CIE4485
Wastewater Treatment

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8. Anaerobic treatment: Introduction/ UASB design base

CT4485 Wastewater Treatment

Lecture 4a: Anaerobic treatment: Introduction / UASB design base

Prof.dr.ir. Jules van Lier
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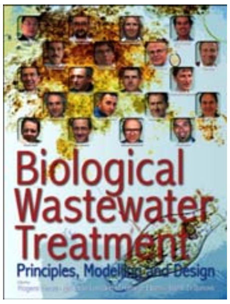
Learning objectives

- Understand principles of anaerobic wastewater treatment (AWWT)
- Understand advantages and constraints of AWWT
- Design base of anaerobic reactors
- Potentials for sewage treatment in warm climates



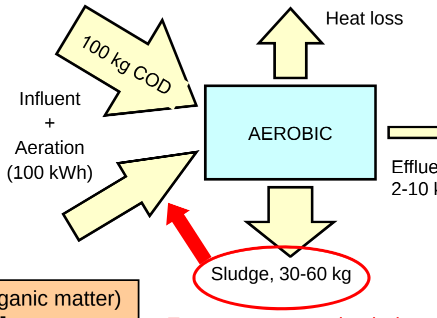
IWA: Chapter 16
Metcalf & Eddy: Chapt.10

Anaerobic Digestion / Anaerobic Treatment

????

- Stabilisation of organic matter without O_2
- Reductive conversion process
- Mineralisation of organic compounds
- Solubilisation of organically bound chemicals: NH_4^+, PO_4^{3-}, S^{2-}
- Plain system for waste(water) treatment
- No fossil fuel requirement
- Bio-energy recovery system
- other?

Anaerobic sludge digestion: recovering the chemical energy in sewage treatment!



100 kg COD

Heat loss

Influent
+
Aeration
(100 kWh)

AEROBIC

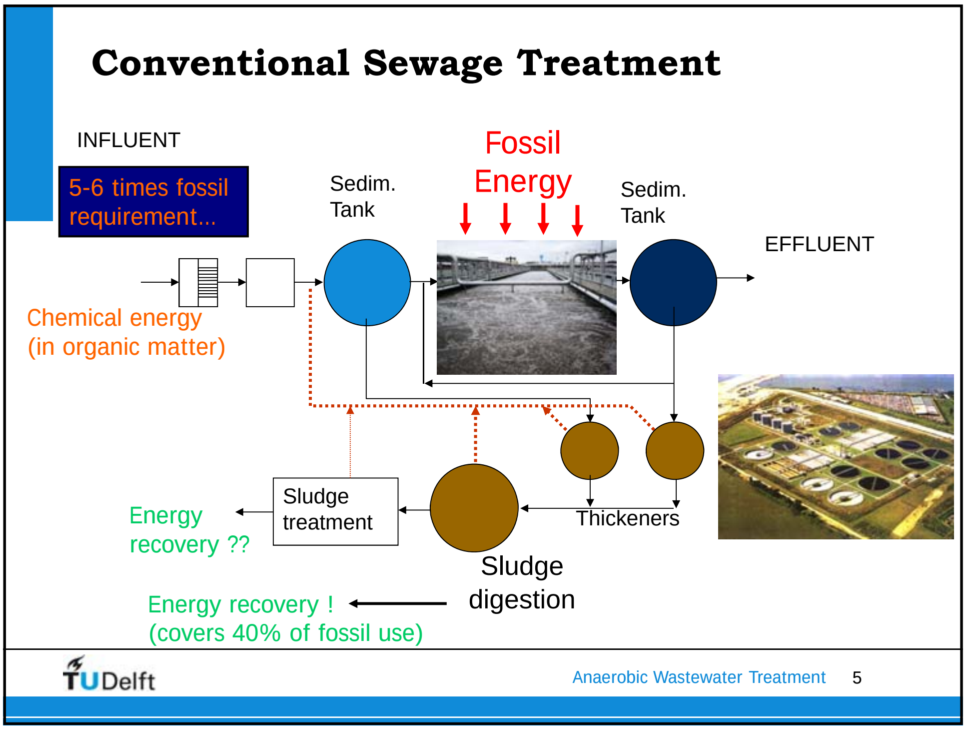
Effluent,
2-10 kg COD

Sludge, 30-60 kg

1 kg COD (organic matter)
≅ 13.5 MJ
≅ 3.8* kWh_{theor}

Energy recovery via sludge digestion
1 kg sludge ≈ 1.5 kg COD
≈ 5.7* kWh_{theor}

Note: Efficiency biogas motor: 35%!



Conventional Sewage Treatment

INFLUENT

5-6 times fossil requirement...

