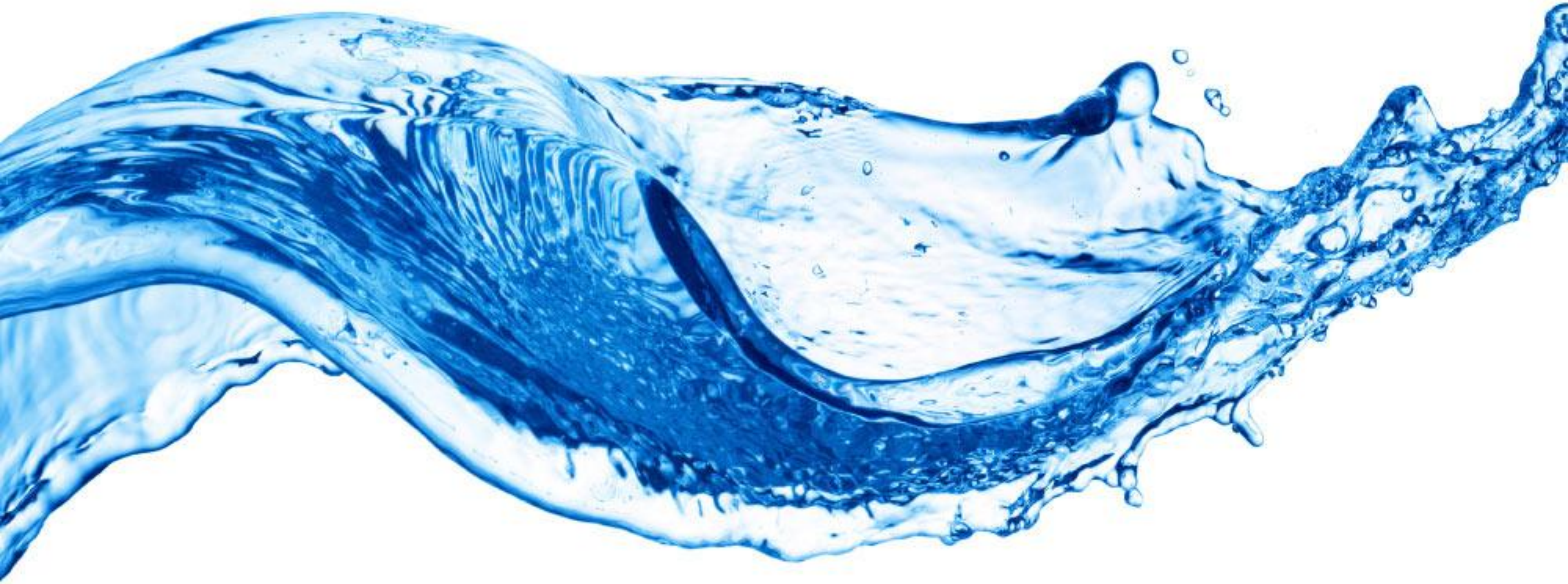

Modern water disinfection methods

Heikki Pulkkanen, M.Sc. (Chemical engineering)

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SUMMARY OF PRESENTATION

Modern water disinfection methods

- Needs and targets of disinfection
- Disinfection technologies and properties
- Peracetic acid in water disinfection
- Introduction of PACS8 System
- Disinfection results with PACS8 System
- Investment and maintenance costs of disinfection

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PURESTAQUACLEANINGSOLUTION

Water safety: water source, treatment, distribution network

- Water safety
  - Quality of raw water
  - Water treatment
  - Distribution network

Multi-barrier thinking: water disinfection is the final barrier to stop existing microbes to enter into water system

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Why post-disinfection of waste water?

- Harmful microbes such as coliforms cause infections and spoilage of water resources
- STP plants are often located near to drinking water sites and swimming areas
- Especially rivers, lakes etc have several activities near to wwtp
- Water resources are getting more limited in future
- Reuse of water become more important
- Legislation requires improved water safety

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Indicator organisms in raw water treatment

- ***E. coli*, *Enterococci,* coliform bacteria*:*** indicators of faecal contamination (e.g. leaks of wastewater).
- ***Clostridium perfringers***: bacterium which forms very resistant spores. Chemical coagulation should remove *C. perfringers*.
- **Heterotrophic bacteria, heterotrophic plate count:** represents general microbiological quality of water. Very non-specific.
- **Coliphages**, viruses that parasizite on colibacteria, presence of coliphages indicates presence of other viruses as well.

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Relevant target organisms in waw water treatment:

- ***Campylobacter spp.***: Faecal bacterium, very small infective amount, doesn't reproduce outside host animals.
- ***Mycobacterium spp.***: Bacterium living in cold water, resistant against conventional disinfection.
- ***Legionella pneumophila*.**: bacterium living in amoebas which live in biofilms, prefers temperatures 30 – 37 ºC, causes pneumonia.
- **Norovirus**: RNA virus, causes 90 % virus originated diarrhea cases, human can't develop immunity.
- **Rotavirus**: very common diarrhea causing virus with children, immunity develops after illness.
- ***Cryptosporidium* spp., *Giardia lambia***: protozoa, very small infective amount (one specimen is enough), resistant to conventional disinfection.

Some generally used indicator organisms in waste water treatment

- ***Escherichia coli***: indicates fresh faecal contamination
- ***Enterococcus faecalis*** and other ***Enterococci***: indicates faecal contamination but non-intestinal species complicate interpretation
- **Faecal coliforms**: indicates typically surface water run-off to wells and groundwater
- **Coliphages**: virus parasitizing on *E. Coli*, indicates presence of enteric viruses, abundant in waste water (easy to analyse compared to other viruses)

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Why indicator organisms?

- Are used instead of the actual pathogenic organisms
- Reason: easier, cheaper and faster to analyze
- Indicator organisms behave similarly to pathogenic organisms in disinfection
- Indicators are not harmful to humans but indicating the microbiologial quality
- However, indicator organism don’t always give correct assesement of the situation: during a water epidemic indicator organism levels can be OK but there are still infections

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PACS PUREST AQUA CLEANING SOLUTION

What are the actual target organisms?

spores > protozoa (cysts) > viruses > bacteria

Most resistant to disinfection

Generally easiest to disinfect

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Bacteria removal during regular wastewater treatment (Source: Wastewater engineering, Treatment and Reuse, 2004)

Process	Percent removal (bacteria)
Coarse screens	0 – 5
Fine screens	10 – 20
Grit chambers	10 – 25
Plain sedimentation	25 – 75
Chemical Precipitation	40 – 80
Activated sludge	90 – 98

→ This is not usually enough, additional disinfection is needed!

