_p) – 2^{ary} settling tank area (A_{ST}) cost optimization:
- TSS mass in reactor is fixed by WW and sludge age, so selecting …
- X_t high makes V_p small but A_{ST} large, or
- X_t low makes V_p large but A_{ST} small.
- Plot reactor and SST costs versus X_t

SELECTING REACTOR X_t (2)

For fixed sludge TSS mass in reactor, increasing X_t makes reactor volume smaller: $V_p = MX_t / X_t$ m^3

For fixed sludge settleability, increasing X_t (or X_F) makes SST surface area larger.

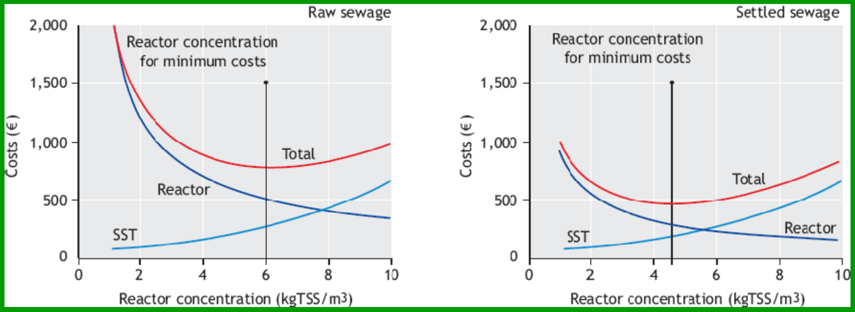


$f_q Q_i / A_{ST} < V_s$ at X_t m/h

$V_s = V_0 e^{(-nXt)}$ m/h

As $X_t\uparrow$, $V_s\downarrow$, $A_{ST}\uparrow$

SELECTING REACTORX_t (3)



Generally, as S_{ti}↓, R_s ↓, PWWF/ADWF↑ and SVI↑, X_t for minimum cost decreases.

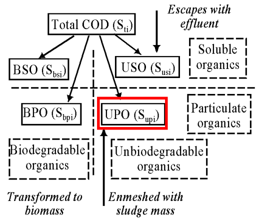
Reactor V_p is governed by organic load.

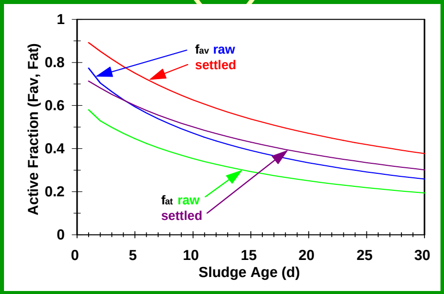
SST area is governed by hydraulic load.

ACTIVE FRACTION (1)

- As biomass is only VSS component to contain biodegradable organics, the active fraction (f_a) is an indicator of WAS stability, i.e. residual biodegradable organics.
- f_{av} (with respect to VSS) = X_{BH}/X_v
- f_{at} (with respect to TSS) = X_{BH}/X_t
- Have equations X_{BH}, X_v and X_t
- Plot f_{av} and f_{at} versus R_s ……

ACTIVE FRACTION (2)





Active fraction…

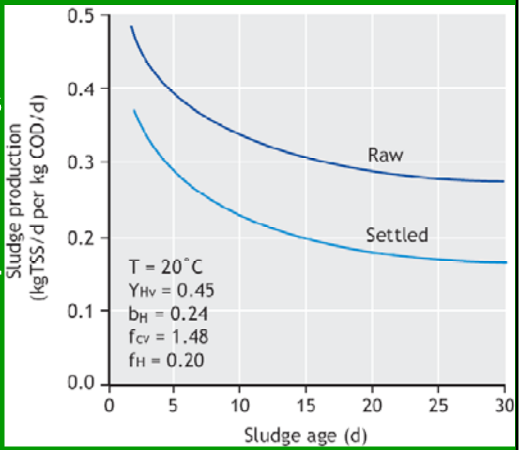
- is higher for settled WW than for raw WW because there is much less influent UPO in settled WW (Raw S_{upi} = 113, Settled S_{upi} = 18).
- decreases with sludge age because endogenous process continues for longer.

