Air emission control

Applied wastewater engineering

Michael Jon MATTLE

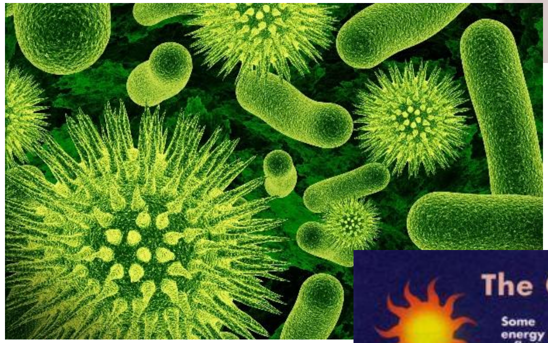
Content of air emission control

- Introduction
  - Reduction of biological hazards
- Treatment of odorous compounds
  - Swiss legislation and other reasons for air emission control
  - Technologies to treat odorous compounds
- Reduction of greenhouse gas emissions
- Emissions from combustion of gases

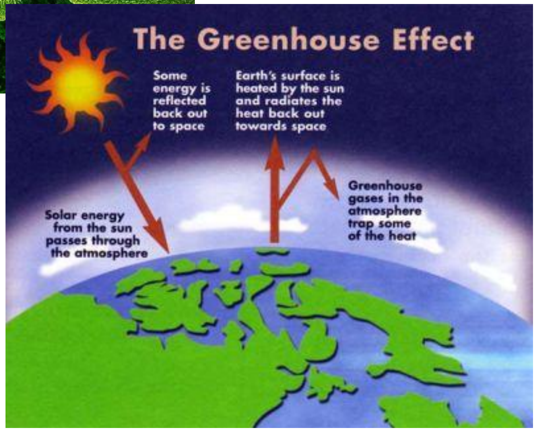
Introduction

- odorous compounds
  - psychological stress rather than harmful to the human body
  - complaints from neighbours

- microbiological emissions
  - potential health risks to employees



- greenhouse gases
  - global warming



- emissions from combustion of gases
  - combustion of biogas

Microbiological hazards

- avoid formation of aerosols
  - choice of aeration system
  - water inlets below water level
- protect against diffusion of aerosols
  - high basins walls
  - protecting walls (e.g. aeration systems)
  - choice of aeration system
  - closed rooms





Air emission control I: treatment of odorous compounds

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Swiss legislation (Ordinance on Air Pollution Control (OAPC))

English is not an official language of the Swiss Confederation. This translation is provided for information purposes only and has no legal force.

Ordinance on Air Pollution Control (OAPC)

of 16 December 1985 (Status as of 1 April 2017)

Annex 1[65]
(Art. 3 para. 1)

General preventive emission limits

Inorganic substances (gas or vapour)

- OAPC: Annex 1

62 Table of inorganic substances in gaseous or vaporous form

Substance	Class
Ammonia and ammonium compounds, expressed as ammonia	3
Arsine	1
Bromine and its gaseous or vaporous compounds, expressed as hydrogen bromide	2
Chlorine	2
Chlorine compounds, vaporous or gaseous inorganic chlorine compounds except cyanogen chloride and phosgene, expressed as hydrogen chloride	3
Cyanogen chloride	1
Fluorine and its vaporous or gaseous compounds, expressed as hydrogen fluoride	2
Hydrogen cyanide	2
Hydrogen phosphide	1
Hydrogen sulphide	2
Nitrogen oxides (nitrogen monoxide and nitrogen dioxide), expressed as nitrogen dioxide	4
Phosgene	1
Sulphur oxides (sulphur dioxide and sulphur trioxide), expressed as sulphur dioxide	4

6 Inorganic substances in gaseous or vaporous form

61 Limit values

The emission concentration of any of the substances listed in Number 62 must not exceed the following values:

a. For a Class 1 substance at a mass flow of 10 g/h or more — 1 mg/m^3

b. For a Class 2 substance at a mass flow of 50 g/h or more — 5 mg/m^3

c. For a Class 3 substance at a mass flow of 300 g/h or more — 30 mg/m^3

d. For a Class 4 substance at a mass flow of 2500 g/h or more — 250 mg/m^3

see also OAPC: Annex 2 Additional or different emission limitation requirements for particular installations
82 Stationary internal combustion engines
824 Nitrogen oxides and carbon monoxides

Organic substances (gas, vapour or particles)

- e.g. methylamine (group 1)
- trimethylamine (group 1)
- thiols (mercaptans (R-SH)) (group 1)

7 Organic substances in gaseous, vaporous or particulate form

71 Limit values

[1] The emission concentration of the substances listed in Number 72 must not exceed the following values:

a. Class 1 substances at a mass flow of 0.1 kg/h or more — 20 mg/m^3

b. Class 2 substances at a mass flow of 2.0 kg/h or more — 100 mg/m^3

c. Class 3 substances at a mass flow of 3.0 kg/h or more — 150 mg/m^3

[3] If the exhaust gas contains several substances belonging to the same class, the limit value applies to the sum of these substances.

[4] If the exhaust gas contains substances of different classes, the sum of the substances at a total mass flow of 3.0 kg/h or more must not exceed the limit value of 150 mg/m^3, in addition to the requirements specified in paragraphs 1 and 2.

Swiss legislation (Ordonnance sur la prévention des accidents et des maladies professionnelles : OPA)

- Ordinance on prevention of accidents and occupational diseases
- work security
  - Art. 50 National occupational injury insurance (suva). b. prevention of occupational diseases

Titre 2	**Organisation**
Chapitre 1	**Sécurité au travail**
Section 1	**Organes d'exécution**

Art. 50 Caisse nationale suisse d'assurance en cas d'accidents.
b. Prévention des maladies professionnelles

1 La CNA surveille l'application des prescriptions sur la prévention des maladies professionnelles dans toutes les entreprises.

2 Le Département fédéral de l'intérieur (département) peut introduire l'obligation d'annoncer des travaux particulièrement dangereux pour la santé; il consulte au préalable la CNA et les organisations intéressées.

3 Après avoir entendu les milieux concernés, la CNA peut émettre des directives sur les valeurs limites de concentration des substances toxiques et sur les valeurs admissibles des agents physiques aux postes de travail.[93]

Swiss legislation (Ordonnance sur la prévention des accidents et des maladies professionnelles : OPA)

- National occupational injury insurance (suva) may define maximum concentrations for toxic substances and admissible values of physical agents at workplaces:
  - VME : valeur (limite) moyenne d'exposition
    - average exposure over 8 hours per day
  - VLE : valeur limite d'exposition calculé sur une courte durée (< 15 min)
    - maximum exposure over a short period

suva

Valeurs limites d'exposition aux postes de travail: liste complète et modifications des valeurs VME/VLE pour 2017

VME 2017	VME		VLE		Notations	Toxicité critique
Substance [CAS]	ml/m3	mg/m3	ml/m3	mg/m3	R S O^B B P C M R SS	
Ammoniac	20	14	40	28	SS_C	Yeux & VRS
Hydrogène sulfuré	5	7,1	10	14,2	SS_C	VRS, Odeur, SN

Other reasons for odour emissions control

- nuisance to 'neighbours'
  - proximity to residential areas
  - wind direction
  - size of treatment plant
  - origin of wastewater (communal or industrial)
  - sewer system (slope, poorly aerated)
  - sludge treatment systems
  - biological treatment (high rate plants : high oxygen demand → important aerosol formation)

→ nuisance factor generally more important than legislation for air emission control installations

Sources of bad odours

- typically contain either nitrogen or sulphur

- mostly a psychological stress rather than harmful to the human body
- however, certain of the odorous gases generated at WWTP can be lethal at higher concentrations (e.g. hydrogen sulphide)
- odour control is important for public acceptance of wastewater treatment facilities

Odorous compound	Chemical formula	Molecular weight	Odor threshold, ppm_v[a]	Characteristic odor
Ammonia	NH_3	17.0	46.8	Pungent, irritating
Crotyl mercaptan	$CH_3\text{-}CH{=}CH\text{-}CH_2\text{-}SH$	90.19	0.000029	Skunk like
Dimethyl sulfide	$CH_3\text{-}S\text{-}CH_3$	62	0.0001	Decayed cabbage
Diphenyl sulfide	$(C_6H_5)_2S$	186	0.0047	Unpleasant
Ethyl mercaptan	$CH_3CH_2\text{-}SH$	62	0.00019	Decayed cabbage
Ethyl sulfide	$(C_2H_5)_2SH$	91.9	0.000025	Nauseating odor
Hydrogen sulfide	H_2S	34	0.00047	Rotten eggs
Indole	C_8H_6NH	117	0.0001	Fecal, nauseating
Methyl amine	CH_3NH_2	31	21.0	Putrid, fishy
Methyl mercaptan	CH_3SH	48	0.0021	Decayed cabbage
Skatole	C_9H_9NH	132	0.019	Fecal odor, nauseating
Sulfur dioxide	SO_2	64.07	0.009	Pungent, irritating
Thiocresol	$CH_3\text{-}C_6H_4\text{-}SH$	124	0.000062	Skunk like, irritating
Trimethyl amine	$(CH_3)_3N$	59	0.0004	Pungent, fishy

[a] Parts per million by volume.