Chemical energy
(in organic matter)

Sedim.
Tank

Fossil
Energy

Sedim.
Tank

EFFLUENT

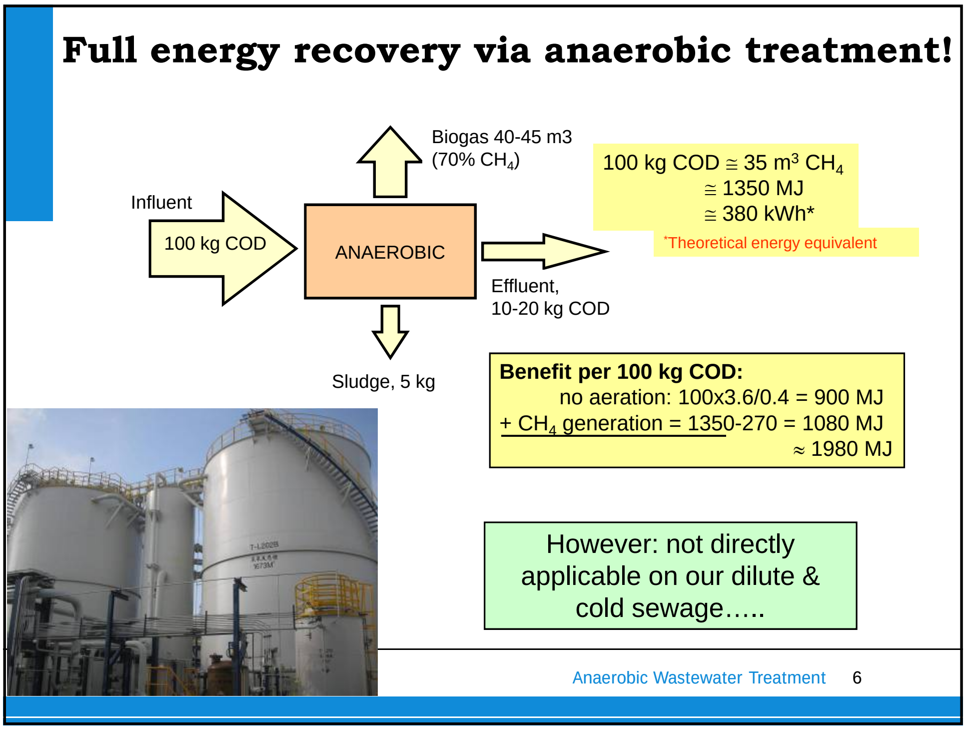
Thickeners

Sludge
treatment

Energy
recovery ??

Sludge
digestion

Energy recovery !
(covers 40% of fossil use)



Full energy recovery via anaerobic treatment!

Biogas 40-45 m3
(70% CH$_4$)

Influent

100 kg COD

ANAEROBIC

Effluent,
10-20 kg COD

Sludge, 5 kg

100 kg COD ≅ 35 m^3 CH$_4$
≅ 1350 MJ
≅ 380 kWh*

*Theoretical energy equivalent

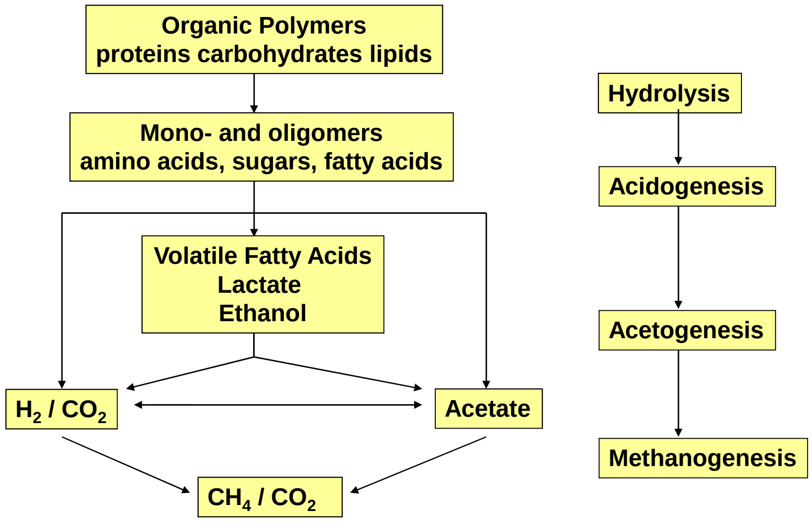
Benefit per 100 kg COD:
no aeration: 100x3.6/0.4 = 900 MJ
+ CH$_4$ generation = 1350-270 = 1080 MJ
≈ 1980 MJ

However: not directly applicable on our dilute & cold sewage…..

