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Synergistic effects using ozone, UV and advanced oxidation in multi barrier treatment processes for potable water and waste water reuse

Outline

- Introduction & Principals
- Pesticide Removal in WTP
- Seasonal Taste & Odor Treatment
- Indirect and Direct Potable Reuse
- Questions & Discussion

Principals

UV

O_3

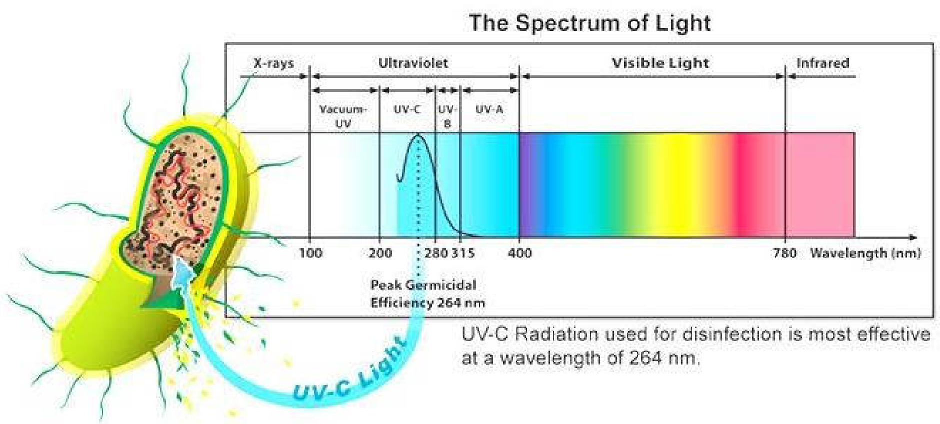
AOP

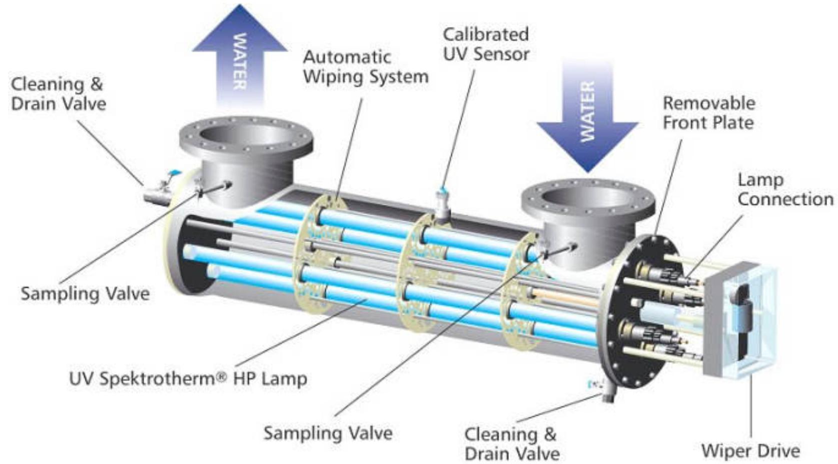
BAF

Principals

UV

- UVC is light with a high energy
- Generated through mercury containing lamps (LP or MP) or LEDs
- Common wave length is 254 nm
- Photolysis is the main mechanism