Sources of bad odour

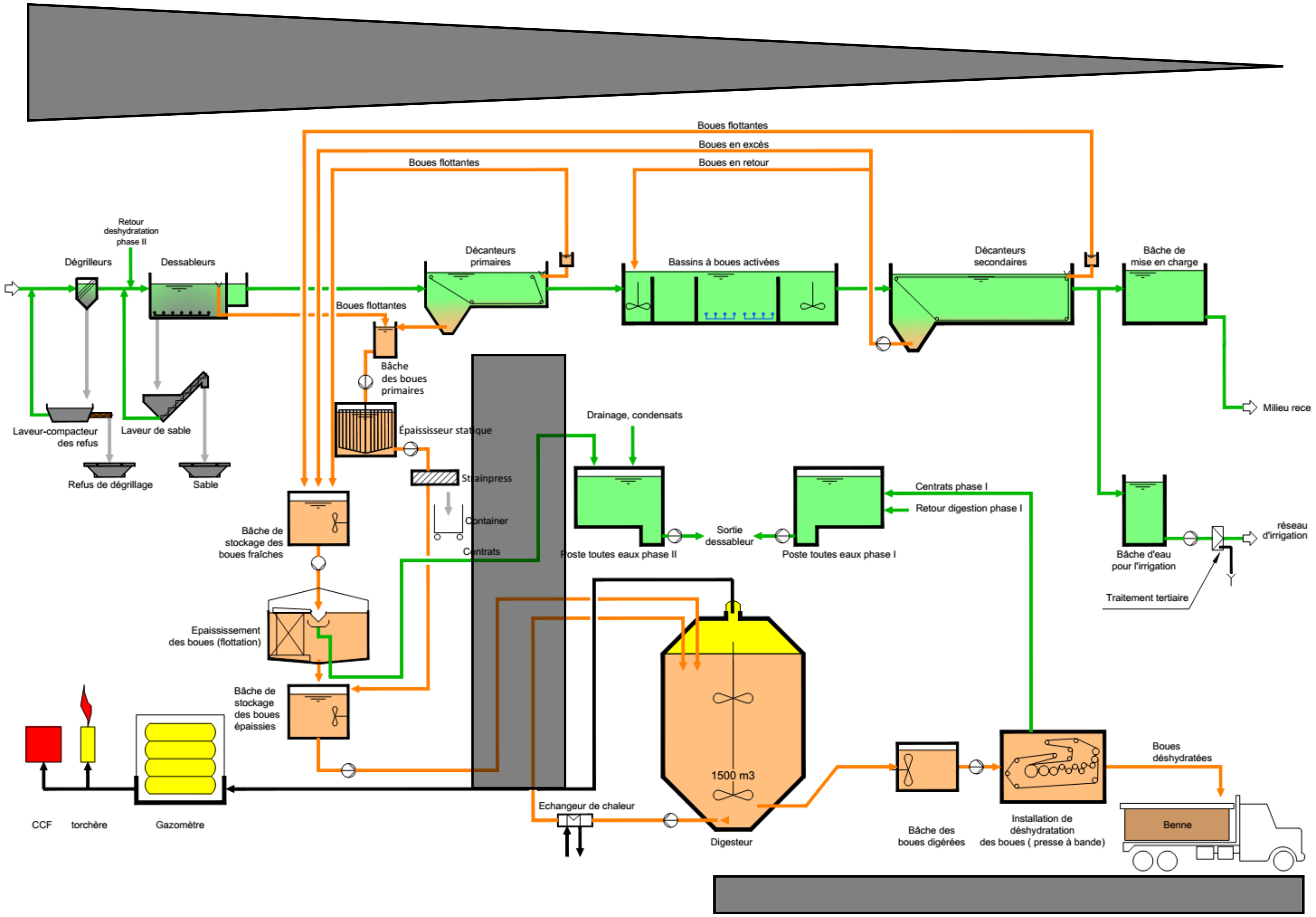
- generally form under anaerobic conditions (absence of oxygen, nitrate,…)

$$SO_4^{2-} + 2H_2O \xrightarrow{anaerobic\ cond.} HS^- + OH^- + H_2O \rightleftharpoons H_2S(gas) + 2OH^-$$

  - sewer system (especially in hot climates and long residence times (flat areas))
  - anaerobic tanks/anaerobic digestion
  - badly aerated zones (sludge sedimentation in aerobic basins)
  - large sludge flocks
- discharge of industrial wastewater
  - may contain odorous compounds
  - may contain compounds that react and form odorous compounds

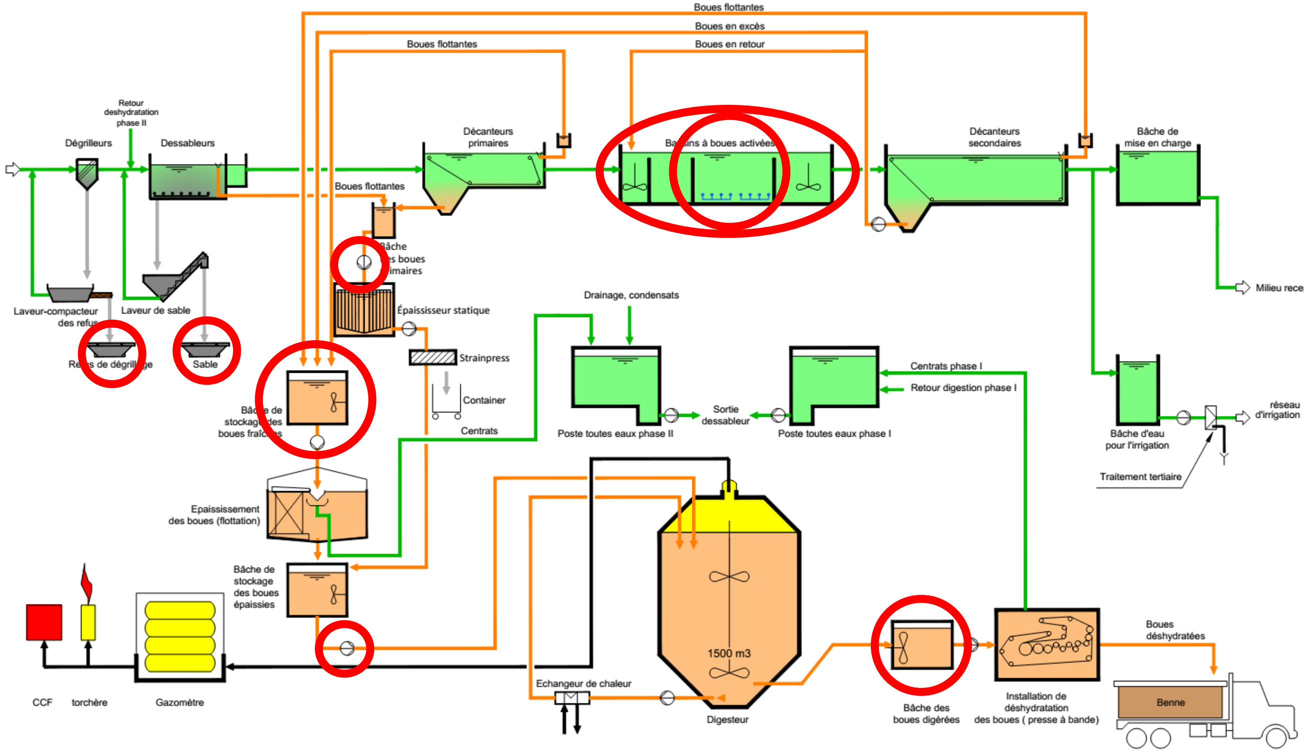
Sources of bad odour

- odour potential
  - sewer collection system: high
  - screening/grit and grease removal: high (especially if aerated)
  - primary clarifier: moderate
  - aeration basins: low/moderate
  - secondary clarifiers: low/moderate
  - sludge treatment (especially unstabilised sludge): moderate/high (especially for primary sludge)
  - septage receiving and handling facilities: high



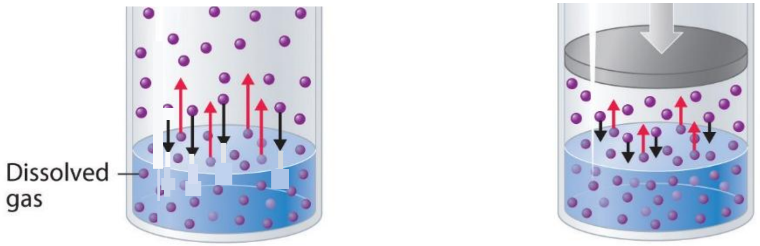
Measures to reduce odorous nuisances

- minimize free-fall turbulence
- reduce overloading of plant processes
- increase aeration rate of biological treatment processes
- increase plant treatment capacity
- reduce solids storage
- increase sludge pumping frequency
- control release of aerosols
- increase disposal frequency of screenings (and grit)



Measures to reduce odorous nuisances

- covering or enclosing of odour-producing sub-units (e.g. screening and grit and grease removal units, sludge treatment train)
  - reduction of odours due to reduced exchange with fresh air (water-surface desorption : Henry's law)



  - problematic for workplaces (e.g. sludge treatment)
  - nuisances to employees and neighbours
  - cheap and no treatment unit to operate

➡ limited air renewal only in spaces where workers rarely have to go (corrosion can become a problem (e.g. H_2S))