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Ideal disinfectant characteristics

(Source: Wastewater engineering, Treatment and Reuse, 2004)

- **No formation of disinfection by-products** (DBP)
- **Availability**: readily available and reasonable price
- **Deodorizing ability**
- **Homogeneity**: uniform composition
- **Should not be absorbed by organic matter other than bacterial cells**
- **Nontoxic to higher forms of life**
- **Penetration through surfaces**
- **Safety**: transport, store, handling and use
- **Solubility**: soluble in water or cell tissue
- **Stability**: low loss of germicidal action as a function of storage time
- **Toxicity to microorganism**
- **Toxicity at ambient temperatures**: also at low temperatures!

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Disinfection methods of raw water

- Chloramines
- Cl_2
- ClO_2
- Ozone
- UV
- Peracetic acid

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PUREST AQUA CLEANING SOLUTION

Modern / advanced waste water disinfection methods

- Peracetic acid (PAA): IN USE
- UV: IN USE
- UV / PAA: RESEARCH LEVEL
- UV / hydrogen peroxide: RESEARCH LEVEL
- Ozone: IN USE
- Ozone / hydrogen peroxide: RESEARCH LEVEL

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Why chlorine is not included in “advanced waste water disinfection methods”?

- Chlorine and its compounds are not considered “advanced” because:
  - Formation of toxic and carsinogenic disinfection-by-products (DBP)
  - Corrosion
  - Toxicity of the chemical (especially Cl_2 gas) and safety hazards
  - Increase of salinity in receiving water body

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Chloramines

- Chloramines:
  - NCl_3 (most effective but causes strong chlorine smell and taste to water)
  - $NHCl_2$
  - NH_2Cl (least effective)
- Formation: reaction between HOCl and ammonia.
- Not as effective as chlorine (e.g. HOCl).
- DBPs: organic chloramines, organic chloramides (not as much DBPs as with chlorine).
- Residual effect in distribution network = REASON FOR USE

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What kind of chlorine dosages should be used (residual concentrations)?

- WHO: max. 5 mg Cl_2 /l in continuous use.
- **Normal**: < 0,5 - 1 mg Cl_2 /l.
- **Water epidemic situation** 1 – 2 mg Cl_2 /l.
- **Shock chlorination** 10 mg Cl_2 /l (during night, water not drinkable).
- Odor treshold about 0,1 mg Cl_2 /l.
- Taste treshold about 0,3 mg Cl_2 /l.

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Ozone (O_3) in raw water treatment

- Produced *in-situ*, usually via electrical discharge method.
- Often used before AC filter -> Ozone decomposes organic material into biodegradable form.
- Contact times usually 10 – 20 min.

Benefits	**Negative aspects**
No additional taste or odor from disinfectant	Safety hazards, complex equipment
Good disinfection power	Disinfection by-products formation
	Increases AOC =Assimiliable organic carbon -> food for microbes

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Effects of temperature and pH on chlorine, ozone, ClO_2 and chloramines disinfection

Ct values at different pH and temperature (*Giardia Lamblia* 99,9 % destruction) (U.S. EPA 1989).

		Temperature			
	pH	**0.5 °C**	**5 °C**	**10 °C**	**15 °C**
Chlorine*	6	165	116	87	58
	7	236	165	124	83
	8	346	243	182	122
	9	500	353	265	177
Ozone	6 - 9	2.9	1.9	1.43	0.95
Chlorine dioxide	6 - 9	63	26	23	19
Chloramines	6 - 9	3800	2200	1850	1500

* Residual chlorine 2 mg/L.

Ct = Concentration * Contact time

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Ozone in waste water treatment

- Not widely used in waste water disinfection
- Produced *in-situ*, usually via electrical discharge method.
- Ozone decomposes to free radicals (HO_2 and HO)
- Disinfection mechanism is cell wall disintegration (cell lysis)
- Produces DPBs: brominated organic compounds (if bromine present) or aldehydes, ketones etc.

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Energy requirements of ozonation

Component	kWh / kg ozone
Air preparation (compressors and dyers)	4,4 – 6,6
Ozone generation (air feed)	13,2 – 19,8
Ozone contacting	2,2 – 6,6
Other	1,2 – 2,2

Total: 21 – 35,2 kWh / kg ozone
Typical dosing: 1 – 40 mg/l depending on wastewater

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Ozone / hydrogen peroxide (Peroxone)

- Advanced oxidation process (AOP)
- Two-step process:
  1. Ozone dissolution
  2. Hydrogen peroxide addition
- Aim is to enhance the formation of radicals
- Possible more effective than ozone itself
- Still at RESEARCH STATE.

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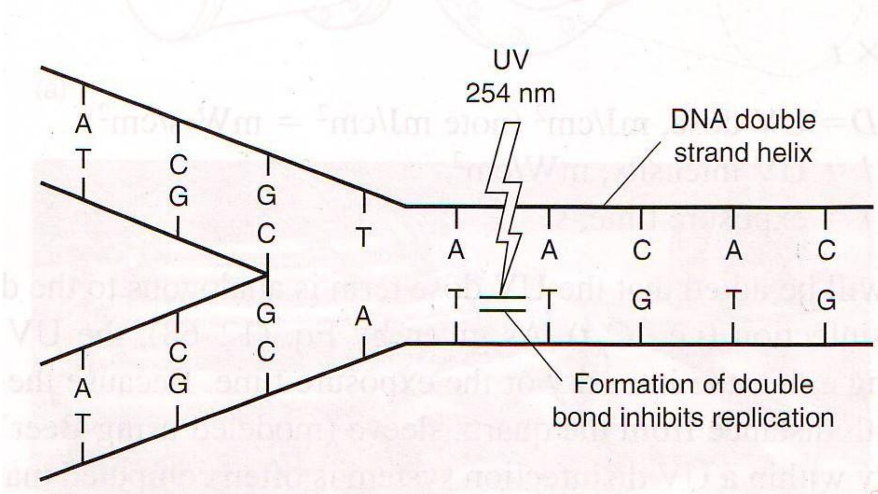
UV disinfection

- UV radiation: 100 – 400 nm, germicidal action: 220 – 320 nm. Water must have high transmittance in this region.
- Disinfection mechanism: damages DNA, inhibits replication
- Not lethal itself