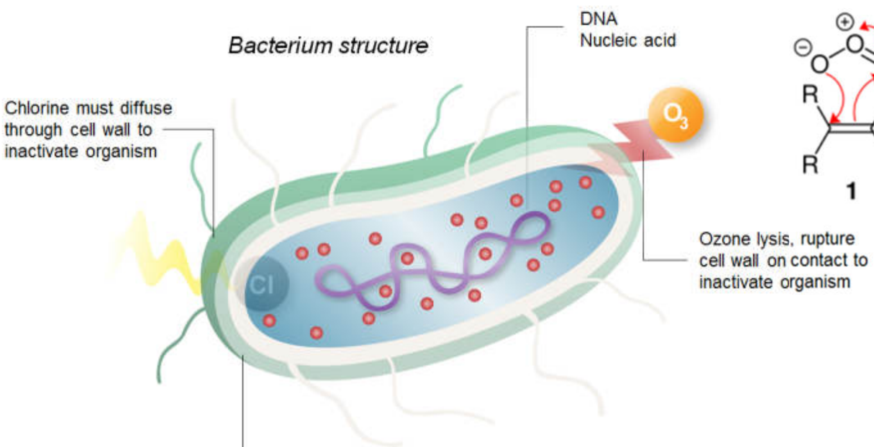




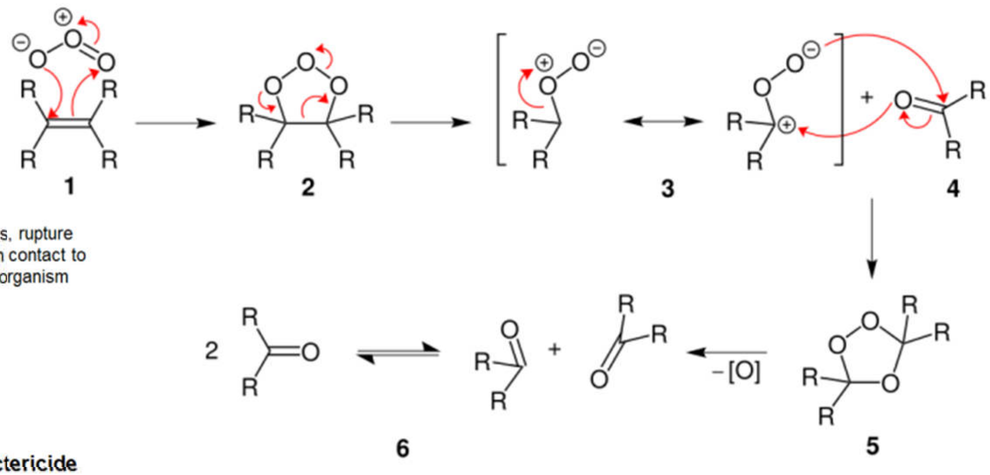
Principals

O_3

- Strong oxidizing and disinfection agent
- Needs to be generated on site
- Selective reactions with organic matter



Ozone acts 3,000 times faster than chlorine as a bactericide



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Principals

AOP

Principals

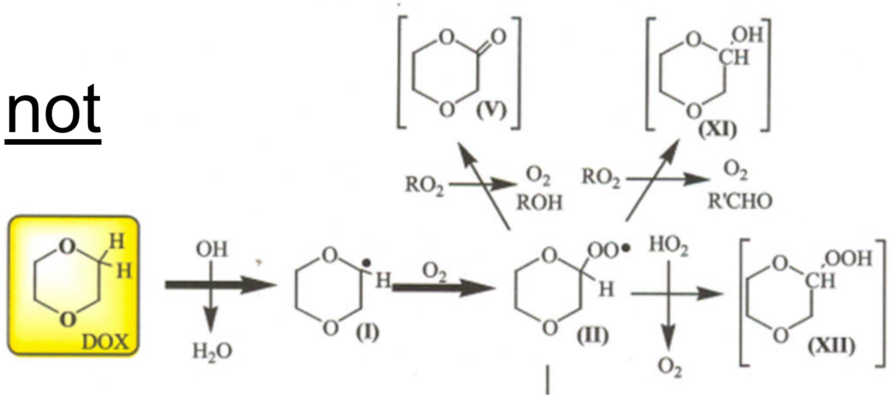
AOP

Oxidant	Oxidation Potential (V)	Oxidation Potential Rel. to Chlorine (V)
Hydroxyl Radical	2.80	2.05
Ozone	2.07	1.52
Hydrogen Peroxide	1.78	1.31
Potassium Permanganate	1.70	1.25
Sodium Hypochlorite	1.49	1.10
Chlorine	1.36	1.00
Chlorine Dioxide	1.27	0.93
Oxygen	1.23	0.90

OH Radicals

AOP

- React very fast with organic and inorganic compounds
- Lifetime is only nano seconds
- Any organic or inorganic compound will decrease the efficiency
- Compounds are usually <u>not</u> mineralized



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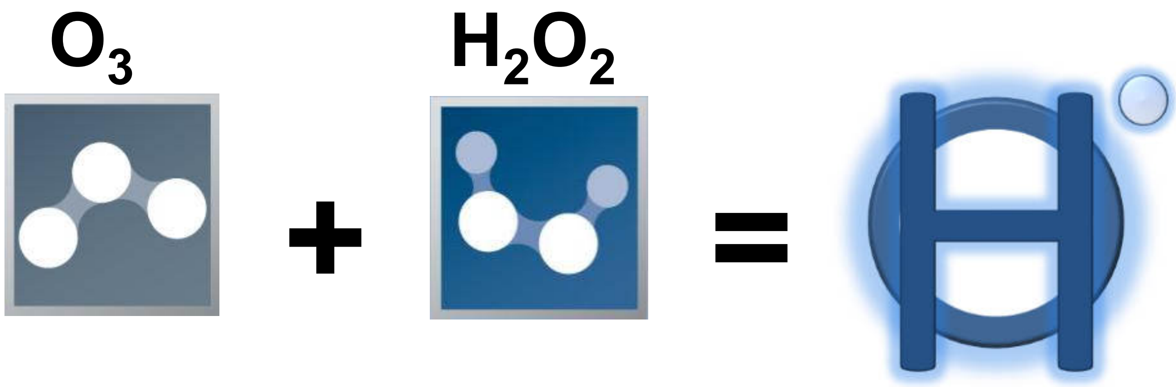
Principals