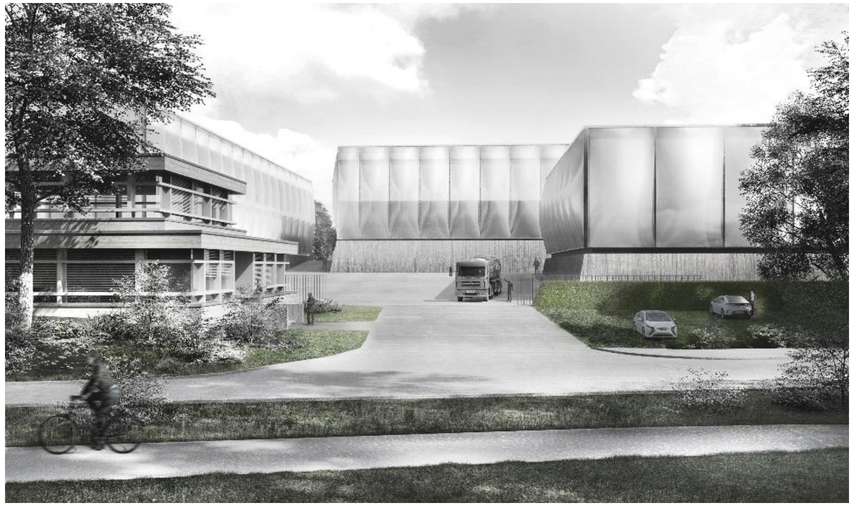
Measures to reduce odorous nuisances

- enclosing of odour-producing sub-units with air treatment
  - enclosing of screening and grit and grease removal units, sludge treatment train
  - slight vacuum assures that bad odours do not leave sub-units
  - fresh air supply to reduce odours within buildings
  - odours are removed to waste air treatment process
  - reduced nuisances to employees and neighbours
  - air treatment unit to operate

➡ medium to large treatment plants; not too close to residential areas

Measures to reduce odorous nuisances

- enclosing of the whole treatment plant
  - enclosing of all sub-units including secondary and tertiary treatment sub-units
  - slight vacuum assures that bad odours do not leave treatment plant
  - fresh air supply to reduce odours within buildings
  - odours are removed by waste air treatment process
  - reduced nuisances to employees
  - strong reduction of nuisances to neighbours (olfactory, visual → psychological)
  - air treatment unit to operate
  - higher investment costs



➡ medium to large treatment plants;
within or close to residential areas

How much air should be treated

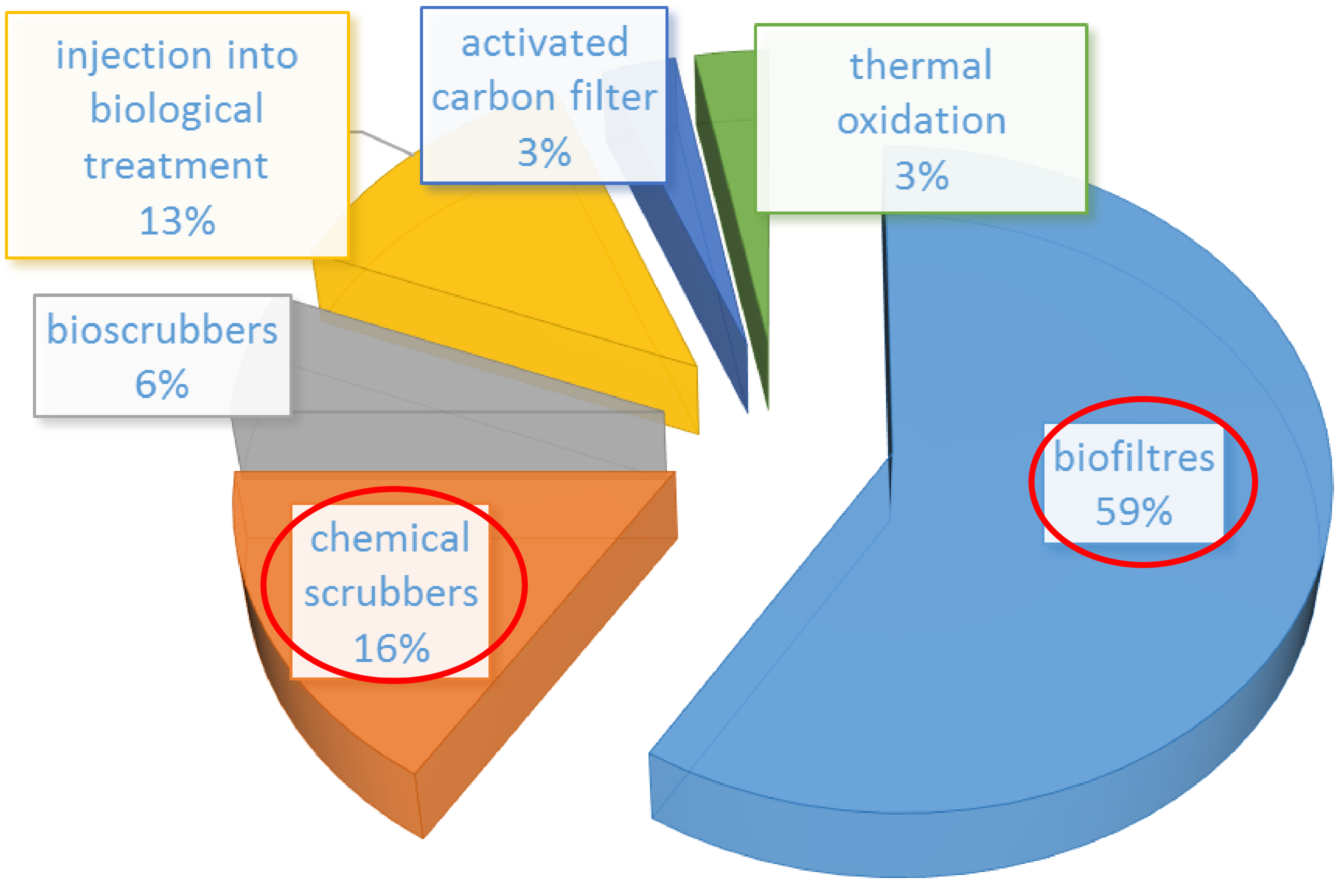
- rather difficult to make a clear estimate; depends on
  - wastewater composition
  - treatment processes (water treatment processes, sludge treatment train)
  - working places or not
  - …
- as a general simple rule

accessible or not?	workplace or not?	air exchange rates
not accessible	no workplace	3 – 4 times/hour
accessible	no workplace	4 – 6 times/hour
accessible	workplace	6 – 12 times/hour

Processes to remove odorous compounds

principle of process	possible processes
biological (oxidation)	biofiltre
	Injection into biology
	biotrickling filter/bioscrubbers
chemical (oxidation or binding)	chemical scrubber
	thermal oxidation
	catalytical oxidation
physical	adsorption
	absorption

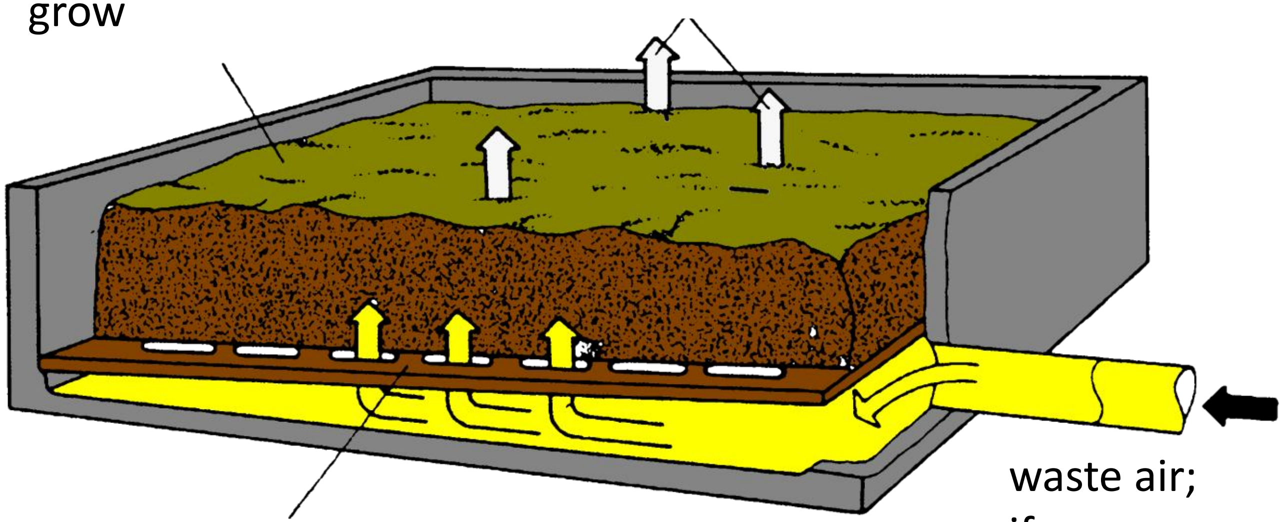
Processes to remove odorous compounds



processes used for emission control in German wastewater treatment plants (1990)

Biofiltre

- sorption into moist surface biofilm layer (absorption)
- bioconversion: microorganisms oxidise odorous compounds
- active microorganisms: bacteria and fungi



