Treatment of wastewater solids

Applied wastewater engineering

Michael Jon MATTLE

Content of treatment of wastewater solids

- solid waste characterisation
- screening and grit removal
- preliminary sludge processing operations
- thickening of sludge
- sludge stabilisation (anaerobic/aerobic, composting and alkaline)
- dewatering and drying
- incineration and land application
- phosphorous recovery

Treatment of wastewater solids I: characterisation and preliminary treatment

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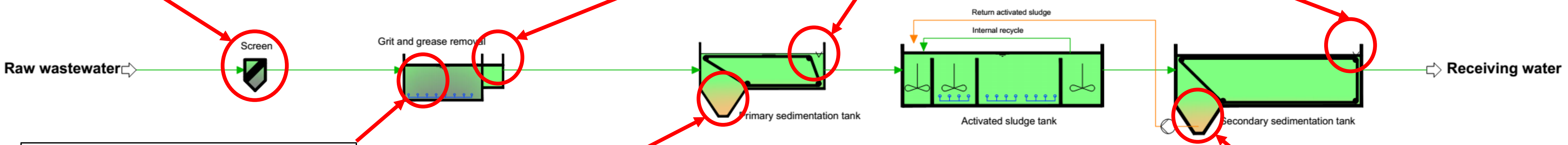
solid waste characterisation

- solid waste production

scum removal: floatable materials like vegetable and mineral oils, soaps, fats, hair, paper, cigarette tips, plastic materials, condoms,… scum from the secondary clarifier may also consist of floating bacteria

screening: removal of coarse solids and small particles with a potentially extremely offensive odour



grit removal: easily settable solids

primary sludge: generally fine but settable particles. This sludge is usually grey and slimy and has an extremely offensive odour

waste activated sludge: suspended solids generally has a brown flocculent appearance with an inoffensive “earthy” odour

Solid waste production

- Which of these solid wastes does generate the biggest volumes?

A) screenings

B) grit

C) grease

D) scum

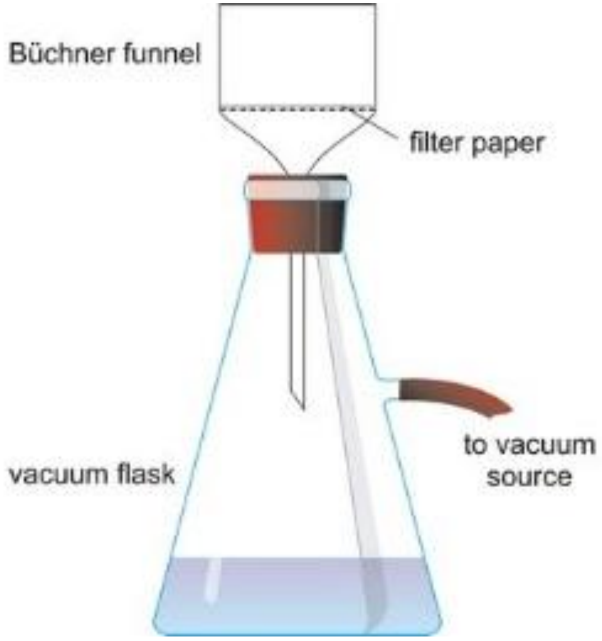
E) primary sludge

F) secondary sludge

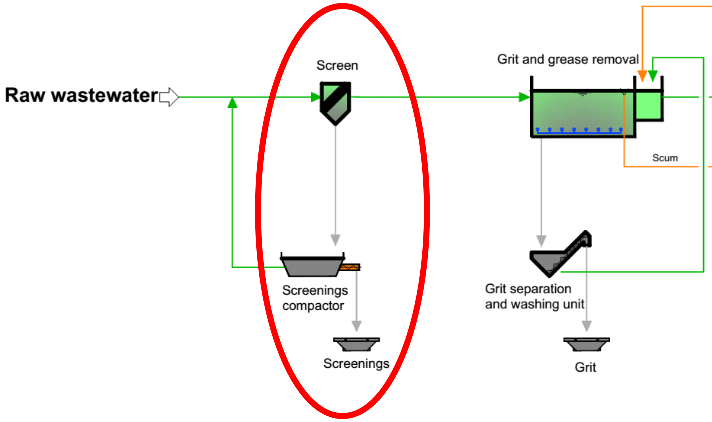
https://web.speakup.info/room/join/11535

Solid waste characterisation

- TS (total solids):
  - Residue remaining after a wastewater sample has been evaporated and dried at a specified temperature (≈ 105 °C)
- TVS (total volatile solids):
  - Those solids that can be volatilised and burned off when the TS are ignited (500 ± 50 °C)
- TSS (total suspended solids; generally used for wastewater characterisation):
  - Portion of the TS retained on a filter (generally 0.45 µm), measured after being dried at a specified temperature (≈ 105 °C)
- VSS (volatile suspended solids; generally used for wastewater characterisation):
  - Those solids that can be volatilised and burned off when the TSS are ignited (500 ± 50 °C)



Screening of wastewater



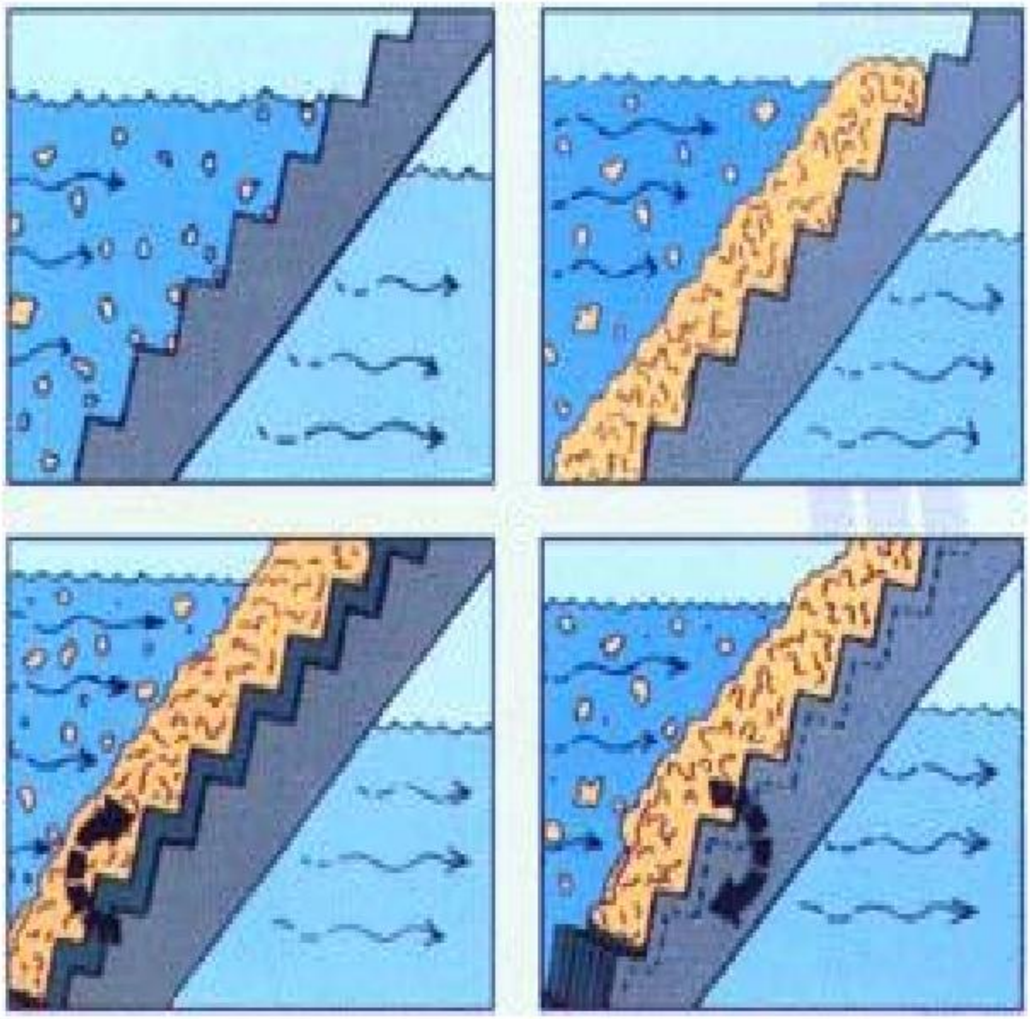
- generally first treatment stage of a wastewater treatment plant: coarse screening (> 8 mm up to 50 mm)
- remove coarse materials from flow stream
  - avoid damage or clogging of other equipment
  - increase reliability of treatment plant
  - minimal treatment for storm water overflows
- fine screening (≤ 8 mm) is optional for additional reduction of solids that could clog further down in the treatment process (e.g. membranes of membrane bioreactors or biofiltres)

step screen

Screening of wastewater

- materials retained are called screenings: paper, plastic, faeces, wrongly disposed garbage (e.g. textiles)
- contains also debris such as gravel, metal pieces and depending on the period of the year leaves
- screenings have low moisture content (TS content: 8 to 15 %) compared to other wastewater solids
    - coarse screenings have a higher moisture content than fine screenings
- often more than 90 % of TS is organic (> 80 % cellulose)

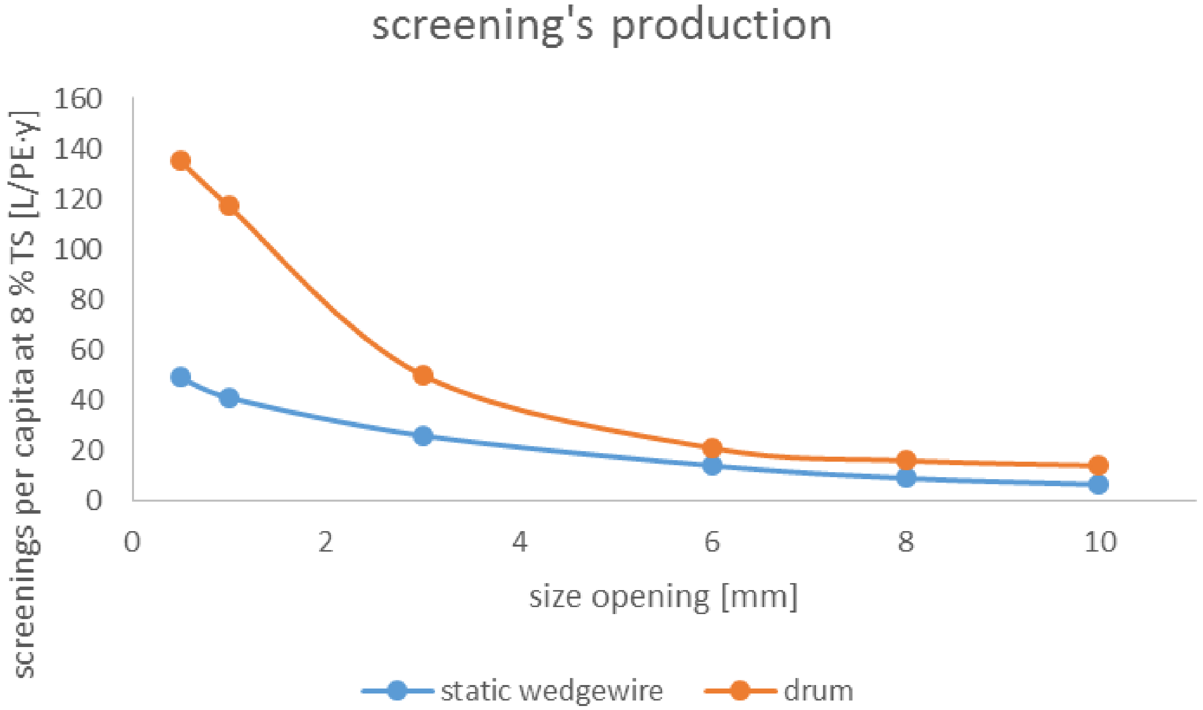
  → bad odour problems

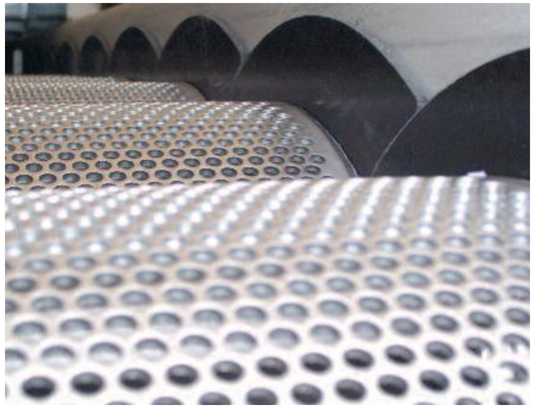


step screen

Type of screen on screenings production

- the smaller the opening of the bars or holes, the larger the volume of screenings retained
- drum screens are much more efficient in removing screenings than static wedgewire screens
- however,
  - they are hydraulically worse (water has to travel through twice)
  - the cleaning requires a lot of water
  - they are more expensive





Screenings production

- practical computation of screenings production (TS between 8 and 15 %):
  - size opening > 3 mm:
    - 30 – 300 L/1’000 m^3
  - size opening < 3 mm
    - static wedgewire screens: 200 – 400 L/1’000 m^3
    - drum screens: 400 – 800 L/1’000 m^3
- at the beginning of a heavy rain event (flushing of the sewer system), the volumes of screenings may increase substantially especially for combined sewer systems (up to 10 times) as compared to normal flow
  - additionally a security factor for rain should be added: 2 - 6

➡ as for other installations in WWTP, the data from the current screen is the best source of information for the design of a new screen

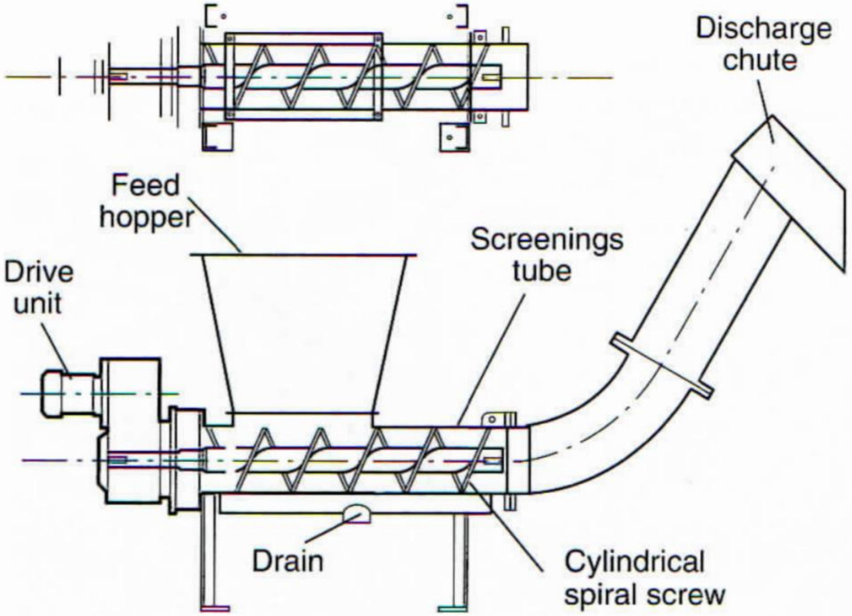
Handling of screenings

Parameter	unit	range	typical
TS	% [kg TS/kg]	8 – 54	30
calorific value	MJ/kg	2 – 10	4.7 (35 % TS)
TVS	%	73 – 98	87
AOX	mg/kg	3 – 250	80
lead	mg/kg	1 – 63	22
copper	mg/kg	13 – 220	56
zinc	mg/kg	47 – 940	246
…			

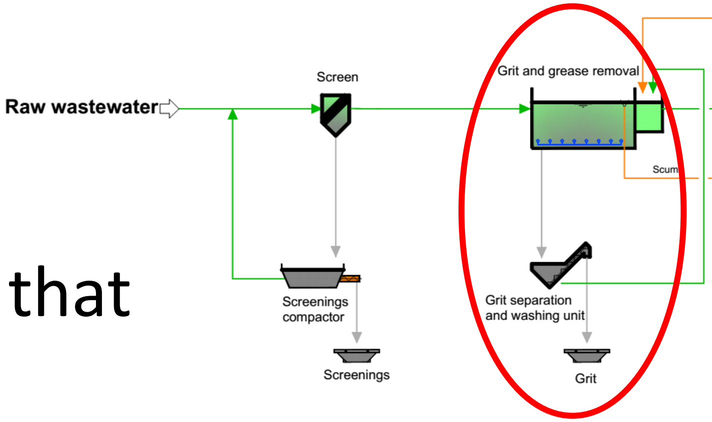
- screenings contain many toxic compounds: e.g. heavy metals, halogenated compounds,…
- fine screenings contain putrescible matter (high TVS content) such as faecal materials, grease and scum (odour problems)
  - manual handling of fine screenings should be minimized

Screenings

- screenings compactors can be used to dewater and reduce the volume of screenings:
  - increases TS to 30 – 50 %
- screenings washer and compactors are often used in Switzerland:
  - removal of organics (bad odour reduction)
  - volume reduction up to 80 % may be obtained
- screenings are then transported to an incineration plant or directly to landfills (depending on legislation)



Grit and grease removal



- grit consists of sand, gravel and other heavy material that settle more quickly than organic material (e.g. glass)
  - residence time is short (≈ 5 - 20 min) compared to other installations
- in the collection system grit particles may come into contact with organic matter and surface active agents that can adhere to the particles
  - it putrefies quickly if not correctly handled

parameter	unit	range
specific volume	L/(PE·year)	2 - 5
specific weight	kg TS /(PE·year)	3 – 7.5
total solids	% [kg TS/kg]	40 - 70
total volatile solids (TVS)	% of TS	10 - 50

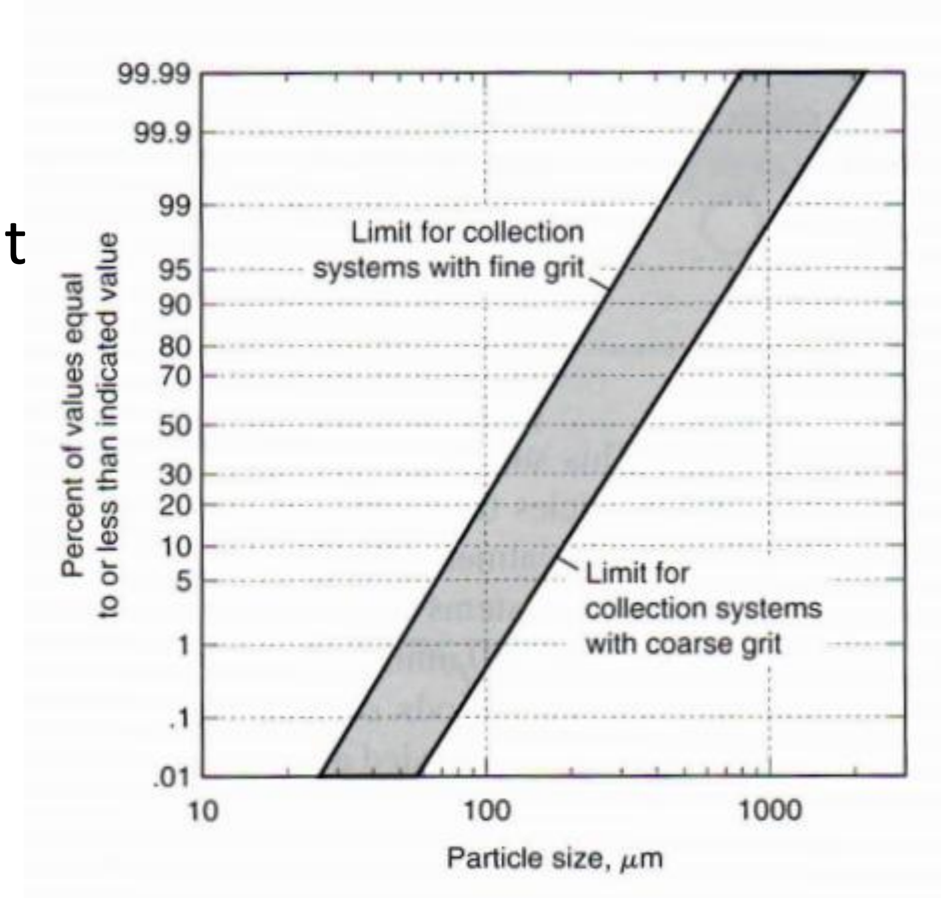
- all values depend highly on the site
- may contain considerable amount of organic material

Grit removal

- grit has to be removed in order to protect aeration basins, digesters and pipes from heavy deposits
- the removal of grit also reduces the abrasion of moving mechanical equipment further down in the treatment train (e.g. pumps, centrifuges, heat exchangers,…)

grit diameter	removal efficiency
0.3 mm	95 %
0.2 mm	85 %
0.15 mm	75 %
0.1 mm	50 %
< 0.07 mm	< 10 %

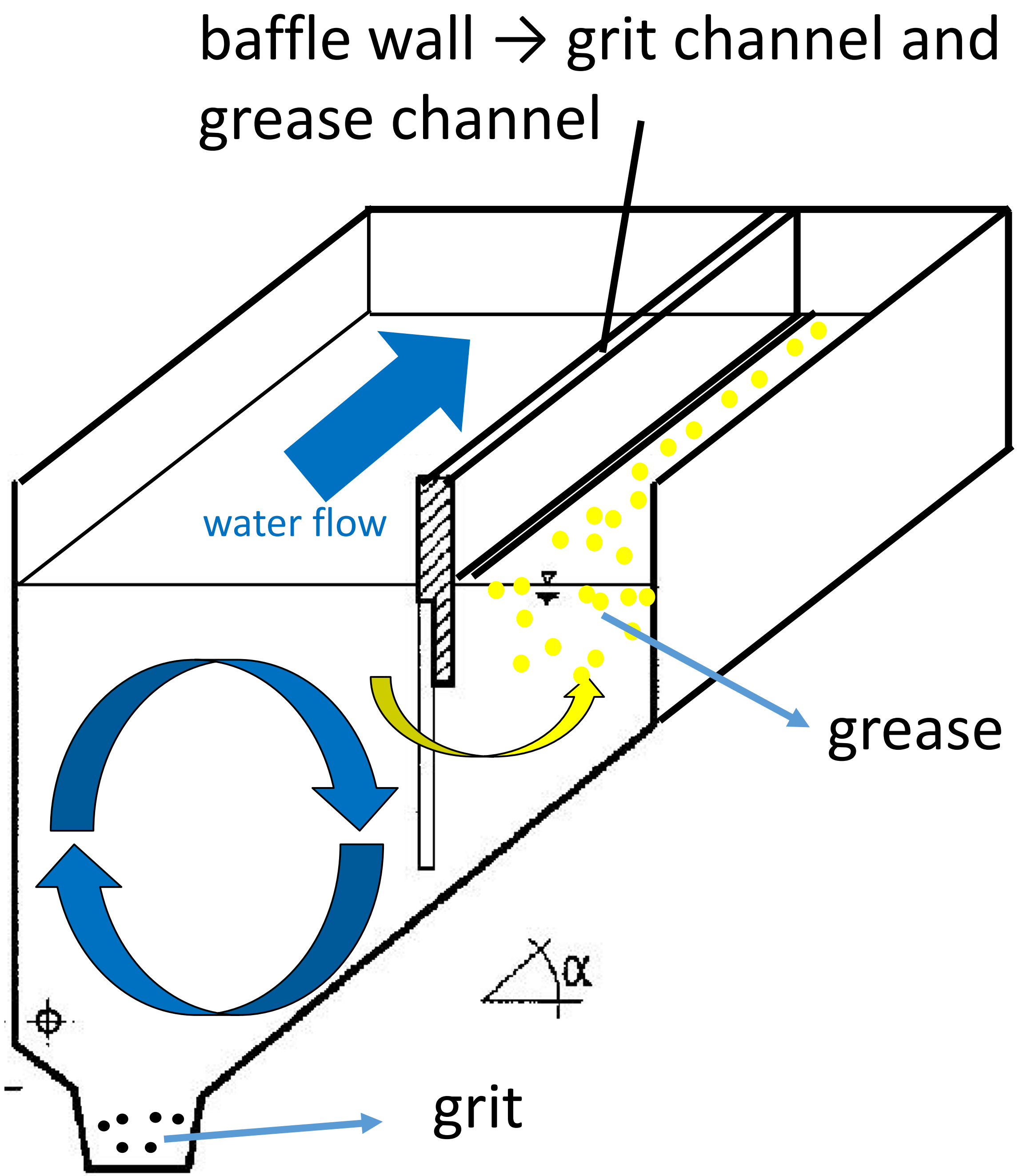
average achievable removal efficiencies of aerated grit removal (depends on hydraulic retention time and design)



typical particle size distribution range

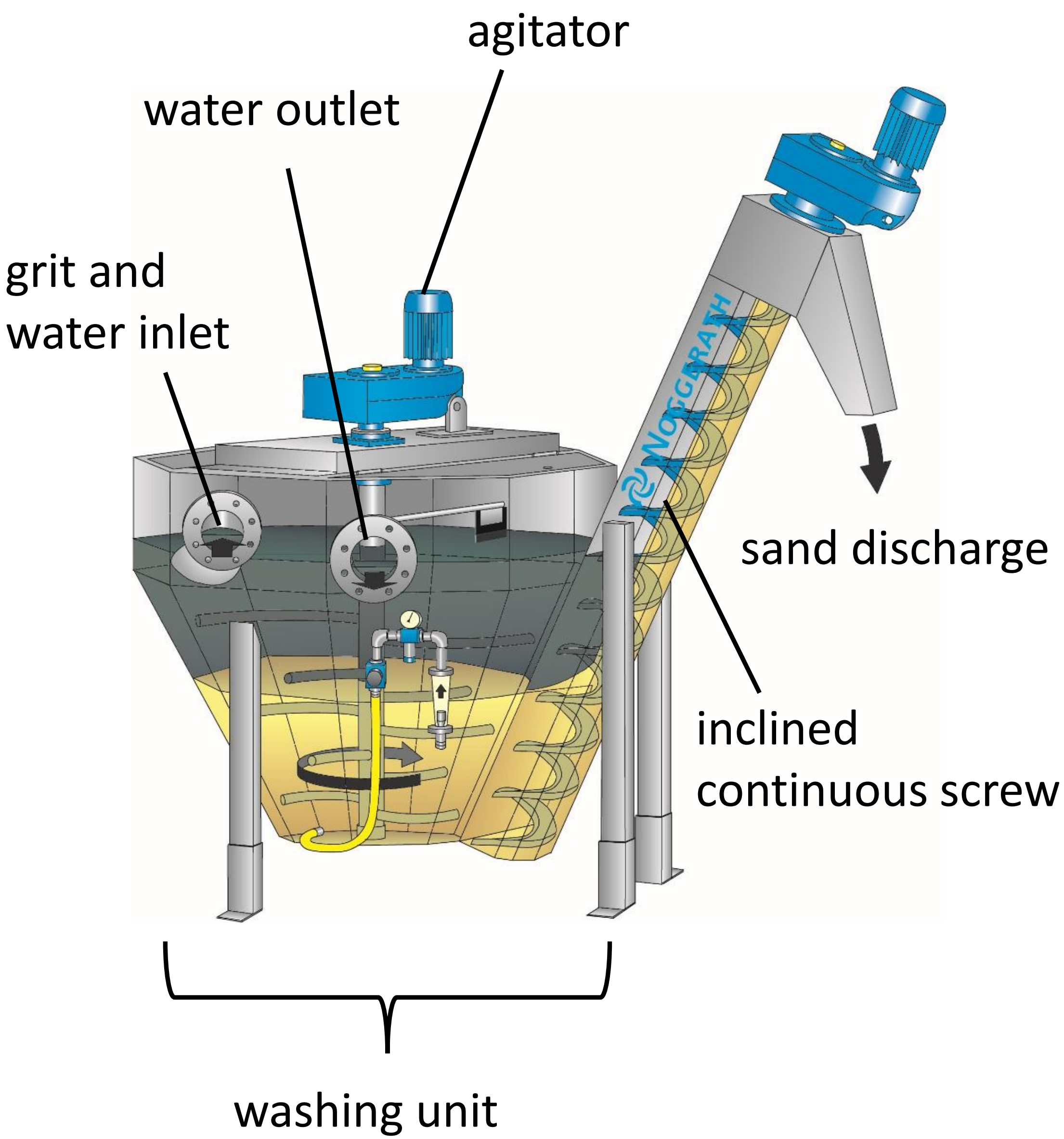
Grit and grease removal

- shape: round or rectangular
- only grit or grit and grease removal
- classical or aerated
  - it is difficult to obtain a constant flow/separation with a classical grit removal unit at different inflow speeds (no aeration)
  - aeration allows a constant separation (independent of flow rate) of grit and organic material due to constant spiral flow
  - aeration produces turbulences which separate part of the organic material from the grit
  - aeration allows grease removal in separate channel