Comparison Aerobic - Anaerobic

	Aerobic	Anaerobic
Reaction	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$	$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$
Energy release	$\Delta G^{\circ\prime}$ = -2840 kJ/mol glucose	$\Delta G^{\circ\prime}$ = -393 kJ/mol glucose
Carbon balance	50% → CO_2 50% → biomassa	95% → $CH_4 + CO_2$ (= biogas) 5% → biomassa
Energy balance	60% → biomassa 40% → heat production	90% retained in CH_4 5% → biomassa 5% → heat production
Biomass production	Fast growth of biomass, Resulting in a sewage sludge problem	Slow growth of biomass
Energy input for aeration	Yes	No

Anaerobic Conversion of Organic Matter



Organic Polymers
proteins carbohydrates lipids

Mono- and oligomers
amino acids, sugars, fatty acids

Volatile Fatty Acids
Lactate
Ethanol

H_2 / CO_2

Acetate

CH_4 / CO_2

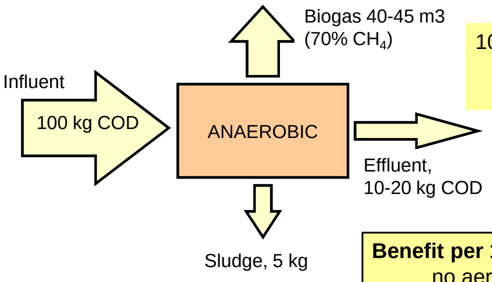
Hydrolysis

Acidogenesis

Acetogenesis

Methanogenesis

So: no loss of the chemical energy!!



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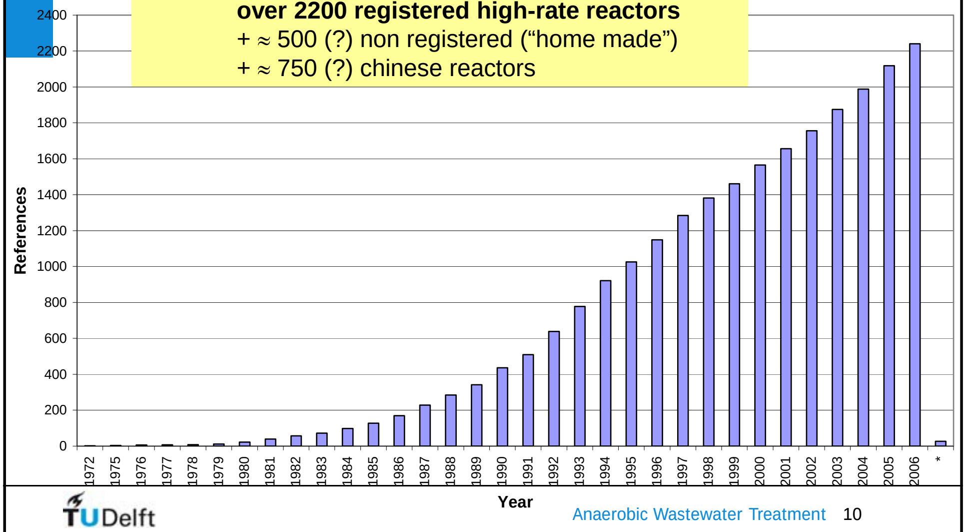
Worldwide cumulative anaerobic references 2007

Anaerobic Industrial Wastewater Reactors, census **2007**
over 2200 registered high-rate reactors
+ ≈ 500 (?) non registered (“home made”)
+ ≈ 750 (?) chinese reactors



High-rate Anaerobic Applications in Industries

Number of installed reactors, N= 2266 (Jan. 2007)

AGRO-FOOD INDUSTRY 36%		BEVERAGE 29%	ALCOHOL DISTILLERY 10%	PULP & PAPER 11%	MISCELLANEOUS 14%
Sugar	Cannery	Beer	Sugar cane juice	Recycle paper	Chemical
Potato	Confectionery	Malting	Sugar cane molasses	Mechanical pulp	Pharmaceutical
Starch	Fruit	Soft drink	Sugar beet molasses	NSSC	Sludge liquor
Yeast	Vegetable	Fruit juice	Grape wine	Sulphite pulp	Municipal sewage
Pectin	Dairy	Wine	Grain	Straw	Landfill leachate
Citric acid	Bakery	Coffee	Fruit	Bagasse	Acid mine water


Yeast, Italy


Beer, Brazil


Distillery, Japan


Paper, Netherlands


Chemical, Netherlands

Benefits of Anaerobic (pre-)treatment

- Reduction of excess sludge production by 90% !
- Reduction of green house gas emissions
  - No use of fossil fuels for treatment (saving 1 kWh / kg organic matter)
  - Production of energy (3.8 kWh* / kg organic matter removed)
- High loading rates (up to 35 kg COD.m^{-3}.day^{-1})
- Up to 90% reduction in space requirements !
- No or very little use of chemicals (e.g. nutrients)
- Plain technology with high treatment efficiencies
- Anaerobic sludge can be stored unfed → campaign industries
- Start up with granular sludge in 1 week
- Perspectives for nutrients recovery (agricultural reuse, struvite)
- Facilitates in-house loop closure

Potentials of carbon credits with AD projects?