Biofiltre

- filter materials used
  - natural materials (compost, peat, and variety of synthetic mediums)
- bulking material to maintain porosity of filter material (wood chips, bark, and a variety of ceramic and plastic materials)
- bacteria and fungi grow on filter material
  - odorous compounds are adsorbed or absorbed by wet surface of filter material
  - biological oxidation of odorous compounds

mixture of fibrous peat and heather

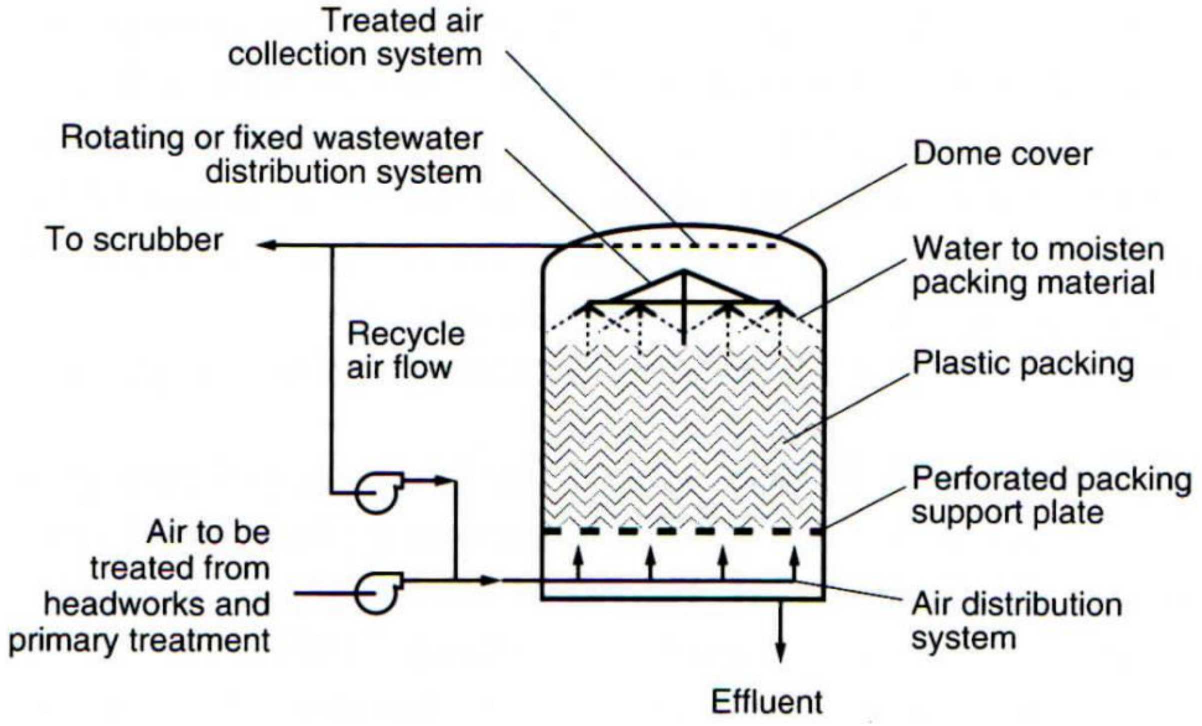
root wood

Essential environmental conditions for biofiltres

- **moisture content**
  - allows microorganisms to grow
  - too high moisture content will restrict air flow and anaerobic conditions may develop
- pH value
  - adapted to microorganisms (not too basic nor acidic)
- oxygen content
  - necessary for microorganisms to oxidise odorous compounds
- **temperature**
  - impacts growth of microorganisms
- nutrients
  - necessary for microorganisms to grow

Biotrickling filters/Bioscrubbers

- similar to chemical scrubbers and biofiltres
- contain packing material and moisture is provided (liquid is recirculated)
- water or water/sludge is brought in contact with waste air to remove odorous compounds
- biological system is used to oxidise odorous compounds



Typical design parameters for biological air treatment

- empty bed residence time in filter/scrubber (EBRT)

$$EBRT = \frac{V_f}{q}$$

- and residence time (RT):

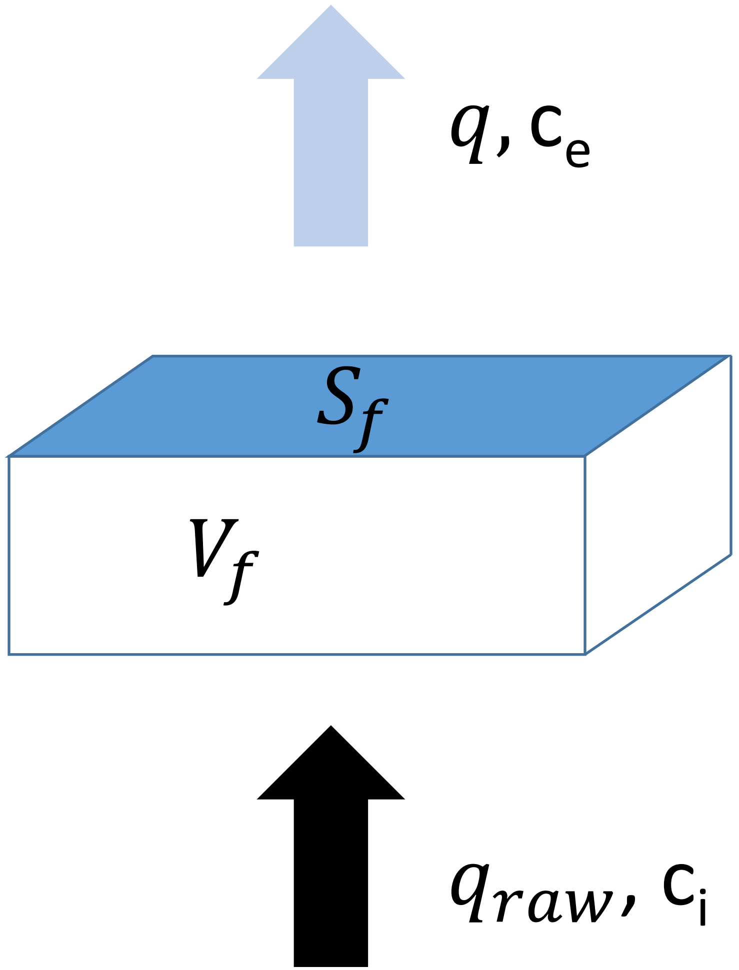
$$RT = \frac{V_f \times \propto}{q}$$

where V_f is the total volume of the filter/scrubber bed (m^3), q the volumetric flowrate (m^3/h) and α the porosity

- surface loading rate (SLR):

$$SLR = \frac{q}{S_f}$$

where S_f is the surface of the filter



Typical design parameters for biological air treatment

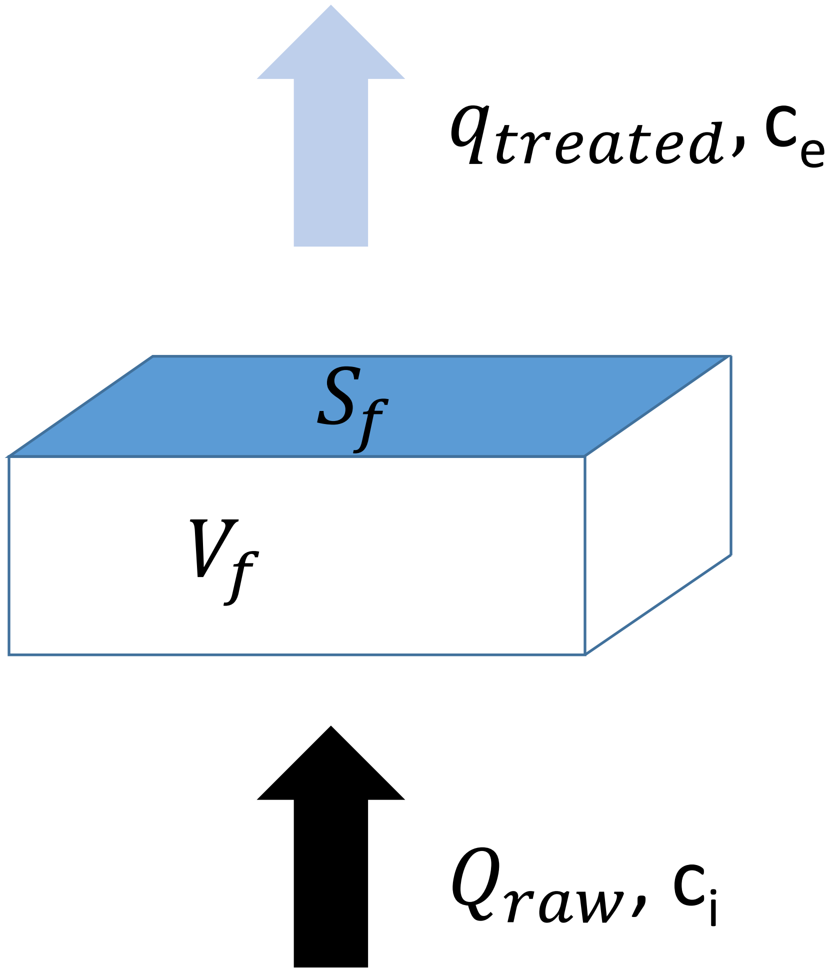
- elimination capacity (EC):

$$EC = \frac{q(c_i - c_e)}{V_f}$$

where c_i is the influent concentration in the air and c_e the effluent concentration in the air

- removal efficiency (RE):

$$RE = \frac{(c_i - c_e)}{c_i} \times 100\%$$



Typical design parameters for biological waste air treatment

parameter	units	biofiltres	biotrickling filters
optimum temperature	°C	15 – 35	15 – 35
moisture content	%	50 – 65	50 – 65
pH	unitless	6 – 8	6 – 8
porosity	%	35 – 50	35 – 50
surface loading rate	$m^3/(m^2 \cdot h)$	50 – 100 (up to 200 possible depending on compound)	10 – 100
depth of medium	m	0.6 – 1.25	1 – 1.25
liquid application rate	$m^3/(m^2 \cdot d)$		0.75 – 1.25
elimination capacity (H_2S)	$mg/(m^3 \cdot h)$	80 – 130	80 – 130
elimination capacity (other odorous gases)	$mg/(m^3 \cdot h)$	20 – 100	20 – 100

