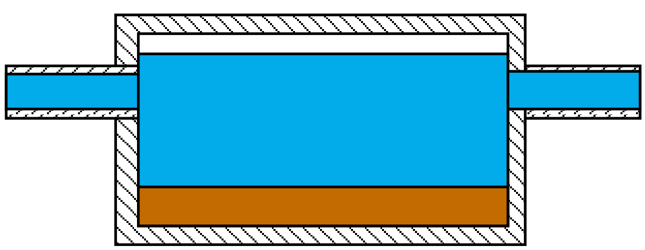
5. Anaerobic reactor technology

History

1881- 82, France

Mouras

Automatic Scavenger

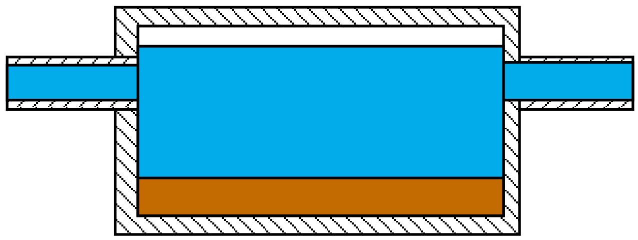


History

1895, England

Donald Cameron

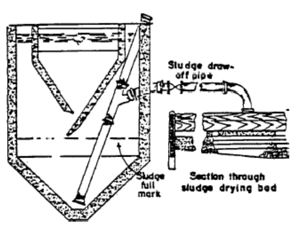
Septic Tank



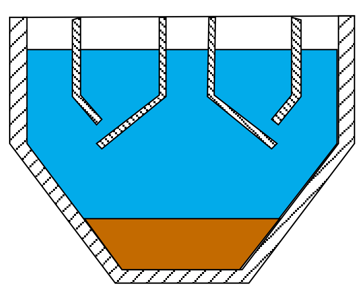
History

Imhoff

1905, Germany



Imhoff Tank

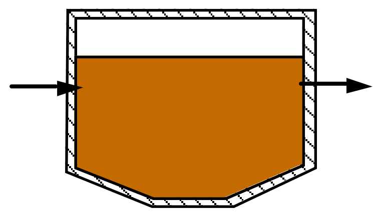


History

1927, Essen-Rellinghausen, Germany

Ruhrverband

Separate Digestion of entrapped solids

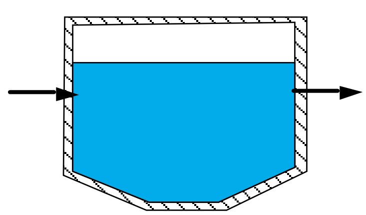


History

1930's

Buswell

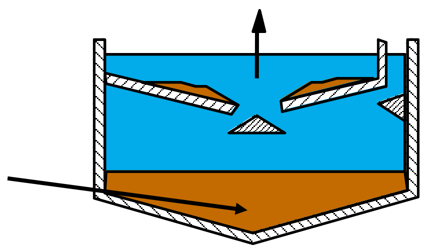
Industrial Wastes



History

1950, Stander, South Africa

Stander Clarigester

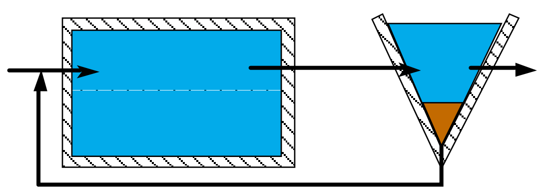


History

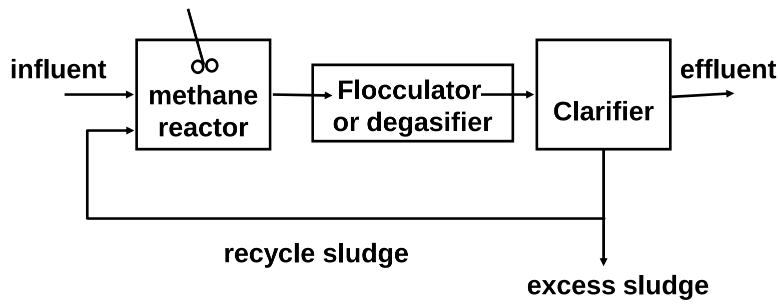
1955, Shroepfer, USA

Schroepfer

Contact process



Contact Process (CP)