AOP

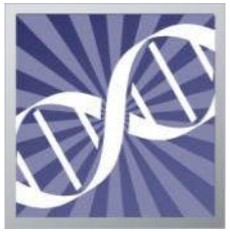


A1:	H_2O_2	$\leftrightarrow$	$HO_2^- + H^+$	pKs = 11,6
A2:	$HO_2^- + O_3$	$\rightarrow$	$HO_2\cdot + O_3^-\cdot$	$k = 2{,}8 \times 10^6\ M^{-1}\ s^{-1}$
A3:	$O_3^-\cdot + H^+$	$\leftrightarrow$	$HO_3\cdot$	pKs = 6,2
A4:	$HO_2\cdot$	$\leftrightarrow$	$O_2^-\cdot + H^+$	pKs = 4,8
A5:	$O_2^-\cdot + O_3$	$\rightarrow$	$O_3^-\cdot + O_2$	$k = 1{,}6 \times 10^9\ M^{-1}\ s^{-1}$
A6:	$O_3^-\cdot + H^+$	$\leftrightarrow$	$HO_3\cdot$	pKs = 6,2
A7:	$2HO_3\cdot$	$\rightarrow$	$2OH\cdot + 2O_2$	$k = 1{,}1 \times 10^5\ s^{-1}$
A ges.:	$H_2O_2 + 2O_3$	$\rightarrow$	$2\ OH\cdot + 3O_2$	[2, 3, 4]

Principals

AOP

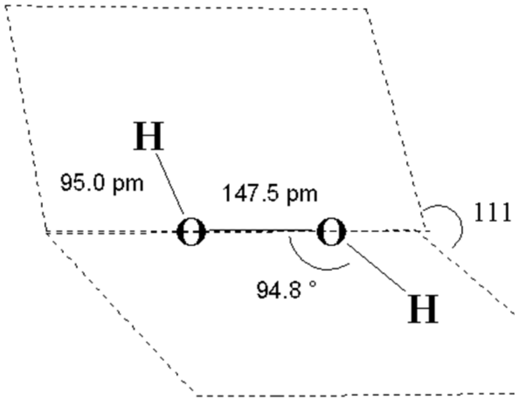
UV



+

H_2O_2

=



Start:

$$H_2O_2 + h\nu \rightarrow 2\ HO\bullet \qquad \Phi_{OH}=1 \qquad (2\text{-}1)$$

Promotion:

$$H_2O_2 + HO\bullet \rightarrow H_2O + HO_2\bullet \qquad (2\text{-}2)$$

$$HO_2\bullet + H_2O_2 \rightarrow H_2O + \bullet O_2\bullet + \bullet OH \qquad (2\text{-}3)$$

$$2\ H_2O_2 \rightarrow 2\ H_2O + \bullet O_2\bullet \qquad (2\text{-}4)$$

Termination:

$$HO\bullet + \bullet OH \rightarrow H_2O_2 \qquad (2\text{-}5)$$

$$HO\bullet + HO_2\bullet \rightarrow H_2O + \bullet O_2\bullet \qquad (2\text{-}6)$$

$$HO_2\bullet + \bullet O_2H \rightarrow H_2O_2 + \bullet O_2\bullet \qquad (2\text{-}7)$$

Principals

BAF

- Uses GAC, Anthrazite, Sand or expended Clay
- Removes ammonia
- Removes TSS

- Reduces trace organic contaminants including NDMA
- Reduces oxidation by-products and lowers TOC

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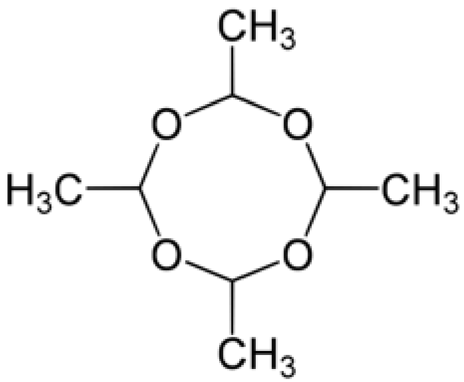
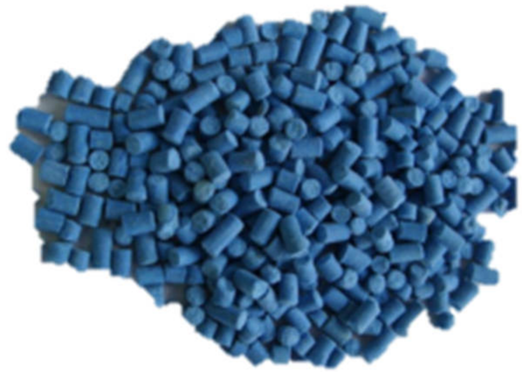
Synergistic Effects