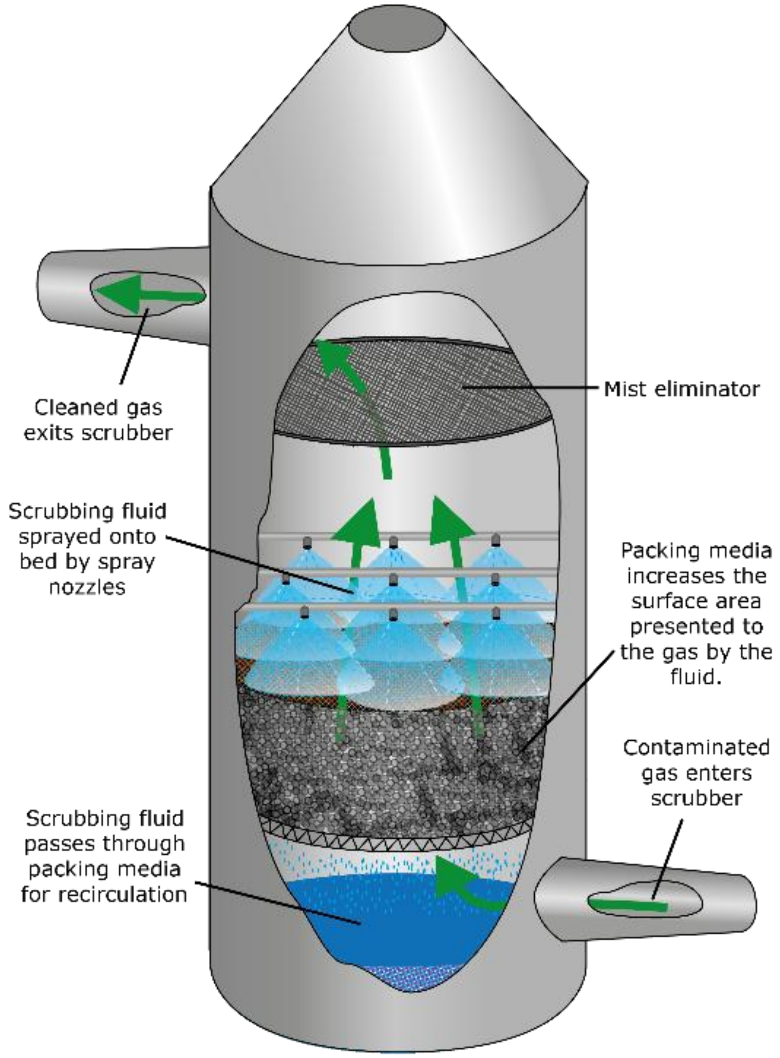
Injection into biological treatment

- waste air injected into biological tank
    - waste air equal or less than air requirements of biology
- odorous compounds are oxidized by bacteria in biology
- high-rate corrosion may be a problem to air pipes and blowers due to the presence of moist air containing hydrogen sulfide
- ability to transfer odorous compounds to the liquid phase may be difficult (nonpolar compounds)

Chemical scrubbers

- absorption of odorous compounds by water containing chemicals

Name	way of functioning	spray chamber
packed tower	water is sprinkled over a bed of packing media (high surface area) and waste air travels through support	packing media may get clogged
spray chamber	water is sprayed as fine droplets (surface area increase) over waste air flow	energy demand to produce fine droplets of water; short retention time or high towers



Chemical scrubbers

chemical binding of odorous compounds in water

- acid towers:

$$NH_3(gas) + H_3O^+ \rightleftharpoons NH_4^+(ion) + H_2O$$

- basic towers:

$$H_2S(gas) + OH^- \rightleftharpoons HS^-(ion) + H_2O$$

- wastewater containing odorous compounds may be returned to the water treatment where they will be biologically degraded (attention when mixing acid and bases!)

Chemical scrubbers

oxidation of odorous compounds in water

- oxidant (chlorine, hydrogen peroxide, ozone,…)

Oxidizer

$$H_2S + 4NaOCl + 2NaOH \rightleftharpoons Na_2SO_4 + 2H_2O + 4NaCl$$

  - odorous compound + oxidant → oxidized compound (generally more soluble)
  - pH must be kept constant (impact on redox potential)
  - chlorine based oxidants produce chlorine containing compounds (e.g. chlorinated hydrocarbons) and may cause ‘swimming pool’ odours

Efficiency of chemical scrubbing

- typical removal efficiencies for single-stage chemical scrubbers (hypochlorite wet scrubbers)
- higher efficiencies may be achieved with multi-stage scrubbers

gas	expected removal efficiency [%]	
	range	typical
hydrogen sulphide	90 – 99	98
ammonia	90 – 99	98
sulphur dioxide	90 – 96	95
mercaptans	85 – 92	90
other oxidisable compounds	70 – 90	85

Typical design parameters for chemical scrubbers (with packing)

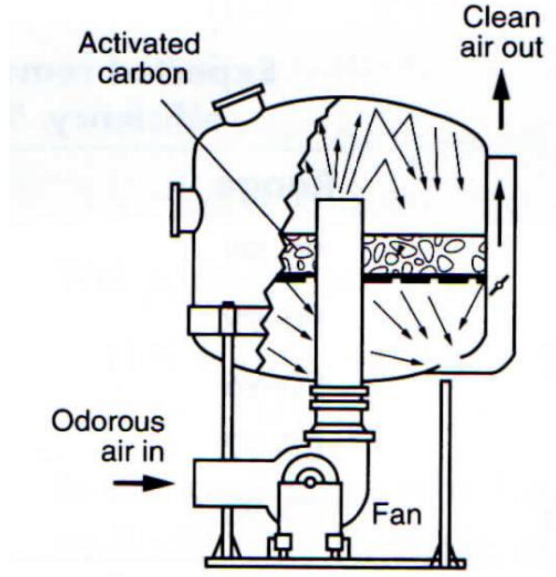
item	unit	value
packing depth	m	1.8 – 3
waste air residence time in packing	s	1.3 – 2.0
scrubbant flow rate	kg H_2O/kg waste air flow	1.5 – 2.5
scrubbant flow rate	L/s per m^3/s air flow	2 – 3
temperature	°C	15 – 40
caustic usage kg NaOH/kg sulphide	kg NaOH/kg sulphide	2 - 3

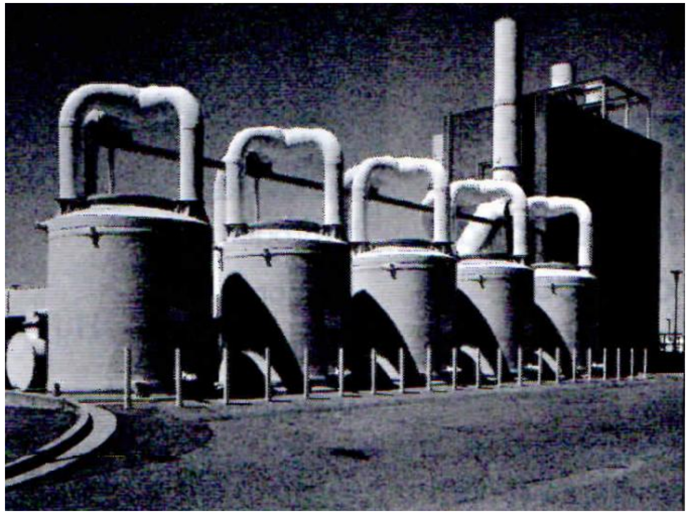
- scrubbant: liquid that circulates in scrubber and removes odorous compounds
- scrubbant flow rate: volume of scrubbant injected/recirculated into scrubber

Adsorption on activated carbon

- odorous compounds are adsorbed on activated carbon
- activated carbon is non-polar and hence adsorbs non-polar compounds more efficiently than polar ones: e.g. hydrocarbons
- compounds are not destroyed but only removed from waste air
- saturated activated carbon may be regenerated and thereafter reused

- activated carbon works fine for air with a well-defined composition (preliminary trials to identify ideal activated carbon)





Other techniques

$$H_2S(gas) + 2O_2(gas) \rightarrow H_2SO_4(vapour)$$

$$CH_4(gas) + 2O_2(gas) \rightarrow CO_2(gas) + 2H_2O(vapour) + \text{heat}$$

- thermal oxidation
  - waste air is oxidized at high temperatures (> 800 °C)
  - only reasonable if oven already existing (external heat necessary to keep oven hot)
- catalytical oxidation
  - temperatures of thermal oxidation are reduced due to the presence of a catalyst (310 – 425 °C)
  - catalysts typically include platinum, palladium, and rubidium
  - catalysts can become fouled (avoid particulate material or constituents that will result in a residue)
- Dry ozonation
  - ozone (gas) is used to directly oxidize odorous compounds (rarely used in WWTP)