THE ANAEROBIC CONTACT PROCESS

basic principles:

- **complete mixing in the digester in order to achieve good contact between sludge and wastewater**
- **sludge recycling (flow rate generally 80-100 % of the influent flow rate) in order to maintain a high sludge content in the digester**

=> high organic removal efficiency stable operation

Online Course on Biological Wastewater Treatment: Principles, Modelling and Design Chapter on Anaerobic Wastewater Treatment by Jules van Lier

The anaerobic contact process

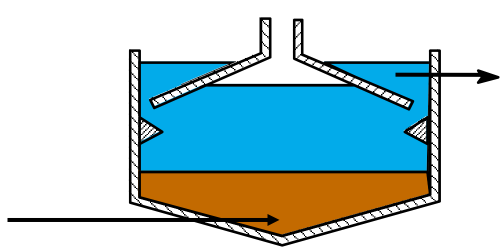
type of waste water	sludge loading (kg COD · kg^{-1} VSS · d^{-1})	load (kg COD · m^{-3} · d^{-1})	reactor volume(m^3)	COD removal efficiency (%)
sugar factory	1.3 - 2.0	0.6 - 12.9	2100 - 16000	90 - 95
distillery	0.17 - 0.24	1.5 - 2.5	300 - 1890	90 - 98
citric acid	0.16 - 0.29	1.3 - 4.0	10000	75 - 83
yeast factory	0.24 - 0.37	2.8 - 3.9	1900	77 - 82
dairy	0.13	0.88	84	-
green vegetable cannery	0.11 - 0.28	2.0 - 4.2	5000	90 - 95
pectin factory	0.03 - 0.22	1.7 - 5.3	3000 - 3618	88 - 93
starch factory	1.4	3.6	900	65
meat processing works	0.5 - 1.1	0.8 - 4.8	2670 - 7117	88 - 95

History

1970s, Gatze Lettinga, The Netherlands

Lettinga

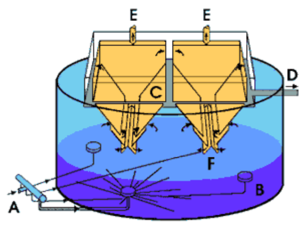
UASB



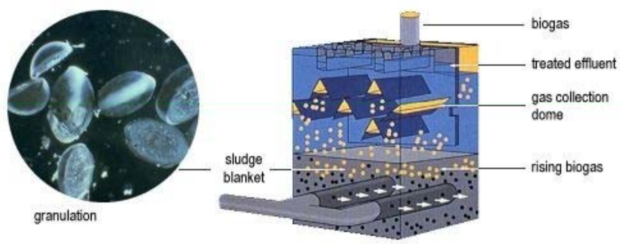
Upflow Anaerobic Sludge Bed (UASB)

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

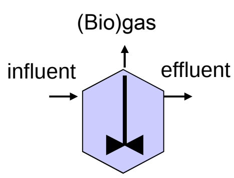


A: INFLUENT
B: SLUDGE BED
C: SEPARATORS
D: EFFLUENT
E: BIOGAS
F: SLUDGE BLANKET



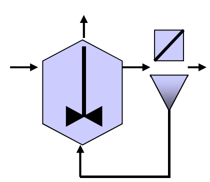
Development of "high-rate" anaerobic treatment systems