Pesticide Removal

Pesticide Removal - Metaldehyde

- Slug and Snail poison
- Metaldehyde is very persistant
- Passes ozone and GAC without significant removal





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Pesticide Removal - Metaldehyde

- WTP in the UK
- Flow rate 800 m^3/h (5 MGD)

- Elevated Metaldehyde levels in the reservoir with seasonal peaks (6 month 0.5 LOG and 3 month 1.0 LOG removal)

- Elevated Bromide levels 70-90 µg/L

- 6 month pilot study to evaluate:

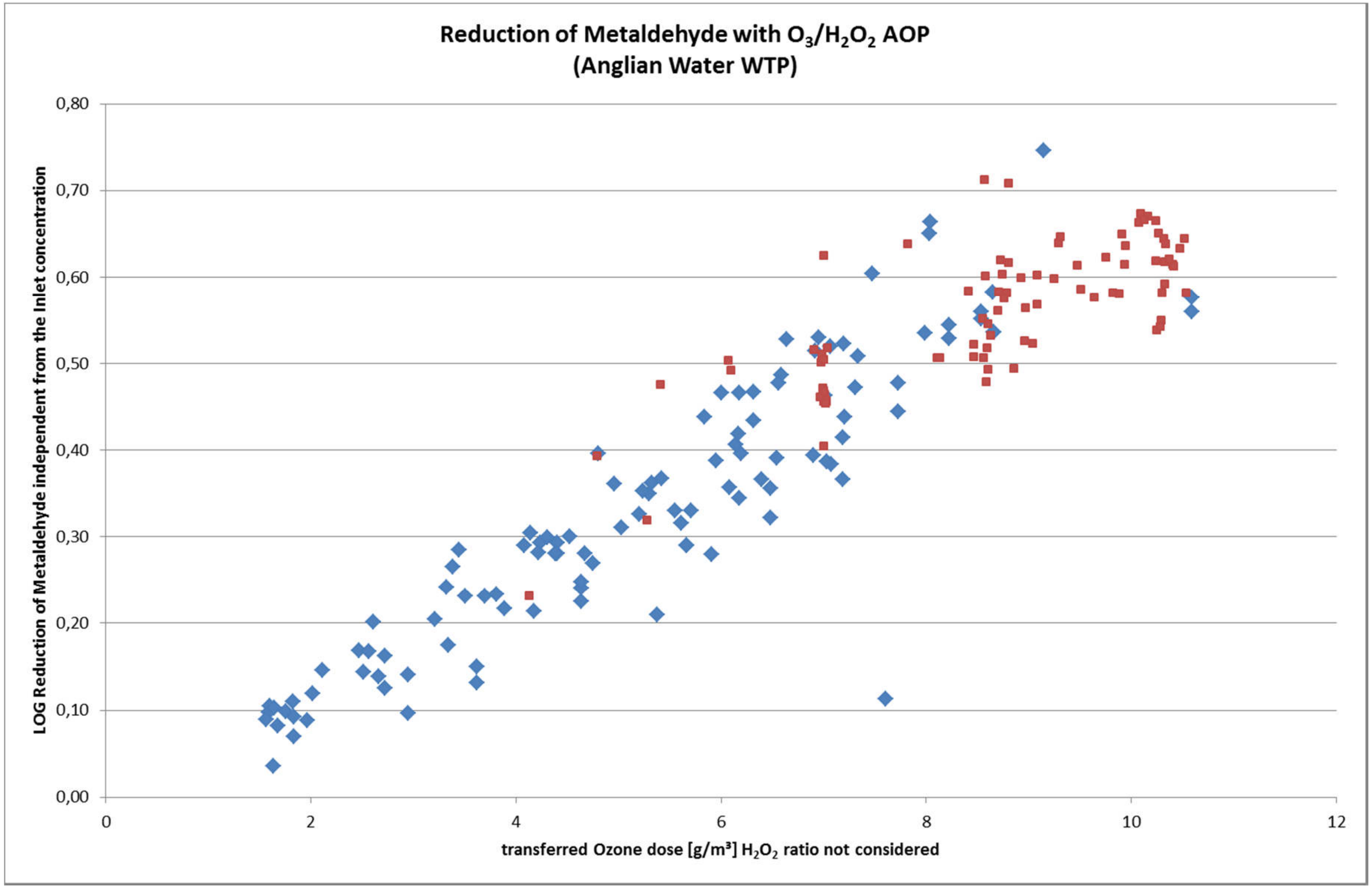
  - UV LP AOP
  - Ozone AOP
  - Ozone AOP+ UV LP AOP