CO_2 emissions with conventional electricity production:

Coal powered electricity plant: **0.86 ton CO_2/MWh-e**
Natural gas powered plant: **0.44 ton CO_2/MWh-e**

If bio-CH_4 is used as renewable fuel:
CO_2 emission reduction !!

Expected stabilised price:
20 €/ton CO_2

Energy & carbon credits in anaerobic wastewater treatment:

- Loading capacity AWWT: **10 – 35** kg COD/(m^3.d)
- Energy output: **0.5 – 1.7** kW-elec/m^3 (80% CH_4 rec., 40% CHP eff.)
- CO_2 emission reduction: **3.8 – 13** ton CO_2/(m^3.y) (coal PP)

PARAMETER	UNIT	Brewery
Flow	m^3/d	2720– 5780
COD average	mg/l	4043
COD range	mg/l	2020– 5790
SS	mg/l	260– 2160
Temperature	°C	21– 40
PH		2.6– 7.0

Reactor:
COD-load: 17 ton/day
Loading: 35 kg COD/(m^3.d)
Reactor: V = 500 m^3 (h=25 m,
d=5 m)
Excess sludge: ≈ 0.6 ton DM/d

Brewery Effluent: Energy & Carbon Credits benefit

Energy recovered:
17 ton COD x 0.8 (eff) x 3820 kWh* x 40% CHP eff. = 21 MWh-e/d ≈ 0.9 MW

No energy consumption:
Assumed energy requirement activated sludge: ≈ 0.5-1 kWh-e/kg $COD_{rem.}$
Saved: 17 ton COD x 0.8 (eff.) = 7-14 MWh-e/day

Total energy benefit: 21 + (7-14) = 28-35 MWh-e/day ≅ 1680-2100 €/d
(with 0.09 €/kWh) or: **1.050.000 €/year**

CO_2 emission reduction
Recovered: 21 MWh-e/d x 0.86 ton CO_2/MWh-e ≈ **18 ton CO_2/day (coal)**
Prevented: 7-15 MWh-e/d x 0.86 ton CO_2/MWh-e ≈ **6-13 ton CO_2/day (coal)**

Potential benefit: 18 x 20 x 365 = **130.000 €/year**

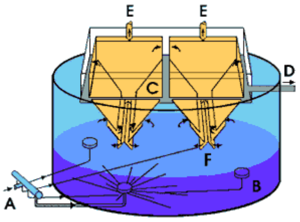
Importance for developing countries:

Energy recovery & CO_2 credits as an incentive to implement environmental technologies in developing countries

Treatment alcohol distillery effluents Cuba (Santa Clara):
- 800 $m^3.d^{-1}$,
- 65 kg $COD.m^{-3}$

Anaerobics: 13,500 m^3 $CH_4.d^{-1}$
or: about **2.2 MW-electric** (40% eff.)
At a price of 0.12 US$ $.kWh^{-1}$ this equals:
2.300.000 US$.$y^{-1}$
CO_2 credits: 330.000 US$.$y^{-1}$ (coal)

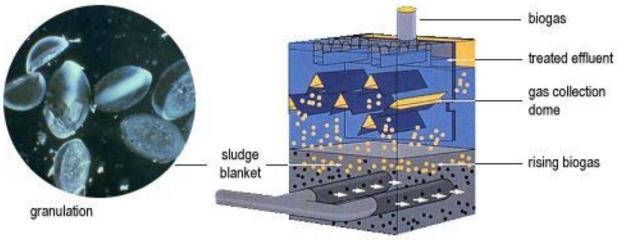
Upflow Anaerobic Sludge Bed (UASB)



Main Features:

- Uncoupling of SRT - HRT
- No electro-mechanical parts inside
- High loading rates (10-15 kg/m^3.d)
- Relative small footprint
- Auto-immobilisation / granulation