Completely mixed



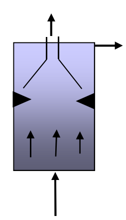
Relative capacity: **1**

Physical retention

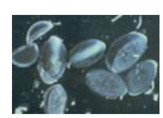


Relative capacity: **5**

Immobilised biomass

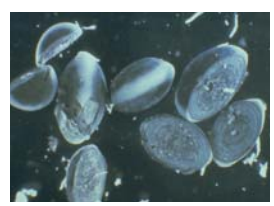


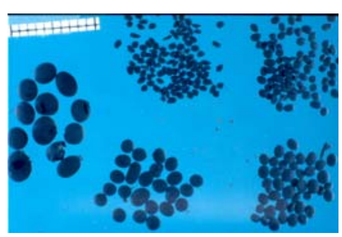
Relative capacity: **25**



First full-scale UASB for sugar mill effluent (CSM)

Anaerobic Granular Sludge





Expanded Granular Sludge Bed (EGSB) Reactors

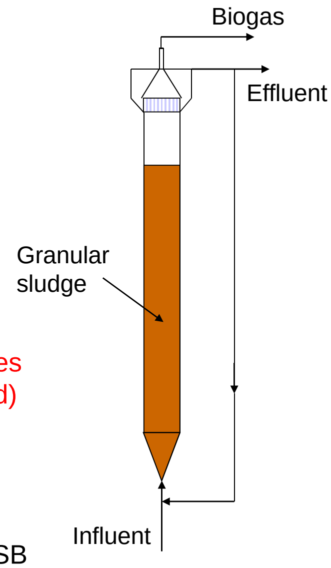
Effective use of granular sludge !!

Main Features

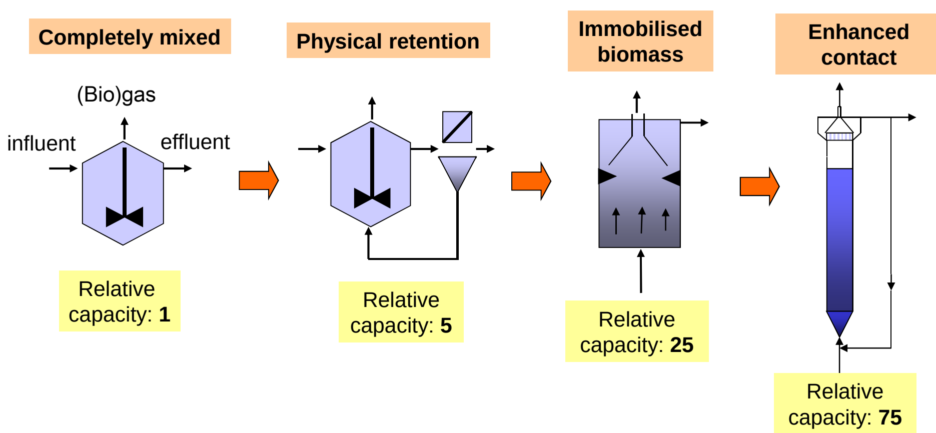
- High upflow velocities (> 8 m/h)
- High concentration of bio-catalyst
- Extreme loading rates (20-40 kg/m^3.d)
- Virtually no mass transfer limitation
- Very small footprint

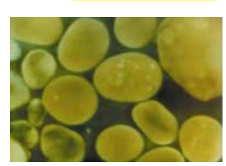
Application:

- cost effective alternative for UASB (2-3 times higher load)
- Cold wastewaters (< 20°C)
- Dilute wastewaters (< 1 g COD/l)
- Presence of degradable toxic compounds
- LCFA containing wastewaters
- Wastewaters with foaming problems in UASB