Grit washing and drying

- without washing unit:
  - volatile solids often higher than 20 %
  - water content about 50 %
- with washing unit:
  - volatile solids < 5 %
  - roughly 1/3 of weight without washing unit
- grit may be reused if sufficiently washed and dried: e.g. roads, paths, landscape building, building materials (depending on legislation)
- otherwise it is transported to landfills or incineration plants

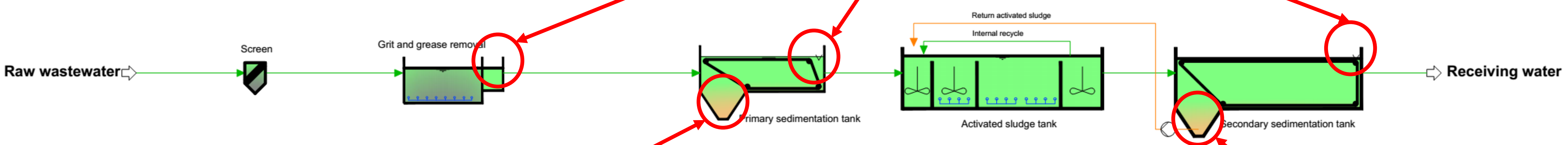


Grit and grease removal

Solid waste characterisation

- solid waste production

scum removal: floatable materials like vegetable and mineral oils, soaps, fats, hair, paper, cigarette tips, plastic materials, condoms,… scum from the secondary clarifier may also consist of floating bacteria

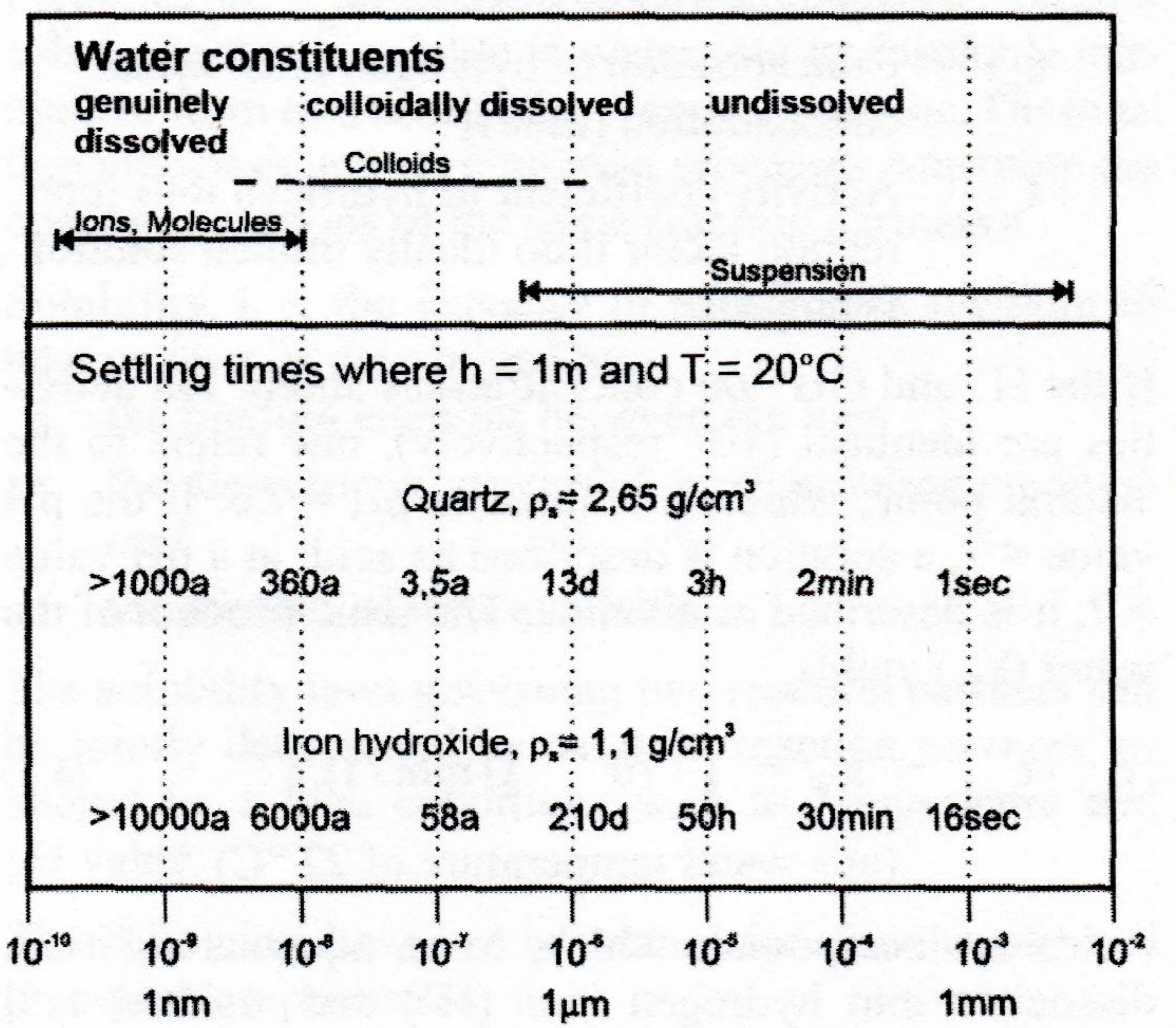


primary sludge: generally fine but settable particles. This sludge is usually grey and slimy and has an extremely offensive odour

waste sludge: suspended solids generally has a brown flocculent appearance with an inoffensive “earthy” odour

Water constituents removal

- clarifiers remove particles down to the range of mm range (≈ 0.1 mm)
- smaller water constituents may be removed by
  - smaller particles: rapid sand filtration
  - colloids: coagulation and sedimentation/rapid sand filtration (or ultrafiltration)
  - molecules and ions: tight membrane filtration (with or without coagulation)



Typical sludge composition

	untreated primary sludge (PS)		waste activated sludge (WAS)	
parameter	range	typical	range	typical
total solids (TS) % [kg TS/kg]	1-6	3	0.4-1.2	0.8
total volatile solids TVS (% of TS)	60-85	75	60-85	70
grease and fats (% of TS)	5-8	6	5-12	8
protein (% of TS)	20-30	25	32-41	36
nitrogen (N, % of TS)	1.5-4	2.5	2.4-5	3.8
phosphorous (P_2O_5, % of TS)	0.8-2.8	1.6	2.8-11	5.5
cellulose (% of TS)	8-15	10	-	
iron (not as sulphide)	2-4	2.5	*	
silica (SiO_2, % of TS)	15-20	-		
pH	5-8	6	6.5-8	7.1
alkalinity (mg/L as $CaCO_3$)	500-1'500	600	580-1'100	790
organic acids (mg/L as HAc)	200-2'000	500	1'100-1'700	1'350
energy content, kJ/kg TVS	23'000-29'000	25'000	19'000-23'000	20'000

PS more concentrated than WAS

PS has higher volatile solids (VS) than WAS

PS contains less nutrients than WAS
→ fertiliser

* no value given as dependent on $FeCl_3$ dosing for phosphorous removal

PS contains more energy than WAS

Typical sludge composition

metal	range of dry solids, mg/kg TS
arsenic	1.18 – 49.2
cadmium	0.21 – 11.8
chromium	6.74 – 1160
cobalt	0.87 – 290
copper	115 – 2580
iron	1575 – 299’000
lead	5.81 – 450
manganese	34.8 – 14’900
mercury	0.17 – 8.3
molybdenum	2.51 – 132
nickel	7.44 – 526
selenium	1.1 – 24.7
tin	7.5 – 522
zinc	216 - 8550

Table: typical metal content in wastewater solids

- most metals that enter a wastewater treatment plant exit it as sludge
  - metal concentrations depend on implementation of pretreatment installations at industries
- untreated sludge also contains many pathogenic microorganisms and potentially prions (e.g. bovine spongiform encephalopathy (BSE): mad cow disease)
- high concentrations of heavy-metals, pathogens and other pollutants (e.g. PFAS) may have a negative impact on agriculture

→ sludge can no longer be used for land application in Switzerland since 2006

Objectives of sludge treatment

- reduce water content (from percent range up to 30 % or higher)
  - less volume required for storage/treatment
  - less energy needed to heat the sludge (e.g. digestion)
  - less weight of sludge (e.g. transport)

- reduce bad odour of sludge
  - more comfortable working environment for employees
  - reduced nuisances to neighbours
  - less waste air treatment required
- remove dangerous or disturbing materials
  - e.g. fibres that disturb good functioning of digesters
  - pathogens that may cause infections

Objectives of sludge treatment

- reduce water content (from percent range up to 30 % or higher)
  - thickening
  - dewatering
  - drying
  - composting

- reduce bad odour of sludge
  - anaerobic digestion
  - aerobic stabilisation
  - alkaline stabilisation
  - reed beds

- remove dangerous or disturbing materials
  - screening and grinding of sludge
  - anaerobic/alkaline/aerobic stabilisation and reed beds (pathogens)

Wastewater solids stabilisation

- Which of these wastewater solids are stabilised by digestion (several answers possible)?

A) screenings

B) grit

C) grease

D) scum

E) primary sludge

F) secondary sludge

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Quantities of primary sludge total solids (TS)

Primary sludge production				
minimal 2h-residence time (dry weather)	85th percentile	50th percentile	yield	TVS fraction
[h]	[g TSS/(PE·d)]	[g TSS/(PE·d)]	[%]	[%]
0.5	30	24	43	75
1.0	35	28	50	75
2.0	40	32	57	75

population equivalent (PE) :

- 70 g TSS in influent wastewater for 85th percentile
- ≈ 56 g TSS in influent wastewater for 50th percentile (≈ 80 %)

Quantities of waste activated sludge (only C-treatment)

only carbon removing activated sludge plant (minimal sludge age 5 days)					
residence time in primary clarifier	temperature	sludge production		total volatile solids (TVS) fraction	
		85th percentile	50th percentile	85th percentile	50th percentile
[h]	[°C]	[g TSS/(PE·d)]	[g TSS/(PE·d)]	[%]	[%]
0.5	10	56	43	77	76
0.5	15	52	40	75	75
0.5	20	49	38	74	73
1.0	10	50	38	76	76
1.0	15	47	36	75	74
1.0	20	44	34	73	73
2.0	10	44	34	76	75
2.0	15	41	32	74	74
2.0	20	39	30	73	72

- reduced waste activated sludge production and reduced volatile solids fraction at higher temperatures

→ higher mineralisa-tion of sludge at higher temperatures

Quantities of waste activated sludge (C- + N-treatment)

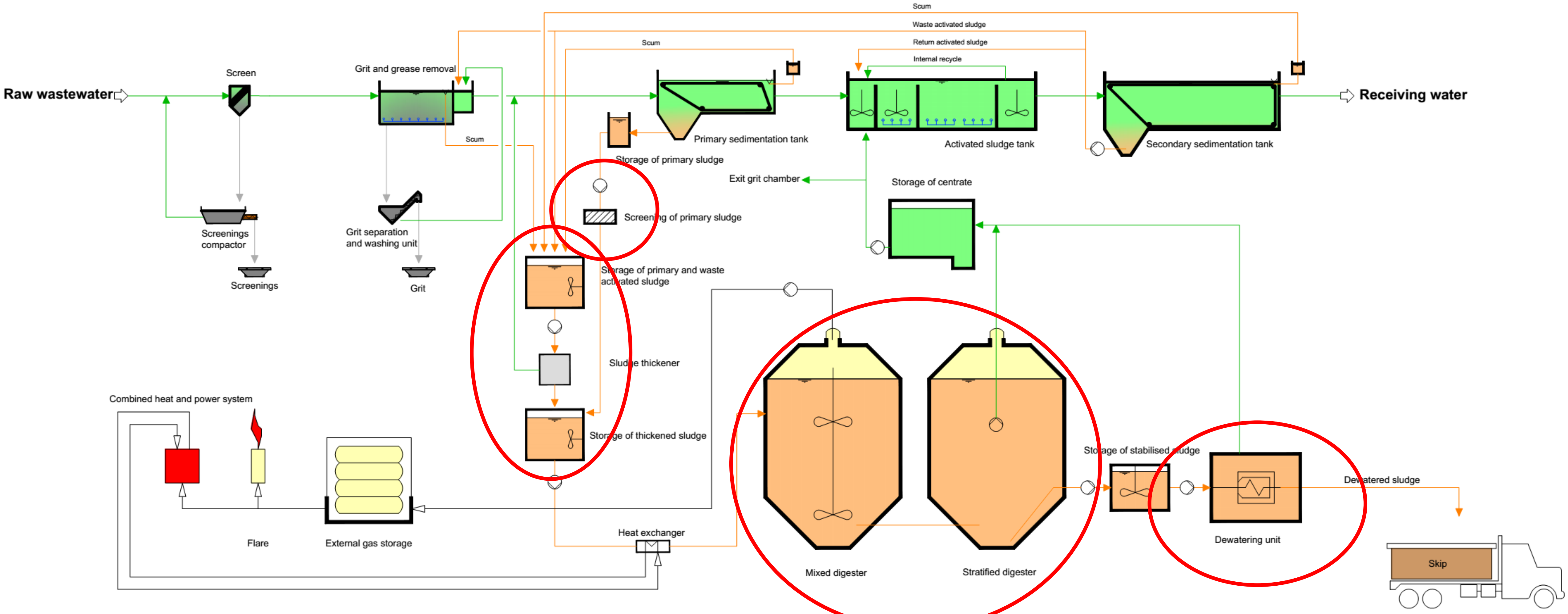
nitrifying activated sludge plant (minimal sludge age 10 days)					
residence time in primary clarifier	temperature	sludge production		total volatile solids (TVS) fraction	
		85th percentile	50th percentile	85th percentile	50th percentile
[h]	[°C]	[g TSS/(PE·d)]	[g TSS/(PE·d)]	[%]	[%]
0.5	10	49	37	73	73
0.5	20	43	34	70	70
1.0	10	43	33	73	72
1.0	20	39	31	70	70
2.0	10	29	29	72	71
2.0	20	28	28	69	71

- lower sludge production and lower volatile solids fraction than without nitrogen treatment due to higher mineralisation of sludge (higher sludge age)

Sludge characteristics (total solids (TS) content)

operation or process application	total solids (TS) concentration (%) [kg TS/kg in %]	
	range	typical
primary sludge	1 - 6	3
primary and waste activated sludge	0.5 – 3	1.5
primary sludge and trickling filter humus	4 – 10	2
primary sludge with iron addition for phosphorous removal	0.5 – 3	2
waste activated sludge with primary settling	0.5 – 1.5	0.8
waste activated sludge without primary settling	0.8 – 2.5	1.3
trickling filter humus	1 – 3	1.5
rotating biological contactor waste sludge	1 -3	1.5

Sludge treatment in wastewater treatment plants



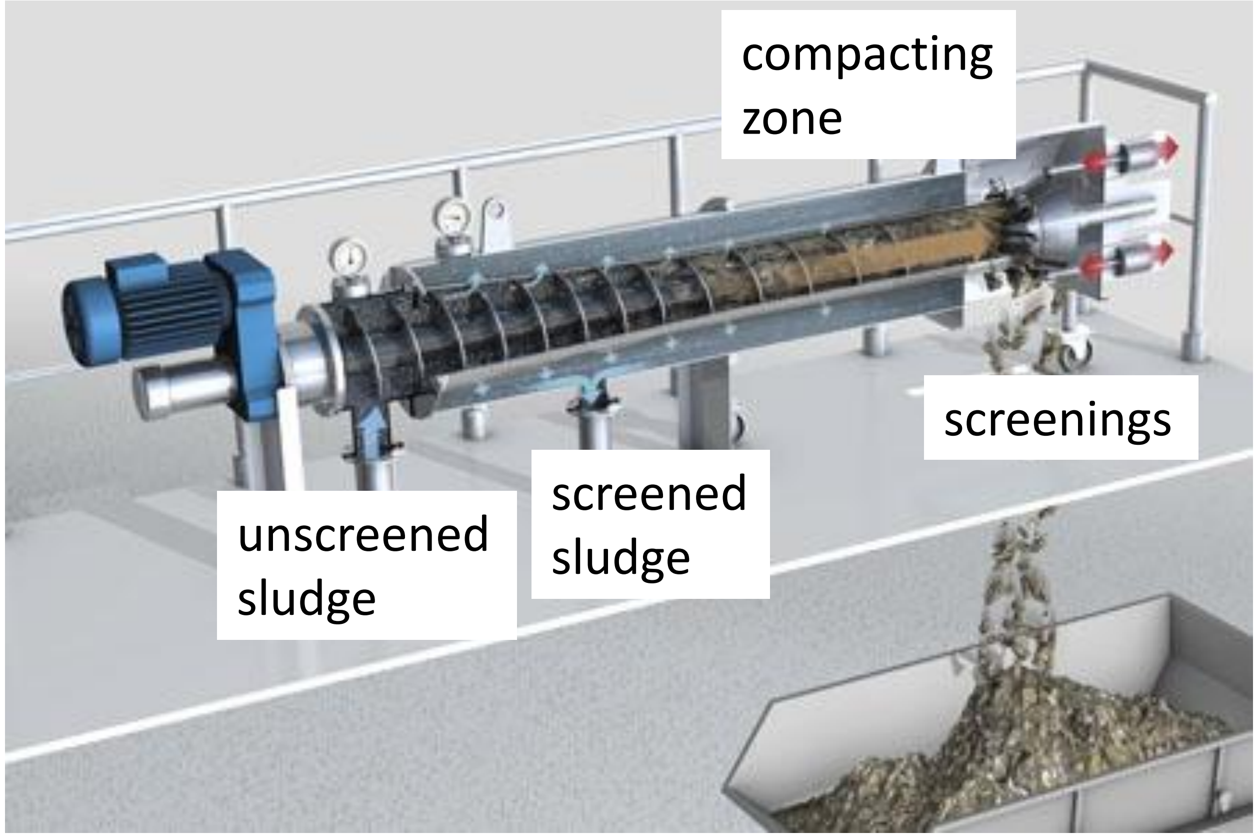
Preliminary sludge processing operations

- provide a relatively constant and homogeneous feed to subsequent processing facilities
- prevent clogging and reduce wear of pumps
- these operations include:
  - screening (remove large materials)
  - grinding (reduce size of large materials; rather rarely done in Switzerland)
  - degritting (if no grit removal facility is ahead of the primary sedimentation tank)
  - blending (sludge is mixed to produce a consistent characteristics of sludge)
  - storage (minimize fluctuations, reparation work)

→ blending and storage: often done together (mixed storage tank)

Preliminary sludge processing operations

- screening has the advantage to remove nuisance materials rather than only reducing its size (grinding)
- screening may be done similarly to wastewater screening (e.g. step screening) but may also be done with inline screens (e.g strainpress see figure) which contain a compacting zone
- screenings removed: paper, plastic, aluminium foil, wood, gum, textiles (fibres),…



Treatment of wastewater solids II: thickening of sludge

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Sludge thickening

- solids content of primary sludge, waste activated sludge, or mixed sludge varies considerably
- thickening is a process to increase the solids content of sludge by removing a portion of the liquid fraction
  - reduced storage/treatment capacity required for thickened sludge
  - reduced energy consumption if heating is required during further sludge treatment
  - filtrate/centrate returned to the wastewater treatment train
- achieved by physical means with or without the addition of polymers (flocculants)
- thickened sludge can be handled as a liquid: density ≈ 1
  - whereas dewatering produces a solid

Sludge thickening

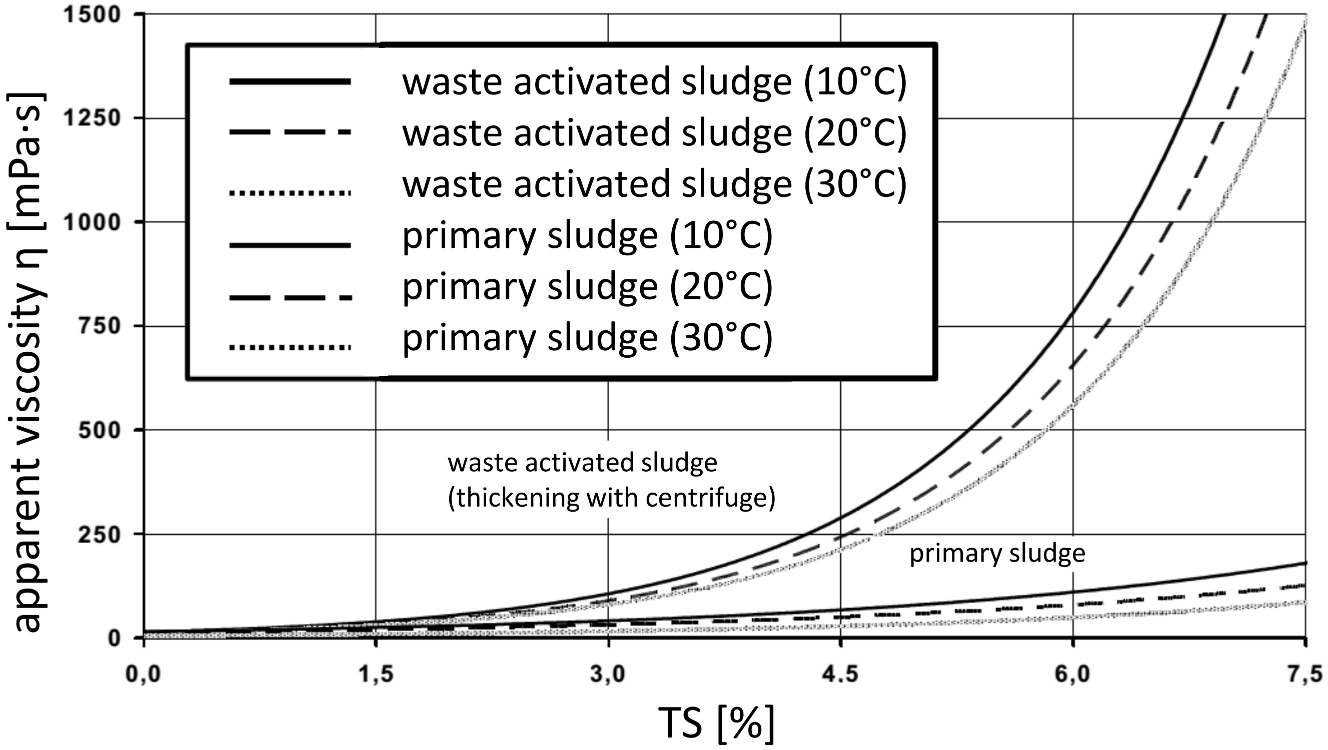
- volume reduction

➡ reduced volumes necessary to treat sludge

- however, viscosity increases with increasing solids content (especially for waste activated sludge)

➡ viscosity has to be low enough to allow pumping, mixing and stabilisation processes

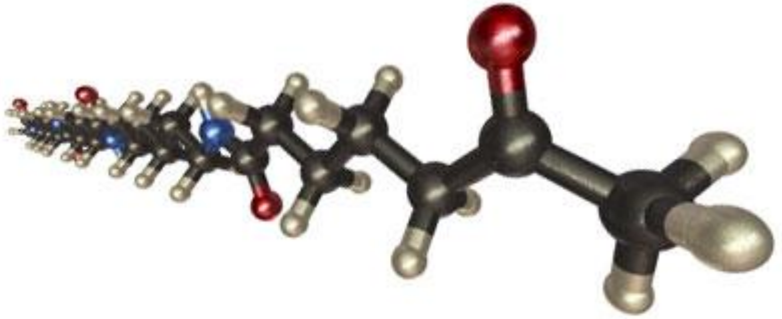
➡ total solids content ideally around 6 %



Bau, K. Schriftenreihe WAR 1986

Chemical conditioning

- flocculants help improve solids and water separation
- mostly done using polymers
  - chemical conditioning with inorganic chemicals (e.g. ferric chloride or aluminium chloride) is less frequently used

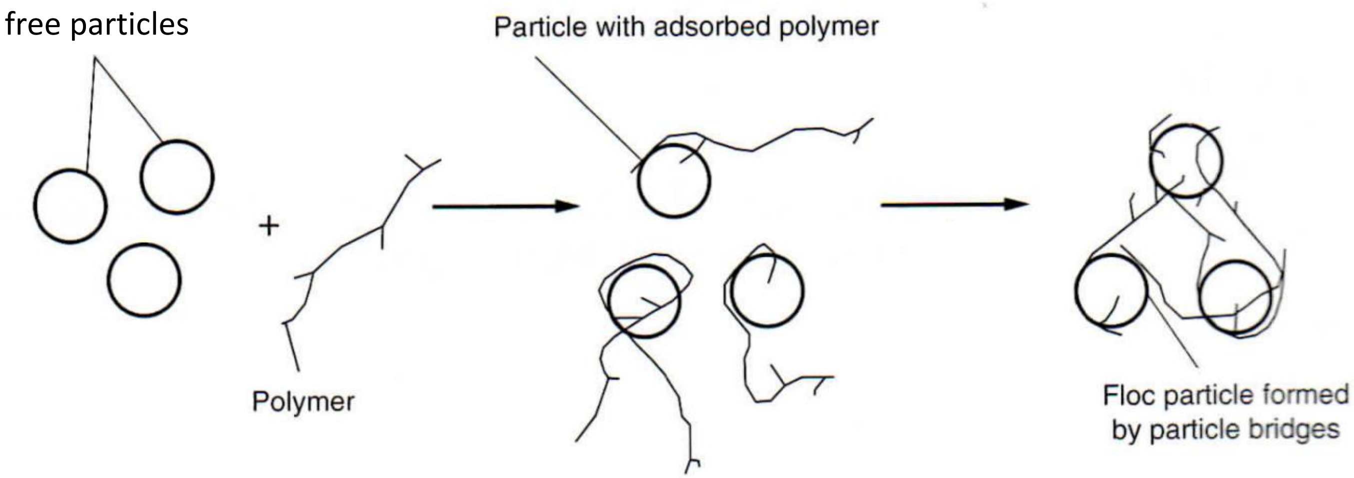


- type and dosage of polymer depends on
  - properties of sludge
  - mixing conditions
  - thickening or dewatering device used
  - desired final solids content

molecular weight	relative molecular weight
very high	> 6’000’000 – 18’000’000
high	1’000’000 – 6’000’000
medium	200’000 – 1’000’000
low	< 200’000