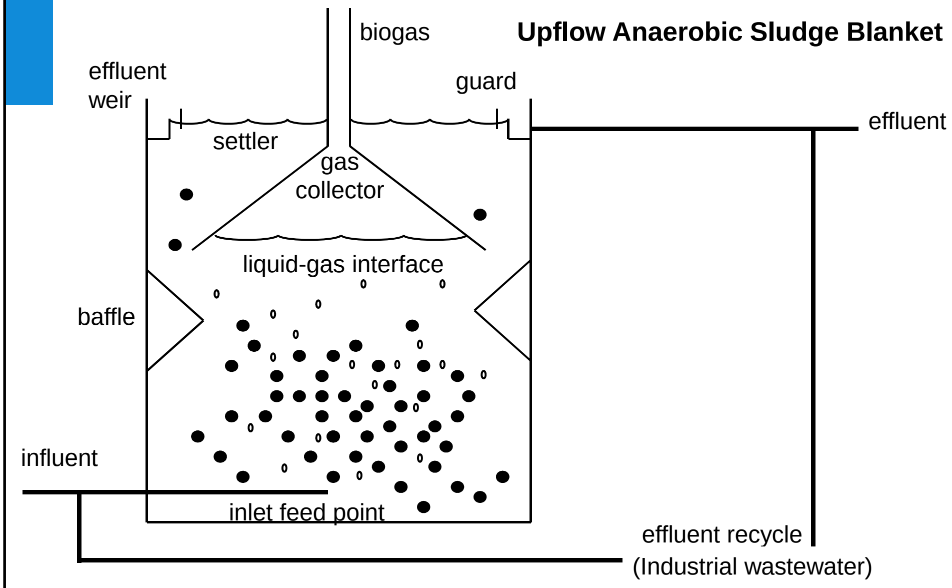
A: INFLUENT
B: SLUDGE BED
C: SEPARATORS
D: EFFLUENT
E: BIOGAS
F: SLUDGE BLANKET



Early full-scale UASB for sugar mill effluent (CSM,1976)

Schematic lay-out UASB reactor

Upflow Anaerobic Sludge Blanket

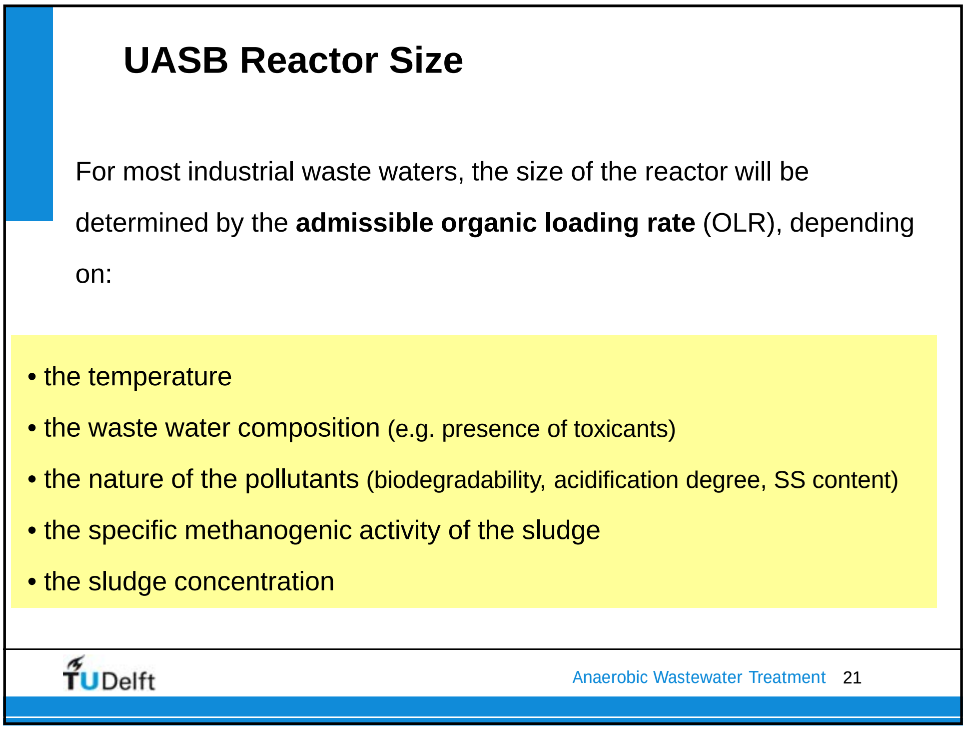


Design Basis UASB reactor

1. Maximum retention of active methanogenic biomass (SRT in d).
2. The maximum hydraulic loading potentials ($m^3/m^3 \cdot d$)
3. The maximum organic loading potentials (kg COD/$m^3 \cdot d$)
4. The maximum applicable gas loading ($m^3/m^3 \cdot d$)