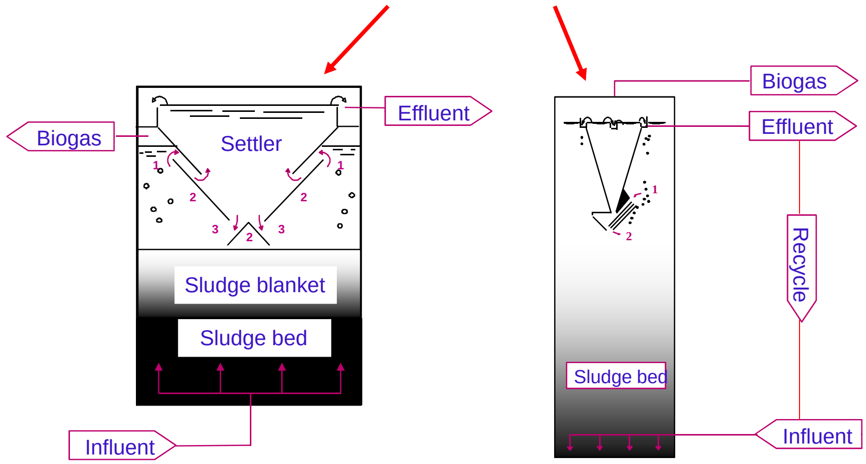


Development of “high-rate” anaerobic treatment systems





From UASB to EGSB

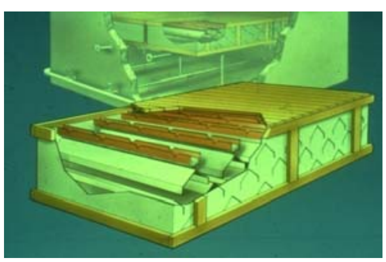


1. Sludge/biomass inlet
2. Gas baffle plates
3. Return settled sludge

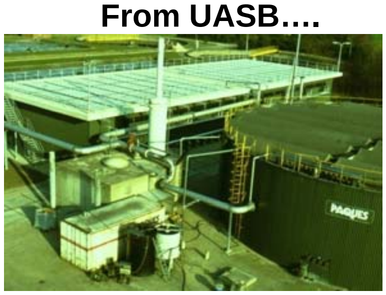
1. Sludge/water mixture
2. Settled sludge

Biothane Systems International

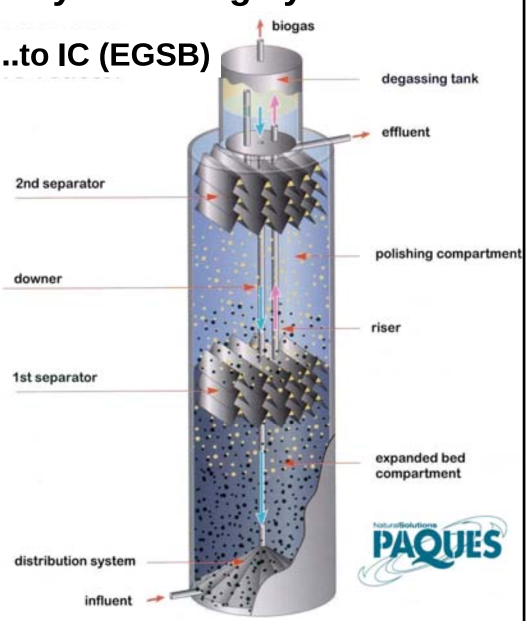
Application of Multi-layer settling system



From UASB….



..to IC (EGSB)

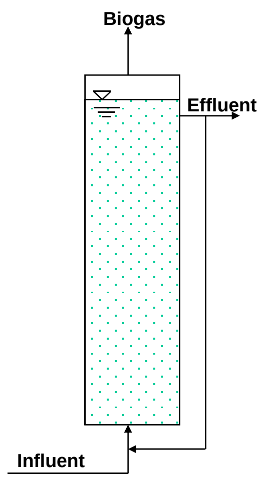


Full scale AWWT at beer brewery

Fluidized Bed Systems

Upflow Anaerobic Attached Fixed Film Expanded Bed (EB)

Attached Growth Anaerobic Fluidised Bed (FB)



BASIC IDEAS UNDERLYING FLUIDIZED BED SYSTEMS

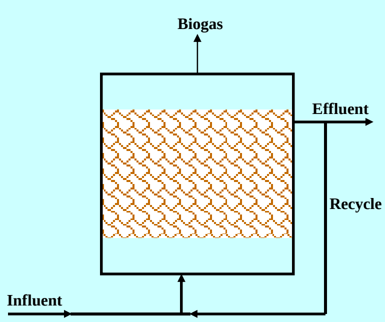
1. Bacterial matter will attach to the surface of non-fixed carrier materials.
2. Mixing of wastewater with biomass is brought about by high recycle ratios / high upflow liquid velocities (bed fluidization)
3. The thickness of the attached bacterial is controlled in order to accomplish a uniform and 'total' fluidization of the bed.