Processes to remove odorous compounds

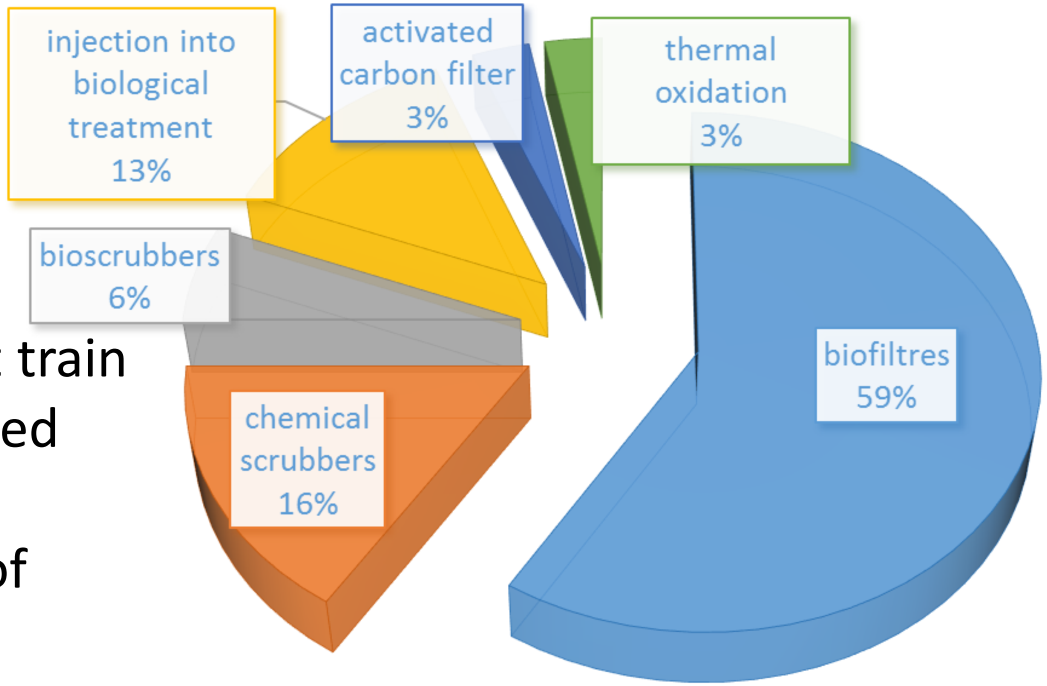
- easy and cheap
- efficiency difficult to control

- efficiency very variable
- small installations (e.g. pumping stations)

often too expensive (heating)

- second biology
- relatively complex

- often complex treatment train
- each step can be controlled (chemistry)
- removal of a vide range of compounds
- ideal for mid-range to large treatment plants



- simple to operate
- removal of a vide range of compounds
- difficult to control (biology)
- large surface-area (footprint)
- ideal for small to mid-range treatment plants

Air emission control II: Emission of greenhouse gases (GHG)

Applied wastewater engineering

Michael Jon MATTLE

Emission of greenhouse gases (GHG)

- based on the Kyoto Protocol, the following six greenhouse gases are usually considered:

greenhouse gas	global warming potential (GWP)*
carbon dioxide (CO_2)	1
methane (CH_4)	25
nitrous oxide (N_2O)	265
hydrofluorocarbons (HFCs)	12-11’700
perfluorocarbons (PFCs)	6’500-9’200
Sulfur hexafluoride (SF_6)	23’900

- * in average over the next 100 years
- CO_2, CH_4 and N_2O are produced at wastewater treatment plants

Emission of greenhouse gases (GHG)

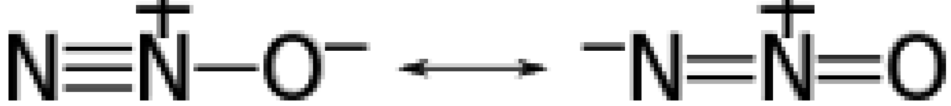
- CO_2 (not counted as carbon is coming from primarily renewable sources)
  - oxidation of organic material by bacteria
  - denitrification
  - combustion of digester gas
- CH_4
  - gas losses after anaerobic digestion (e.g. sludge storage)
  - anaerobic degradation in the sewer or receiving water
- N_2O
  - biological nitrogen transformations (mainly during wastewater treatment but also in sewer and the receiving water
- receiving water body will also produce N_2O and CH_4 if wastewater treatment is not complete (carbon and nitrogen removal)

Methane (CH_4) from wastewater

- WWTPs contribute to approximately 5 % of worldwide methane emissions
- methane formed in absence of oxygen and presence of organic matter
- methane emissions happen:
  - In sewer systems (especially if high hydraulic retention times, low O_2 and high temperatures)
  - during sludge processing after anaerobic digestion (e.g. methane loss during sludge storage)
  - methane loss after anaerobic treatment step in wastewater treatment line (mainly applied in hot climates or industrial wastewater)

→ most importantly: avoid methane leakage by covering the sludge storage tank and extracting methane

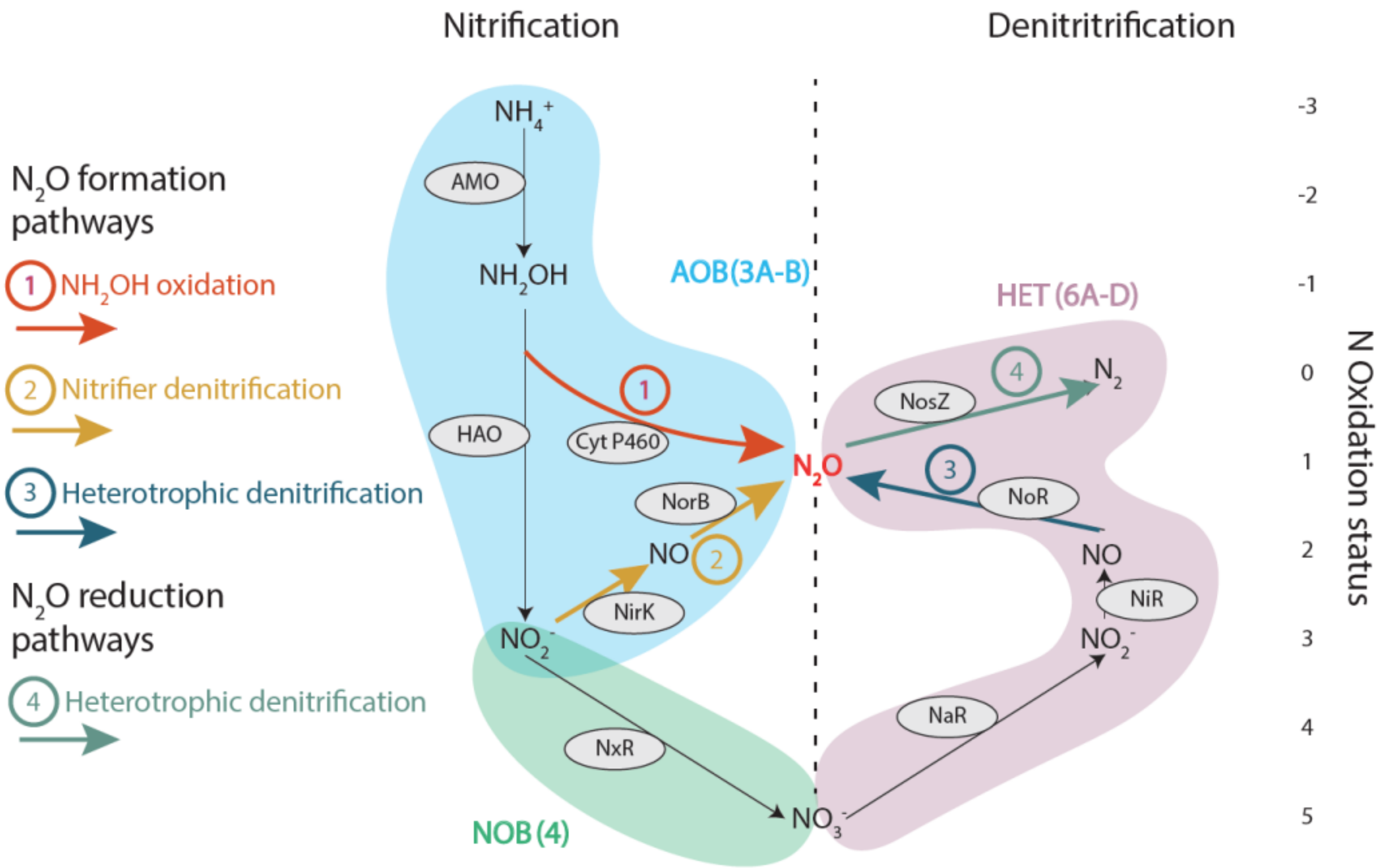
Nitrous oxide (N_2O) from wastewater



- nitrous oxide is commonly known as laughing gas
- up to half or more of greenhouse gas emissions from wastewater facilities
- Most important ozone-depletion substance
- N_2O from WWTP: 0.3 – 1.4 % of Swiss greenhouse gas emissions
- large differences of emissions between different installations: from 0.1 to 3 percent of influent nitrogen (up to 15 percent measured)
- formed during wastewater treatment and sludge incineration