Chemical conditioning: addition of polymers

- formation of larger particles
  - charge neutralisation: polymers act as coagulants that neutralise or lower the charge of the particles (cationic, anionic or non-ionic polymers)
  - polymer bridge formation: a bridge is formed when more than one particle adsorbs on the same polymer



→ most wastewater treatment plants use polymers for improved solid - water separation, especially for dewatering of sludge but also for mechanical thickening

Chemical conditioning: addition of polymers

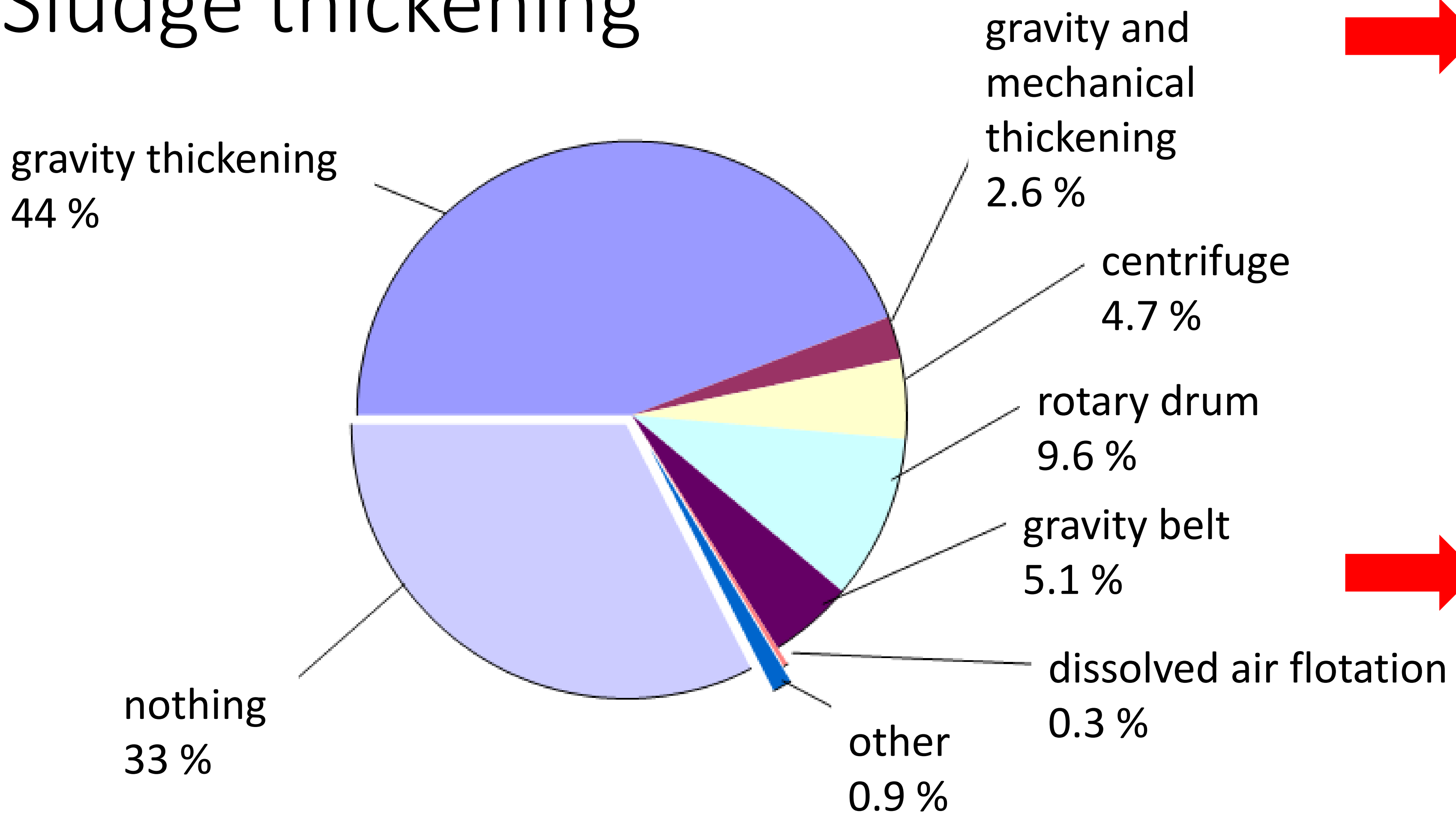
- polymers can be purchased as solids or already in liquid form

state	product	description
solid	powder, granules	polymer content 95 %
liquid	emulsion (contains water and oil)	polymer content 25 % to 50 % rest: water, oil and emulsifier
	dispersion (contains oil and little water)	polymer content up to 50 % rest: mainly oil, water (less than 10 %) and stabilisers

➡ a maturation period of at least 45 minutes is needed once the polymer product is mixed with dilution water

➡ maturated polymer solution should be used ideally within 4 to 6 hours but at least within 24 hours

Sludge thickening



statistical analysis of waste active sludge thickening in Germany 2003 (DWA)

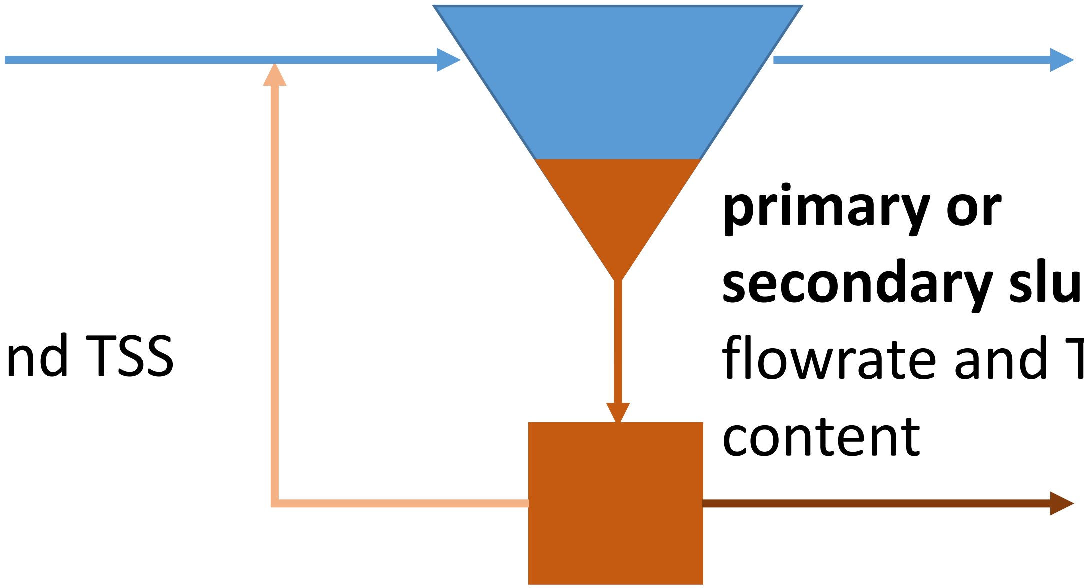
- the proportion of mechanical thickening is higher in Switzerland (e.g. gravity belt thickening)
- however, gravity thickening is very rare

Sludge thickening

wastewater
flowrate and pollutant concentrations (TSS, COD,…)

primary or secondary clarifier
yield for TSS, COD,… removal

primary or secondary clarified wastewater
flowrate and pollutant concentrations



overflow
flowrate and TSS content

primary or secondary sludge
flowrate and TS content

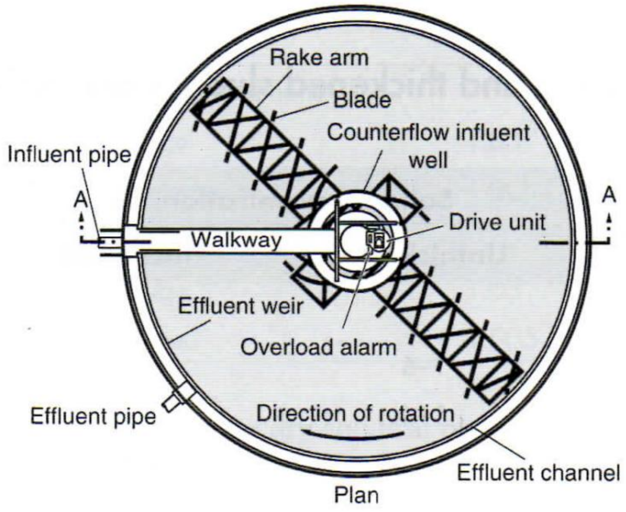
thickened sludge
flowrate and TS content

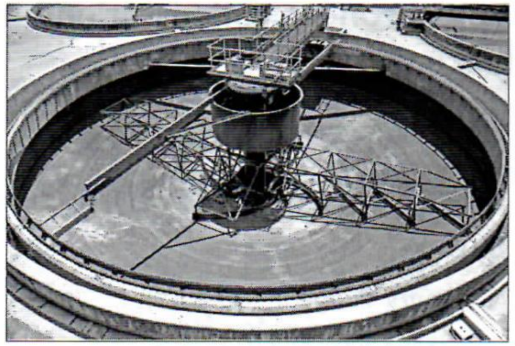
sludge thickening
capture rate (%)

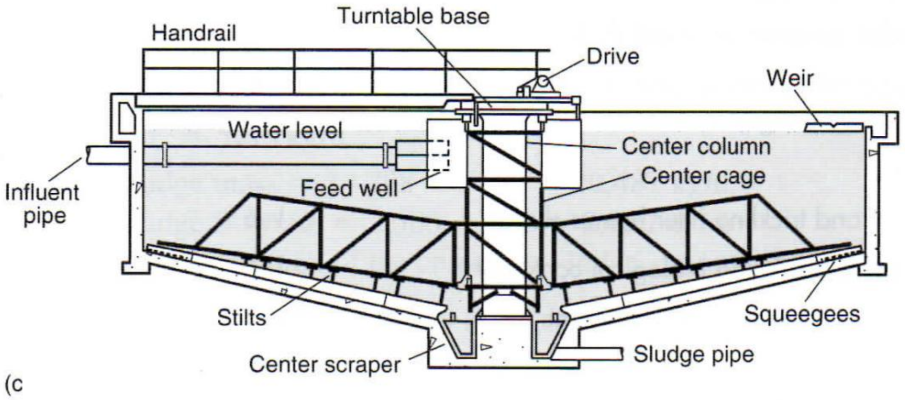
→ this is a dynamic system!

Gravity thickening

- natural gravity force separates sludge particles (heavier than water) from water
- relatively simple process
    - sludge blanket at the bottom
    - sludge gently stirred which allows water to escape and sludge densification
    - supernatant removed and generally pumped back to the primary settling tank

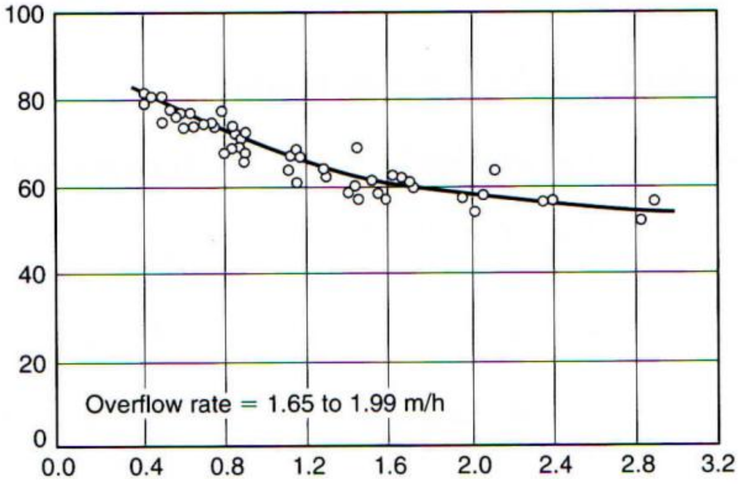






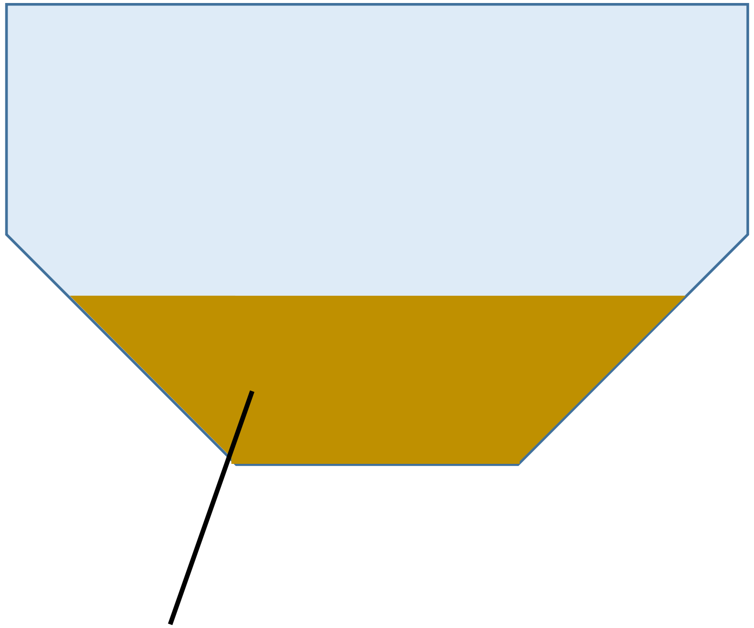
Gravity thickening

- ‘competition’ between:
- capture rate (%) : quantity of solids in thickened sludge (kg TS) divided by quantity of solids in unthickening sludge (kg TS)·100%
- solids content of thickened sludge



TS removal [%]

sludge blanket retention time [d]



sludge blanket: the thicker (higher sludge retention time), the higher the solids content of the thickened sludge, but also of the supernatant

Typical design parameters for gravity thickening

- solids loading rate:

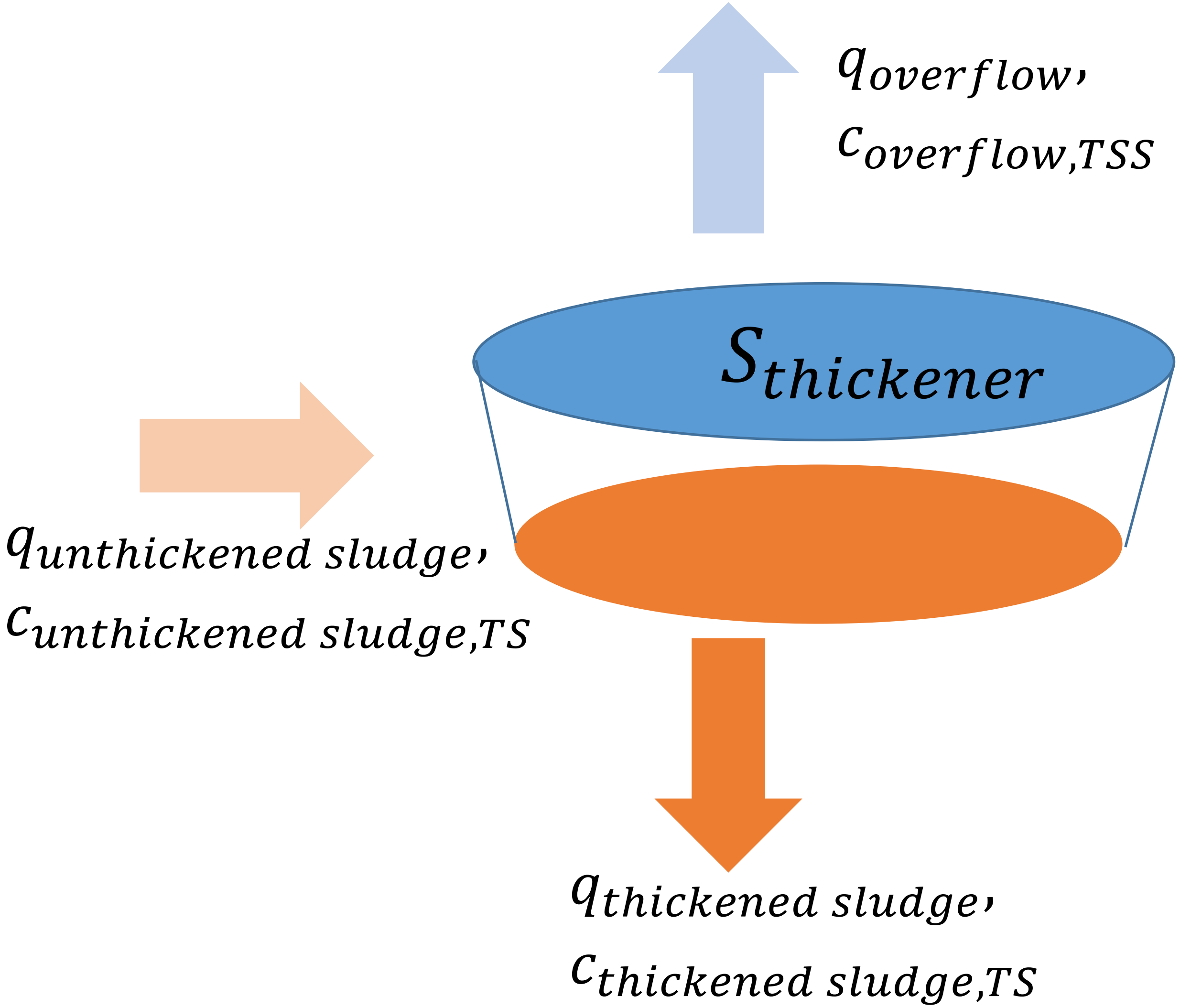
$$= \frac{q_{unthickened\ sludge} \cdot c_{unthickened\ sludge}}{S_{thickener}}$$

$$= \frac{m^3/d \cdot kgTS/m^3}{m^2} = \frac{kgTS/d}{m^2}$$

- overflow rate:

$$= \frac{q_{overflow}}{S_{thickener}}$$

$$= \frac{m^3/d}{m^2} = \frac{m}{d}$$



Typical design parameters for gravity thickening

sludge sedimentation characteristics	sludge type	solids loading rate	maximum hydraulic overflow	solids concentration, % TS [kg TS/kg]	
		[kg TS/m^2·d]	[m^3/m^2·d]	unthickened	thickened
bad	waste activated sludge	20 -50	4 - 8	0.5 – 1.5	2 – 3
intermediate	primary and waste activated sludge digested sludge	40 – 80	6 - 12	0.5 – 4	2 - 7
good	primary sludge	up to 100	15 – 31	1 – 6	3 - 10

Gravity thickener overloaded

- What would you suggest if your gravity thickener is overloaded (too high loading rate and overflow rate) ?

A) I would try to extract more concentrated sludge from the primary or secondary clarifier

B) I would try to extract more diluted sludge from the primary or secondary clarifier

C) I would decrease the sludge extraction from the gravity thickener

D) I would increase the sludge extraction from the gravity thickener

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Gravity thickening

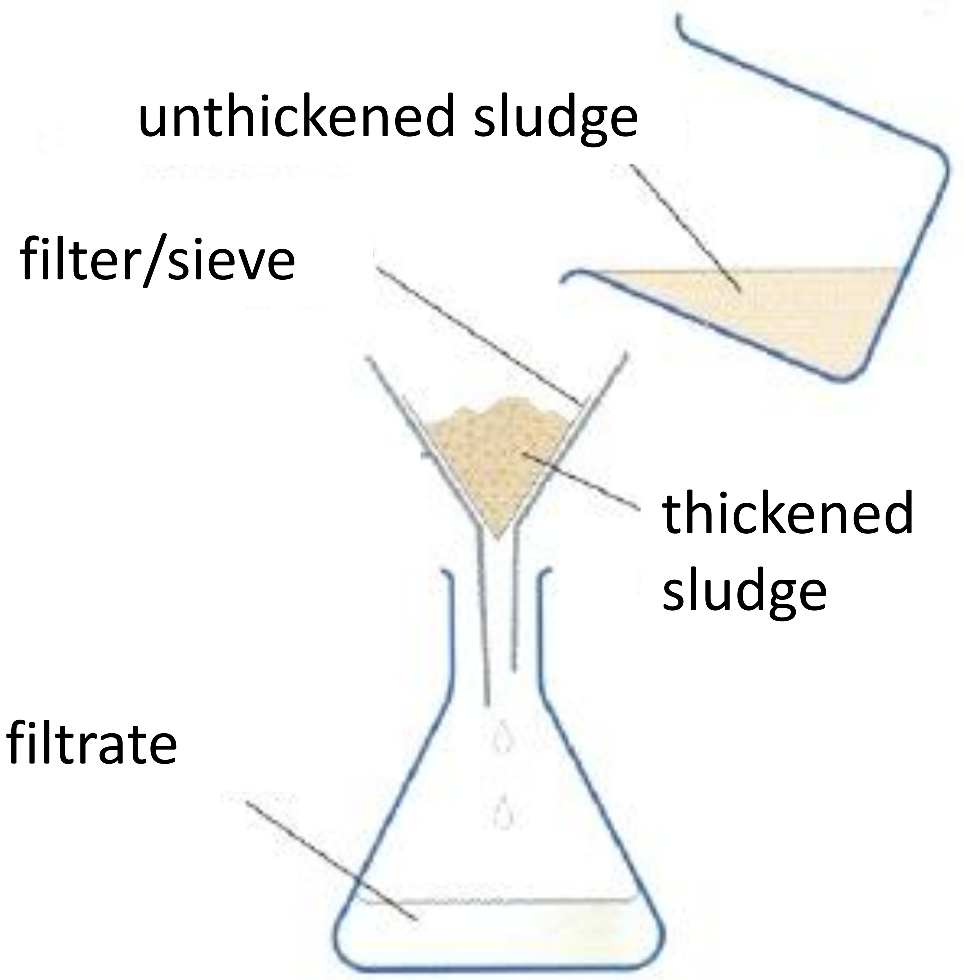
- process not very stable and reproducible (important variations in final dry solid content → very rarely used in Switzerland but still common abroad)
  - heat fluxes and digestion can occur, these processes may disturb good settling
    - retention time of unstabilised sludge should be below 1.5 days
    - occasional chlorine addition
    - addition of dilution water (maintain aerobic conditions)

➡ conduct pilot-testing if possible to determine design criteria

➡ mechanical sludge thickening is a more stable and reproducible process

Mechanical thickening using natural gravity force

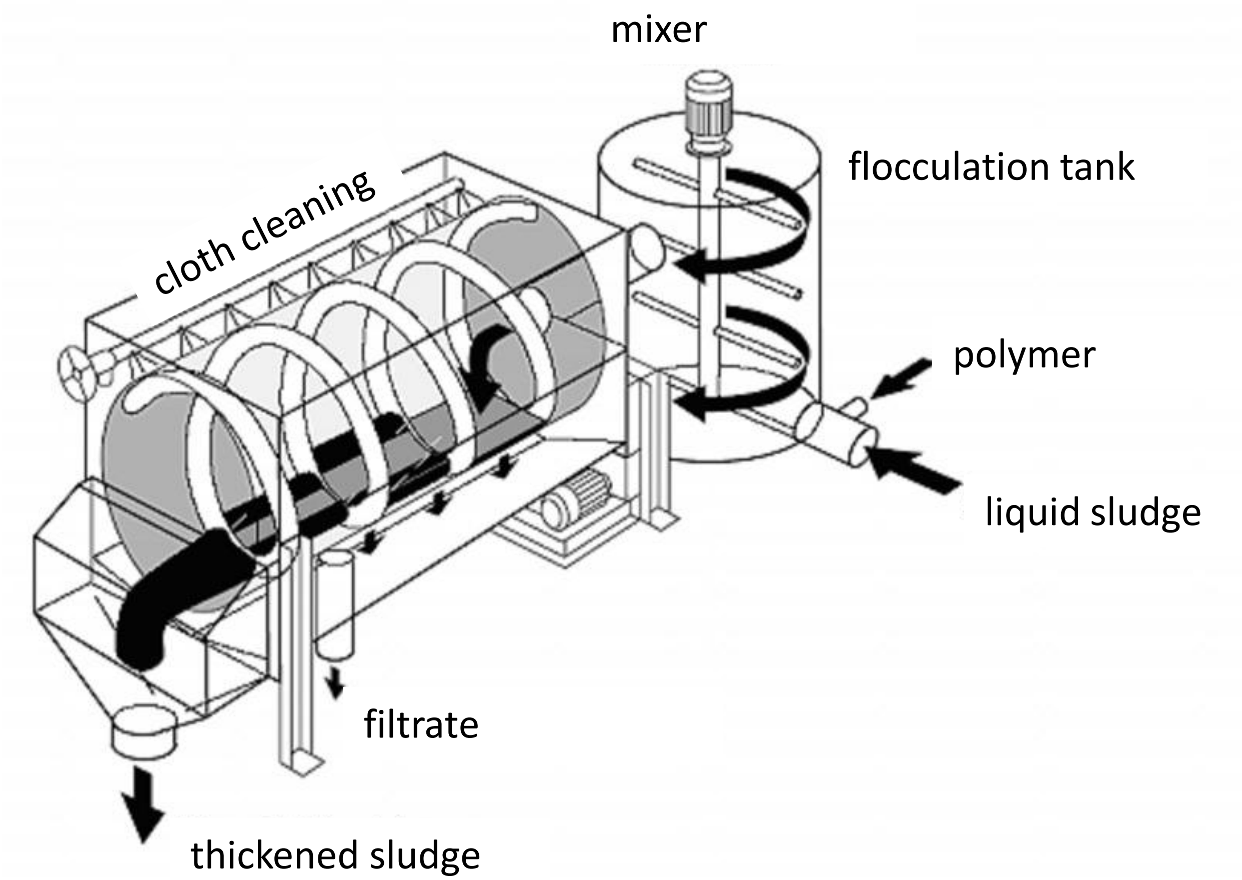
- physical separation of sludge and water by filtering/sieving
- natural gravity forces used for thickening
- several types of equipemnts based on same principles
- addition of polymers required to produce sludge flocks