(Source: Wastewater engineering, Treatment and Reuse, 2004)

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Emerging UV lamp technologies

- Pulsed energy broad-band xenon lamp
  - High temperature plasma is produced by pulsing UV radiation.
  - Spectrum includes UV, visible, IR wavelengths.
  - 20 000 times more intense as sunlight at sea level.
- Narrow-band excimer UV lamp
  - Excited dimers are produced and as they collapse, energy (radiation) is released. Radiation characteristics depend on used gas (e.g. Xe or Kr)
  - Very monochromatic radiation is produced (e.g. 172, 222 or 308 nm)

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UV in raw water treatment

- Effective against viruses, bacteria and protozoa
- Causes no smell or taste (no residual chemicals)
- No by-products
- No overdose risk
- <u>No residual disinfection effect in the water distribution system!</u>
- Water must have low turbidity, color and Fe. Otherwise UV loses its disinfection power due absorption and shielding.
- Recommended UV dosage generally: 40 mWs / cm^2 = 400 J / m^2

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Negative aspects of UV disinfection

- High investment and maintenance costs.
- Energy consumption (around 70 – 500 W / lamp)
- Re-activation of microorganisms after UV treatment: 21-52% of viruses and 1% of bacteria due to the UV radiation from the sun (independent university study).
- Color, turbidity, suspended solids decrease UV transmittance and disinfection efficiency.
- No odor control.

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Re-activation of pathogens after UV treatment

- UV treatment does not generally kill pathogens but only damages their DNA.
- For example, Linden *et al.* (2002) and Li *et al.* (2008) have studied reactivation of *Giardia Lamblia* after treatment with widely used low pressure UV lamps.
- Residual disinfection is needed in distribution network.

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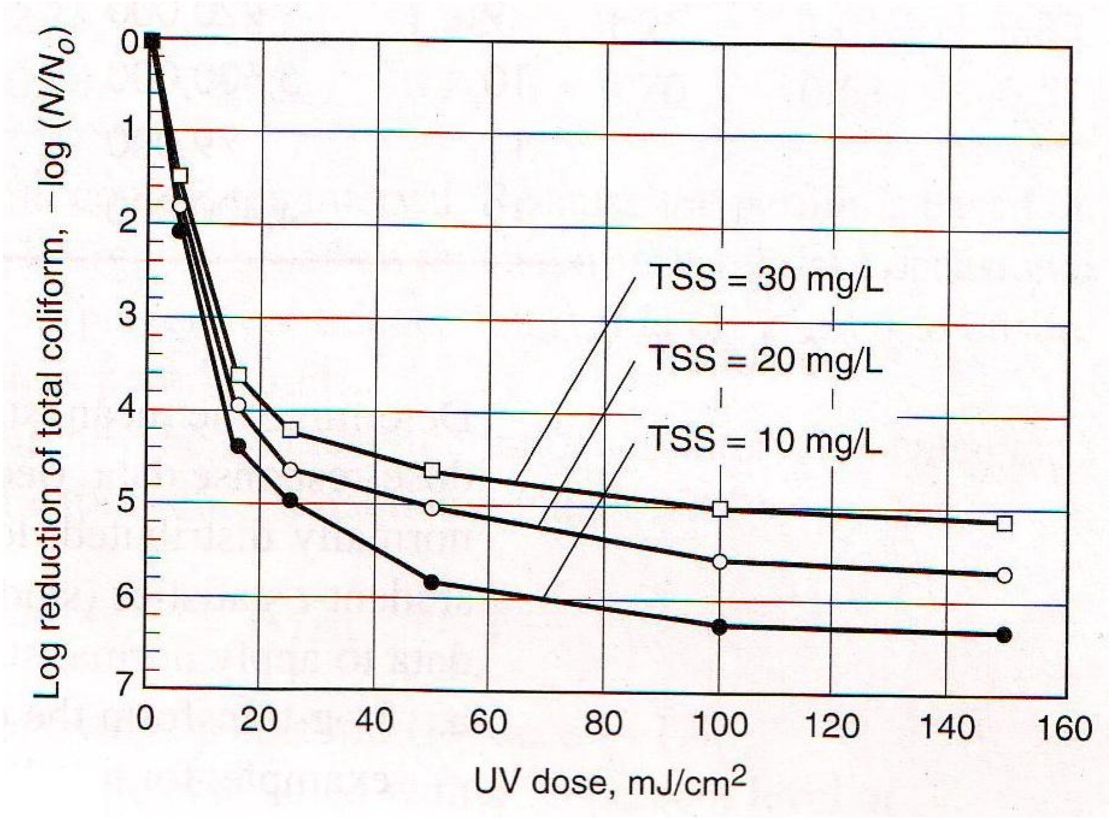
UV: effect of suspended solids



(Source: Wastewater engineering, Treatment and Reuse, 2004)

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UV of Fe and SS: a case example

- Wastewater included Fe about 3 mg/l and SS about 30 mg/l
  - → UV_{254} transmission only 32 %.
  - → also singnificant fouling effects.
- Fe absorbs UV radiation and fouls quartz sleeves.
- Source: Gehr, R., Wright, H. *Water Science and Technology*, 38, 15-23.

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UV / PAA

- Synergistic system still at RESEARCH LEVEL.

	UV (120 mW s / cm^2)	**PAA 4,8 ppm + UV (120 mW s / cm^2)**
E. Coli inactivation (log N_0/N)	3,1	3,7
Faecal coliforms inactivation (log N_0/N)	2,9	3,4
Total coliform inactivation (log N_0/N)	3,0	3,6

Lubello et al. *Wat Sci Tecnol: Wat. Supply*, 2002, 2, 205-212.

UV / hydrogen peroxide

- Hydrogen peroxide has relatively weak additional effect on wastewater disinfection

	UV (120 mW s / cm^2)	H_2O_2 4,8 ppm + UV (120 mW s / cm^2)
E. Coli inactivation (log N_0/N)	3,1	3,2
Faecal coliforms inactivation (log N_0/N)	2,9	2,8
Total coliform inactivation (log N_0/N)	3,0	3,1

Lubello et al. *Wat Sci Tecnol: Wat. Supply*, 2002, 2, 205-212.