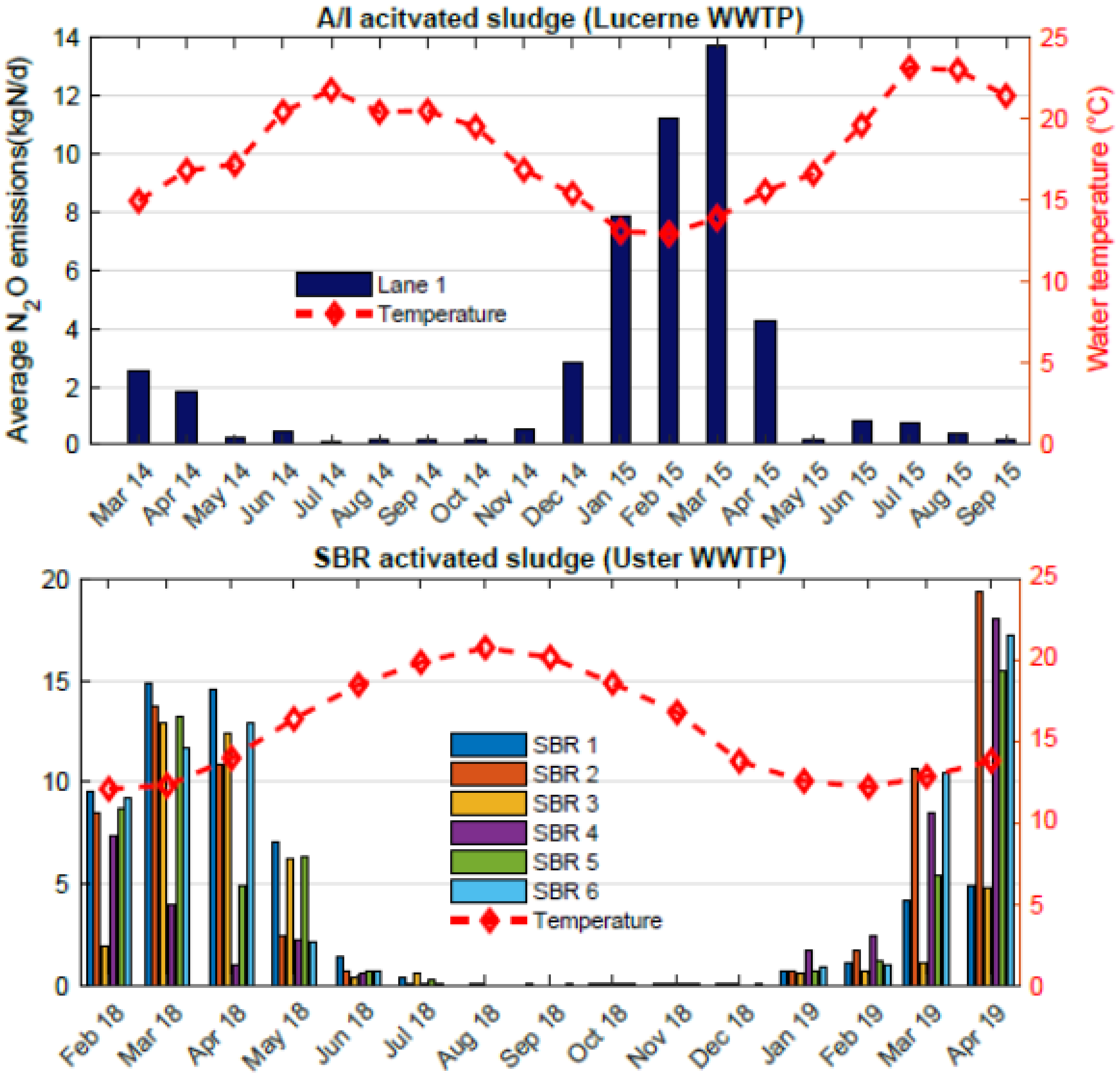
Pathways of N_2O-formation in WWTP

- pathways of N_2O-formation are highly complex and not yet fully understood
- N_2O can be formed during nitrification and also during denitrification
- normally, aerated zones emit more N_2O than anoxic zones (stripping effect)
- generally, N_2O-formation is strongly linked with nitrite accumulation in the wastewater



N_2O-formation is highly dynamic

- N_2O-formation is highly dynamic:
  - during the year
  - during a month
  - and even during a day
- reasons for the dynamic behaviour are not always the same and may depend on various factors
- modelling N_2O-emissions without measurements is not yet reliable
  - measurement campaigns are necessary to estimate emissions of a WWTP
  - measurements need to be conducted over a long period of time (e.g. one year) to be able to estimate emissions



Ways to reduce N_2O-formation

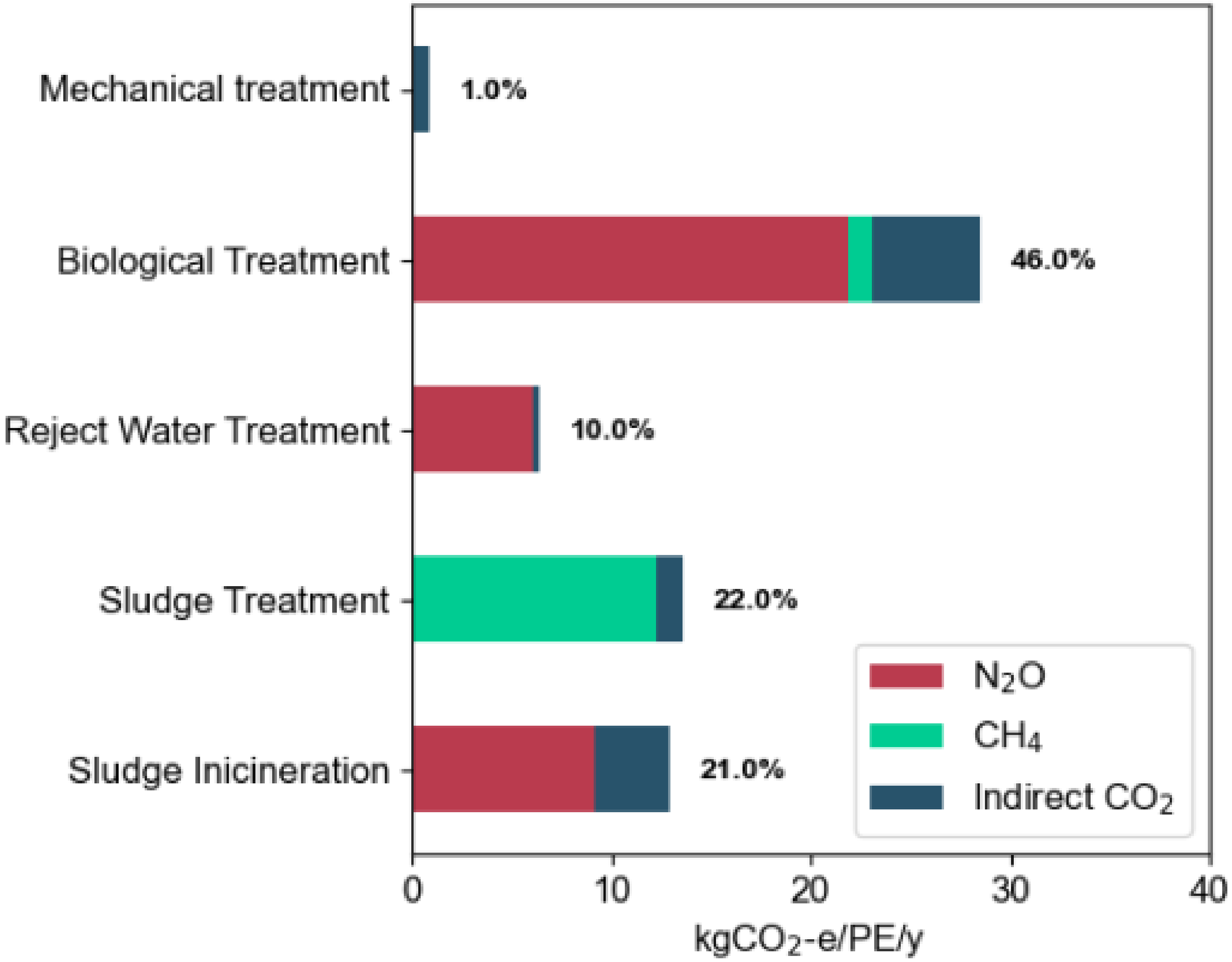
- avoid nitrite accumulation (nitrite is a toxic substance if protonated (nitrous acid)):
  - higher sludge age: higher microbial diversity and process-stability
  - better process control
  - control sludge floc: during sludge floc decay nitrite-oxidising bacteria (NOB) can be lost
  - avoid substances in wastewater that inhibit NOB (e.g. industrial sources but often difficult to find)
- install a permanent denitrification zone (this also helps to avoid a too strong pH drop which may also enhance N_2O-formation)
- add centrate only when sufficient carbon is available for denitrification (e.g. avoid addition of centrate at night when little COD enters the WWTP)

Ways to reduce N_2O-formation

- inject sufficient oxygen in aerated basins
- avoid uncontrolled nitrification (in only C-treating WWTP)
- avoid high-peaks in ammonium-concentrations (transient conditions) or high-rate processes: less compact processes like activated sludge treatment have lower peaks due to dilution in the basins
- install off-gas treatment of high-rate centrate treatment processes (e.g. Annamox)
- remove laughing gas from off-gas of sludge incineration

Greenhouse gases emission from WWTP

- Modelled GHG emissions (by Gruber et al.) for WWTP with 100'000 PE with European electricity mix:
  - biological treatment step is most important contributor due to laughing gas formation
  - indirect CO_2 due to electricity mix is rather small (even smaller with Swiss electricity mix)
  - sludge treatment is also important if methane is lost and laughing gas is not removed after incineration



Greenhouse gas reduction at WWTP

improvements in solids removal (higher methane production in digester), but less carbon for denitrification!