Mechanical thickening using natural gravity force

rotary drum thickening

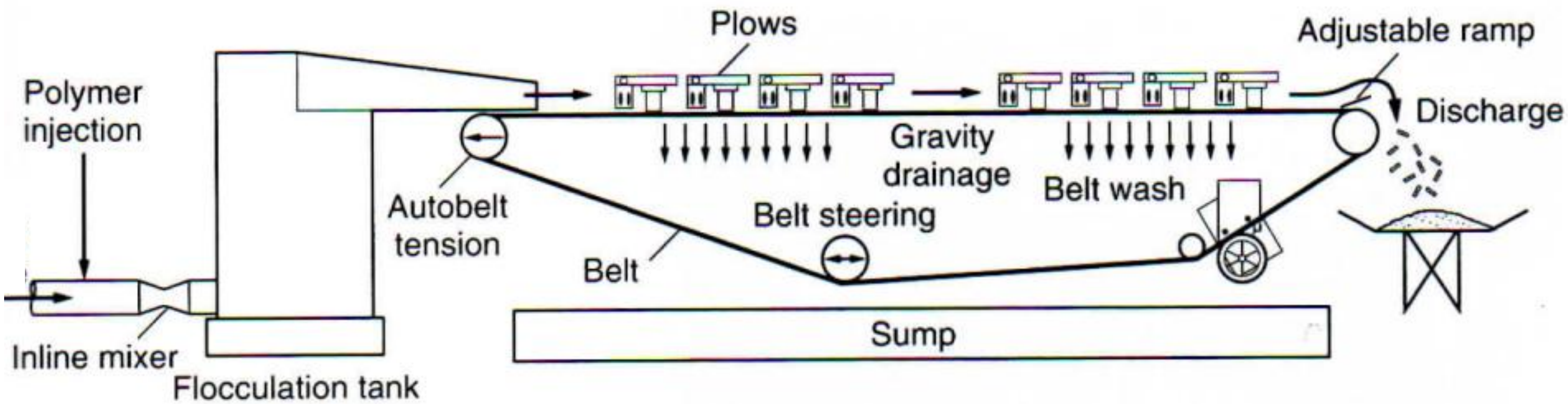
- cloth/screen retains sludge but allows water to pass (filtrate)
- rotation of drum moves sludge forward
- rotation of drum mixes sludge and improves thickening (water removal)
- cloth clogging is prevented by spraying water on it



Mechanical thickening using natural gravity force

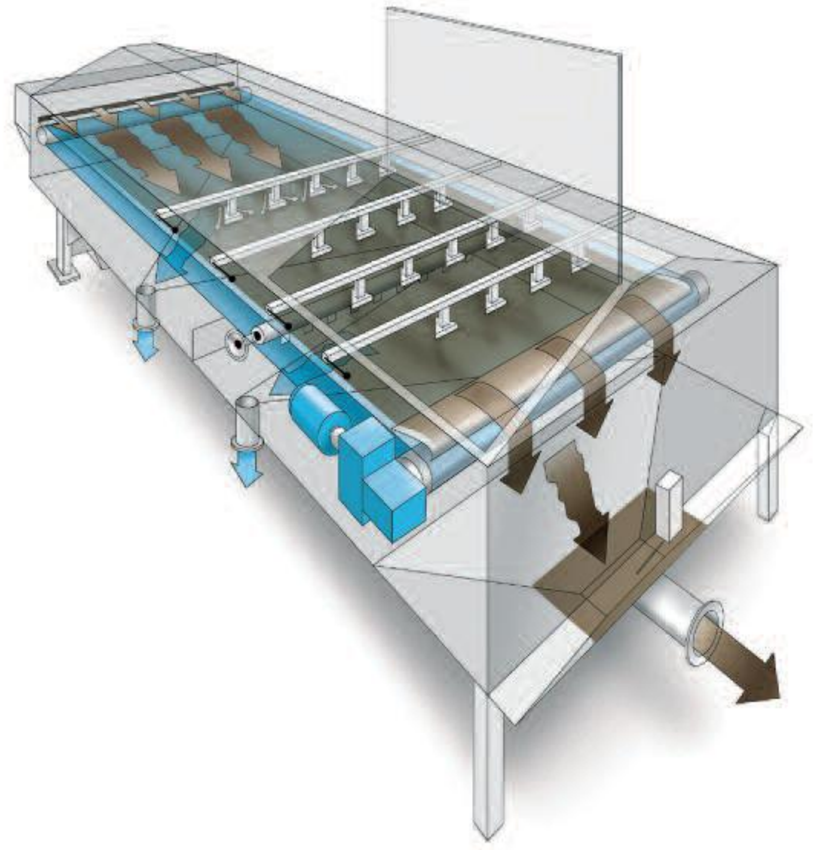
gravity-belt thickening

- belt retains sludge but allows water to pass through
- 'fixed' plows move sludge around to improve the thickening process
- belt is washed in the lower part



Mechanical thickening using natural gravity force

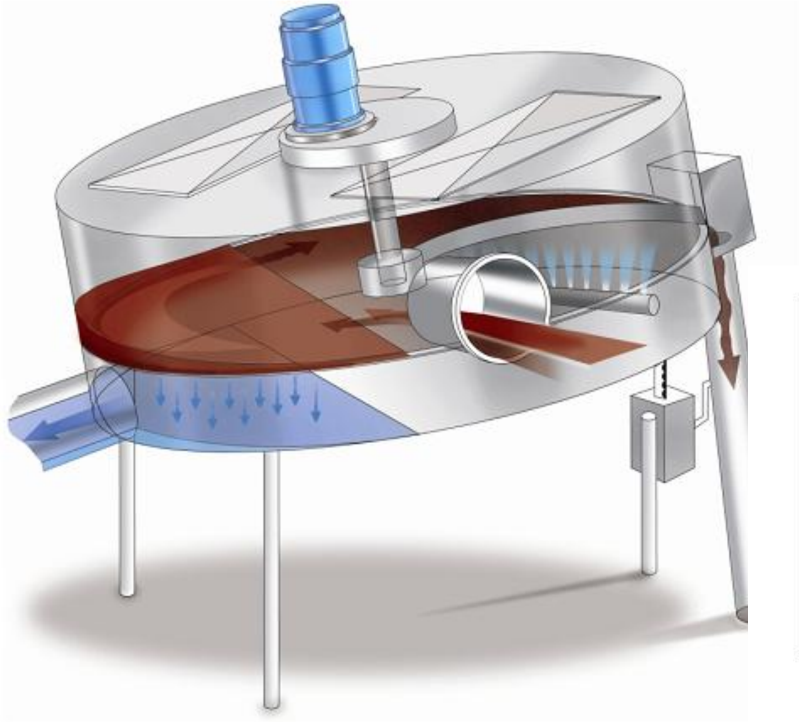
- hydraulic loading rates for gravity-belt thickeners (influent sludge at 0.5 – 1 %)



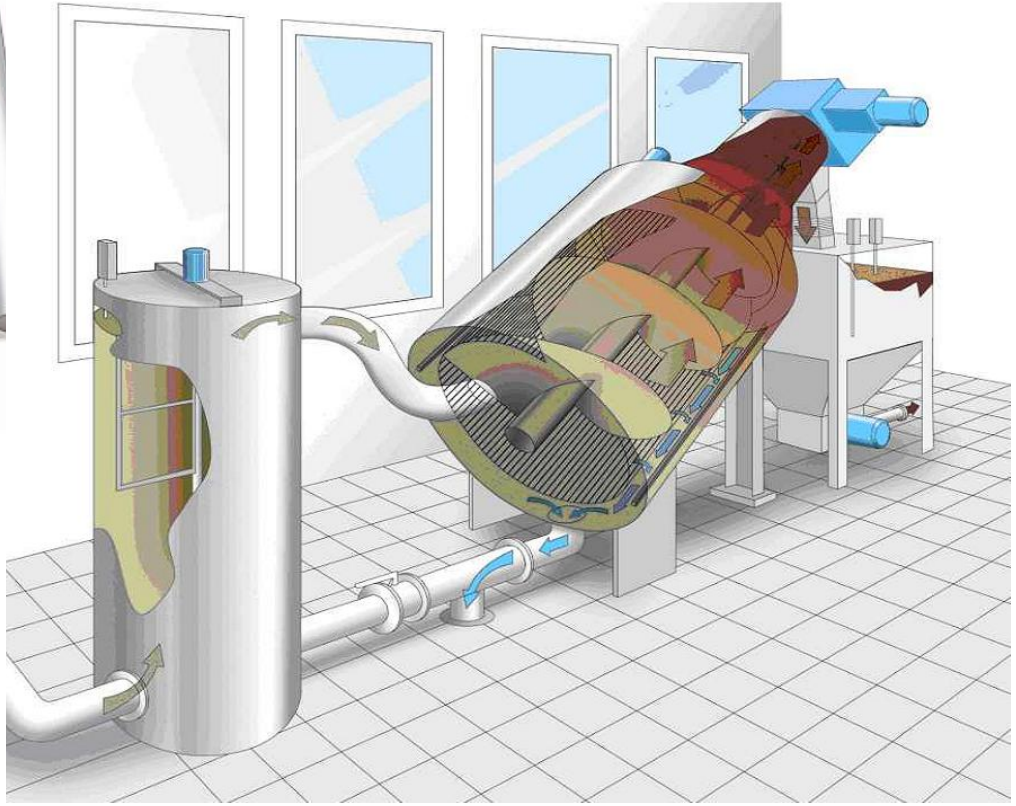
belt size (effective dewatering width)	hydraulic loading range
[m]	[l/s]
1.0	6.7 – 16
1.5	9.6 – 24
2.0	12.7 – 32
3.0	18 - 47

Mechanical thickening using natural gravity force

- disc thickener

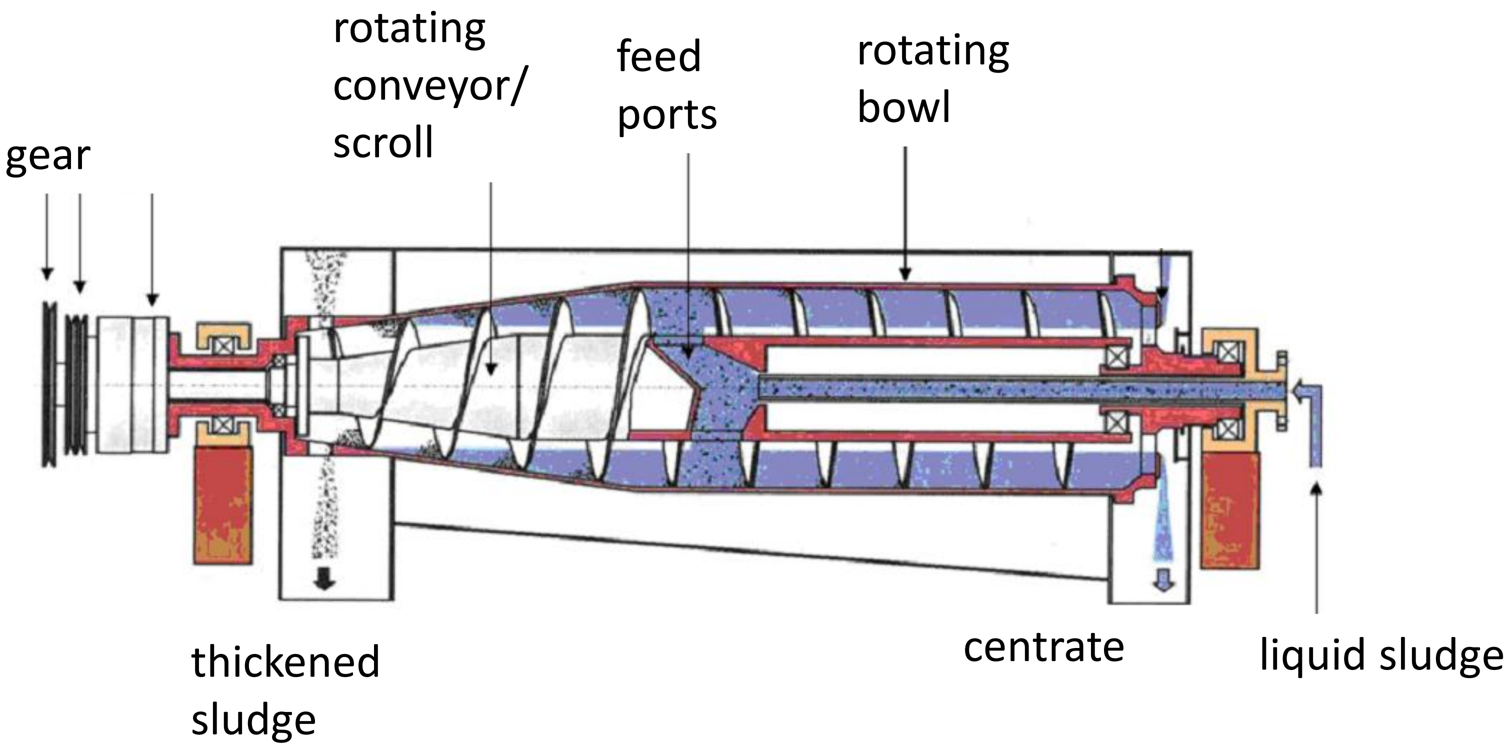


- screw thickener



Centrifugal thickening (artificial gravity force)

- centrifugal thickening creates an artificial gravity field to separate sludge and water more efficiently
- solids concentrate on the periphery due to rotation of bowl
- a helical scroll (rotation at different speed) moves accumulated sludge toward tapered end (cone)
- additional solids thickening in the cone

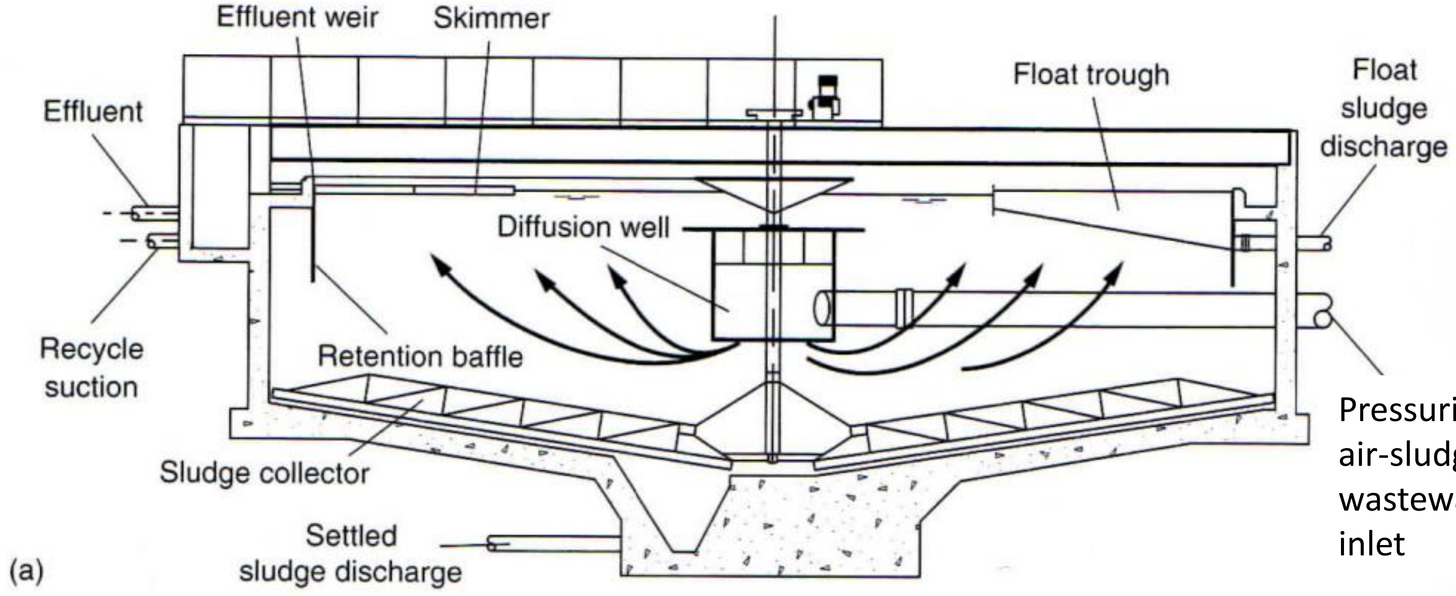


Centrifugal thickening (artificial gravity force)

- polymers may be employed but are not needed for thickening
- maintenance and revision investments are generally high
- power costs may be substantial
- only employed in larger facilities
  - limited space requirements
  - skilled operators available
- centrifuges can be used to thicken and dewater sludge at the same time

Flotation thickening

- air introduced to sludge under elevated pressure before entering flotation unit
- fine air bubbles form when solution is depressurised (once in flotation unit) and move sludge to the top
- sludge is removed at the surface (skimmer) and at the bottom (sludge collector)



Pressurised air-sludge or wastewater inlet

Flotation thickening

- smaller than gravity thickeners (higher surface loading rates)
- capture rate improved when using polymer (from 85 to 98 or 99 %)

type of sludge	surface loading rate [kg/m²·h]	
	without chemicals	with polymers
mixed liquor (no clarification) waste activated sludge	1.2 – 3	up to 10
settled waste activated sludge	2.4 – 4	up to 10
primary and waste activated sludge	3 – 6	up to 10
primary sludge only	4 – 4	up to 12

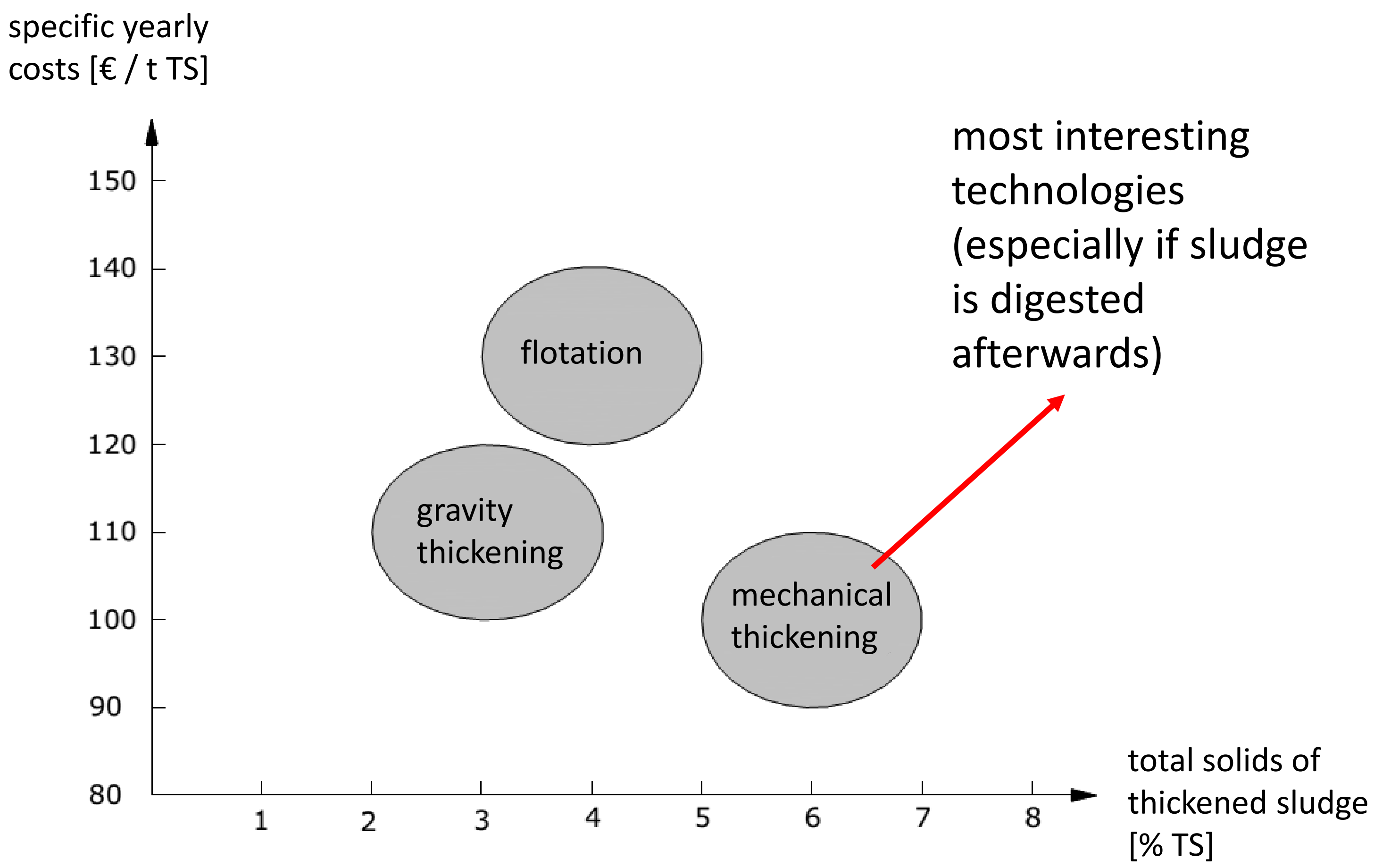
Summary of sludge thickening

		gravity thickening		flotation	mechanical thickening	
		without polymers	with polymers		using natural gravity force	centrifuge
primary sludge	% TS [kg TS/kg]	5 – 10	-			
mixed sludge	% TS [kg TS/kg]	4 – 6	5 – 8		5 – 8	5 – 8
waste activated sludge	% TS [kg TS/kg]	2 – 3	3 – 4	3 – 5	5 – 7	5 – 8
polymer use	kg/t TS	0	0.5 – 3	0	3 – 7	0 – 1.5
specific energy use	kWh/m^3	< 0.1	< 0.1	0.6 – 1.2	< 0.2	1 – 1.4
specific energy use	kWh/t TS	< 20	< 20	100 – 140	< 30	180 – 220

- flotation and centrifugal thickening consume substantially more energy than other thickening methods
- capture rates 85 – 92 % without polymer use and 92 – 96 % with polymer use
- solids content of approximately 6 % are ideal for digestion
- density of thickened sludge (6 %) ≈ 1

Economical comparison

- costs calculated (DWA) for waste activated sludge thickening for a wastewater treatment plant with 100’000 population equivalents (PE)
- cost of further treatment (e.g. digestion) or transport were taken into account for comparison



Treatment of wastewater solids III: sludge stabilisation

Applied wastewater engineering

Michael Jon MATTLE

Sludge stabilisation

- eliminate offensive odours
- inhibit, reduce, or eliminate the potential for putrefaction
- reduce quantity of sludge to evacuate
- reduce pathogens content
- produce energy (digestion)

→ reduction of organic fraction (TVS)
  - transformation of organic fraction often produces bad odours (particularly under anaerobic conditions)
- production of biosolids that can further be used according to legislation
- the objective of sludge stabilisation is not volume reduction

Sludge stabilisation

process	description	advantages/disadvantages
anaerobic digestion	biological conversion of organic matter by fermentation in a (heated) reactor to produce methane gas and carbon dioxide	+ methane can be used to generate heat and/or electricity - requires skilled personnel
aerobic digestion	biological conversion of organic matter in the presence of air (oxygen)	+ simpler to operate than anaerobic digestion - energy-intensive process
composting	biological conversion of solid organic matter in an enclosed reactor or in piles (mostly aerobic conditions)	- addition of bulking agent to provide an environment suitable for biological activity - volume increase of compost as compared to sludge
alkaline stabilisation	addition of an alkaline material, usually lime, to achieve a high pH level to inactivate microorganisms (e.g. pathogens)	+ soil like product is produced + low pathogens content - product mass is increased

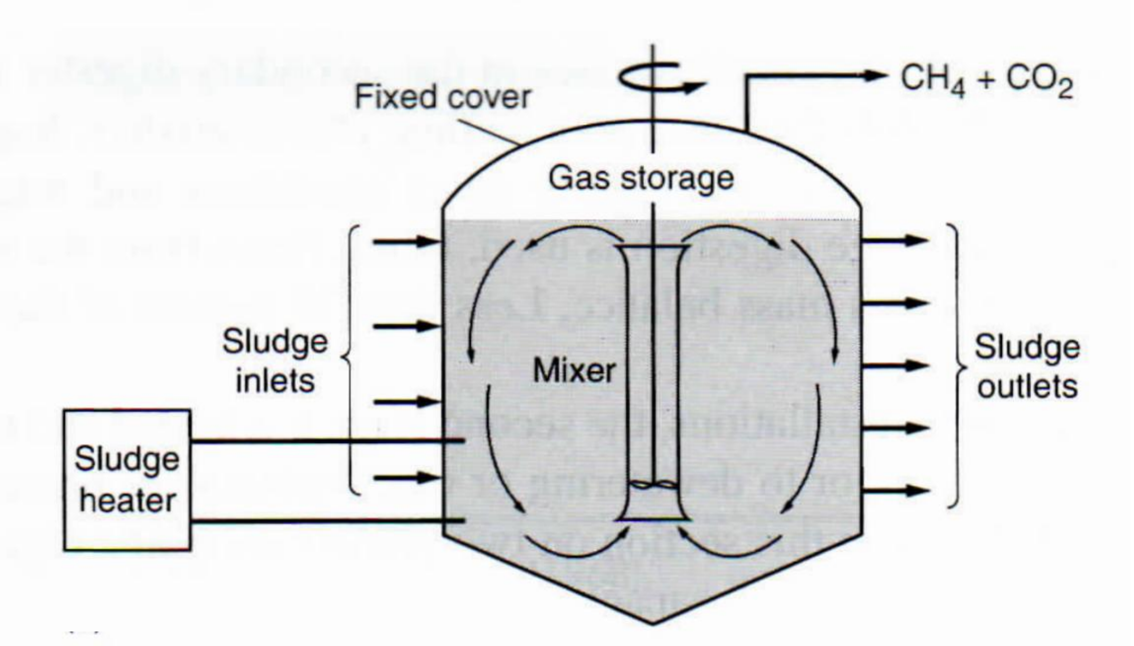
Sludge stabilisation

process	degree of attenuation		
	pathogens	putrefaction	odour potential
anaerobic digestion	fair	good	good
advanced anaerobic digestion (higher temperatures)	excellent	good	good
aerobic digestion	fair	good	good
alkaline stabilisation	good	fair	fair
composting	good	good	fair to good

- further use of sludge dictates the requirements of sludge stabilisation
- if sludge is reused (e.g. land application), pathogens have to be removed to a certain level (according to law and use)
- for easy sludge storage, putrefaction and odour potential should be low
- stabilised sludge is often called biosolid

Anaerobic digestion

- "Biological stabilisation process operated in the absence of oxygen in which biodegradable matter in primary and secondary sludge is converted to methane (CH_4), carbon dioxide (CO_2) and other end-products."
- process provides less energy to bacteria than oxidation processes (low free energy change under anaerobic conditions)
  - low biomass yields
  - high sludge age and elevated temperatures required to sustain anaerobic bacteria in reactor