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Application of peracetic acid (PAA) in raw water treatment

- Applications of PAA in raw water treatment.
  1. Raw water pretreatment
  2. Improvement of humic substances removal
  3. Reduction of odor, taste and color of drinking water
  4. Disinfection
- Controlled use of PAA is essential!
- PACS8 system allows correct and safe dosing of PAA chemical

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Peracetic acid (PAA)

- Available as stabilized equilibrium solution (PAA-% typically 5 to 15):
  - $CH_3COOH + H_2O_2 \leftrightarrow CH_3COOOH + H_2O$
- Widely used by food industry, paper mills and medical facilities as a disinfectant. FDA and EPA approved in the USA.
- Disinfection efficiency depends on water characteristics, dose, and contact time.
- No (harmful) disinfection by-products
- PAA can also oxidize DPB-type (disinfection by-product) compounds (e.g. aldehydes) and several other odor compounds (like mercaptanes), drug residues etc
- No re-activation of microbes after treatment

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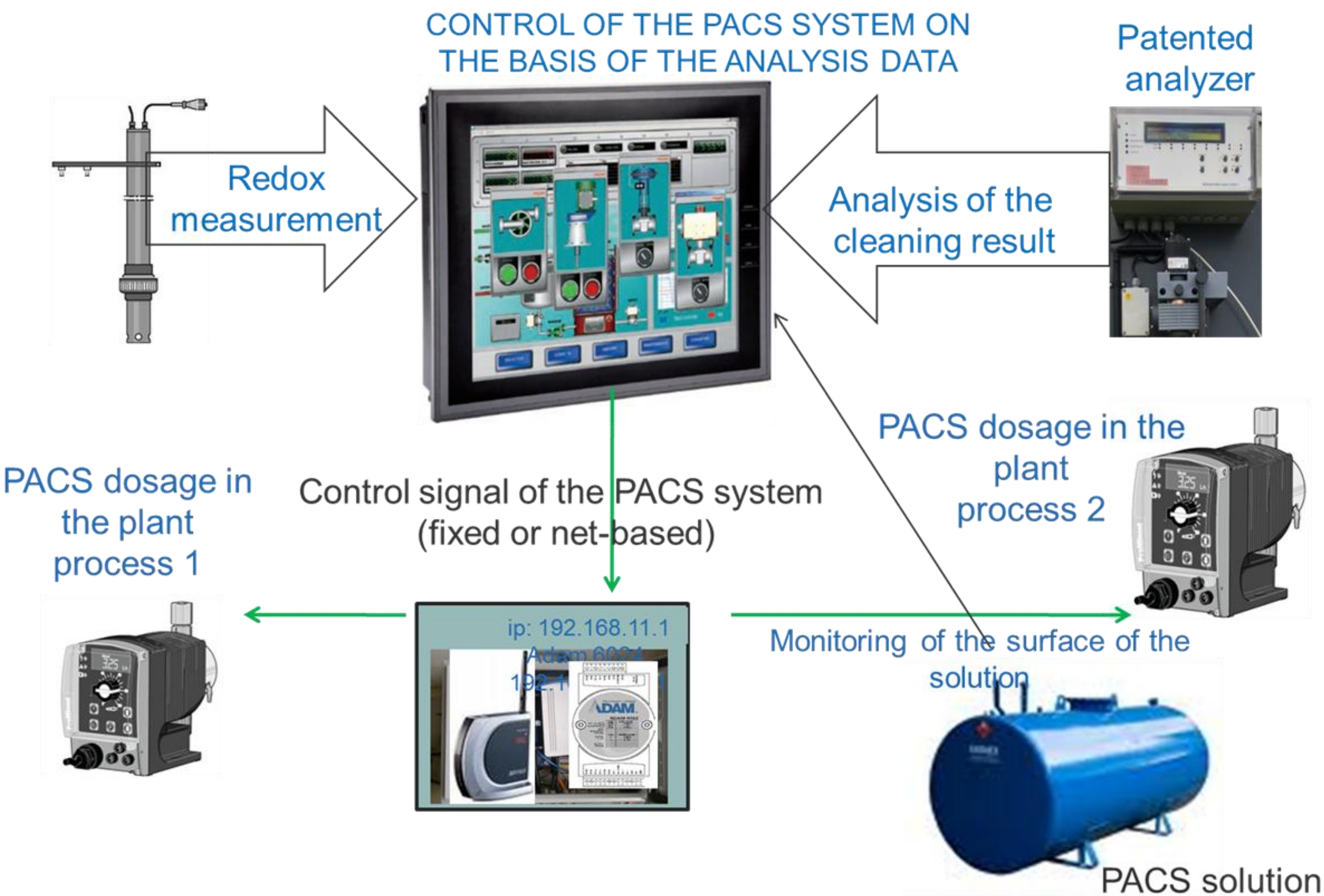
Controlled use of PAA: PACS8 -system in raw water pretreatment



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Raw water pretreatment with PAA

- Pretreatment of raw water before it enters water treatment process.
- Best suited for surface water.
- PAA can be used like chlorine is used in pre-chlorination.
- Goals: disinfection of bacteria and viruses and oxidation of organic material. Also optimization of rest of the water treatment process.

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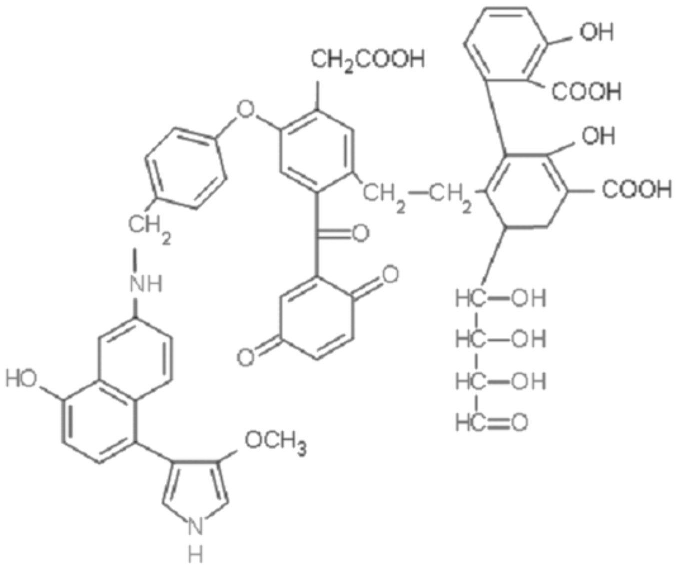
Improvement of humic substances removal

- Why is it important to remove?
  - Odour and taste problems
  - Formation of DBPs (disinfection by-products)
  - Health hazards: DBPs are carsinogenic