FB reactors rebuilt to EGSB reactors at DSM-yeast factory

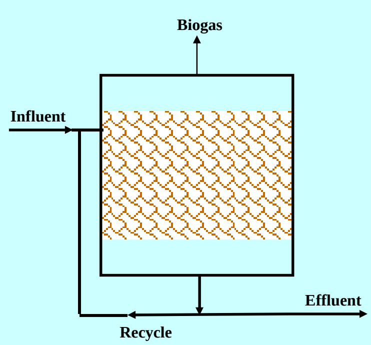
Anaerobic Attached Growth Processes

Anaerobic Filter Systems (1)

Upflow Anaerobic Filters (UAF)



Downflow Stationary Fixed Film (DSFF)



Anaerobic Filter Systems (2)

SLUDGE RETENTION IN ATTACHED FILM SYSTEMS

In attached film systems, the maximum sludge retention depends on:

- the surface area put available for bacterial attachment
- the film thickness
- the space occupied by the carrier material
- the extent to which dispersed sludge aggregates are retained

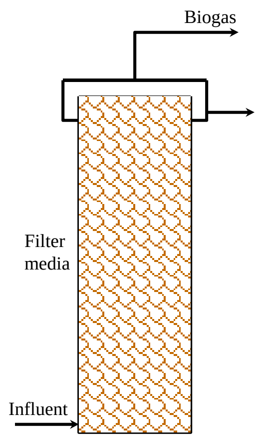
Anaerobic Filter Systems (3)

Upflow Anaerobic Filter (UAF)

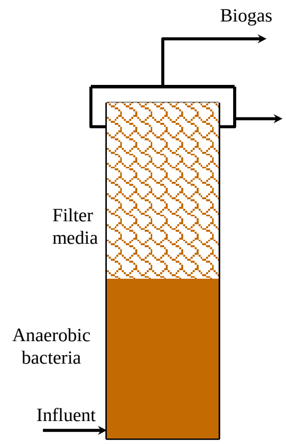
based on:
- attachment of a biofilm to a solid (stationary) carrier material
- sedimentation and entrapment of sludge particles between the interstices of the packing material
- formation of well settling sludge aggregates

Major disadvantage
- difficult to realise required contact between sludge and wastewater
- applicable loads are relatively low, I.e. generally below 10 kgCOD/m^3.day

Lay-out of upflow filters



Anaerobic filter (AF) reactor



Anaerobic hybrid (AH) reactor

Anaerobic Filter Systems (4)

<u>Downflow Stationary Fixed Film (DSFF)</u>
<u>Attached Anaerobic Film (AFF)</u>

Sludge retention based on:
Attachment of biomass to the packing.
(sludge retention is relatively low, because hardly any suspended material retained)

- generally no channelling problems
- low loading potentials

High Rate Anaerobic Reactor Systems

- high retention of viable sludge in the reactor
- sufficient contact between viable biomass and waste water
- high reaction rates and absence of serious transport limitations of substrate and metabolic end products
- sufficiently adapted and/or acclimatised viable biomass
- prevalence of favourable environmental conditions for all required organisms inside the reactor under all imposed operational conditions