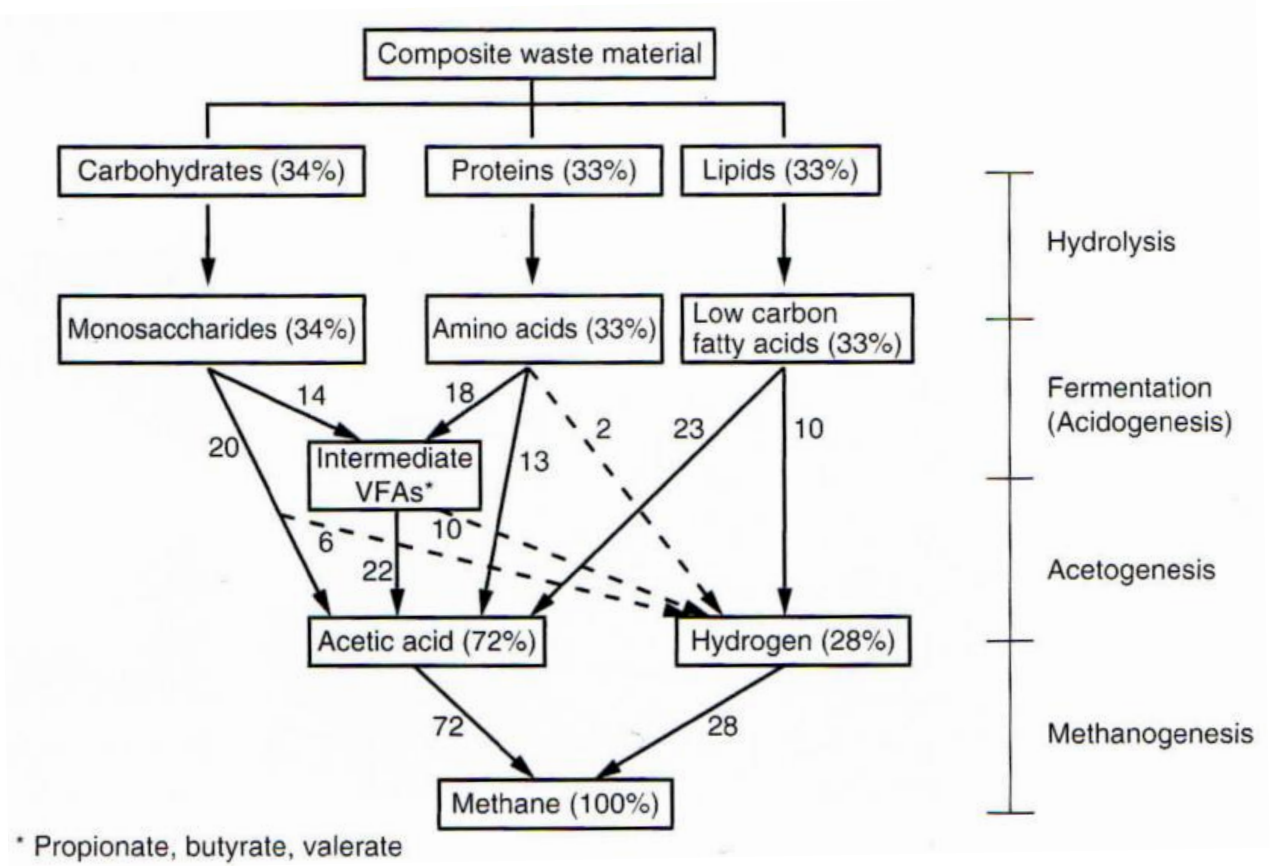
Anaerobic digestion

Onça wastewater treatment plant in Belo Horizonte, Brazil

- psychrophilic fermentation (below 30 °C)
- mesophilic fermentation (30 – 40 °C)
  - more than 90 % of primary and secondary sludge is digested mesophilically in Switzerland
- thermophilic fermentation (50 – 60°C)
  - higher pathogen inactivation
  - difficult to operate and high requirements on concrete
- mesophilic and thermophilic fermentation used to treat organic wastes
- psychrophilic/mesophilic fermentation also used to pre-treat communal wastewater in warm climates or industrial wastewater (higher concentrations of organic material, sometimes higher water temperatures)
- psychrophilic fermentation is used in certain older wastewater treatment plants in Switzerland

Anaerobic digestion

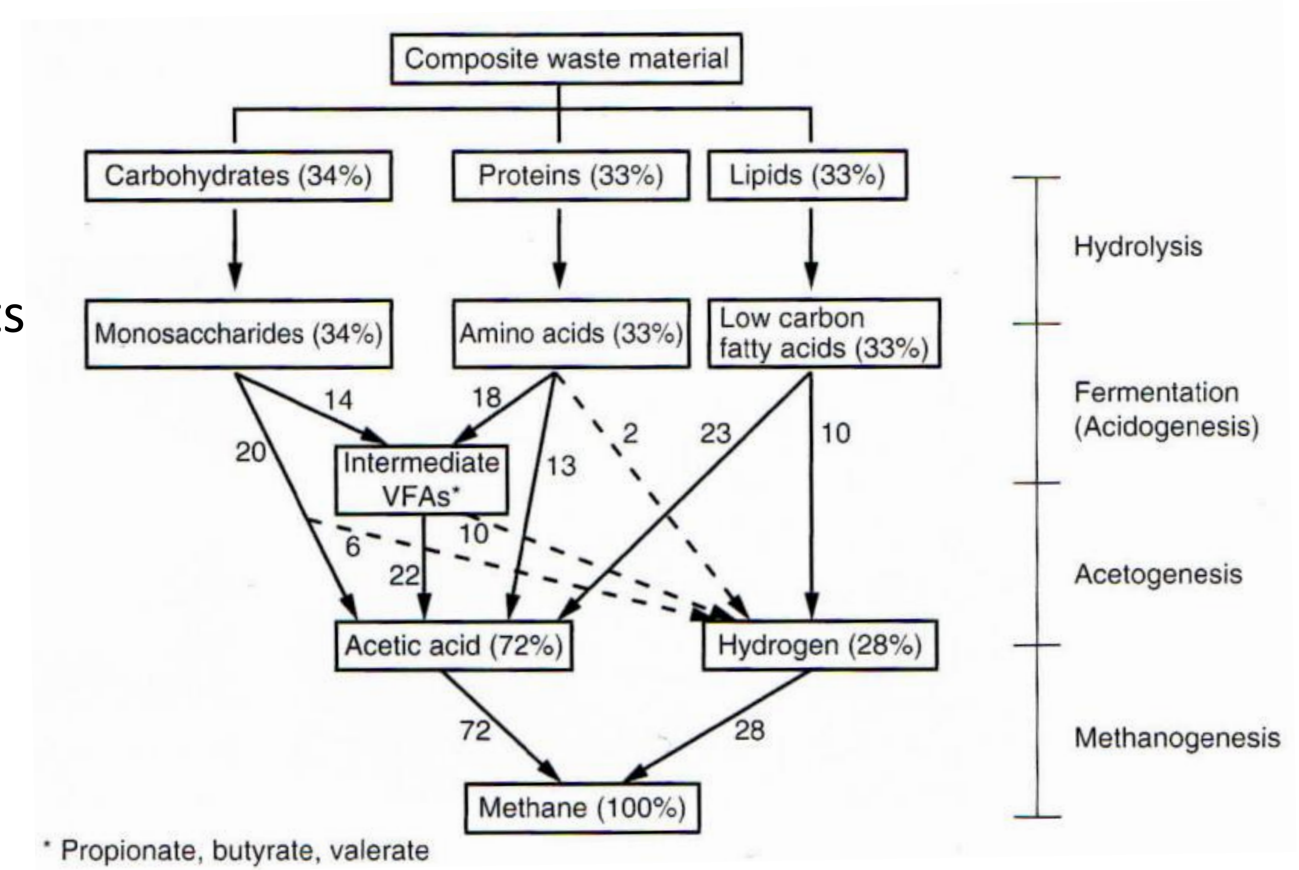
- anaerobic digestion includes several stages:
  - hydrolysis
  - fermentation (acidogenesis)
  - acetogenesis
  - methanogenesis



- hydrolysis
  - particulate material converted to soluble compounds and monomers (amino acids, monosaccharides and fatty acids)
  - performed by extracellular enzymes
  - often limiting step

Anaerobic digestion

- fermentation (acidogenesis)
  - bacteria produce volatile fatty acids (VFAs), CO_2 and hydrogen (H_2)
  - pH reduction
- Acetogenesis
  - bacteria convert intermediate products (intermediate VFAs) to acetate
- Methanogenesis
  - production of methane from acetate (or formate/methanol)
  - production of methane from CO_2 and H_2
  - acidity reduction
- Gas produced in sludge digesters generally contains about 65 % of methane and 35 % of CO_2



Anaerobic digestion (other reactions)

- sulphate reducing organisms

gas

$$SO_4^{2-} + CH_3COO^- + H^+ \rightarrow H_2S + 2HCO_3^-$$
$$2HCO_3^- + 2H^+ \rightarrow 2CO_2 + 2H_2O$$

  - sulphide (S^{2-}) is toxic to methanogenic bacteria at elevated concentrations
  - iron can be used to precipitate sulphites

$$Fe(II) + H_2S \rightarrow \text{FeS} + 2H^+$$

precipitate

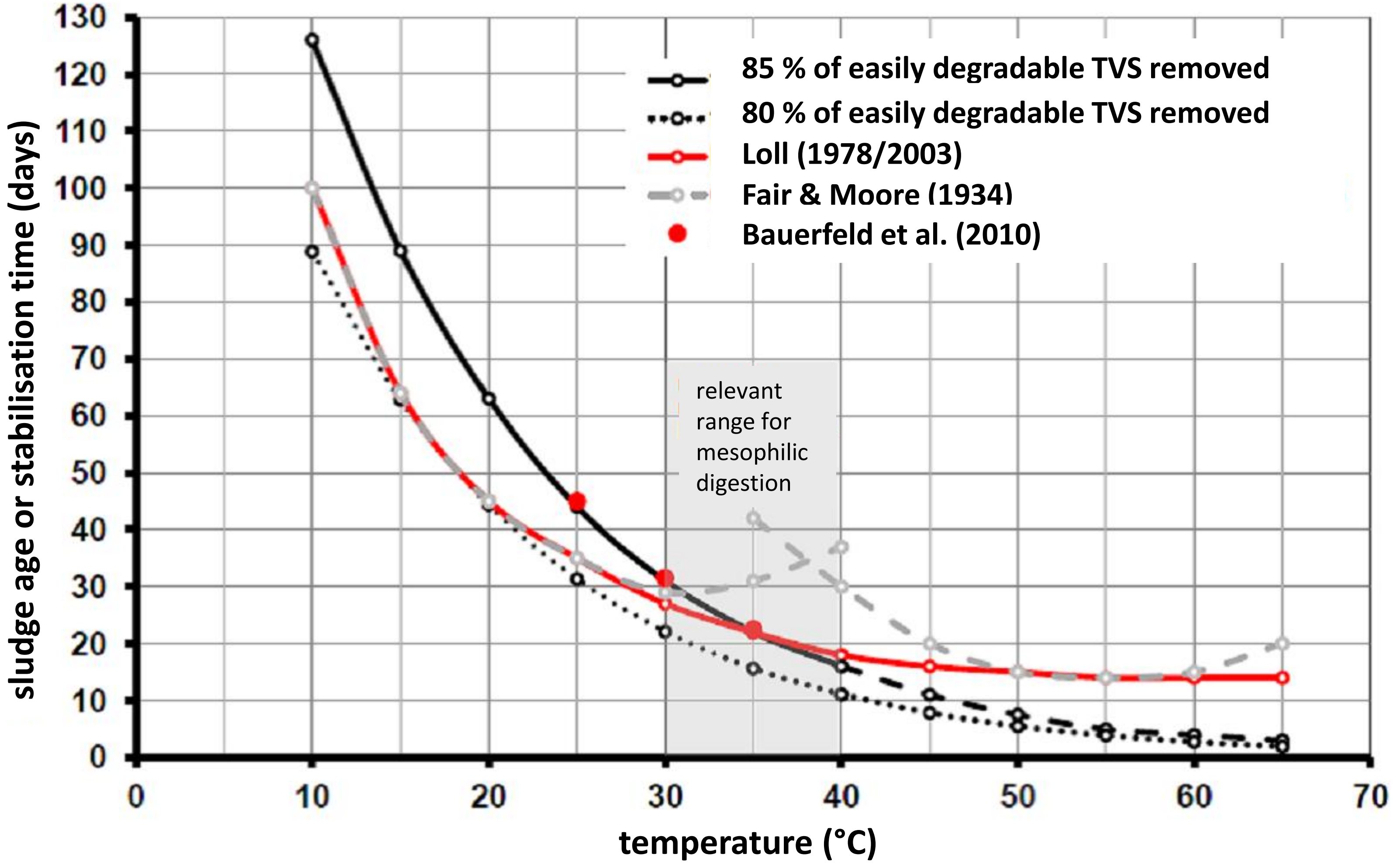
- nitrogen contained in organic matter (e.g. methylamine degradation)

$$4(CH_3)_3N + H_2O + 4H^+ \rightarrow 9CH_4 + 3CO_2 + 6H_2O + 4NH_4^+$$

  - ammonium returns to the wastewater (centrate after dewatering of digested sludge) and increases the influent N-loading rate by up to 10 – 20 %
  - centrate containing high ammonium concentration may be treated separately in large treatment plants (e.g. anaerobic ammonium oxidation (Anammox))

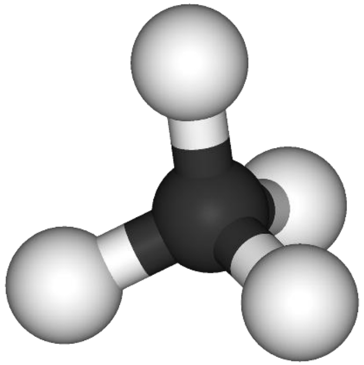
Anaerobic digestion

- increased temperatures reduce required sludge age
- temperatures above 40°C have little impact on required sludge age
- mesophilic range is most commonly used (requires heating)
- relatively high sludge age necessary to obtain a stable operation
- about 70 % of primary sludge total volatile solids (TVS) and 45 % of secondary sludge TVS are easily degradable



anaerobic sludge age required for single-staged digester using mixed sludge

Biogas production



- about 0.95 Nm^3 per kg of TVS removed for primary sludge
- about 0.85 Nm^3 per kg of TVS removed for waste activated sludge
- about 20 Nlitres (normal litres) per population equivalent (PE) and per day
- COD balance can also be used to compute methane produced

$$influent\ COD = effluent\ COD + COD\ of\ methane$$

- 1 mole of methane consumes two moles of oxygen

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

- how much gas (L) is produced if 1 g of COD is transformed in an anaerobic digestor?
  - under standard conditions (0°C and 1 atm) 1 mole of methane occupies 22.4 L

Biogaz production

- how much gas (L) is produced if 1 g of COD is consumed?

A) 0.05 L

B) 0.5 L

C) 5.0 L

D) 50 L

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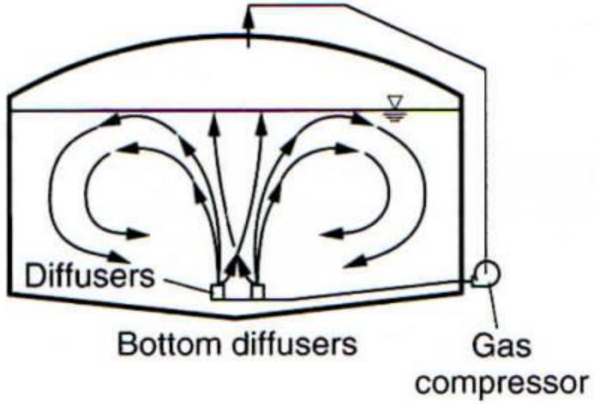
Design parameters for anaerobic digesters

Size of wastewater treatment plant		< 50'000 PE	50'000 – 100'000 PE	> 100'000 PE
sludge age	days	20 – 28	18 – 25	16 – 22
loading factor with easily degradable volatile solids	kg $TVS_{easily\ deg.}/(m^3 \cdot d)$	1.0 – 1.4	1.1 – 1.5	1.2 – 1.7
	kg $COD_{easily\ deg.}/(m^3 \cdot d)$	1.7 – 2.3	1.8 – 2.6	2.1 – 2.9

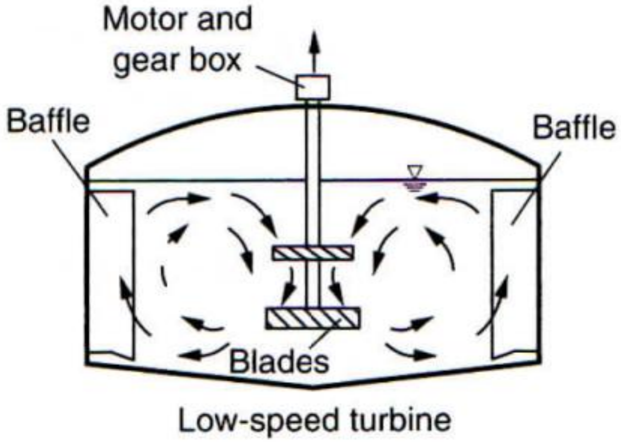
- larger plants have less fluctuations in sludge production
  - they can be designed with lower sludge ages
- the higher the sludge age, the higher the gas production
  - but also the higher the investment, heating (especially in winter) and maintenance cost

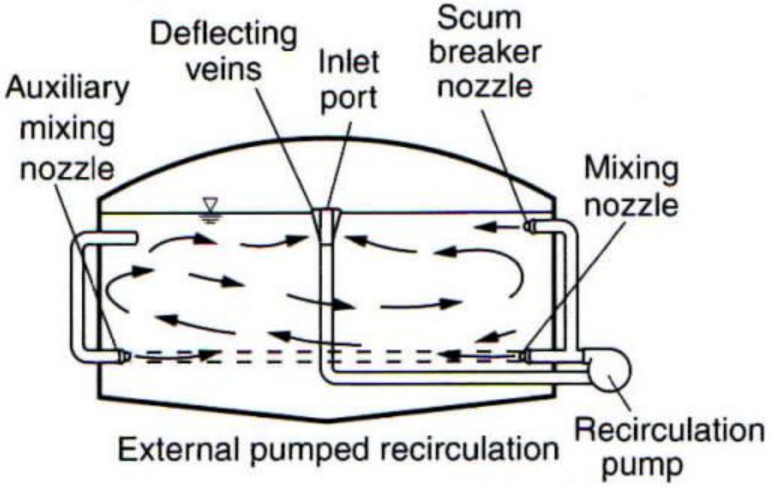
Mixing of digesters

- digesters have to be mixed to:
  - avoid concentration and temperature gradients
  - avoid short circuiting
  - avoid sedimentation and dead areas
  - enhance degassing
  - avoid floating sludge (e.g. grease)



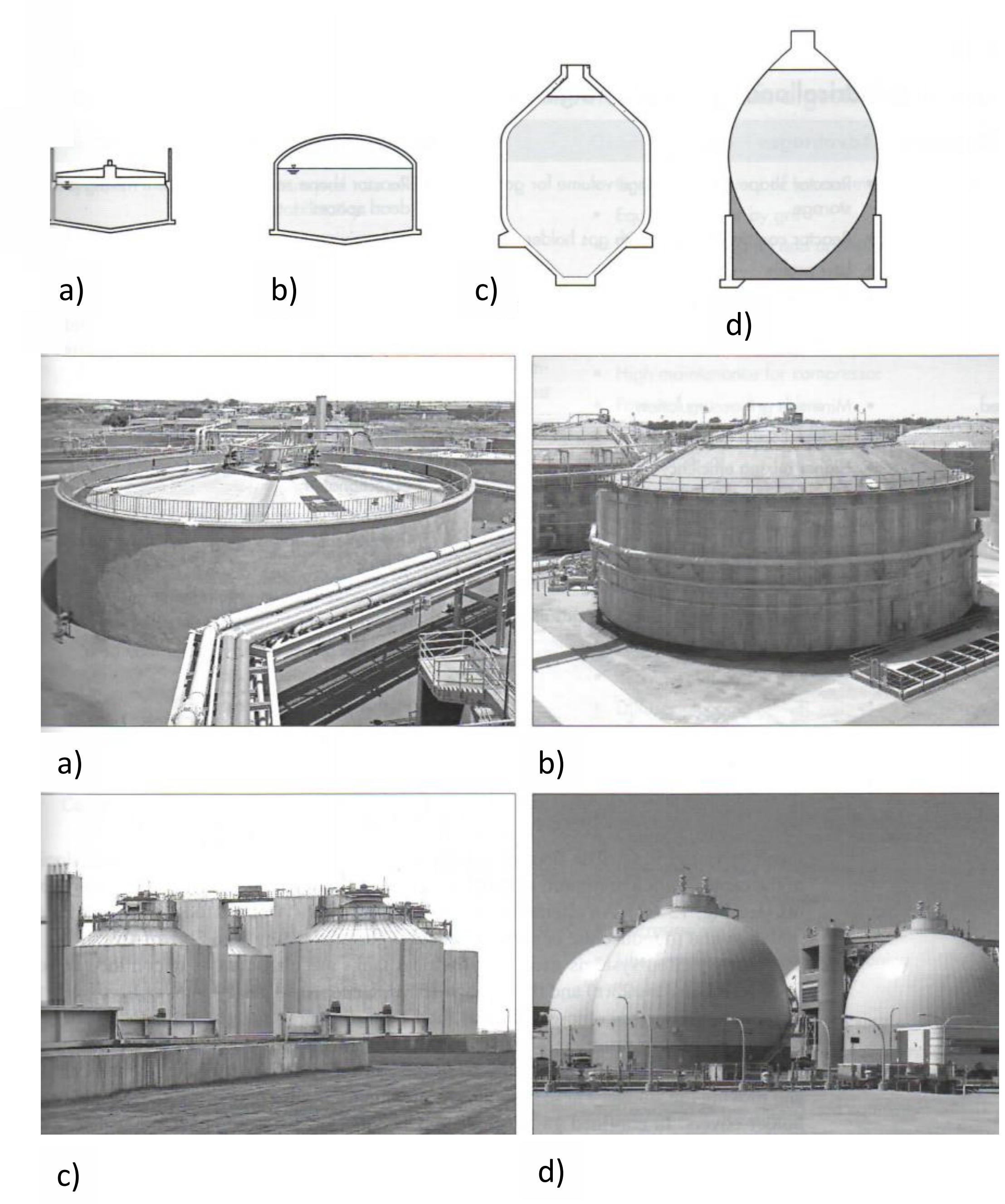
- ways of mixing digesters
  - mechanical stirring
  - gas injection (higher energy requirements)
  - mechanical pumping





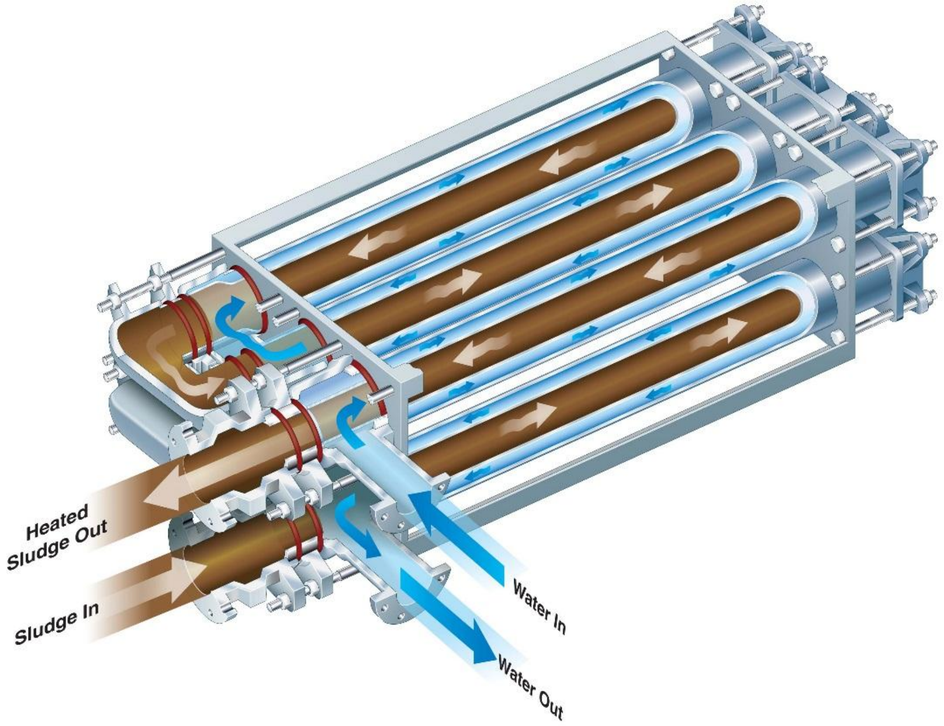
Shapes of digesters

- a) cylindrical with floating cover
  - adaptable for gas storage
  - easier to construct than the German design
- b) cylindrical with fixed cover
  - common design in Switzerland
  - easier to construct than the German design
- c) conventional German design
  - steeper sloped top and bottom cones
  - better mixing
- d) egg-shaped with steel shell
  - easy mixing
  - used in large plants



Heating of digesters

- sludge has to be heated to achieve mesophilic conditions
- good insulation of digester reduces heating requirements
- methane producing bacteria are very sensitive to temperature changes (> 2°C)
  - temperature has to be kept constant (in the short term)
- sludge is heated by external heat exchangers (water temperature below 68°C)
- heat may be produced by a cogeneration unit but a boiler is always required



Gas storage and pre-treatment

- gas production varies during the day and from day to day
  - gas storage required to produce constant gas flow
- gas can be stored in upper part of digester (e.g. floating cover) or in a separate gas tank (larger plants)

- gas contains water when it leaves the digesters (elevated temperature)
  - condensation occurs when gas cools down (equipment of piping system with appropriate traps required)
  - chilling of gas can be used to further reduce water content

- gas also contains H_2S which may corrode pipes and gas use equipment
  - condensation removes part of H_2S
  - additional removal can be obtained by various techniques (e.g. oxidation processes, biological scrubbers, chemical systems, adsorptive resins and activated carbon)

Gas use

- cogeneration is a system that produces electricity and another form of energy (e.g. heat)
- different co-generation systems (internal combustion engines, turbines) have different efficiencies
  - electricity generation: 26 – 42 %
  - heat recovery: 30 – 57 %
  - interesting if heat is really required (during summer?)
- gas can also be sold as natural gas
  - advanced purification often necessary (e.g. CO_2 removal)
  - heat generated only when needed (decoupling of processes)
  - interesting for larger wastewater treatment plants or if no purification is required
- excess gas has to be flared (e.g. cogeneration unit out of service)

Aerobic digestion

- "Biological stabilisation process operated in the presence of oxygen in which the biodegradable matter in primary and secondary sludge is oxidised to carbon dioxide and other end products."
  - either directly in biological tank (extended aeration → higher sludge age in biological tank)
  - or separately in an aerobic digester
- bacteria start to consume 'themselves' as little/no food is available (oxic conditions)

$$C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + 3H_2O + HNO_3$$

production of acid, alkalinity reduction

- under anoxic conditions, nitrate can be used as an oxygen source

$$C_5H_7NO_2 + 4NO_3^- \rightarrow 5CO_2 + 2N_2 + NH_3 + 4OH^-$$

production of base, alkalinity increase

- denitrification can be achieved by cycling the aerobic digester between aeration and mixing (similar to SBR operation)
  - improved pH control of sludge