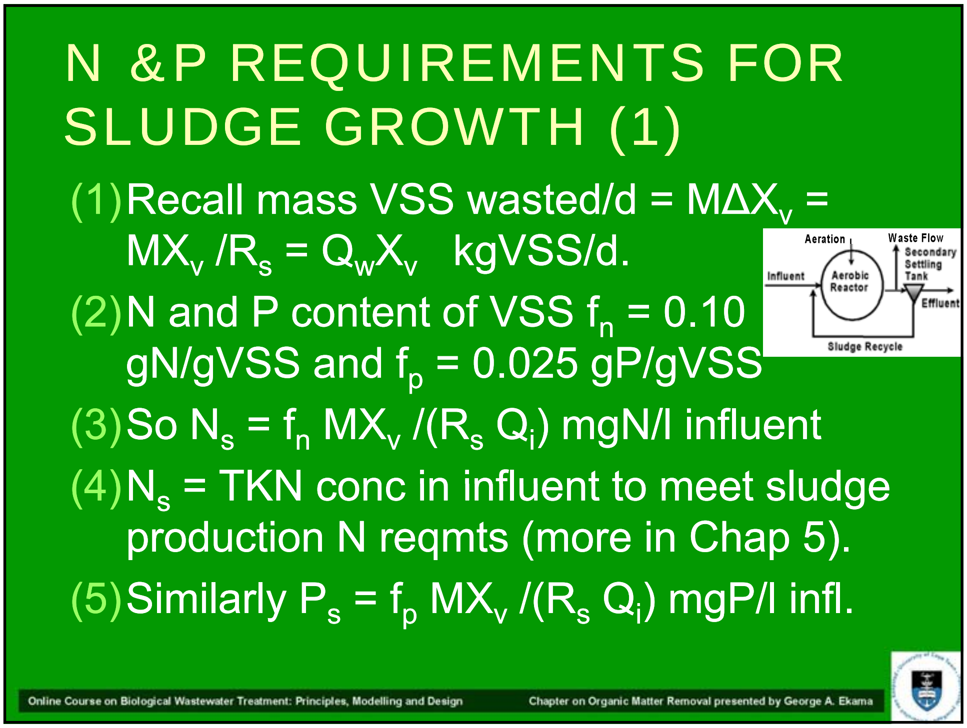
SLUDGE PRODUCTION

- Secondary sludge (WAS) production to maintain sludge age is

$$M\Delta X_t = MX_t / R_s \text{ or}$$
$$= Q_w X_t \quad \text{kgTSS/d.}$$

- Note: kgTSS/d WAS…
- …decreases as $R_s \uparrow$
- …higher for raw WW than for settled (but raw is lower overall).





N &P REQUIREMENTS FOR SLUDGE GROWTH (1)

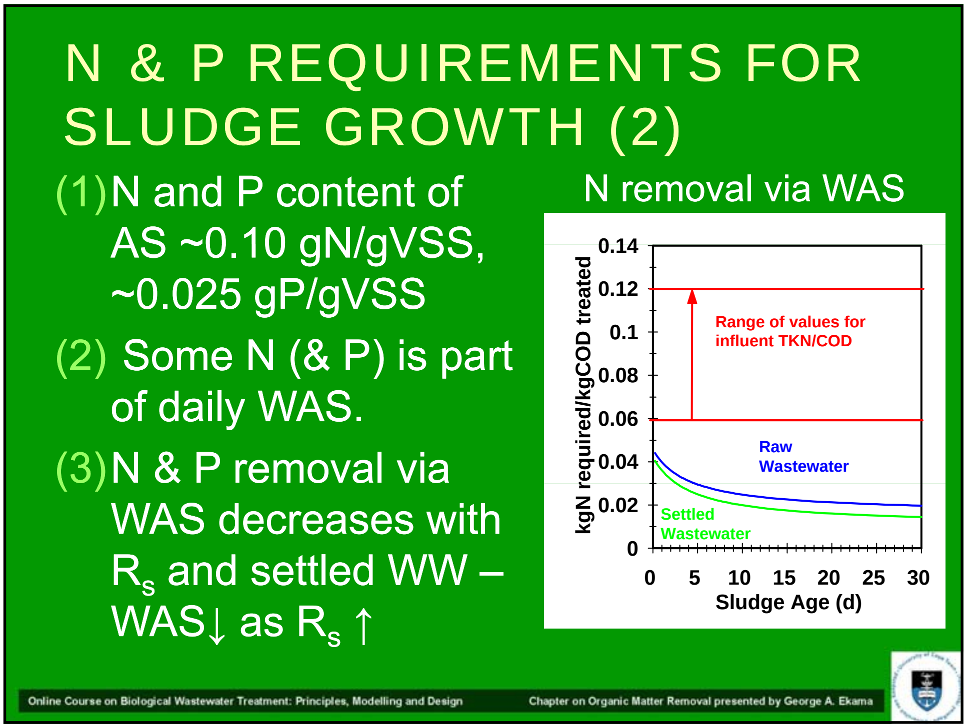
(1) Recall mass VSS wasted/d = $M\Delta X_v$ = $MX_v / R_s = Q_w X_v$ kgVSS/d.