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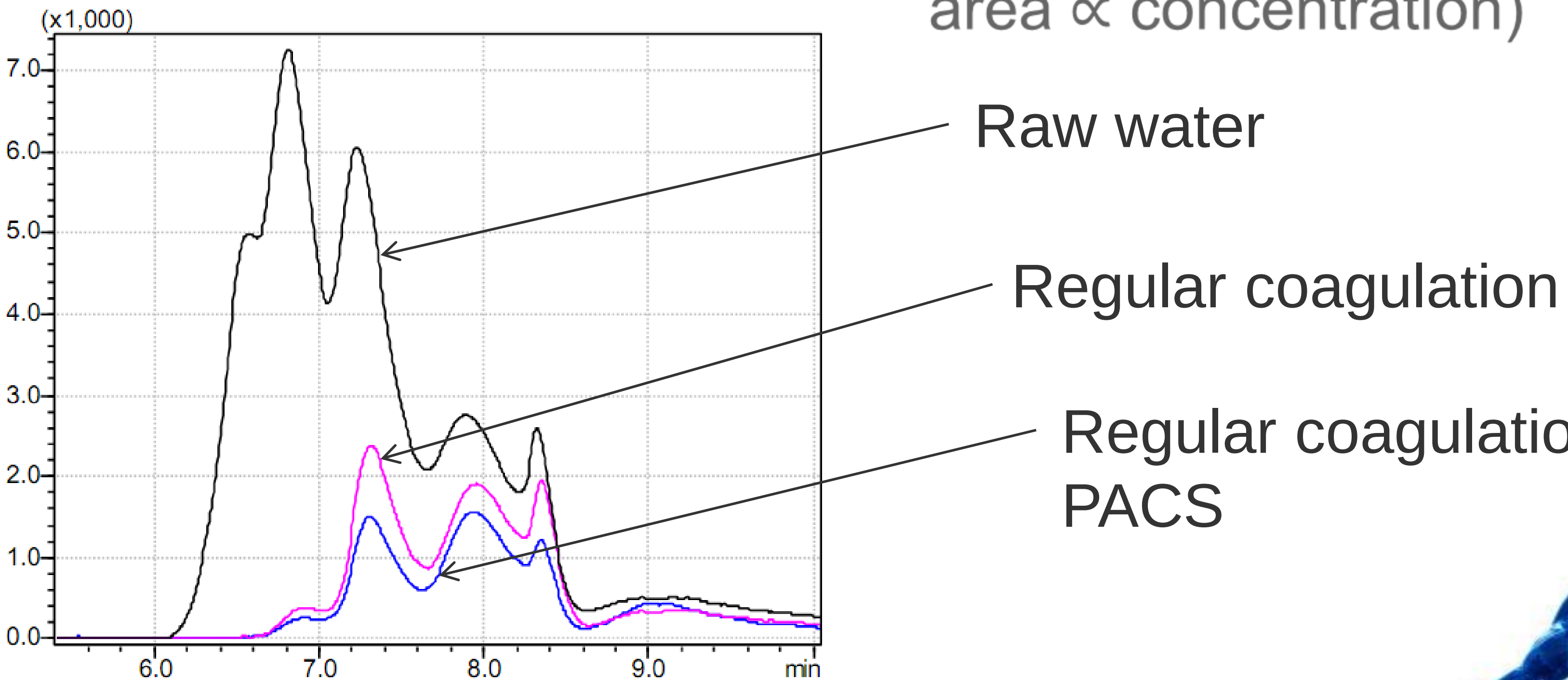
Improvement of humic substances removal

- High performance size exclusion chromatography (peak area ∝ concentration)



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Improvement of humic substances removal

- Coagulation process can be significantly improved with PAA.
- Improvement of humic substances removal is 30 %.
- Saving in coagulation chemical amount is 30 – 40 %.
- Works with ferric coagulants (Fe^{3+}).

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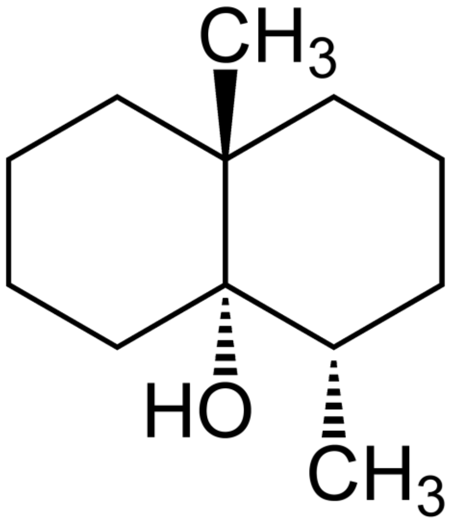
Improvement of odor, taste and colour of drinking water

- PAA can be applied to oxidation of odourous and taste causing compounds
- Oxidation of organic, odour causing compound geosmin with PAA has shown very promising results: 60 – 100 % with optimized process.