All 4 parameters set limits to the maximum hydraulic surface loading

$$V_{upward}(m/h) = \frac{Q_{infl}(m^3/h)}{A(m^2)}$$

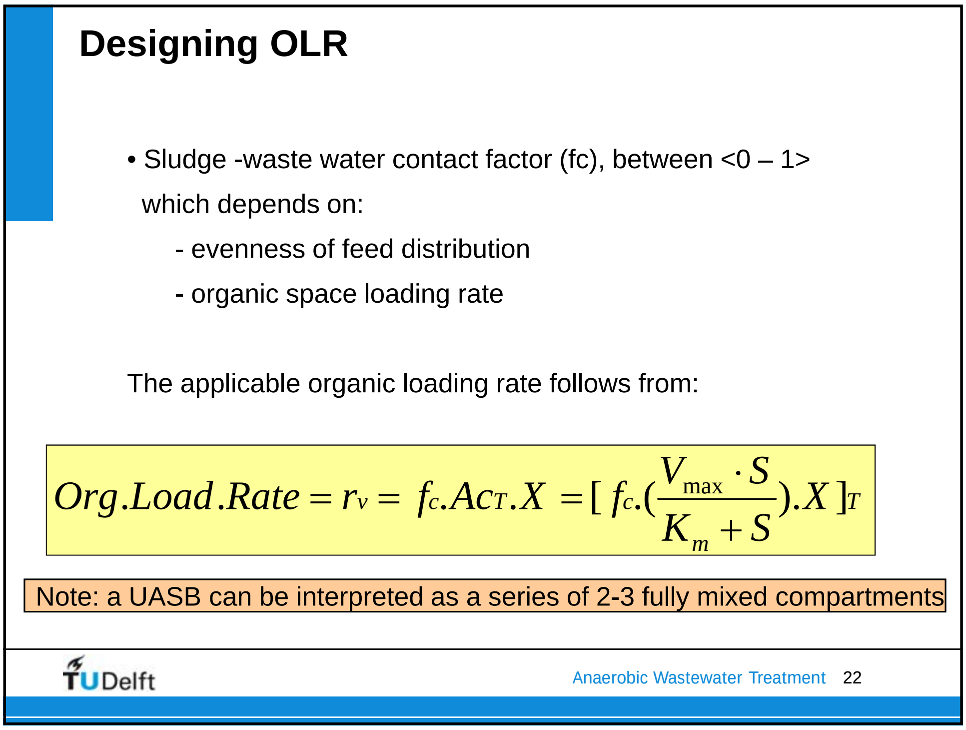


UASB Reactor Size

For most industrial waste waters, the size of the reactor will be determined by the **admissible organic loading rate** (OLR), depending on:

- the temperature
- the waste water composition (e.g. presence of toxicants)
- the nature of the pollutants (biodegradability, acidification degree, SS content)
- the specific methanogenic activity of the sludge
- the sludge concentration

TUDelft



Designing OLR

- Sludge -waste water contact factor (fc), between <0 – 1> which depends on:
  - evenness of feed distribution
  - organic space loading rate

The applicable organic loading rate follows from:

$$Org.Load.Rate = r_v = f_c.Ac_T.X = [\, f_c.(\frac{V_{max}\cdot S}{K_m + S}).X\,]_T$$

Note: a UASB can be interpreted as a series of 2-3 fully mixed compartments

TUDelft

Reactor volume based on applicable organic loading rates

$$V_r = (c \cdot Q) \cdot r_v^{-1}$$

r_v depends on:

- amount of viable biomass
- reactor temperature
- feed composition:
  - suspended solids concentration
  - degree of pre-acidification