(2) N and P content of VSS f_n = 0.10 gN/gVSS and f_p = 0.025 gP/gVSS

(3) So $N_s = f_n\, MX_v / (R_s\, Q_i)$ mgN/l influent

(4) N_s = TKN conc in influent to meet sludge production N reqmts (more in Chap 5).

(5) Similarly $P_s = f_p\, MX_v / (R_s\, Q_i)$ mgP/l infl.



N & P REQUIREMENTS FOR SLUDGE GROWTH (2)

(1) N and P content of AS ~0.10 gN/gVSS, ~0.025 gP/gVSS

(2) Some N (& P) is part of daily WAS.

(3) N & P removal via WAS decreases with R_s and settled WW – WAS↓ as R_s↑

N removal via WAS

DESIGN PROCEDURE (1)

(1) Select WW characteristics (raw or settled)

- USO ($f_{S'us}$), UPO ($f_{S'up}$),
- Influent ISS (X_{Ioi}) or AS VSS/TSS ratio (f_i)
- Establish COD load from flow weighted ave.

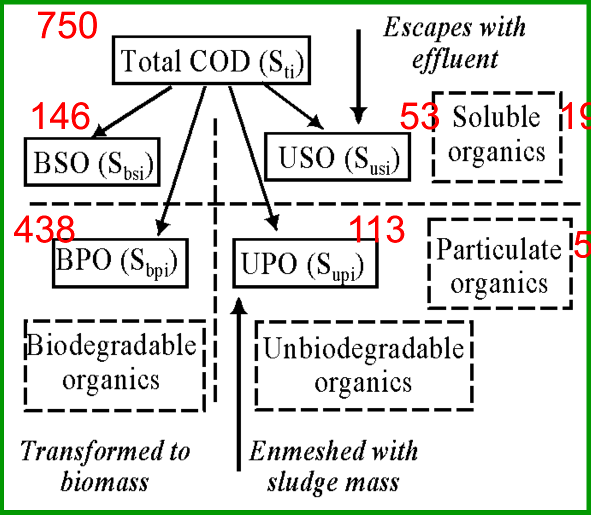
(2) Calculate influent COD components

- $S_{usi}=f_{S'us}S_{ti}$, $S_{upi}=f_{S'up}S_{ti}$, $S_{bi} = (1-f_{S'us}-f_{S'up})S_{ti\ ave}$.

(3) Calculate COD mass fluxes into reactor – COD mass/d = conc x Q_i kgCOD/d

(4) Select sludge age (R_s) for system.

CHARACTERIZE WW



Units – mgCOD/L

0.45µ filtered - Sol COD =199

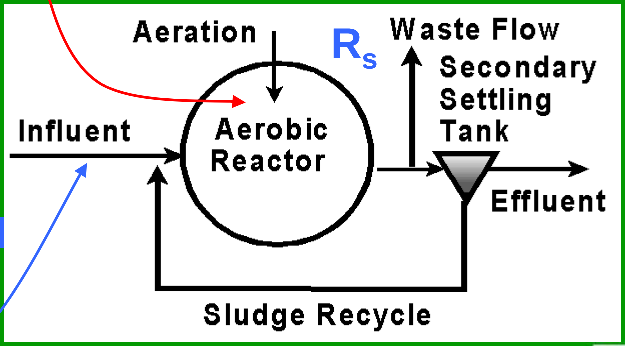
$f_{S'us}= S_{usi}/S_{ti}$
$= 0.07$

$f_{S'up}= S_{upi}/S_{ti}$
$= 0.15$

CALCULATE REACTOR MASSES FROM WW LOADS

Unknowns – MX_{BH}, MX_E, MX_I, MX_v, MX_{Io}, MX_t, MO_c (kg)

Knowns – Q_i, MS_{ti}, MS_{bi}, MS_{upi} (MX_{Ii}), (kg COD/d) S_{usi} mgCOD/l



DESIGN PROCEDURE (2)

(5) Calculate solids masses in reactor –

- MX_{BH}, MX_E, MX_I, MX_v (kgVSS) and MX_t kgTSS.