Aerobic digestion (comparison with anaerobic digestion)

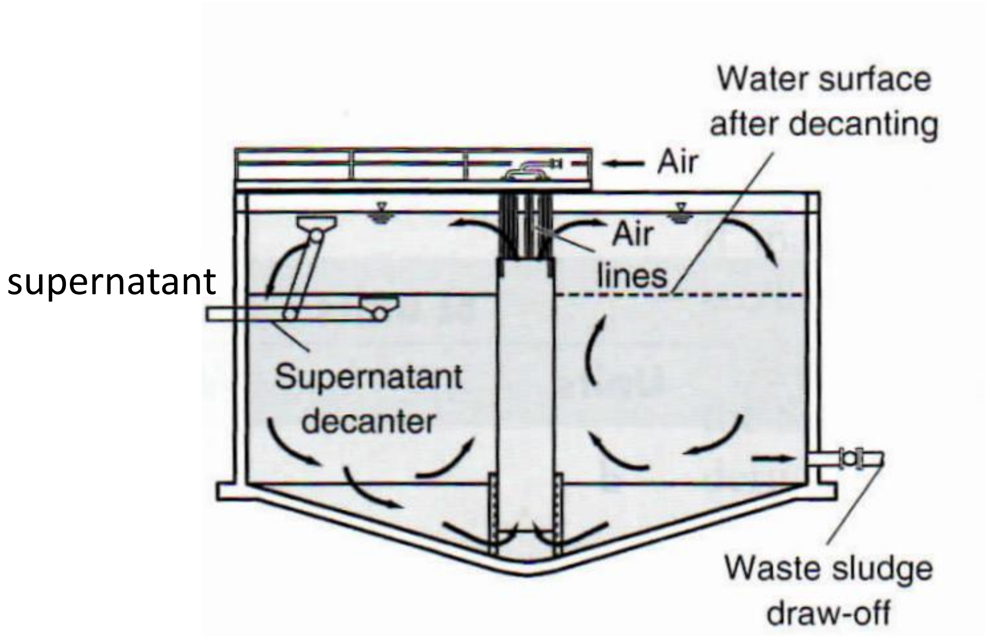
advantages	disadvantages
lower BOD and ammonia concentration in side streams	high power cost due to oxygen requirements
low capital cost for small utilities	does not produce methane gas (energy recovery)
no risk of explosions	aerobically digested biosolids have poorer mechanicals dewatering characteristics (as compared to anaerobically digested solids)
easy to construct and operate	process consumes alkalinity (limited denitrification)

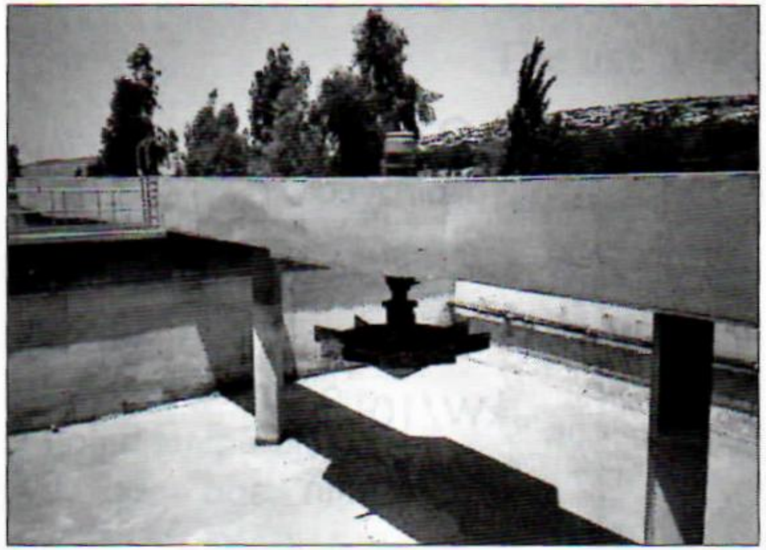
- used in smaller wastewater treatment plants
- used to reduce complexity of treatment (if skilled personal is difficult to find)
- constructed to reduce investment costs

➡ technology unimportant in Switzerland

Design of aerobic digesters

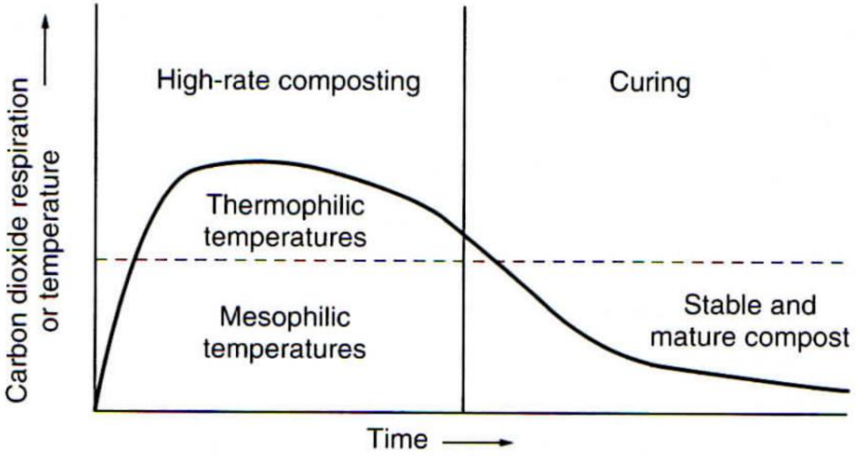
- sludge age ≥ 20 days at temperatures ≥ 10°C
- total solids (TS) between 2 % and 4 % in reactor
- oxygen requirements about ≈ 18 g/(PE·d) at 10°C and ≈ 24 g/(PE·d) at 20°C
- easily removable volatile solids reduction between 45 and 65 %
- reactors can be operated as batch or continuous flow systems



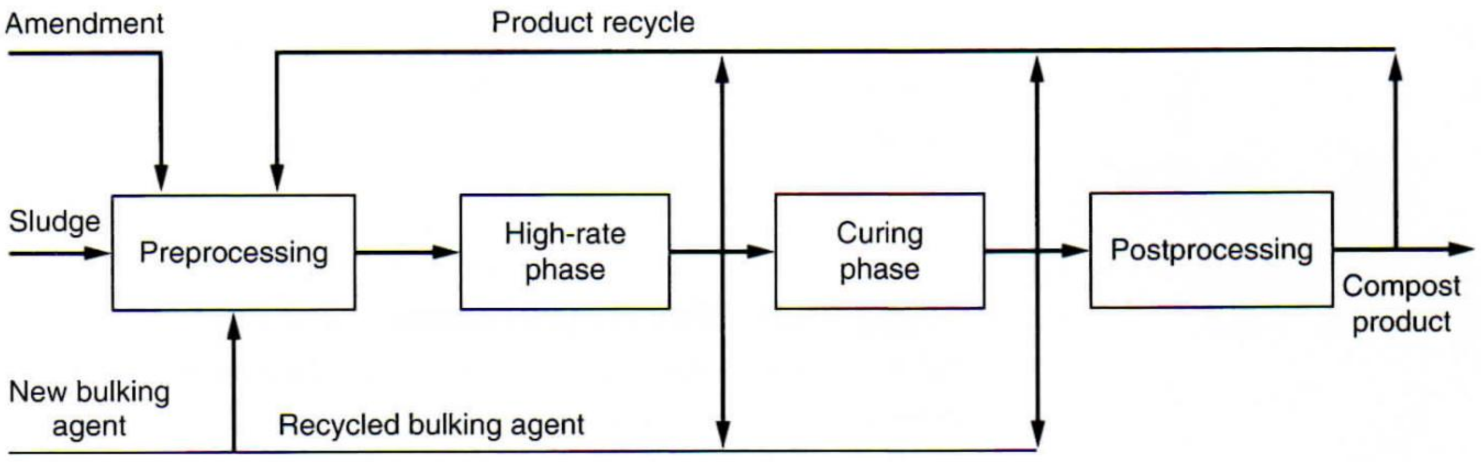


Composting

- "A stabilisation process that relies on the aerobic decomposition of organic matter in sludge and biosolids by bacteria and fungi"
- organic material undergoes biological degradation to a stable end-product
- under mostly aerobic conditions (composting is never completely aerobic)
- decomposition of organic material produces heat
    - compost heats to temperatures in the pasteurisation range of 50 to 70°C
    - pathogenic microorganisms are destroyed
- still largely applied if sludge can used for land application (depending on legislation)



Composting

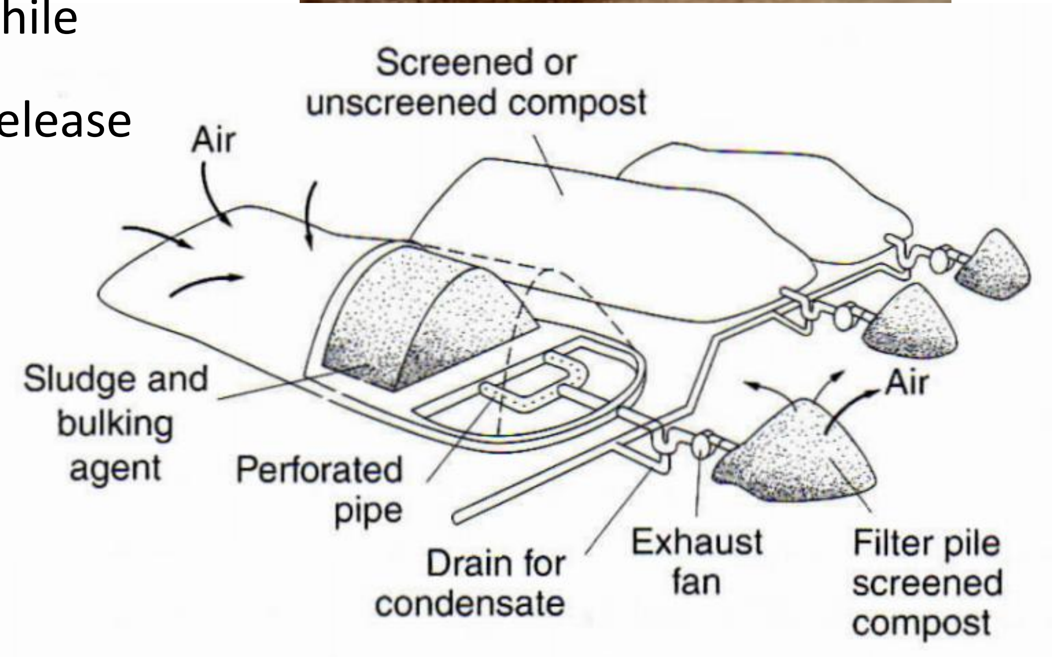


- sludge is dewatered prior to composting and ideally digested (reduced odour production)
- an amendment (an organic material) is added to the substrate to reduce the moisture content, and increase the air voids for proper aeration
  - e.g. sawdust, straw, recycled compost
- a bulking agent is used to provide structural support and to increase porosity of the mixture for effective aeration
  - e.g. wood chips
  - mostly recovered at the end of the process

Composting

- composting period about 21 to 28 days
- curing period 30 days or longer

- two composting systems:
  - windrow system
    - typically 1 to 2 m high and 2 to 4.5 m at the base
    - windrows are turned a minimum of five times while the temperature is maintained at or above 55°C
    - turning the windrows is often accompanied by release of offensive odours (especially when anaerobic conditions occur)
  - aerated static pile
    - grid of aeration piping over which sludge and bulking agent is placed
    - may or may not be covered
    - pile heights about 2 to 2.5 m



Alkaline stabilisation

- use of an alkaline material to render sludge unsuitable for survival of microorganisms
  - increase of pH value to 12 or higher
  - halts or retards microbial reactions
  - sludge will not putrefy or create odours (as long as pH remains at elevated values)
  - high pH values inactivate viruses, bacteria and other pathogenic microorganisms

- e.g. addition of quicklime

$$2CaO + H_2O \rightarrow 2CaOH$$

  - produces heat (exothermic reaction)
  - ‘consumes’ water
  - increases the pH (OH^-)

Alkaline stabilisation

advantages	disadvantages
well proven process	the volume of stabilised sludge is increased by approximately 15 % to 50 % in comparison to other stabilisation techniques
simple technology	potential of odour generation both at processing and end use site
easy to install	nitrogen content in final product is lower due to ammonia volatilisation (less nutrients)
small footprint	resulting product is not suitable for use on all soils (especially high alkaline soils)

- technology employed to reduce investment costs and to keep the process simple
- may be employed with other stabilisation techniques in order to achieve increased stabilisation and disinfection of sludge
- not used in Switzerland for wastewater sludge stabilisation

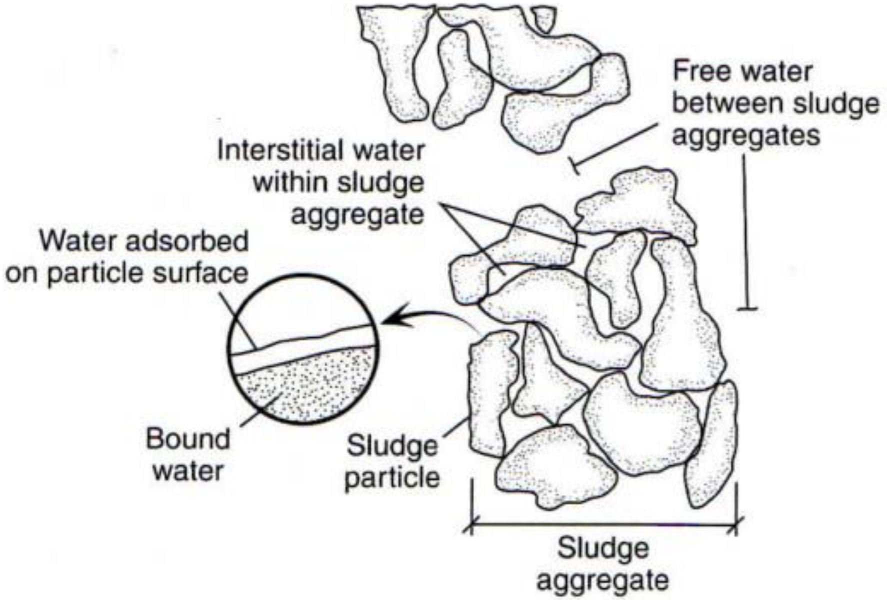
Treatment of wastewater solids IV: dewatering of sludge

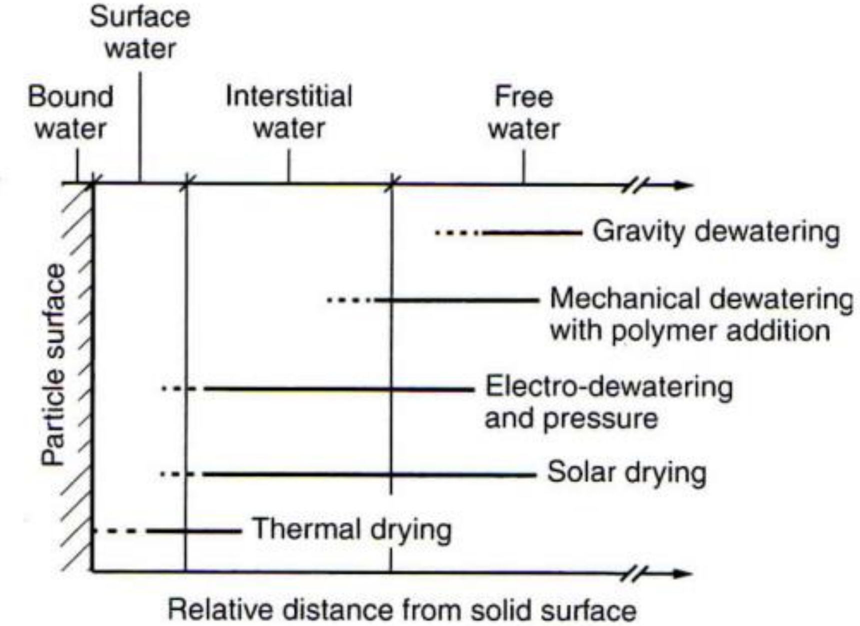
Applied wastewater engineering

Michael Jon MATTLE

Dewatering of sludge

- “A process that removes a portion of water contained in solids. Dewatering is distinguished from thickening in that the resulting dewatered cake may be handled as a solid, not as a liquid.”
  - reduction of transportation costs to final destination of sludge
  - increase in calorific value (incineration)
  - required for composting (reduction of required supplementary bulking agents)
  - reduction of energy needed for drying (dewatering and drying requires less energy than only drying)
  - necessary before landfilling sludge to reduce leachate production at landfill site
  - generally easier to handle than thickened sludge





Dewatering of sludge

- mechanically assisted physical means are used to dewater sludge more quickly (sludge is pressed together)
- certain dewatering applications rely on heat energy and electric energy (not treated in this course)

- for effective solid-liquid separation, chemical conditioning is required
- liquid stream (centrate or filtrate) is typically returned to the wastewater treatment but can also be treated separately
- dewatered cake can be handled as a solid although water content is still around 70 – 80 %

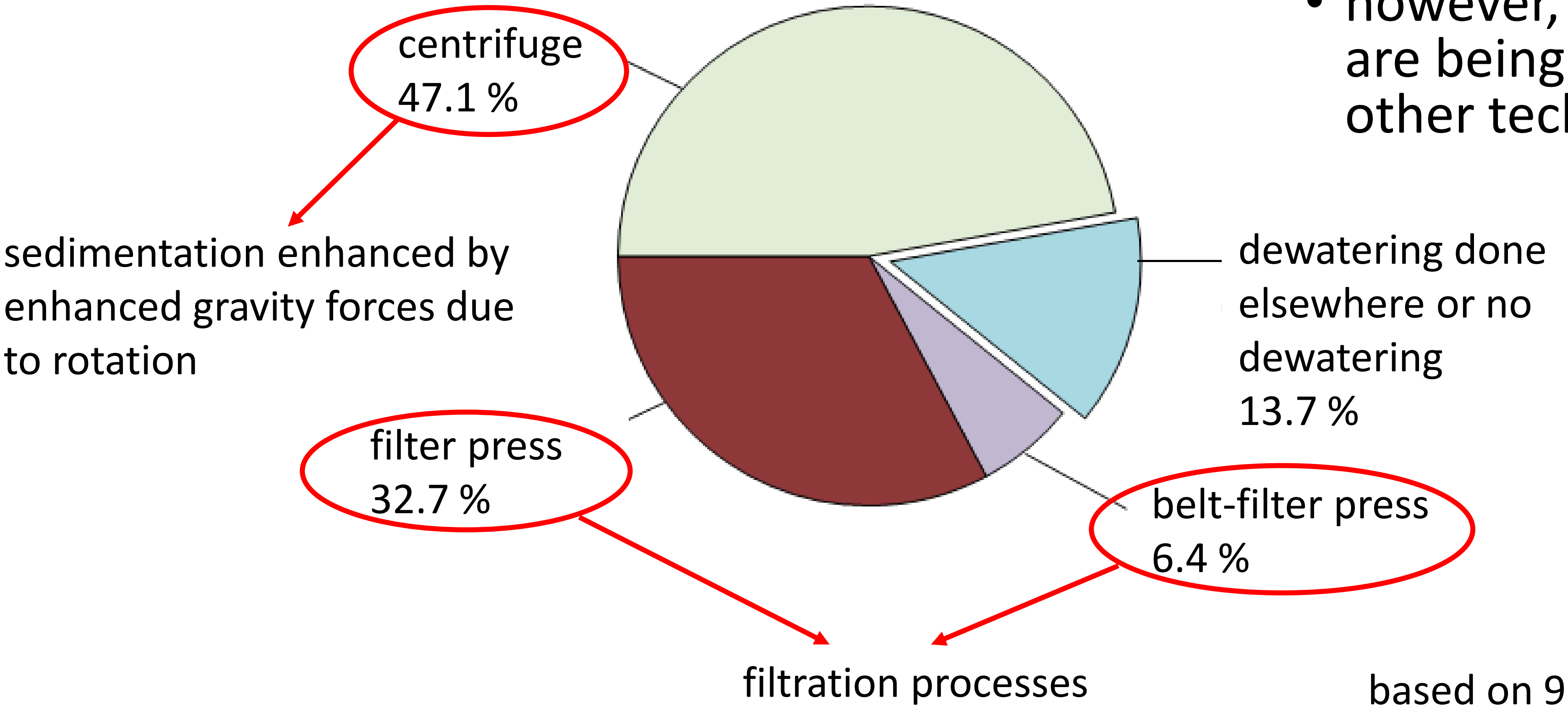
Dewatering of sludge

- dewatering characteristics of sludge depends on many criteria (e.g. sludge origin, composition (primary, waste activated, digested sludge or external sludge), concentration,…

- dewatering is required for the final disposal of sludge:
  - co-incineration and deposition in landfills
  - mono-incineration and deposition in special landfills (future phosphorous-removal)
  - use in agriculture or landscape building
  - direct deposition in landfills

Dewatering of sludge

- in Switzerland screw presses are also quite often used
- however, filter presses are being replaced by other technologies



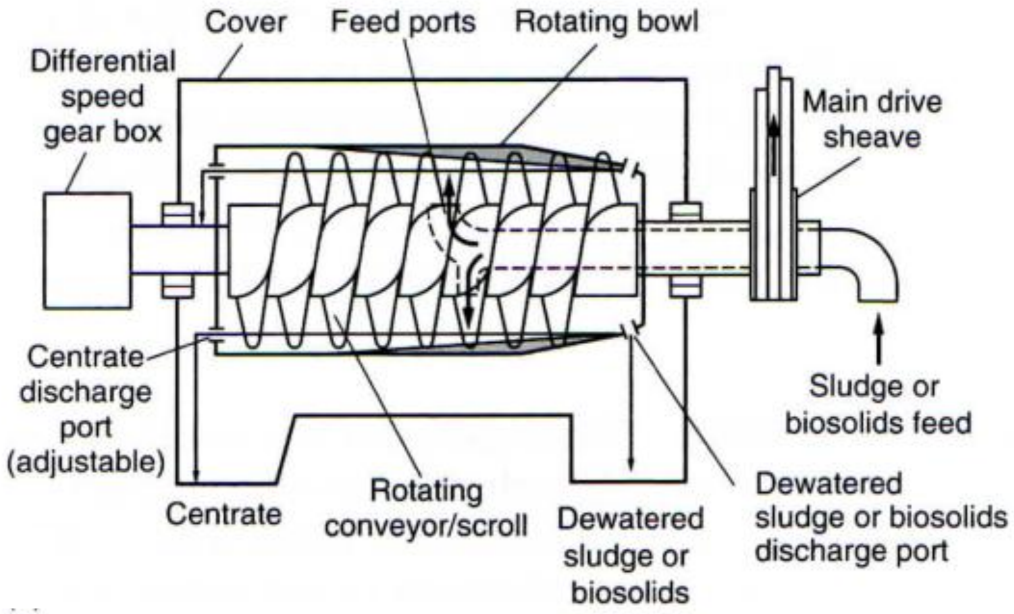
based on 97 million PE

statistical analysis of German dewatering of sludge (2003): fraction of sludge treated related to PE

Centrifuges (dewatering)

- rotation of bowl generates centrifugal forces that sediment the sludge on the outer part of the bowl
  - centrifugal force > 2’800 g (gravity force)
- rotating scroll pushes sludge in direction of the exit
  - rotation is either slightly slower or faster than the bowl rotation
- continuous operation

- optimising the functioning of a centrifuge is complicated and often requires the intervention of an expert
  - technology less ‘ideal’ in areas where such experts are not locally present



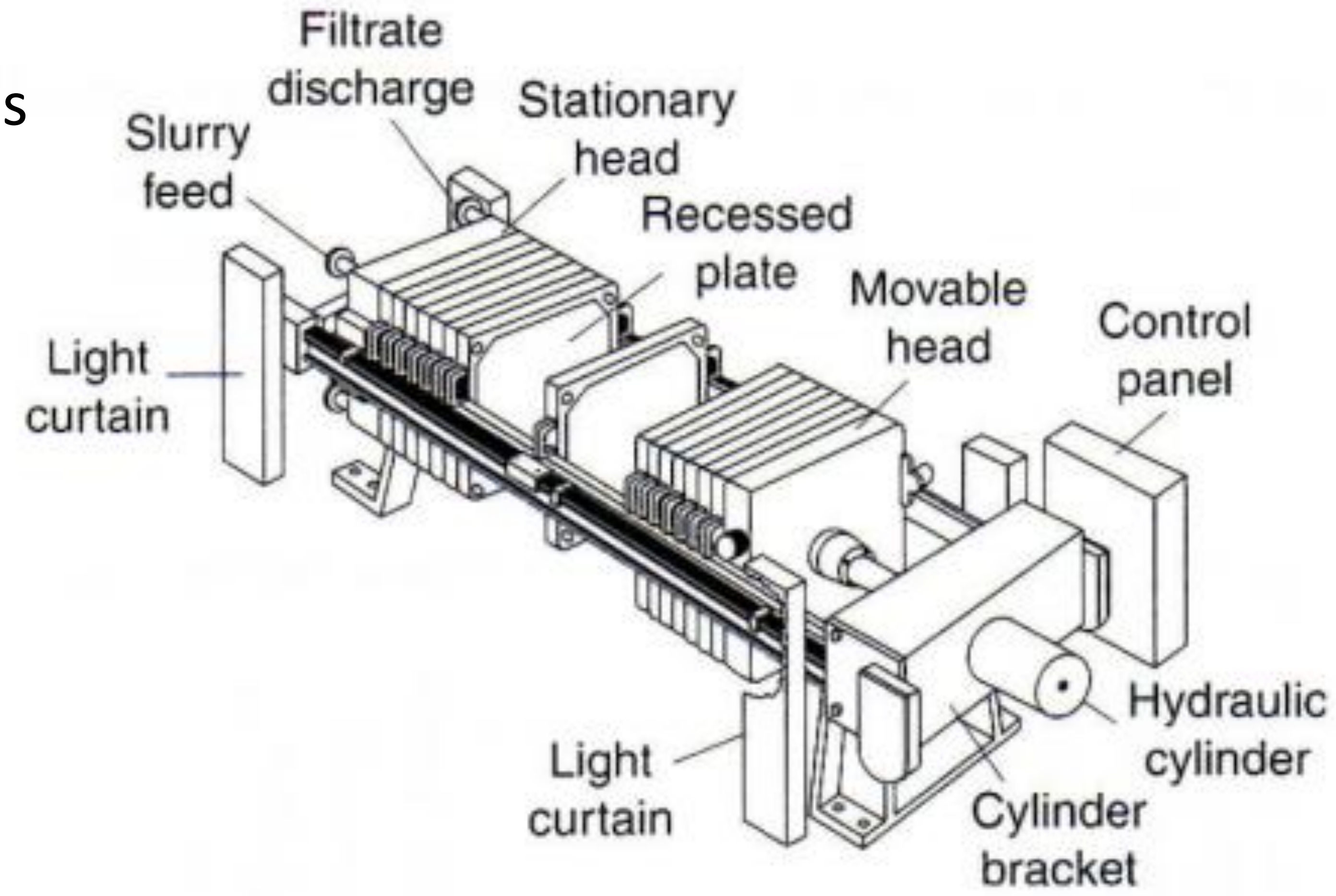
Centrifuges (dewatering)

advantages	disadvantages
high sludge cake concentration	skilled maintenance personnel required
low capital cost to capacity ratio	requires grit removal and possibly sludge screening/grinder in the feed stream
easy to install	moderately high suspended solids content in centrate
fast start-up and shut-down capacities	scroll wear potentially a high maintenance problem
enclosed design contains odours and aerosols	observation of dewatering zone not possible to optimise/adjust performance
clean appearance	high electricity consumption