Average sludge concentration in UASB reactors: 35-40 kg VSS /m^3 reactor

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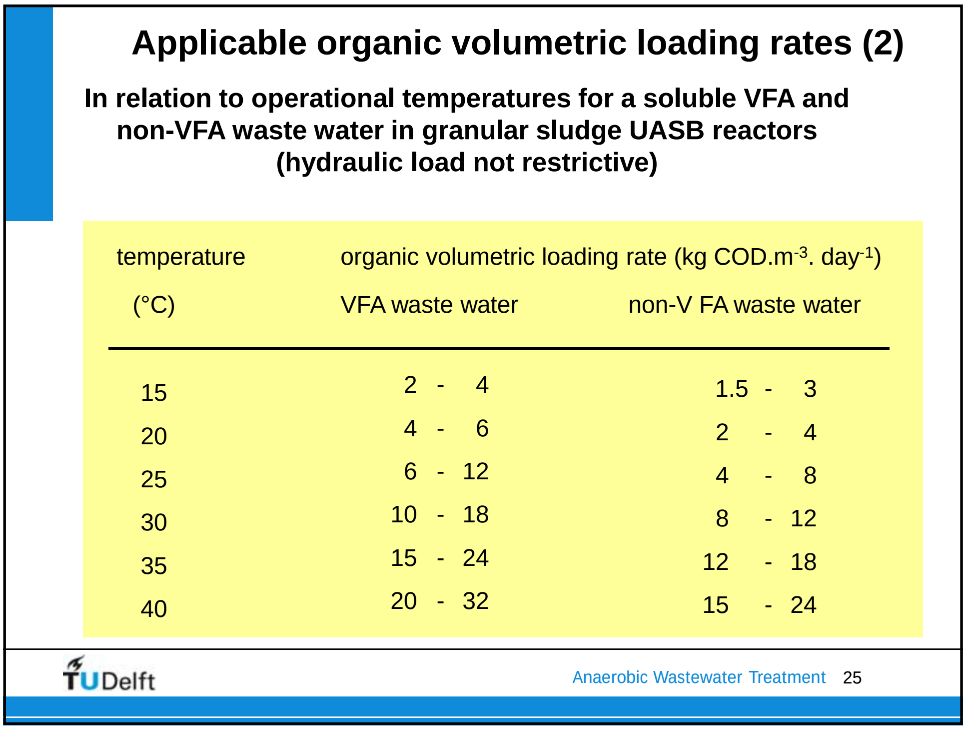
Applicable organic volumetric loading rates (1)

In relation to operational temperatures for a soluble and a partially soluble waste water in granular sludge UASB reactors (hydraulic load not restrictive)

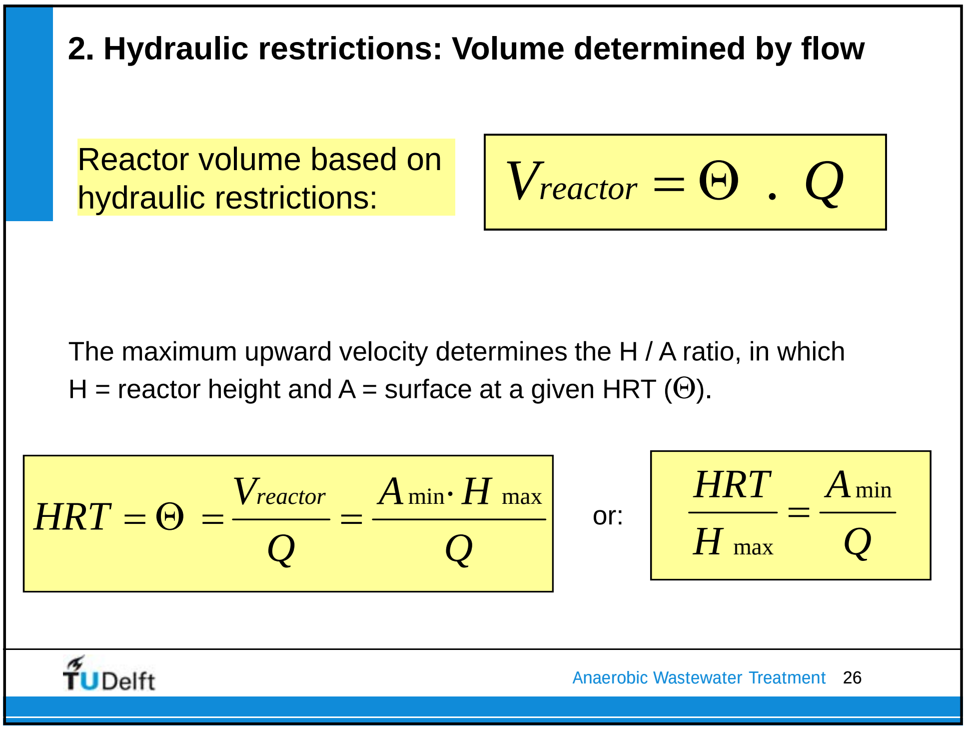
temperature	organic volumetric loading rate (kg COD.m^{-3}. day^{-1})	
(°C)	waste water with less than 5% SS-COD	waste water with 30-40% SS-COD
15	2 - 3	1.5 - 2
20	4 - 6	2 - 3
25	6 - 10	3 - 6
30	10 - 15	6 - 9
35	15 - 20	9 - 14
40	20 - 27	14 - 18



Applicable organic volumetric loading rates (2)

In relation to operational temperatures for a soluble VFA and non-VFA waste water in granular sludge UASB reactors (hydraulic load not restrictive)

temperature	organic volumetric loading rate (kg COD.m^{-3}. day^{-1})	
(°C)	VFA waste water	non-V FA waste water
15	2 - 4	1.5 - 3
20	4 - 6	2 - 4
25	6 - 12	4 - 8
30	10 - 18	8 - 12
35	15 - 24	12 - 18
40	20 - 32	15 - 24



2. Hydraulic restrictions: Volume determined by flow

Reactor volume based on hydraulic restrictions:

$$V_{reactor} = \Theta \ . \ Q$$

The maximum upward velocity determines the H / A ratio, in which H = reactor height and A = surface at a given HRT (Θ).

$$HRT = \Theta = \frac{V_{reactor}}{Q} = \frac{A_{min} \cdot H_{max}}{Q}$$

or:

$$\frac{HRT}{H_{max}} = \frac{A_{min}}{Q}$$

2. Hydraulic restrictions: reactor height

The UASB reactor height is determined by the applicable maximum admissible upflow velocity, preventing sludge wash-out.