(6) Calculate Oxygen Demand MO_c (kgO/d).

(7) Select reactor TSS conc (X_t).

(8) Calculate reactor volume (V_p).

(9) Calculate hyd. retention time (R_{hn}).

(10) Calculate reactor solids concs & OUR

- X_{BH}, X_E, X_I, X_v (gVSS/l), X_t gTSS/l, O_c mgO/(l.h)

DESIGN PROCEDURE (3)

(11) Calculate active fractions of solids –

- $f_{av} = X_{BH}/X_v$, $f_{at} = X_{BH} / X_t$.

(12) Calculate waste flow rate Q_w (m^3/d) and sludge production ($M\Delta X_t$, kgTSS/d).

(13) Calculate nutrient reqmts - N_s, P_s

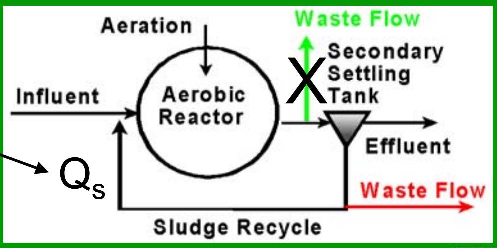
(14) Check COD balance !

$MS_{te} + MO_c + f_{cv}\ MX_v/R_s = MS_{ti}$?

If not 100±0.1% Check calculations!

SYSTEM CONTROL (1)

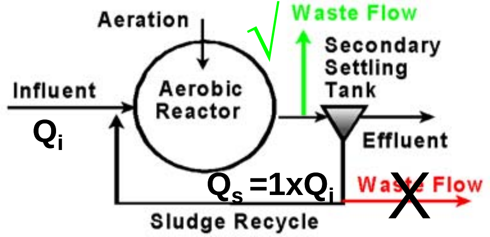
- It is common practice to waste sludge from the SST underflow.
- This is onerous and complex for operator – requires much reactor and underflow MLSS measurement to establish approx. sludge age.
- Is done to benefit from thickening in SST when sludge recycle (Q_s) is low (0.25-0.33:1)



SYSTEM CONTROL (2)

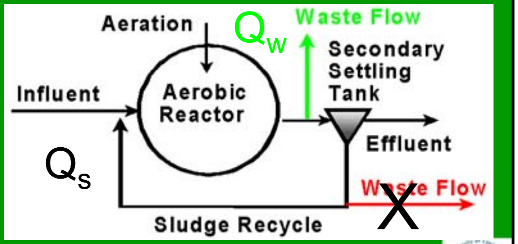
- If nitrification takes place, cannot have low recycle flow (Q_s) due to rising sludge problems in SST – sludge flotation with N_2 gas from denitrification in SST (especially at high temp).
- Q_s must be high (>0.75Q_i) to minimize this.
- With high Q_s, WAS does not thickening in SST.