Structure of geosmin

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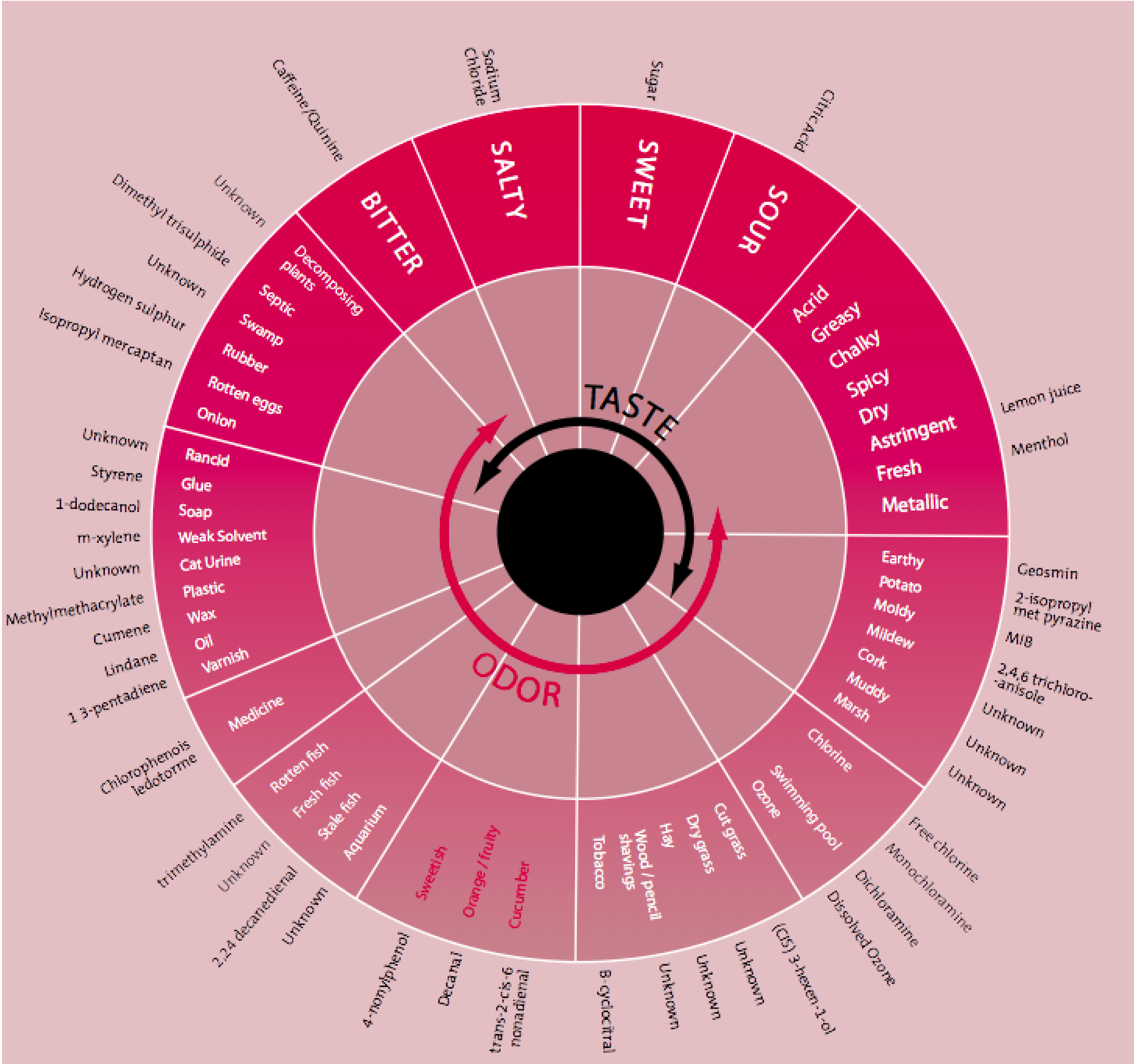
TASTE
ODOR
BITTER
SALTY
SWEET
SOUR
Acrid
Greasy
Chalky
Spicy
Dry
Astringent
Fresh
Metallic
Earthy
Potato
Moldy
Mildew
Cork
Muddy
Marsh
Chlorine
Swimming pool
Ozone
Cut grass
Dry grass
Hay
Wood / pencil shavings
Tobacco
Cucumber
Orange / fruity
Sweetish
Aquarium
Stale fish
Fresh fish
Rotten fish
Medicine
Varnish
Oil
Wax
Plastic
Cat Urine
Weak Solvent
Soap
Glue
Rancid
Onion
Rotten eggs
Rubber
Swamp
Septic
Decomposing plants
Caffeine /Quinine
Sodium Chloride
Sugar
Citric Acid
Lemon juice
Menthol
Geosmin
2-isopropyl met pyrazine
MIB
2,4,6 trichloro--anisole
Unknown
Unknown
Unknown
Free chlorine
Monochloramine
Dichloramine
Dissolved Ozone
(CIS) 3-hexen-1-ol
Unknown
Unknown
Unknown
B-cyclocitral
trans-2-cis-6 nonadienal
Decanal
4-nonylphenol
Unknown
2,2,4 decanedienal
Unknown
trimethylamine
Chlorophenols Iedotorme
1 3-pentadiene
Lindane
Cumene
Methylmethacrylate
Unknown
m-xylene
1-dodecanol
Styrene
Unknown
Isopropyl mercaptan
Hydrogen sulphur
Unknown
Dimethyl trisulphide
Unknown

At the source of water's flavour

Compound	Smell	Detection threshold	Emission source
GEOSMIN actinomycetes	earthy	4 ng/l	cyanobacteria and actinomycetes
2-METHYLISOBORNEOL (MIB	moldy	15 ng/l	cyanobacteria and actinomycetes
2-ISOPROPYL-3-METHOXYPYRAZINE	fermentation	0.2 ng/l	actinomycetes
CYCLOCITRAL	fruity	2,000 ng/l	cyanobacteria
TRANS, CIS-2,6-NONADIENAL	cucumber	60 ng/l	algae
CIS-3-HEXEN-1-OL	grass	70,000 ng/l	algae
1-PENTEN-3-ONE	fishy, rancid	1,250 ng/l	algae, cyanobacteria
IONONE	violet	7 ng/l	algae, cyanobacteria
2,4,6-TRICHLOROANISOLE networks	moldy	0.02 ng/l	transformation into chlorophenol in
2,6,4-TRIBROMOANISOLE networks	earthy, moldy	0.03 ng/l	transformation into chlorophenol in
2,6-DI-TERT-BUTYL-4-METHYLPHENOL(BHT)	plastic	nd	polyethylene pipes

PACS water treatment container

- Demonstration and piloting environment for testing PACS8 System.
- Suitable solution for small villages, industries etc