Principles of Sludge Retention in High-Rate Reactors

Bacterial attachment on non-fixed carriers

e.g. FB (Fluidised Bed) reactors

Bacterial attachment on fixed support materials

e.g. Anaerobic filters

→ Attached Film

Auto immobilisation / granulation

e.g. UASB (Upflow Anaerobic Sludge Bed) reactors

→ Sludge Bed

Sludge settling and membrane filtration

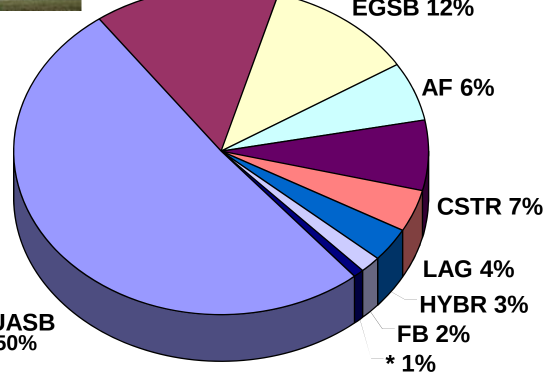
e.g. CP (Contact Process) reactors
AMBR (Anaerobic membrane bioreactors)

→ Separation

Comparison full-scale anaerobic high rate systems

Reactor	Organic Loading Rate (kg COD/m^3.d)	Problems
CP	0.5 - 5	low loading rate
AF	5 - 10	clogging
		entrapment of inert material
UASB	10 - 20	sludge flotation
		entrapment of inert material
FB	20 - 40	expensive
EGSB / IC	20 -40	“high-tech”

Historically applied anaerobic processes (1981 – 2007 (Jan.) N= 2266)



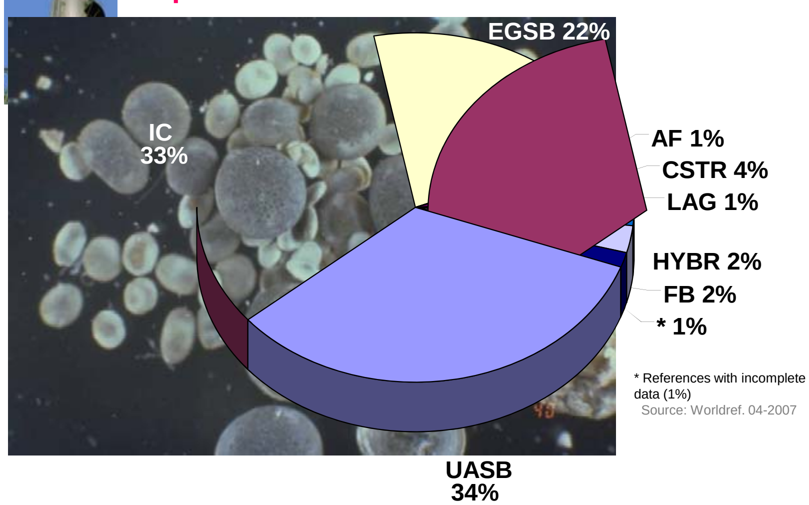
(Granular) sludge bed based: 77%

* References with incomplete data (1%)

Source: Worldref. 04-2007

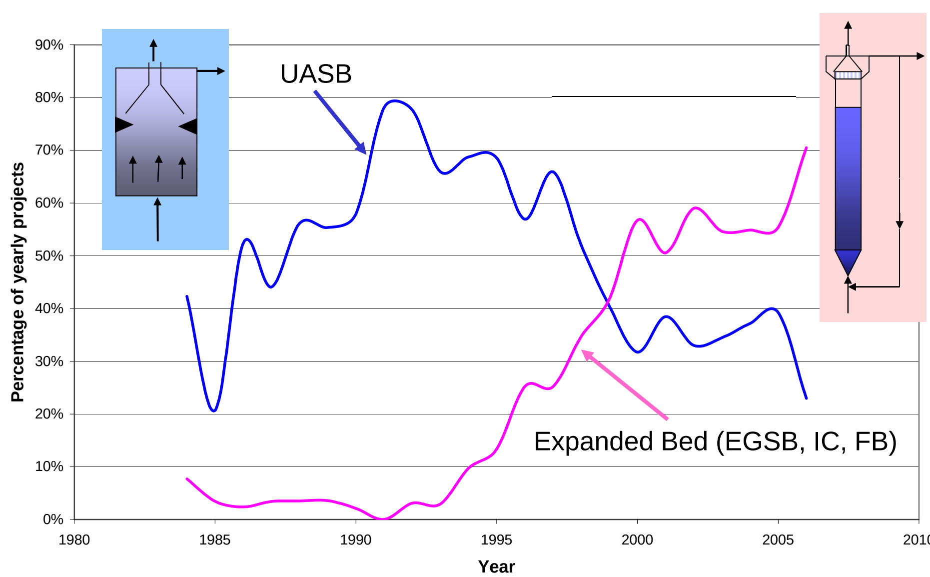
Currently Applied Anaerobic Processes (2002 – 2007 (Jan.), N= 610)