- even waste activated sludge can be directly dewatered, however it is recommended to thicken sludge first

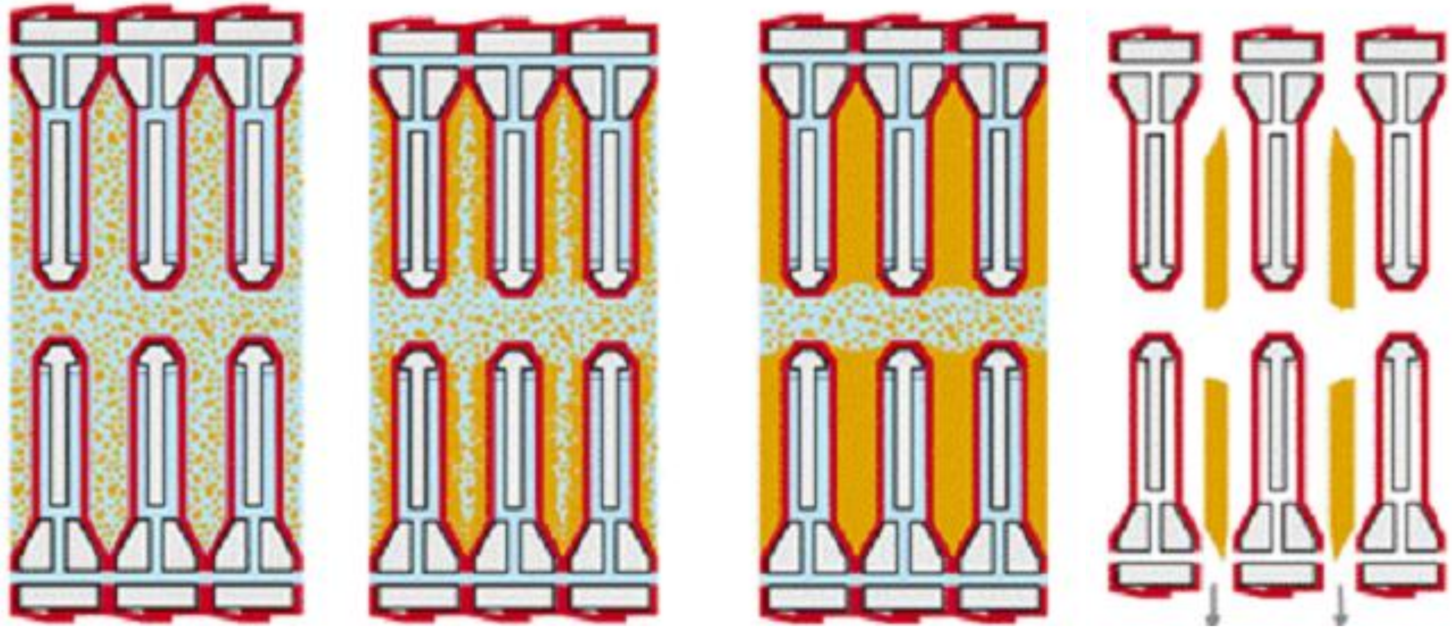
Filter press

- dewatering is achieved by retaining the sludge or biosolids with a filter (cloth/membrane)
- high pressure applied (700 to 2’100 kPa)
  - can achieve very high solid contents, especially if treated with iron salts or lime
  - high solids capture rate: close to 100 %
- cyclic operation



Filter press

- cycle of operation (2 to 5 hours)
    - closing of press
    - filling the press (filtration)
    - stop supply pump of sludge
    - open the press
    - wash and discharge the sludge cake (often requires intervention of personal)



filter press full with sludge suspension

sludge cake partially built (pressure increases)

sludge cake fully built (high pressure)

water core removed, then cake removal

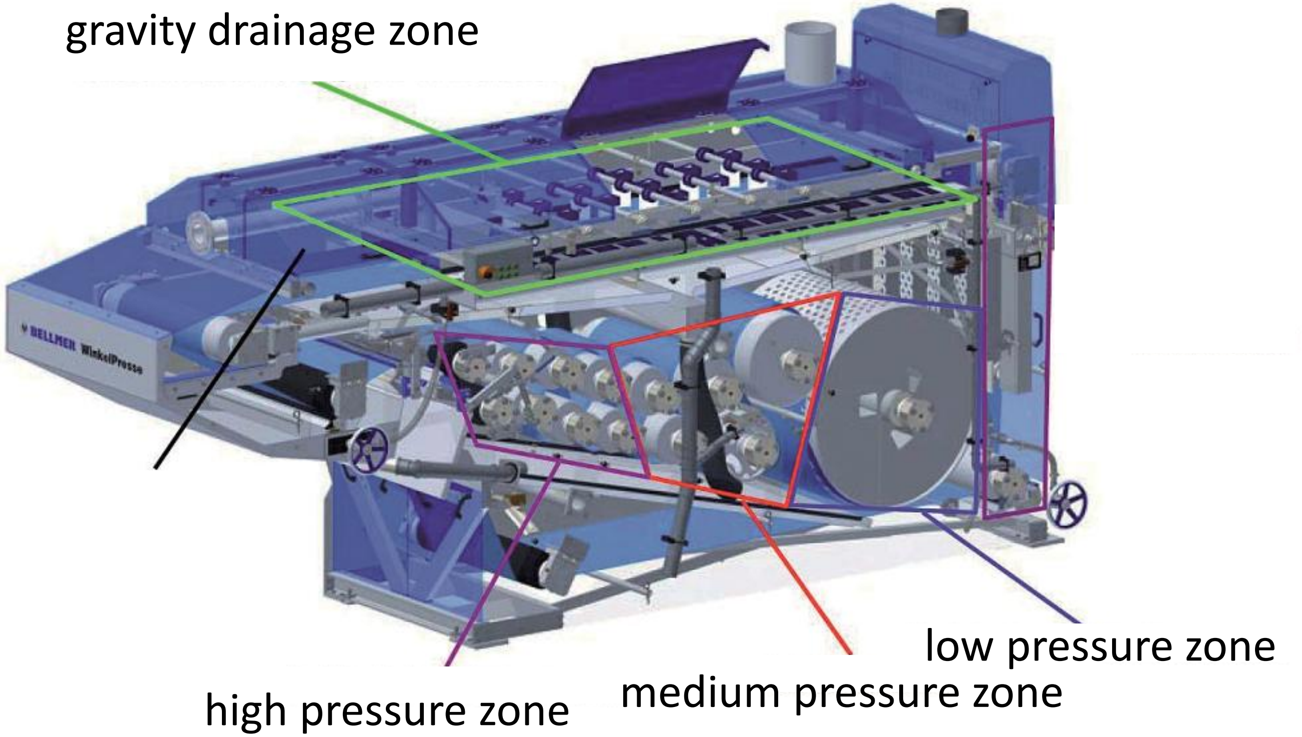
Filter press

advantages	disadvantages
high cake solids concentration	high labour cost
low suspended solids in filtrate	high pressures used → danger
simple operation	high equipment cost
	batch operation
	large floor area required
	skilled maintenance personnel required

→ high labour requirements (uncomfortable (smell) and potentially dangerous work) and landfilling restrictions (alkaline stabilised sludge) reduced the use of this technology in Switzerland

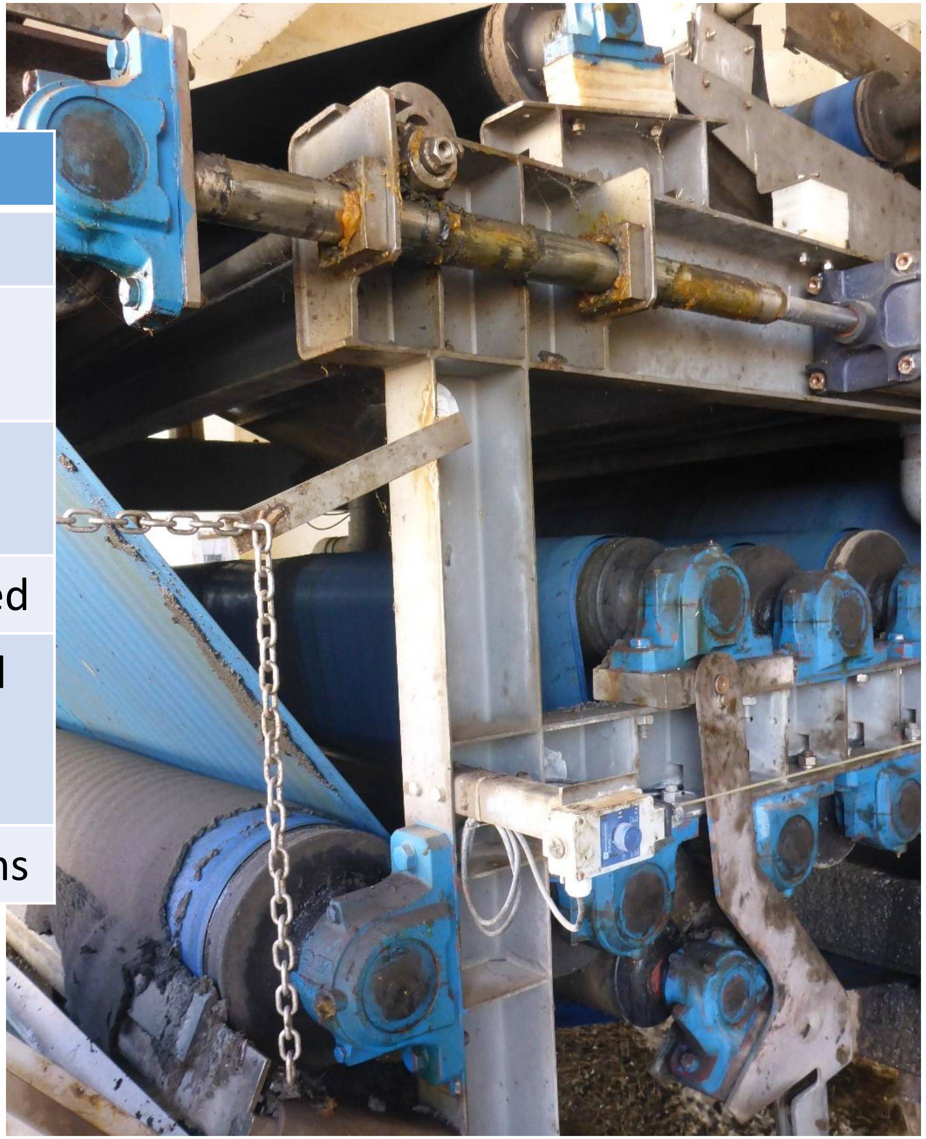
Belt-filter press

- gravity drainage and mechanically applied pressure dewatering
- sludge is kept between two porous cloth belts
- machine has various zones (pressure is inversely proportional to drum size):
  - gravity drainage
  - low pressure zone (large drum)
  - medium pressure zone (medium drum)
  - high pressure zone (small drum)
- operation has to be constantly adapted to entering sludge consistency (sludge should be homogenous)
- dewatering capacity rather low for sludge containing little structure forming materials (e.g. waste activated sludge from activated sludge plants)
- continuous operation



Belt-filer press

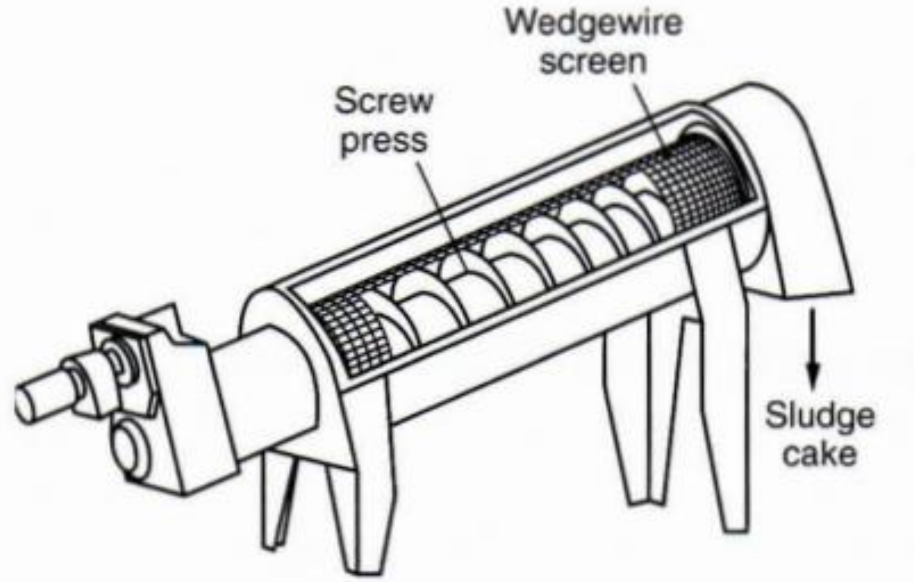
advantages	disadvantages
low energy requirements	hydraulically limited in throughput
relatively low capital and operation costs	very sensitive to incoming sludge feed characteristics
less complex from a mechanical point of view	short media life as compared to other devices
relatively easy to maintain	automatic operation generally not advised
minimal effort required for system to shut down	requires sludge screening/grinder in feed stream
	aerosol formation due to cleaning systems



➡ technology little used in Switzerland or Germany but otherwise still widely used (easy to repair and maintain)

Screw press

- low-speed, enclosed cylindrical unit
- sludge fed at a relatively low pressure into a stationary wedge wire screening basket
- rotating screw transfers the sludge through the wedge wire screening basked
- the pressure increases as sludge moves to exit depending on the outlet restriction (back pressure)
  - different zones (thickening zone, intermediate (formation of filter cake) and dewatering zone)
- wash-water required to clean the wedge wire screening assembly
- continuous operation



Screw press

advantages	disadvantages
low speed 0.3 to 1.5 rpm	capacity limitations will require multiple units for large wastewater facilities
low noise < 68 dB	cannot observe dewatering zone to optimise/adjust performance
enclosed design contains odours and aerosols	wash-water required periodically throughout operating cycle
low energy use drive motor	
low shearing force reduces odours in dewatered cake	
overdosing of polymer does not clog screen and hinder dewatering	

➡ interesting technology for small to middle size treatment plants

Summary of mechanical dewatering technologies

sludge type	unit	centrifuge	belt-filer press	filter press	screw press
final solids content % [kg TS/kg]					
primary sludge	%	32 – 40	30 – 35	32 – 40	30 – 40
mixed sludge	%	26 – 32	24 – 30	26 – 32	24 – 30
extended aeration sludge (no primary decantation)	%	18 – 24	15 – 22	18 – 24	18 – 24
anaerobically digested sludge	%	22 – 30	20 – 28	22 – 30	20 – 28

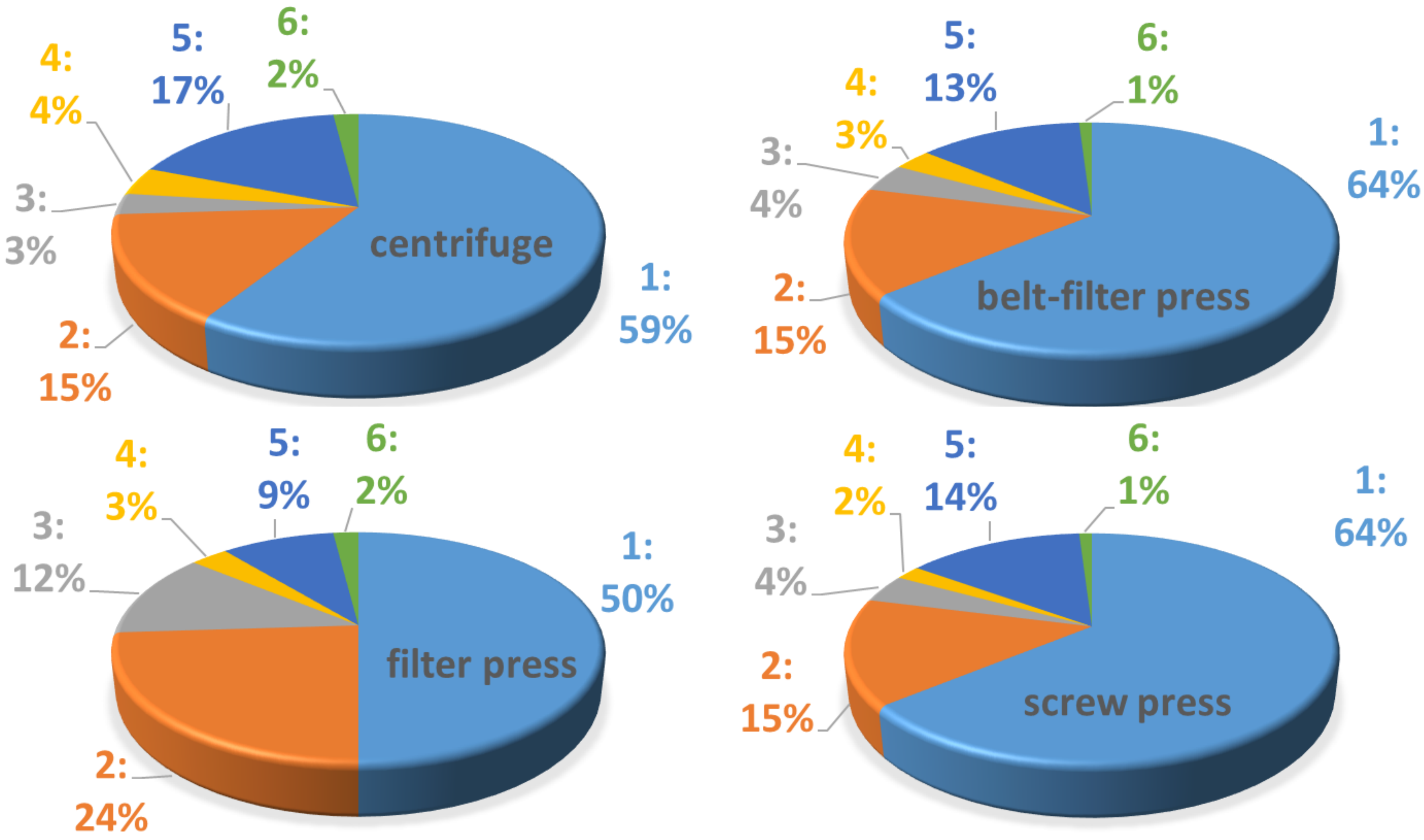
- centrifuges and filter presses achieve the highest solids content in the filter cake
- variation of final solids content is strongly dictated by characteristics of sludge to be dewatered
- constant optimisation of the dewatering unit is crucial for good dewatering results

Summary of mechanical dewatering technologies

sludge type	unit	centrifuge	belt-filer press	filter press	screw press
energy consumption (including conditioning and feed pump)					
specific energy consumption	kWh/m³	1.6 – 2.2	1.1 – 1.4	1.5 – 1.8	0.6 – 1.0
specific energy consumption	kWh/t TS	60 – 90	40 – 50	60 – 70	20 – 40
polymer use					
polymer consumption	kg/t TS	8 – 14	6 – 12	6 – 12	6 – 12

- screw press has clearly the lowest energy demand
- centrifuges have the highest energy demand
- polymer use depends less on technology used but rather on characteristics of sludge to be dewatered

Costs related to mechanical dewatering technologies (expressed in % of total cost)



- study of DWA (German prizes)
- for wastewater treatment plants with 100'000 PE

- 1: disposal
- 2: investment
- 3: personal
- 4: electricity
- 5: conditioning
- 6: maintenance

Cost of mechanical dewatering technologies

- main cost due to disposal (at least 50 %)
    - final total solids content is highly important for total cost
- conditioning (polymers) is more expensive than electricity costs
- costs related to personal is rather limited as compared to total cost
    - however, filter press has relatively high personal costs
- investment cost should not influence choice as it has little influence on total cost (for large wastewater treatment plants: 100’000 PE)
- however, investment costs may be much more important for small wastewater treatment plants

Other dewatering technologies: sludge drying beds

"Devices used for dewatering and drying of sludge and biosolids in which a semi-solid solution is spread over a porous (e.g. sand) or impervious medium and allowed to separate and air dry or decant."

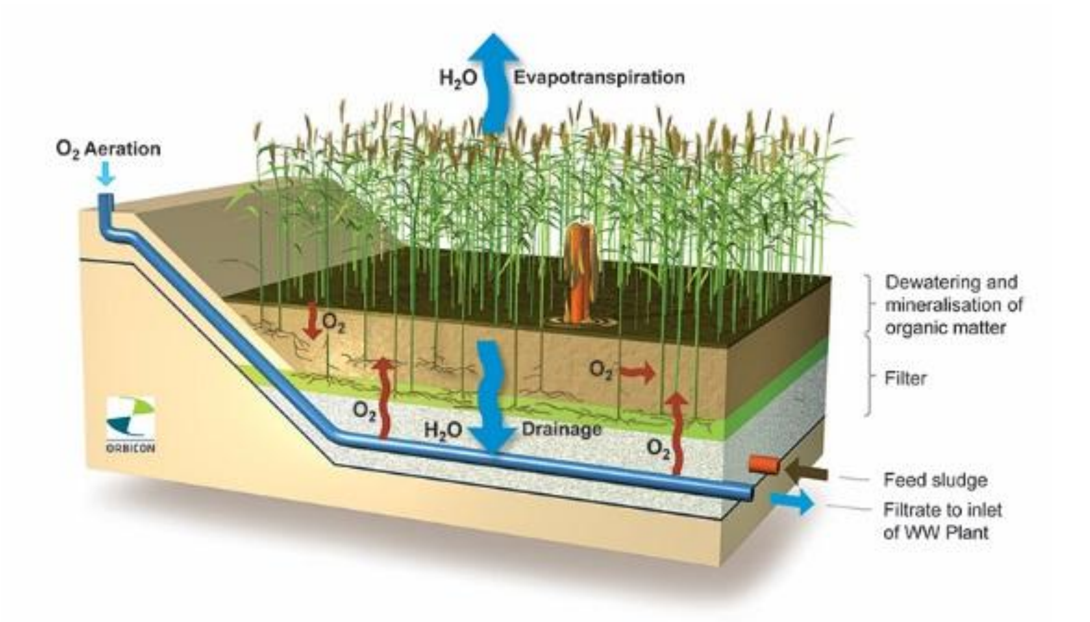
- functioning of sludge drying beds
  - thickened sludge put onto a (sand) bed
  - sludge is dried (weeks)
  - sludge is removed (often manually)
  - sand bed is refilled with thickened sludge
  - …
- drained water has to be returned to the wastewater treatment

Other dewatering technologies: sludge drying beds

- high space requirements (depends strongly on climatic conditions)
- often labour-intensive
- odour problems should not be underestimated
- sand has to be replaced as part of it is removed with the dried sludge
- solid content of dried sludge is highly variable and depends on climatic conditions
- efficiency of process can be increased by covering the drying bed

Other dewatering technologies: reed beds

- functioning of reed beds
  - thickened sludge is applied regularly on reed bed
  - water is either drained or consumed/ evaporated by planted reed or grass
  - sludge is not only dried but also stabilised (reduction in total volatile solids)
  - before harvesting of stabilised sludge, no thickened sludge is applied for several months (maturation process)



- very high space requirements (higher than drying beds)
- relatively low labour required apart from initial phase (planting of reed) and final phase (stabilised sludge evacuation after several years)
- high total solids content of stabilised sludge (up to 40 %)

Other dewatering technologies: heat drying

- "Application of heat to evaporate water and reduce the moisture content in biosolids below that achievable by conventional dewatering methods."
- sludge (dewatered) is dried to very high solids content
  - reduced transportation costs
  - significant pathogen inactivation
  - enhanced heat value of sludge/biosolids
  - small footprint (as compared to other drying technologies)
- however,
  - large fuel/electricity requirements (heat)
  - bad odour potential
  - relatively complex system, requires highly trained operating staff
  - relatively high capital cost

Treatment of the liquid stream

- during dewatering process solids are separated from the liquid phase
- liquid phase still contains
  - solids (separation process is not 100 % efficient)
  - ammonia, especially if dewatered sludge was previously anaerobically stabilised
  - and other pollutants (BOD, COD, phosphorous,…)

→ liquid phase has to be treaded before it can be discharged

- liquid phase is generally returned to main liquid treatment train
- specific treatments (e.g. Anammox) can be applied if liquid contains a lot of ammonium:
  - reduces load to main treatment train (particularly ammonium)
  - reduces energy consumption of whole wastewater treatment plant
  - increased complexity of wastewater treatment plant operation

Treatment of wastewater solids V: Resource recovery and disposal of sludge

Applied wastewater engineering

Michael Jon MATTLE

Resource recovery from sludge and biosolids

- sludges or biosolids can serve as a source of
  - nutrients (uptake by bacteria or precipitation from wastewater) that can be used as a fertilizer
    - phosphorous
    - organic nitrogen
    - but also iron, calcium, magnesium and various other macro- and micro-nutrients which are essential for plant growth
  - feed stock for energy production
    - organic matter generates heat when burned
  - in the fabrication of value-added products
    - e.g. conversion of sludge to liquid and oil fuel (currently hindered by high capital cost and requirement of large amount of sludge feed)



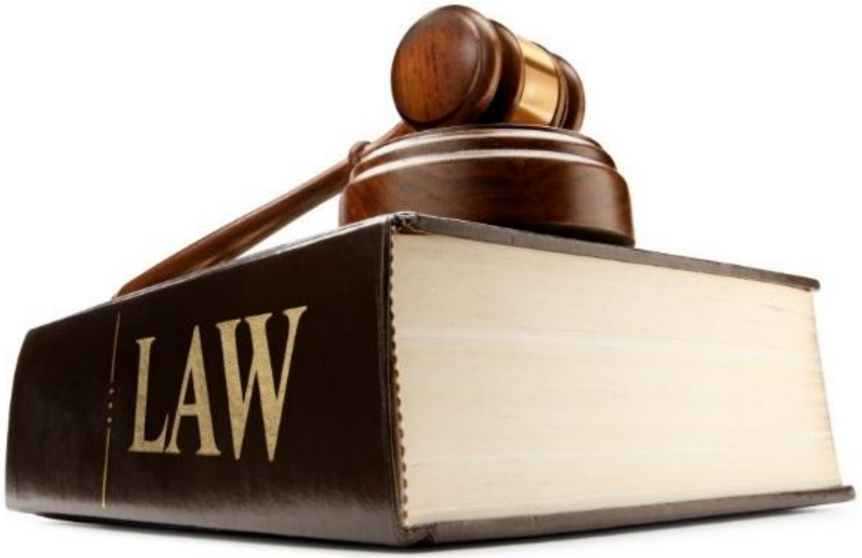
Land application of sludge or biosolids

- potential benefits
  - cheaper for farmers than buying chemical fertilisers
  - reduced energy requirements than for nutrients production
  - carbon sequestration
- agricultural land application (depends on legislation)
  - pathogens removal
  - metal contents
  - organic content (TVS content)
- non-agricultural land application (e.g. reclaiming mining sites, landscaping, and forest crops) (depends on legislation)
  - pathogens removal
  - metal contents
  - organic content (TVS content)
- land filling requirements (depends on legislation)
  - pathogens removal
  - organic content (TVS content)
  - water content (TS content)

Sludge or biosolids disposal

- as discussed earlier in this chapter, land application of sludge or biosolids is forbidden in Switzerland since 2006 (heavy-metals, pathogens and other pollutants)
    - sludge is nearly always incinerated (a fraction of sludge is dried and sold to cement factories)
    - the ashes produced in incineration plants are then landfilled

- however, the Swiss legislation is for the moment rather exceptional as many other countries (e.g. France, Germany, the US) still permit the use of sludge or biosolids for land application
    - However, this may change in the future



Sludge incineration

- Which fractions are incinerated during sludge incineration (transfer into the gas phase)?