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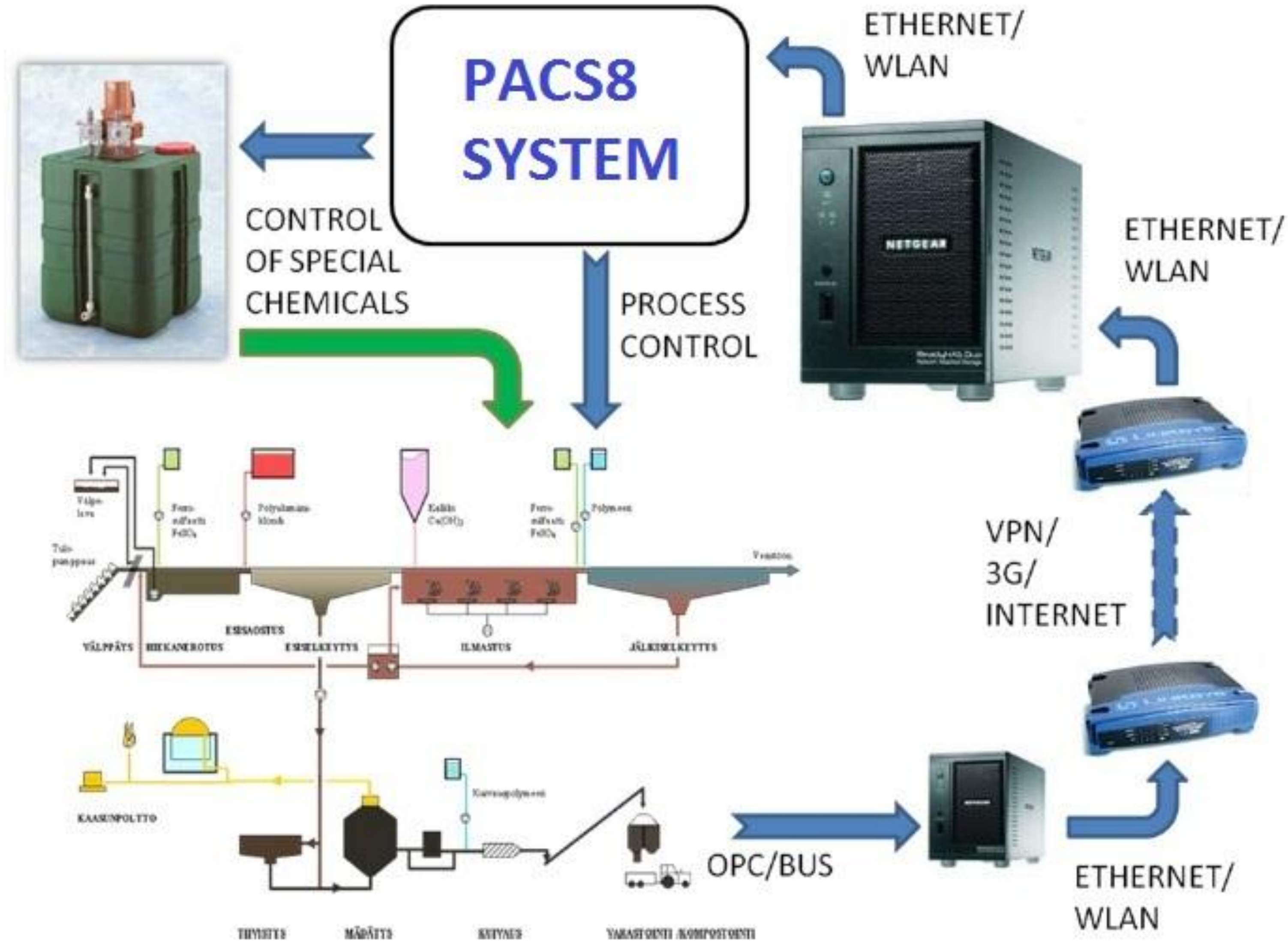
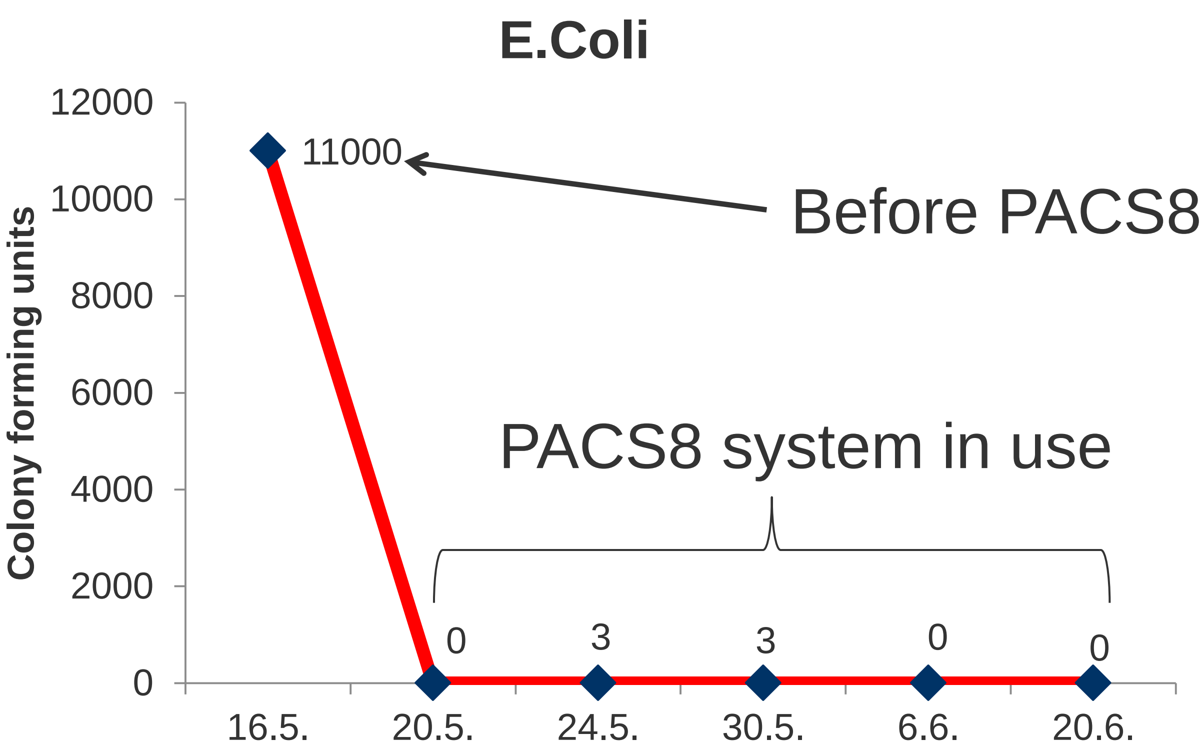
PACS PUREST AQUA CLEANING SOLUTION

Controlled use of PAA: PACS8 System in waste water post-disinfection



Peracetic acid: Results of post-disinfection of Mikkeli STP effluent in Finland (summer 2011)



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Disinfection mechanisms of PAA

1. Release of “active” oxygen which disrupts sulfhydryl (–SH) and sulphur (S-S) bonds in proteins, enzymes and other metabolites.
2. Release of hydroxyl radicals (OH·) and superoxide anions (O_2^-).
3. Double bonds of biomolecules are reacted.
4. Disruption of chemiosmotic function of lipoprotein cytoplasmic membrane and transport through the cell wall.
5. Protein denaturation.
6. Possibly inactivation of catalase enzyme.