Expanded Bed Reactors: 55%



(Granular) sludge bed based: 89%

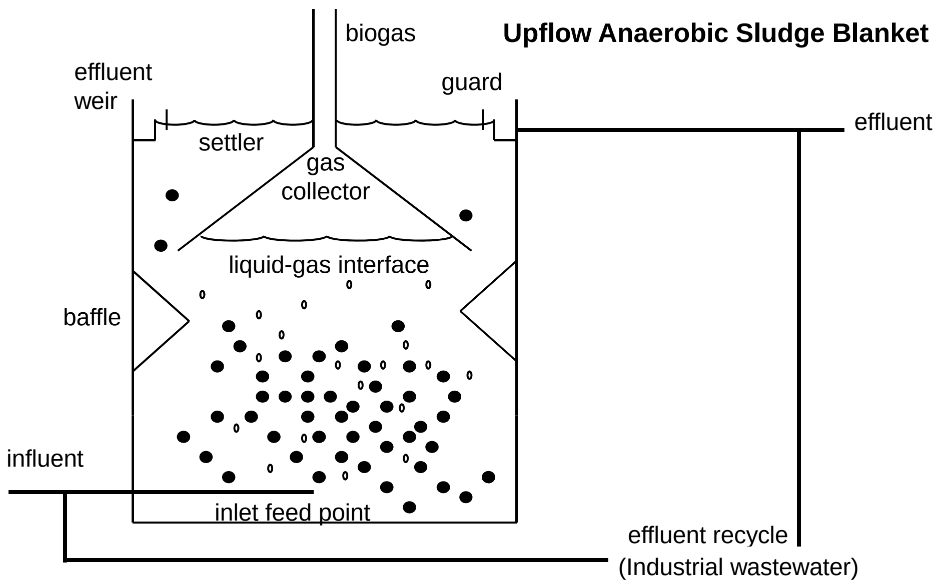
Full Scale Expanded Bed versus UASB Systems



6. Upflow anaerobic sludge blanket (UASB) reactor

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

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

UASB Reactor Size

For most industrial waste waters, the size of the reactor will be determined by the admissible organic space load. This space load greatly depends 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

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:

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

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

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 (°C)	organic volumetric loading rate (kg COD.m^{-3}. day^{-1}) 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 (°C)	organic volumetric loading rate (kg COD.m^{-3}. day^{-1}) 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. REACTOR HEIGHT

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

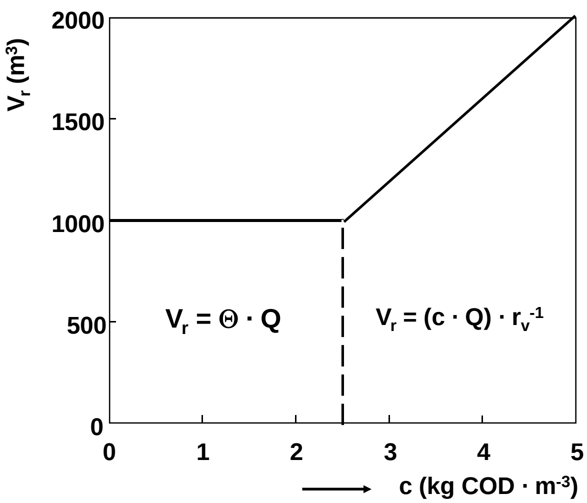
$$V_{upward}(m/h) = \frac{Q_{infl}(m^3/h)}{A(m^2)} \quad \text{or:} \quad A_{min} = \frac{Q_{infl}}{V_{upward,\,max}}$$

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

$$\Theta = \frac{V_{reactor}}{Q} = \frac{A_{min} \cdot H_{max}}{Q} \quad \text{or:} \quad V_{reactor} = \Theta \,.\, Q$$

UASB REACTOR DESIGN

Relationship between pollution strength and reactor volume.