A) Phosphorous

B) Carbon

C) Nitrogen

D) Water

E) Heavy metals

F) Anions (like bromide or chloride)

https://web.speakup.info/room/join/58969

Incineration of dewatered sludge

- "The reduction of the volume of solids by the total conversion of organic solids to oxidised end products, primarily carbon dioxide, water and ash."
- ash contains the mineral fraction, like $FePO_4$ and (heavy-)metals
- water content of dewatered sludge should be as low as possible in order to decrease auxiliary fuel requirements (TS: 30 – 35 %)
- no addition of lime or quick lime (increased ash formation)

solid waste and sludge incineration plant in Posieux/Hautrive FR

$$C_aO_bH_cN_d + (a + 0.25c - 0.5b)O_2 \rightarrow aCO_2 + 0.5cH_2O + 0.5dN_2$$

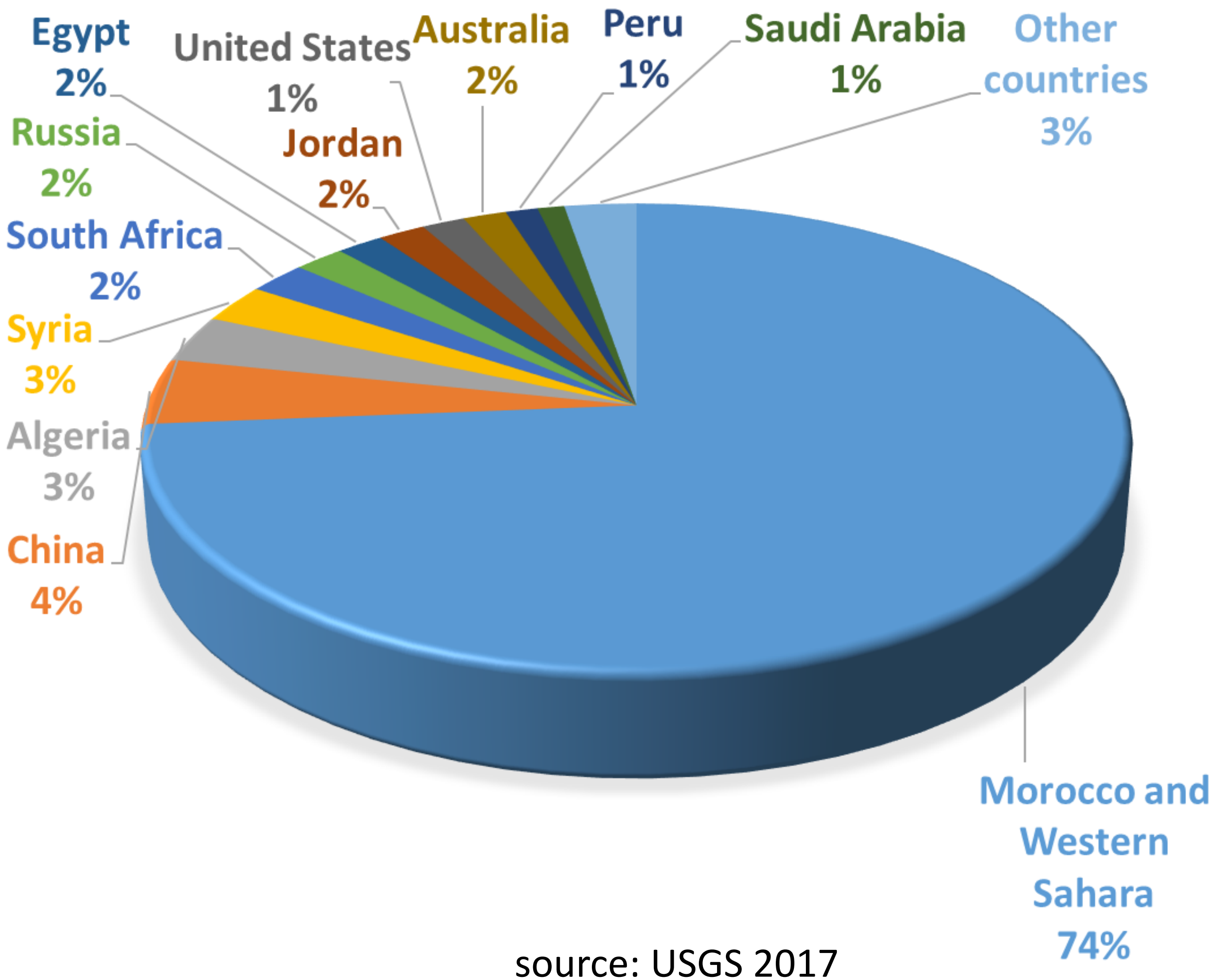
Incineration of dewatered sludge

- waste sludge or biosolids can
  - be incinerated together with municipal waste (co-incineration will probably be stopped in Switzerland due to phosphorous recovery)
  - be incinerated separately (mono-incineration)
  - be dried and eliminated with cement industry

advantages	disadvantages
maximum volume reduction and end product stability	high capital and operating cost
maximum destruction of pathogens and toxic compounds	complex system that requires highly trained operating staff
relatively small process footprint	requires exhaust air treatment
energy recovery potential	CO_2-Emissions
well proven process	

Phosphorous recovery: world phosphorous reserves

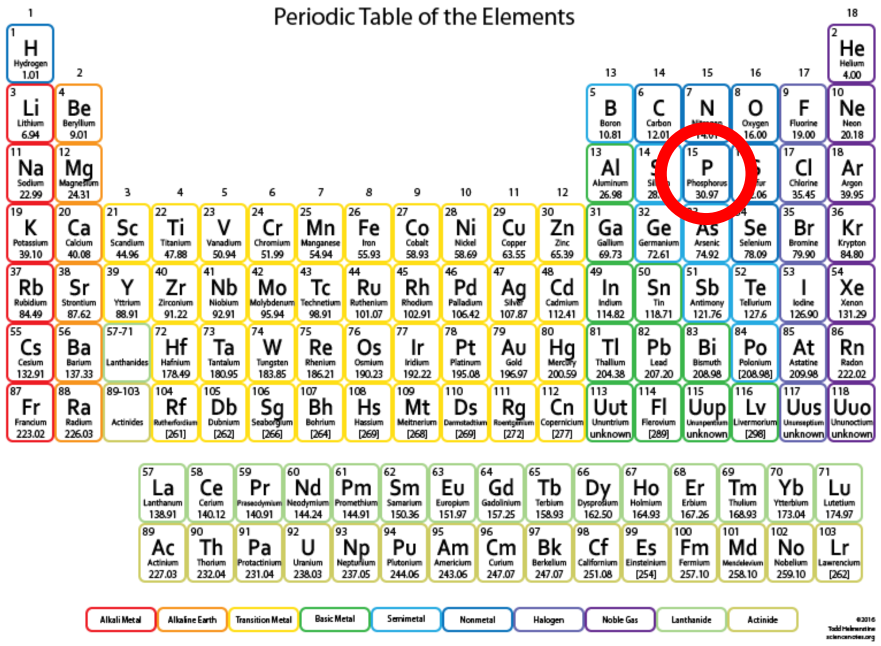
- current mine production: below 0.5 % of reserves of phosphate rock
- sufficient phosphorous available, but quality of phosphate rocks deteriorates → negative impacts on the environment



source: USGS 2017

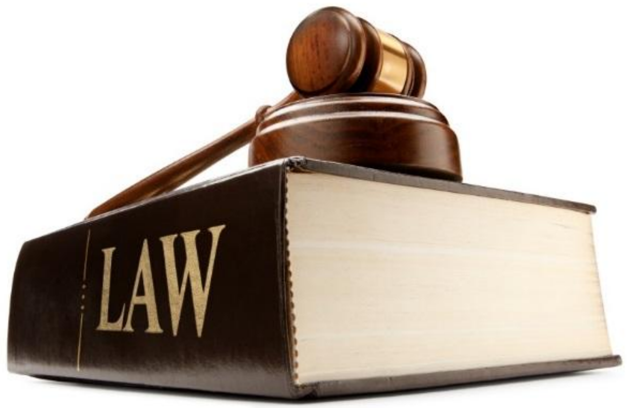
Why phosphorous recovery from sludge?

- since 2006 it is forbidden (in CH) to apply wastewater solids to fields (environment)
  - → the biggest losses of phosphorous happen in the waste industry



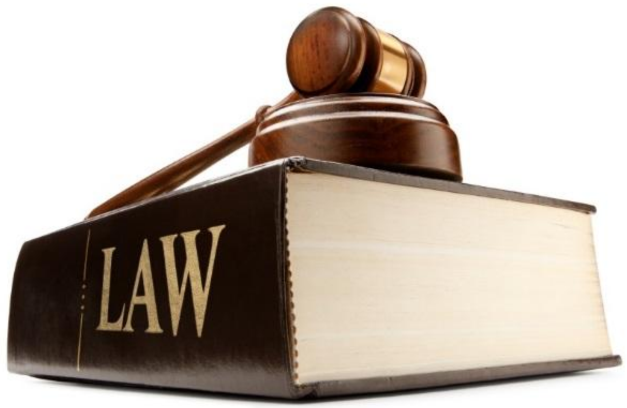
- motivations stated by the FOEN:
  - phosphorous is an essential element for life on earth
  - phosphorous is not substitutable
  - phosphorous is a fundamental element for our food supply
  - about 90 % of phosphorous is used in fertilizers
  - currently known phosphorous reserves are finite
  - phosphorous reserves contain more and more pollutants
  - **Switzerland does not possess a primary phosphorous reserve: today 100 % of phosphorous is imported**

Phosphorous recovery



- the Swiss government changed the legislation concerning solid waste which is now called the decree on limitation and elimination of waste (ordonnance sur la limitation et l'élimination des déchets (OLED)). The new legislation came into effect on January 1st 2016.
- it obliges to recycle the phosphorous contained in wastewater, wastewater sludge or ashes (if the sludge is incinerated)
- OLED, Art. 15 Déchets riches en phosphore: *"[1]Le phosphore contenu dans les eaux usées communales, les boues d'épuration des stations centrales d'épuration des eaux usées ou les cendres résultant du traitement thermique de ces boues doit être récupéré et faire l'objet d'une valorisation matière."*

Phosphorous recovery



- if the phosphorous is reused as a fertilizer, pollutants need to be removed so that the fertilizer respects annex 2.6 ch. 2.2 of ORRChem (Ordinance on the Reduction of Risks relating to the Use of Certain Particularly Dangerous Substances, Preparations and Articles)
- the obligation to recycle phosphorous is applicable by January 1st 2026 (OLED, Art. 51 Déchets riches en phosphore: *"L'obligation de récupérer le phosphore selon l'art. 15 est applicable à partir du 1 er janvier 2026."*)

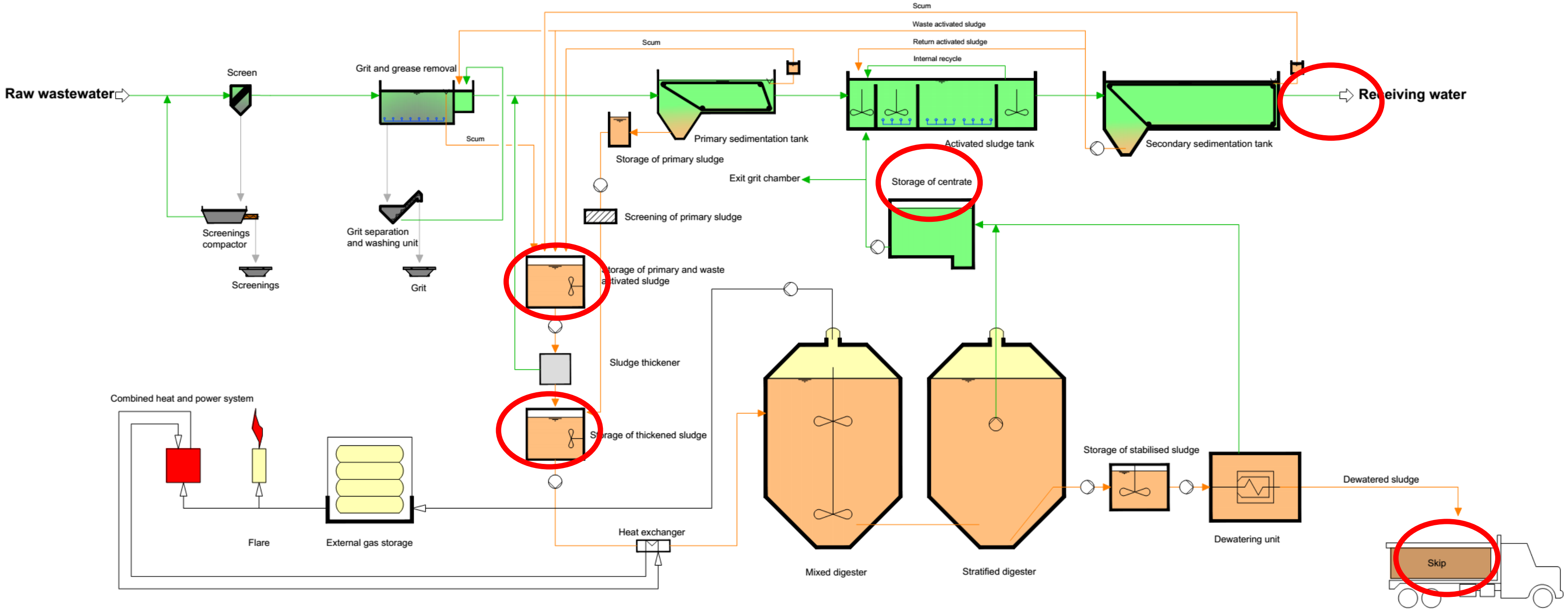
→ Deadline will be postponed as it was too optimistic

Phosphorous recovery technologies

- objectives of phosphorous recovery
  - recycle as much as possible of phosphorous entering a WWTP
  - the final product has to respect the Swiss legislation (e.g. heavy metals removal)
  - generate a product that can be sold on the market at a competitive prize
  - the final total costs (investment and operation) should be ‘supportable’
  - recovery process(es) should be robust
  - recovery process(es) should be ‘green’: generate as little waste as possible, consume little energy and chemicals
  - recycle other elements if possible

Phosphorous recovery technologies

- phosphorous can be recovered at different stages of the wastewater or sludge treatment processes:
  - directly from wastewater or centrate
  - from sludge
  - from ashes of incinerated wastewater sludge



Phosphorous recovery technologies

- many different technologies are currently being developed and tested at small up to large scale
  - many technologies produce a precipitate of phosphorous (solid)
  - certain technologies generate phosphoric acid (liquid)

Phosphorous recovery technologies

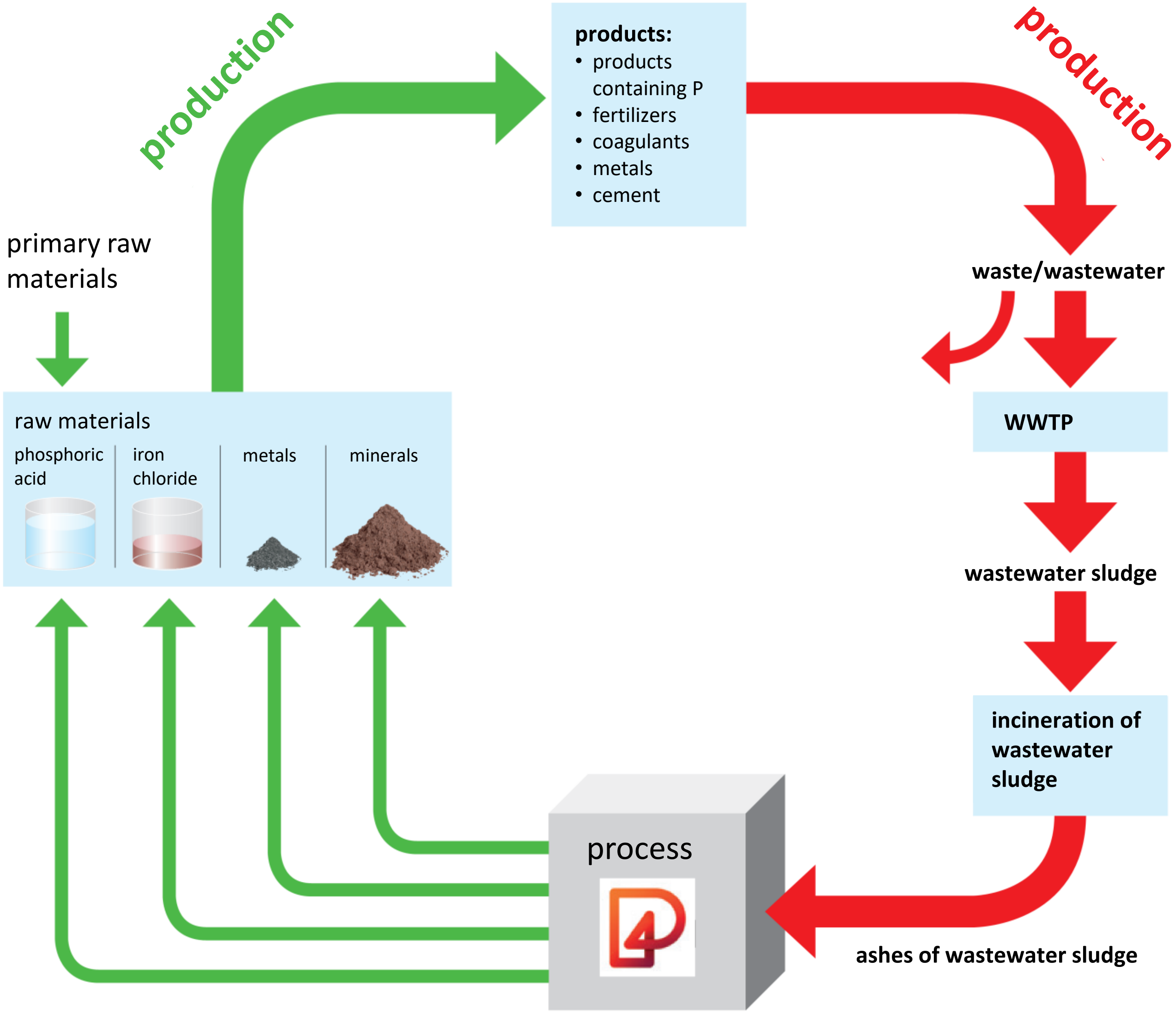
- technologies recovering phosphorous directly from wastewater stream or from sludge (at WWTP) (generally)
  - have a phosphorous source which is rather diluted
  - have low phosphorous recovery rates (< 50 %)
  - dissolve precipitated phosphates using acids
  - precipitate phosphorous into a relatively insoluble product (e.g. struvite)
    - lower solubility of phosphorous than fertilizer sold on the market
    - is there a market for these products?
  - employ relatively simple processes
  - require new installations at WWTP → renders running of WWTP more complex

Phosphorous recovery technologies

- technologies recovering phosphorous from ashes (incineration of sludge) or HTC-coal (hydrothermal carbonization) (generally)
  - have a phosphorous source which is concentrated
  - have high phosphorous recovery rates (> 75 %)
  - require new complex installations
    - however, one installation may recover phosphorous for many WWTP
    - WWTP can be run in the same way as today
  - depending on process chosen, generate a product which may be soluble (phosphoric acid) or solid
  - depending on process chosen, may recycle other elements as well

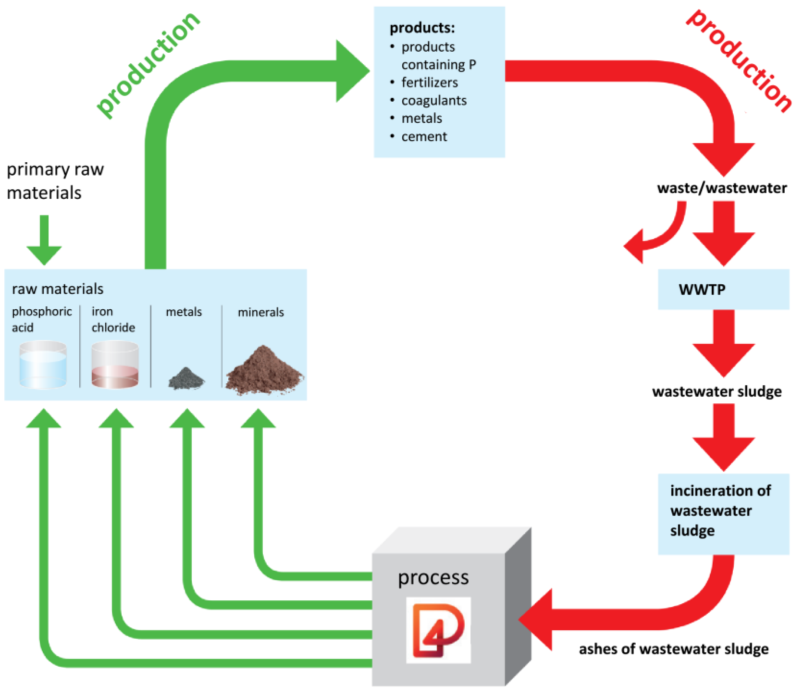
One technology: Phos4life process

- technology development financed by the Canton of Zurich and the foundation ZAR
- the process is developed jointly by ZAR and Tecnicas reunidas
- ashes of mono-incinerated sludge as starting material
- phosphorous recovery: > 95 %
- but also
  - iron recovery: > 90 %
  - metals recovery: > 85 %
  - minerals recovery: > 95 %



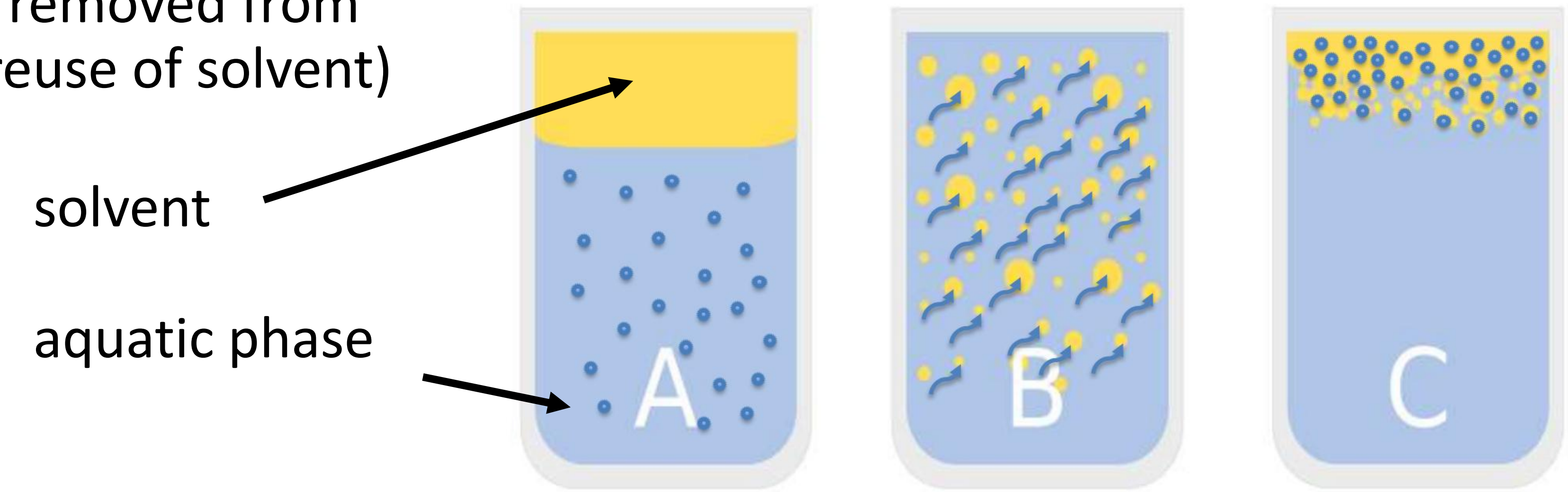
An interesting technology: Phos4life process

- A multi-step process:
  - dissolution of metals and phosphorous using acid → recovery of minerals (solid phase)
  - solvent extraction of iron → stripping of ferric chloride using hydrochloric acid
  - solvent extraction of phosphorous → stripping of phosphoric acid employing hot water
  - precipitation of other metals by lime addition (pH increase) → metal recovery



An interesting technology: Phos4life process

- compound specific solvent extraction:
  - A: compound to be recovered is in the aquatic phase, addition of solvent
  - B: mixing of the two phases → compound enters solvent phase because of the higher affinity to it; specific interaction required with compound (e.g. interaction of compound with molecules added to solvent)
  - C: phases are left to separate → compound is present in solvent phase
  - D: compound is removed from solvent phase (reuse of solvent)



An interesting technology: Phos4life process

- Phos4life is one technology developed among many (due to limited time we are not going into details about other technologies)
  - it recovers not only phosphorus at a high yield but also iron, other metals and minerals (cement industry)
  - after treatment, land-filling of ashes is hardly required anymore (cost reduction; nearly complete recycling of products)
  - the process is complex:
    - high initial investment costs
    - highly skilled personal required
    - high chemical consumption
    - high energy consumption
      - recovery costs are much higher than buying phosphorous on the international market
  - one single central plant could potentially solve the phosphorous recovery problem from wastewater sludge ashes for entire Switzerland!

Phosphorous recovery

- different methods have been developed or are in development to recover phosphorous from wastewater sludge
  - direct recovery from liquid or sludge
    - several methods, however, they often have relatively low yields
  - recovery after a thermal treatment
    - HTC-treatment (interesting by-product: coal) of wastewater sludge
    - mono-incineration of wastewater sludge and phosphorous recovery from ashes

➡ apart from micropollutants removal another parallel challenging theme in the field of wastewater treatment

➡ how this issue will continue will be decided in the next two years (FOEN and parliament)

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Thanks for their help

- Manfred Tschui and Stefan Schlumberger