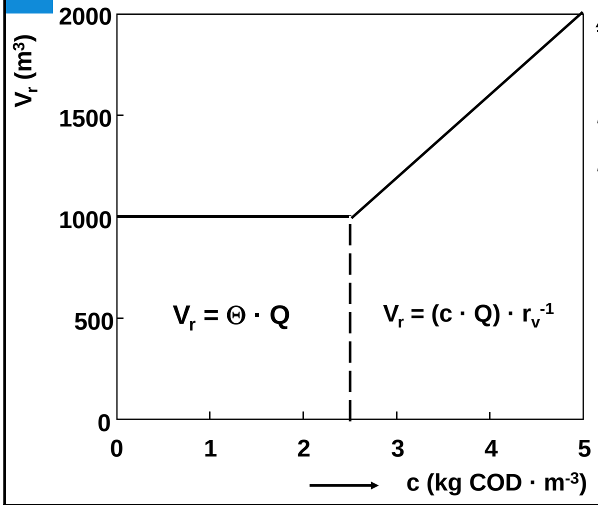
$$V_{upward}(m/h) = \frac{Q_{\inf}(m^3/h)}{A(m^2)}$$

or:

$$A_{\min} = \frac{Q_{\inf l}}{V_{upward,\max}}$$

UASB REACTOR DESIGN

Relationship between pollution strength and reactor volume.



Assumptions:
$\Theta_{min} = 4$ h
$Q = 250\ m^3 \cdot h^{-1}$
$r_v = 15$ kg COD $\cdot\ m^{-3} \cdot d^{-1}$

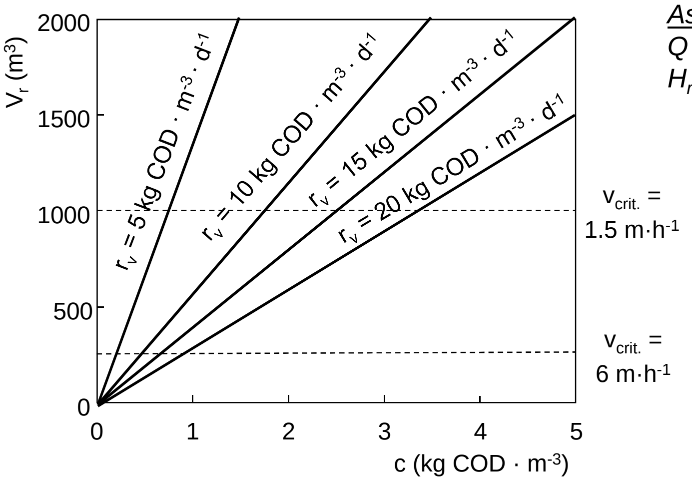
hydraulic load = $6\ m^3 \cdot m^{-3} \cdot d^{-1}$

(hydraulic load = 6 $m^3 \cdot m^{-3} \cdot d^{-1}$

$V_{reactor} = 1000\ m^3$)

UASB REACTOR DESIGN

Reactor volume at different loading rates and critical upflow velocities.



Assumptions:
$Q = 250\ m^3 \cdot h^{-1}$
$H_r = 6\ m$

MAXIMUM APPLICABLE BIOGAS LOADING

Cumulating biogas may limit solids retention

$$V_{biogas} = CODconc. \frac{E_{ff-meth}}{100} \cdot \frac{0.35}{F_{meth-biogas}} \cdot \frac{(T+273)}{273} \cdot V_{upw,\ liquid}$$

In which:
$E_{ff\text{-}meth}$ = amount of COD converted to CH_4 = COD efficiency based on CH_4 production
$F_{meth\text{-}biogas}$ = fraction of methane in biogas (e.g. 0.6 for 60% CH_4)
T = operational temperature of UASB reactor in °C
$V_{upw,\ liquid}$ = Upward liquid velocity in UASB reactor

Maximum hydraulic surface loading depends on **maximum allowable biogas loading (V_{biogas})**
(generally 2-3 m^3/m^2.h for UASB reactors with conventional GLSS devices).