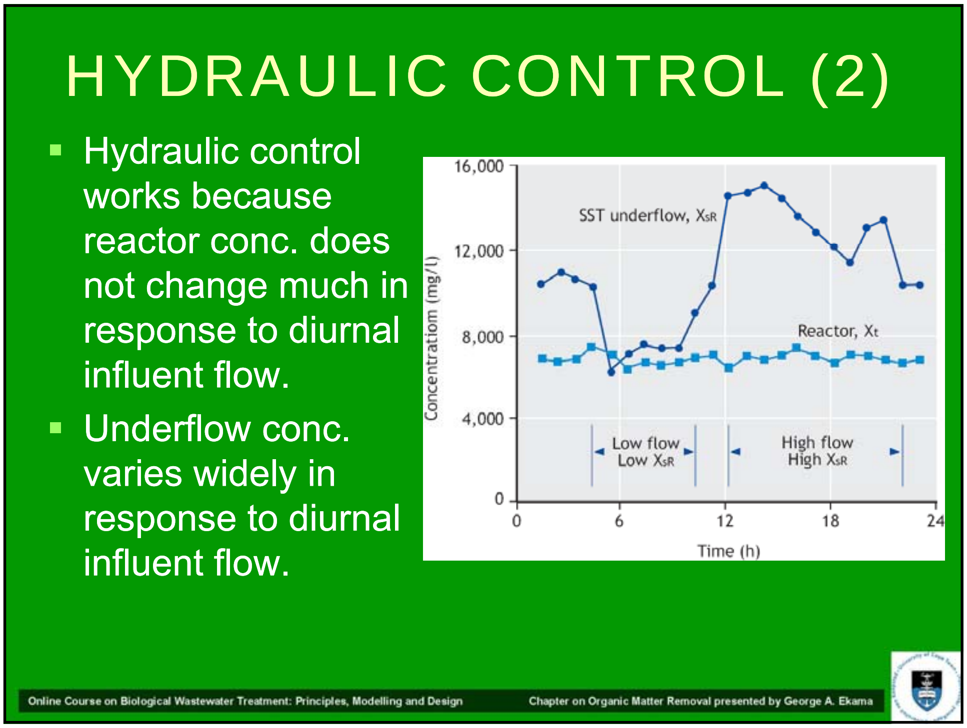
Its best to waste from reactor and establish sludge age hydraulically!



HYDRAULIC CONTROL (1)

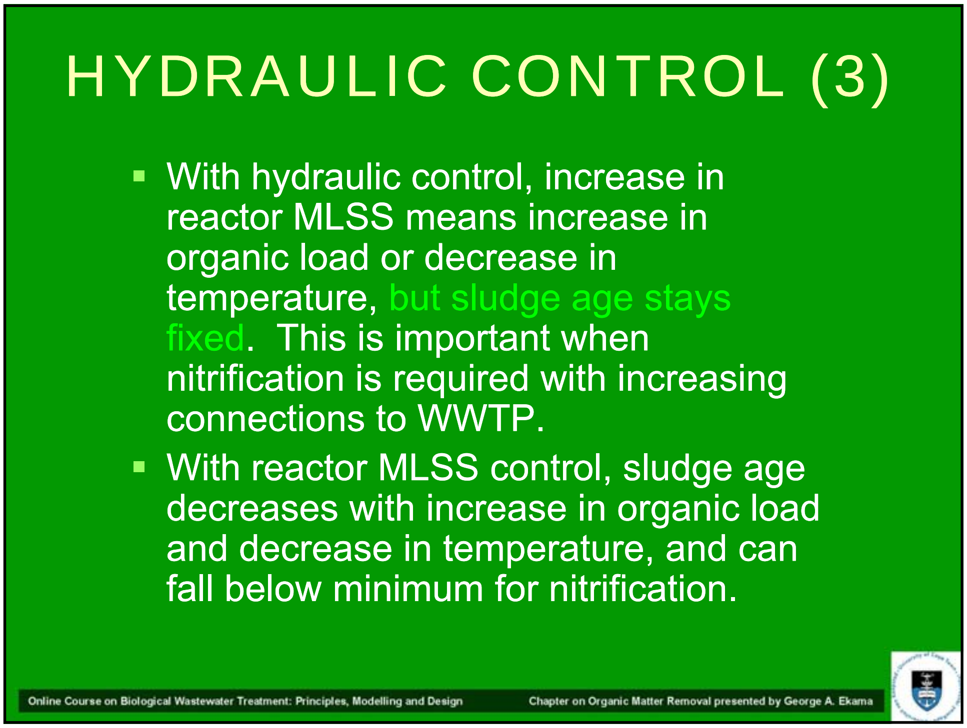
- With hydraulic control of sludge age, Q_w is set to required flow rate $Q_w = V_p/R_s$ m^3/d !
- Operator only checks that flume is not blocked.
- No reactor or underflow MLSS tests required.
- Hydraulic control establishes sludge age – it is not sludge mass control!
- Wasting from underflow is sludge mass control, not sludge age control – very different !.





HYDRAULIC CONTROL (2)

- Hydraulic control works because reactor conc. does not change much in response to diurnal influent flow.
- Underflow conc. varies widely in response to diurnal influent flow.



HYDRAULIC CONTROL (3)

- With hydraulic control, increase in reactor MLSS means increase in organic load or decrease in temperature, but sludge age stays fixed. This is important when nitrification is required with increasing connections to WWTP.
- With reactor MLSS control, sludge age decreases with increase in organic load and decrease in temperature, and can fall below minimum for nitrification.