Assumptions:

Θ_{min} = 4 h

Q = 250 $m^3 \cdot h^{-1}$

r_v = 15 kg COD · $m^{-3} \cdot d^{-1}$

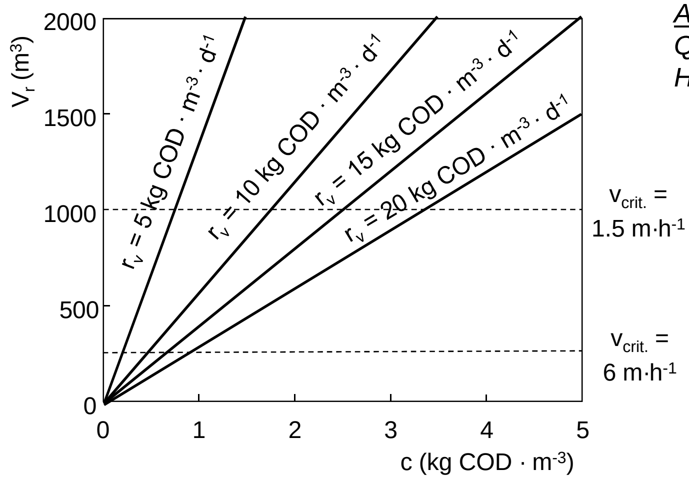
hydraulic load = 6 $m^3 \cdot m^{-3} \cdot d^{-1}$

(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

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

➡ 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). T = temperature in ºC.

Feed inlet system

The feed inlet distribution system is a crucial part of the reactor

It is important to accomplish optimal contact between sludge and waste water, i.e.

- to prevent channelling of the waste water through the sludge bed
- to avoid the formation of dead corners in the reactor

The danger of channelling will be bigger at low gas production rates (less than 1 $m^3 \cdot m^{-3} \cdot day^{-1}$)

Guidelines for number of feed inlet points

in UASB reactors treating mainly soluble waste waters

Type of sludge	Loading rate ($kg\ COD\ .\ m^{-3}\ .\ day^{-1}$)	Area (m^2) per feed inlet point
Dense flocculant sludge (>40 kg DS/m^3)	< 1	0.5 - 1
	1 - 2	1 - 2
	> 2	2 - 3
Medium thick flocculant sludge (20 - 40 kg DS/m^3)	<1 - 2	1 - 2
	> 3	2 - 5
Granular sludge	< 2	0.5
	2 - 4	1 - 2
	> 4	>2

Online Course on Biological Wastewater Treatment: Principles, Modelling and Design   Chapter on Anaerobic Wastewater Treatment by Jules van Lier

The GLSS Device (GLSS = Gas Liquid Solids Separator)

Functionality of GLSS device for UASB systems:

- separation of biogas from the liquid for discard from the reactor
- to prevent the wash out of viable bacterial matter by biogas bubbles
- to create a secondary clarifier at the top of the reactor enabling the settled sludge to slide back into the digester compartment
- to serve as a barrier for rapid excessive expansions of the sludge blanket (mainly composed of flocculant biomass sludge) into the settler
- to provide a polishing effect
- to prevent the wash out of floating granular sludge

Summary guidelines design GLSS device

- The slope of the settler bottom (i.e. the inclined wall of the gas collector) is between 45-60º.
- The surface area of the apertures between the gas collectors is not less than 15-20% of the reactor surface area.
- The height of the gas collector is 1.5-2m at reactor heights of 5-6 m.
- A liquid-gas interface is maintained underneath the GLSS.
- The overlap of the baffles installed beneath the apertures is 15-20 cm (avoiding up-flowing gas bubbles entering the settler compartment)