optimise or adapt biological treatment process to limit laughing gas production

dosage of centrate only if sufficient carbon is entering WWTP

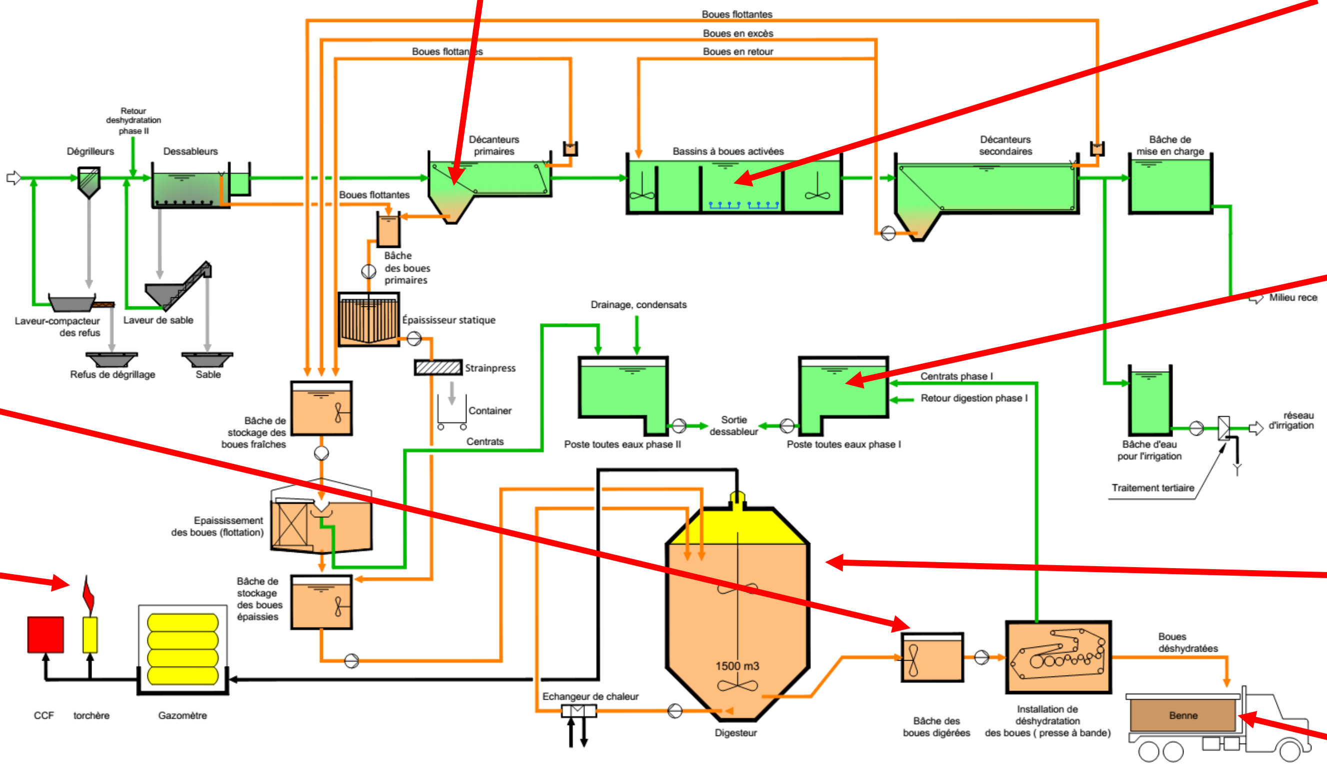
Treat off-gas from centrate treatment (if existing)

enhanced digester gas production

Remove laughing gas from sludge incineration

elimination of unaccounted and un-combusted methane emissions

complete utilisation of digester gas



Opportunities for energy consumption and (minor) GHG reduction at WWTP

selection of processes requiring less oxygen (e.g. denitrification)

- control of dissolved oxygen
- control of aeration with NH_4-N monitoring (stop aeration system if not needed)

energy efficient mixing system

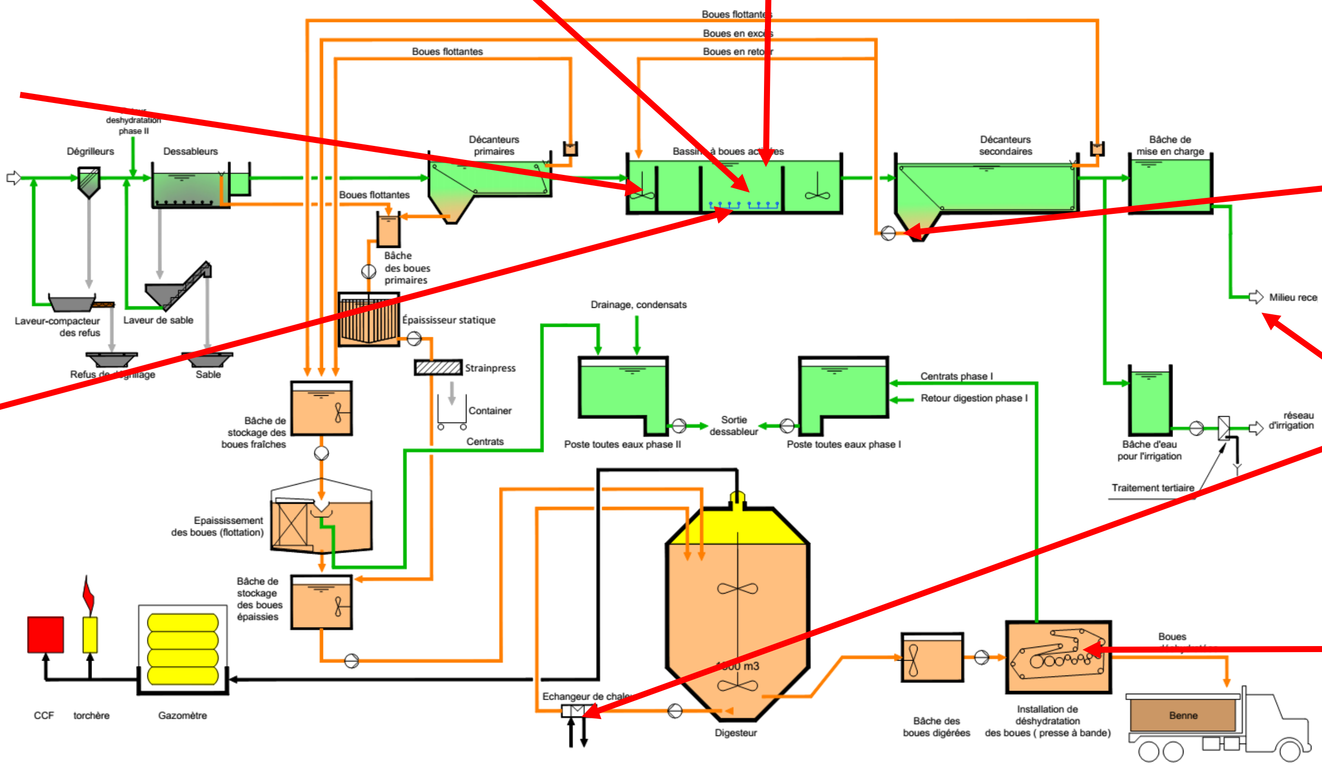
diffusers with high oxygen transfer efficiencies

selection of blowers or combination of blowers with high efficiencies and sized to allow operation in high efficiency range

pump efficiencies

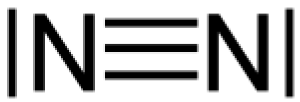
heat recovery

optimisation of sludge thickening and dewatering



Emissions from combustion of gases

- carbon monoxide (CO)
  - due to incomplete combustion
  - complete oxidation: at temperature of 850°C or above and combustion time of 3 s or longer
  - post-combustion catalytic oxidation system ($CO + {}^{1}/_{2}\, O_2 \rightarrow CO_2$)
- NO_x
  - combustion at high temperatures (1200°C)
- SO_2
  - presence of sulphur in fuel
  - removal of sulphur before combustion
- particulate matter
  - incomplete combustion of organic matter
  - inorganic fraction: salts and metals
- hazardous pollutants such as formaldehyde
  - incomplete combustion



strong bond only broken with high activation energy

$$SO_2 + {}^{\cdot}OH \rightarrow HOSO_2^{\cdot}$$

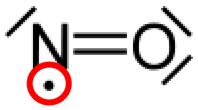
$$HOSO_2^{\cdot} + O_2 \rightarrow HO_2^{\cdot} + SO_3$$

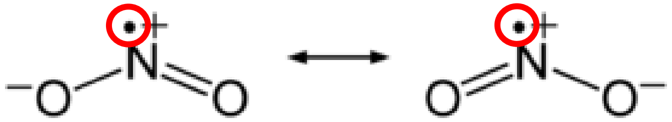
$$SO_3 + H_2O \rightarrow H_2SO_4$$

acid rain

The problematic of NO_x

- both are radicals





- in the atmosphere NO is rapidly oxidised to NO_2
- NO_2 is a toxic air pollutant and a contributor to smog
- Additionally, NO_2 reacts with $^{\cdot}OH$ to from nitric acid (acid rain)

$$NO_2 + \ ^{\cdot}OH \rightarrow HNO_3$$

average NO_2 concentrations of 2014 produced by NASA: www.nasa.gov/

The problematic of NO_X

- Combined heat and power (CHP) turbines operate at high temperatures and produce NO_x
- hence, they might need a selective catalytic reduction of NO_x

$$4NO + 4NH_3 + O_2 \xrightarrow{catalyst} 4N_2 + 6H_2O$$
$$2NO_2 + 4NH_3 + O_2 \xrightarrow{catalyst} 3N_2 + 6H_2O$$
$$NO + NO_2 + 2NH_3 \xrightarrow{catalyst} 2N_2 + 3H_2O$$

- The flaring of digester gas should be controlled at temperatures between 850 to 1200°C to avoid the formation of NO_x

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Thanks for their help

- Wenzel Gruber