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PAA as virucidal and bactericidal agent

- PAA is an effective virucidal and bactericidal agent. This is because PAA (undissociated form) can penetrate cell membranes and form reactive oxygen radicals (ROS) *in situ*.
- Viruses have either RNA or DNA based genome. Usually DNA consists of single molecule and breakage in that molecule causes inactivation. RNA is usually in several small RNA chains and breakage of some chains can be tolerated. That is why RNA viruses are more difficult to disinfect.

Source: Salkinoja-Salonen, M., *Peracetic acid use for disinfecting treated waste water,* presentation at Oulu, 2nd September 2011.

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Disinfection systems: investment and maintenance costs

Chlorination (example plant Q = ca. 20.000 m^3/d):

- Basic equipment cost ca. 2 MSAR
- Emergency chlorine scrubber ca. 0,5 MSAR
- Buildings, chlorination tanks etc ca. 1 MSAR
- Total investment cost ca. 3-4 MSAR

- $Ca(OCl)_2$ cost ca. 7-8 SAR/kg
- In addition chemicals storage, handling cost, and other maintenance cost of the chlorination process

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Disinfection systems: investment and maintenance costs

UV disinfection (example plant Q = ca. 250.000 m^3/d):

- Equipment cost with installation ca. 1 MEUR
- Main electric power connection ca. 250-300 kW
- Energy consumption 70 – 500 W / lamp (depends on water quality, flow etc)
- With raw water UV dosage generally 400 J / m^2
- High investment and maintenance costs
    - Lamp cost ca. 300 EUR / lamp, need to be changed frequently

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Disinfection with PACS8 System:

Plant sizes from 10.000 m^3/d to 1.000.000 m^3/d:

- Service agreement with customer (3 years - 20 years)

- **Investment cost for customer: 0 EUR**
- **Indicative DBOO -service cost: 0.03 – 0.06 EUR/m^3**

- Service cost includes:
  - Complete equipment of PACS8 System
  - System installation
  - Optimization and start-up
  - Operation and maintenance during the contract period
  - Chemical (PAA)

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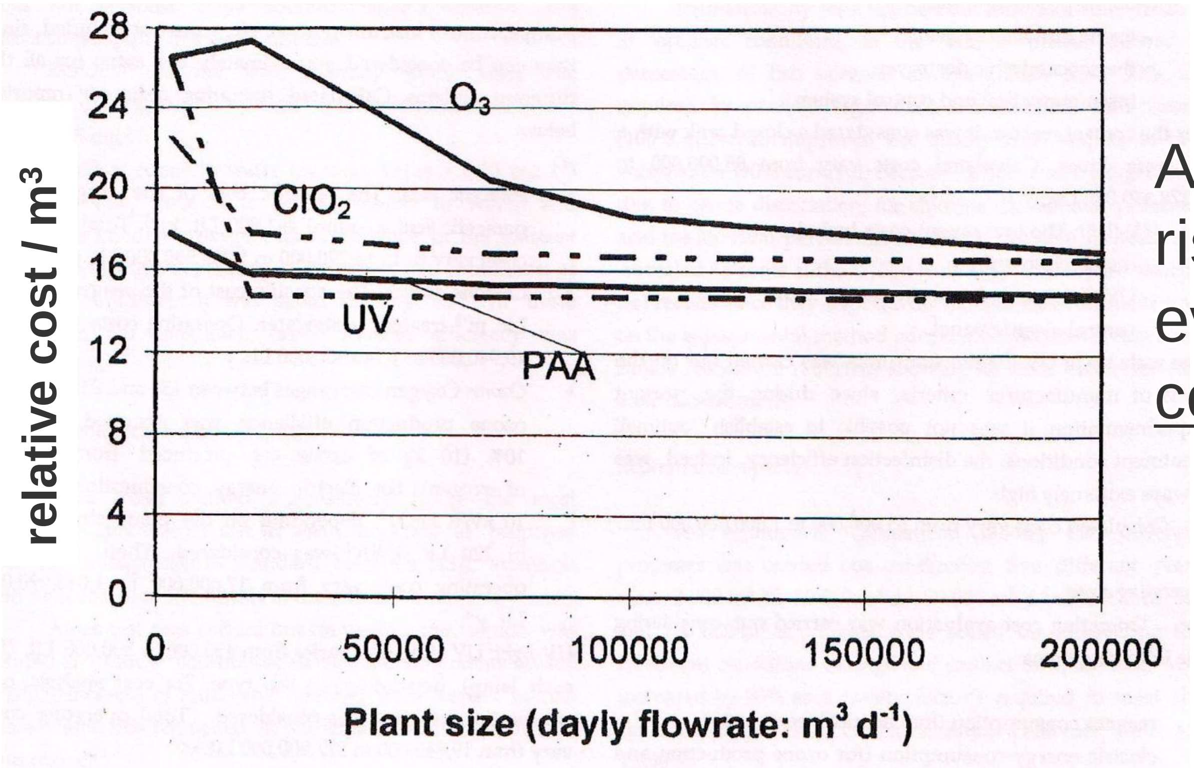
Comparison of PAA, UV, Ozone and ClO_2 in wastewater disinfection
Total costs (investment + operation) at different sized WWTPs



As energy price rises PAA becomes even more <u>cost effective</u>

source: Lubello & et al. Water Science and Technology: Water Supply, 2, 205-212, 2002.

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DISINFECTION – TECHNOLOGY COMPARISON

	PACS8 – SYSTEM	OZONATION	UV	CHLORINATION
Full service available (DBOO -model) **	Yes	No	No	No
Capital cost	0 (included in DBOO service)	High	High	High
Operation and maintenance cost	Included in DBOO service fee	High	High	Moderate
Chemical cost	Included in DBOO service fee	Low	No	Low/Moderate
Civil work	Low	High	High	High/Moderate
Project time	Short	Moderate/Long	Moderate/Long	Moderate
Utilities cost	Low	High (power)	High (power)	Moderate
Toxic by-product formation	No	Yes	No	Yes
Occupational safety risk at site	Low	Moderate	Low	High
Corrosion	No	Yes	No	Yes
Reactivation of mictrobes and viruses	No rectivation	No	Yes (21-52% of viruses and 1% of bacteria)	No
Performance when high variation of (waste) water flow and load	Good	Poor	Poor	Moderate (if nominal capacity allows)

** DBOO : Design, Build, Own and Operate

Building new sustainable water safety for us and for next generations.

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