HYDRAULIC CONTROL (4)

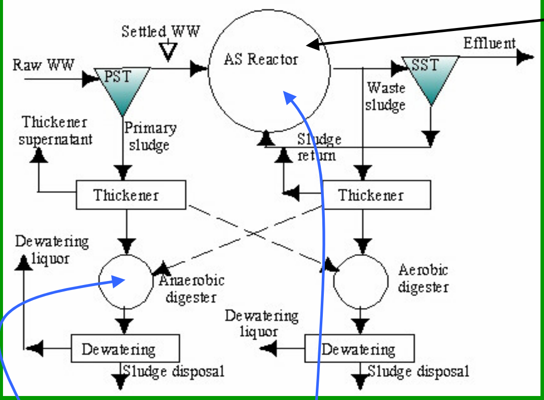
- Reactor MLSS control, low SST recycles and wasting from underflow is OK for AS systems in developed countries – competent operation and few new connections, cold WW temperature.
- but not good for AS systems in developing countries – low operator skills, high WW temperature (nitrification unavoidable) and increasing organics loads - for these situations, hydraulic control of sludge age is essential -
  - Little operator intervention and low MLSS testing
  - High SST recycle minimizing rising sludge in SSTs.

SELECTION OF SLUDGE AGE (1)

- Selection of sludge age (R_s) is THE most important decision in design.
- It depends on WW temperature, effluent quality and sludge stability requirements.
- Broadly there are two types of WWTP -

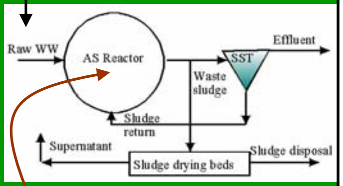
(1) WWT and sludge treatment in separate units -
Short R_s for AS unit (<20d), digestion of PS and WAS
(2) WWT and sludge treatment in same AS unit
very long R_s for AS unit (>25d) – called extended aeration – Treat raw WW and WAS stable.

SELECTION OF SLUDGE AGE (2)



TYPE 1: Short R_s

TYPE 2 : Long R_s
Extended Aeration

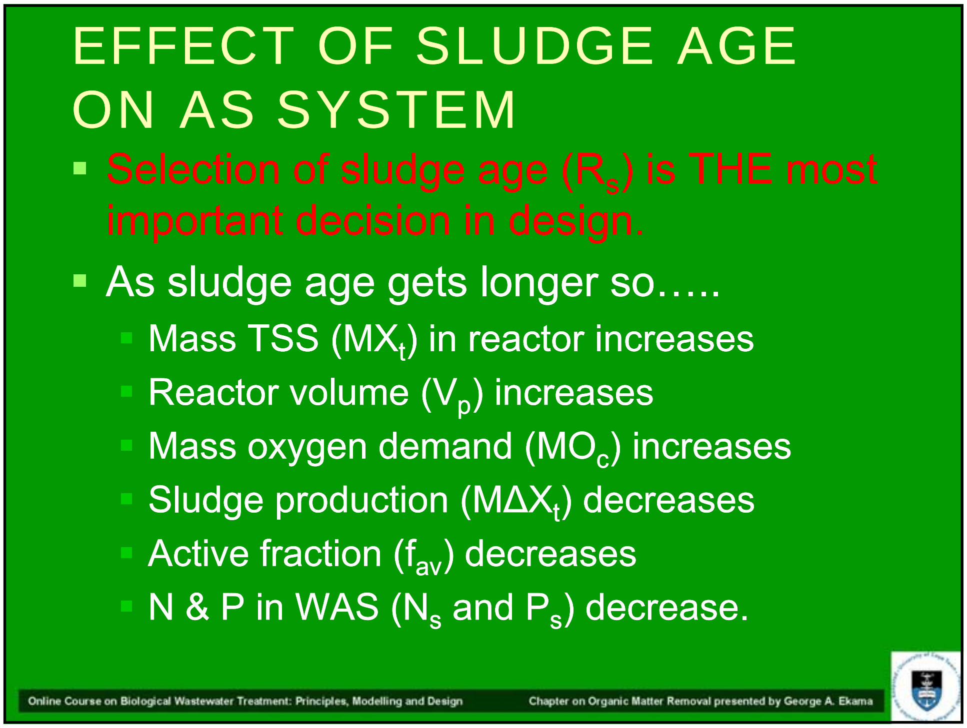


Energy recovery, small reactor, high operator skills.

High energy input, Large reactor, Low operator skills

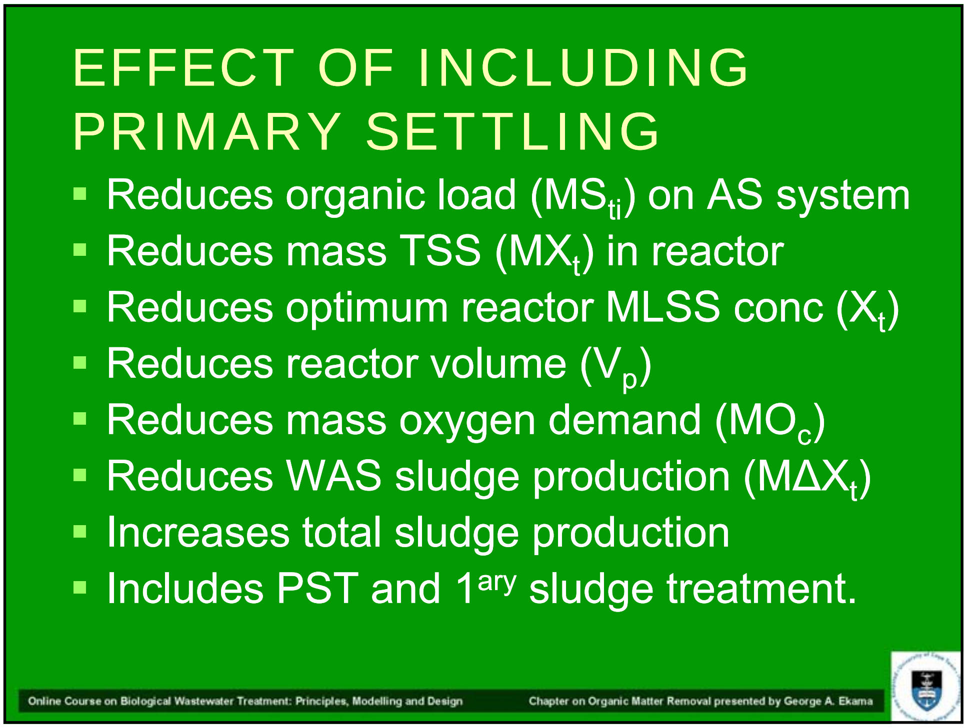
SELECTION OF SLUDGE AGE (3)

- Selection of sludge age (R_s) is THE most important decision in design.
- For WW temperature ~14°C….
  - Organics removal…….. R_s 2-5d.
  - + Nitrification ……. R_s 5-10d
  - + N removal (Nit & Denit)…. R_s 10-15d
  - + Bio P removal ……… R_s 8-12d
  - + Bio P and N removal…… R_s >12d
  - + N removal & stable WAS.. R_s > 25d (extended aeration)



EFFECT OF SLUDGE AGE ON AS SYSTEM

- Selection of sludge age (R_s) is THE most important decision in design.
- As sludge age gets longer so…..
  - Mass TSS (MX_t) in reactor increases
  - Reactor volume (V_p) increases
  - Mass oxygen demand (MO_c) increases
  - Sludge production ($M\Delta X_t$) decreases
  - Active fraction (f_{av}) decreases
  - N & P in WAS (N_s and P_s) decrease.



EFFECT OF INCLUDING PRIMARY SETTLING

- Reduces organic load (MS_{ti}) on AS system
- Reduces mass TSS (MX_t) in reactor
- Reduces optimum reactor MLSS conc (X_t)
- Reduces reactor volume (V_p)
- Reduces mass oxygen demand (MO_c)
- Reduces WAS sludge production ($M\Delta X_t$)
- Increases total sludge production
- Includes PST and 1^{ary} sludge treatment.

CLOSURE

- Selection of sludge age is the most important design decision.
- Mass of sludge in reactor and reactor volume are function of organic load, sludge age, WW characteristics and selected reactor TSS concentration.
- Hydraulic control of sludge age is best for situations where operator skills are low, nitrification is unavoidable, and organic load increases over time.

ACKNOWLEDGEMENTS

- University of Cape Town

- And any others