Pesticide Removal

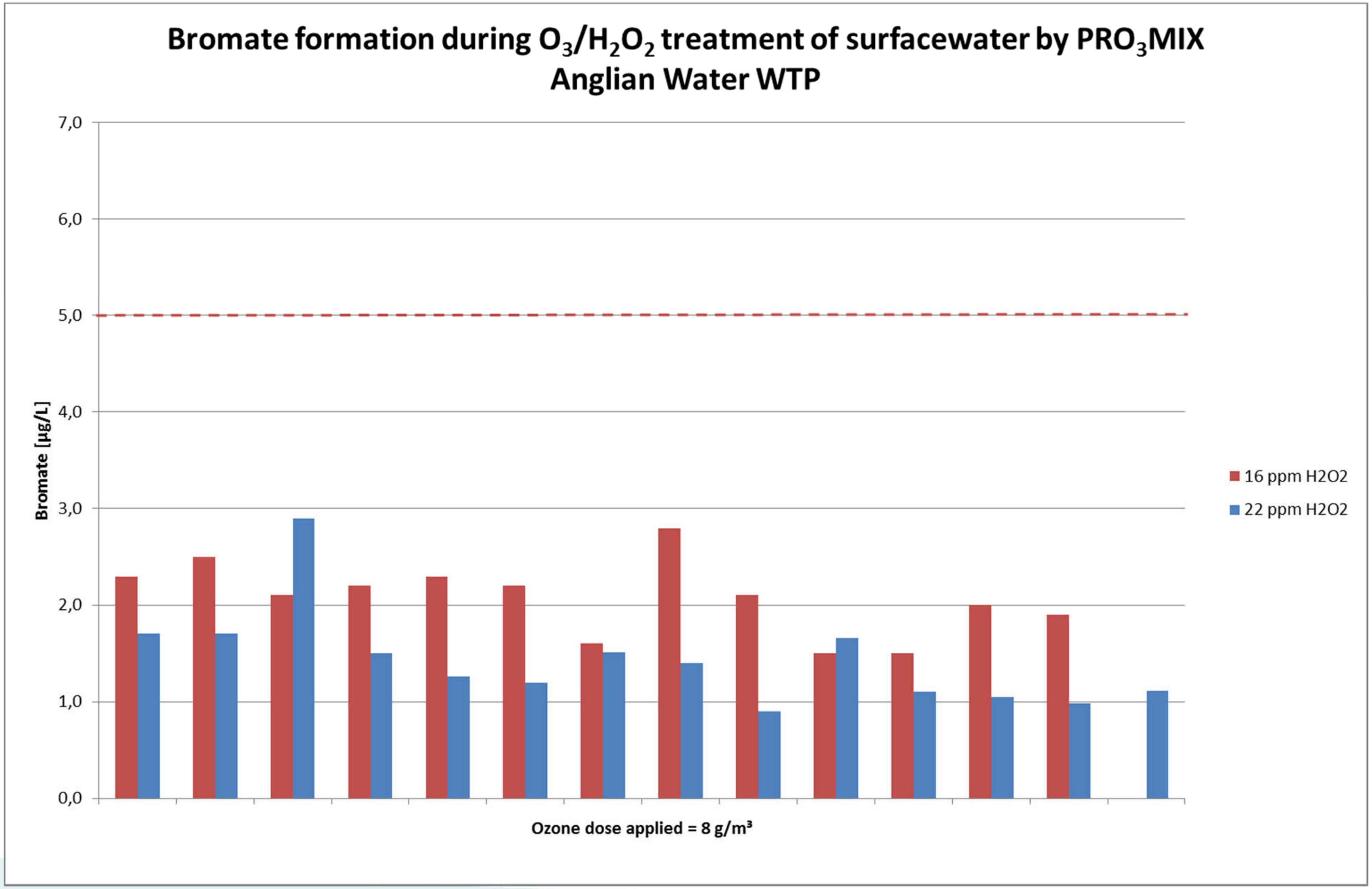
Wedeco Pro$_3$mix

Wedeco LBX 10

Pesticide Removal



Pesticide Removal



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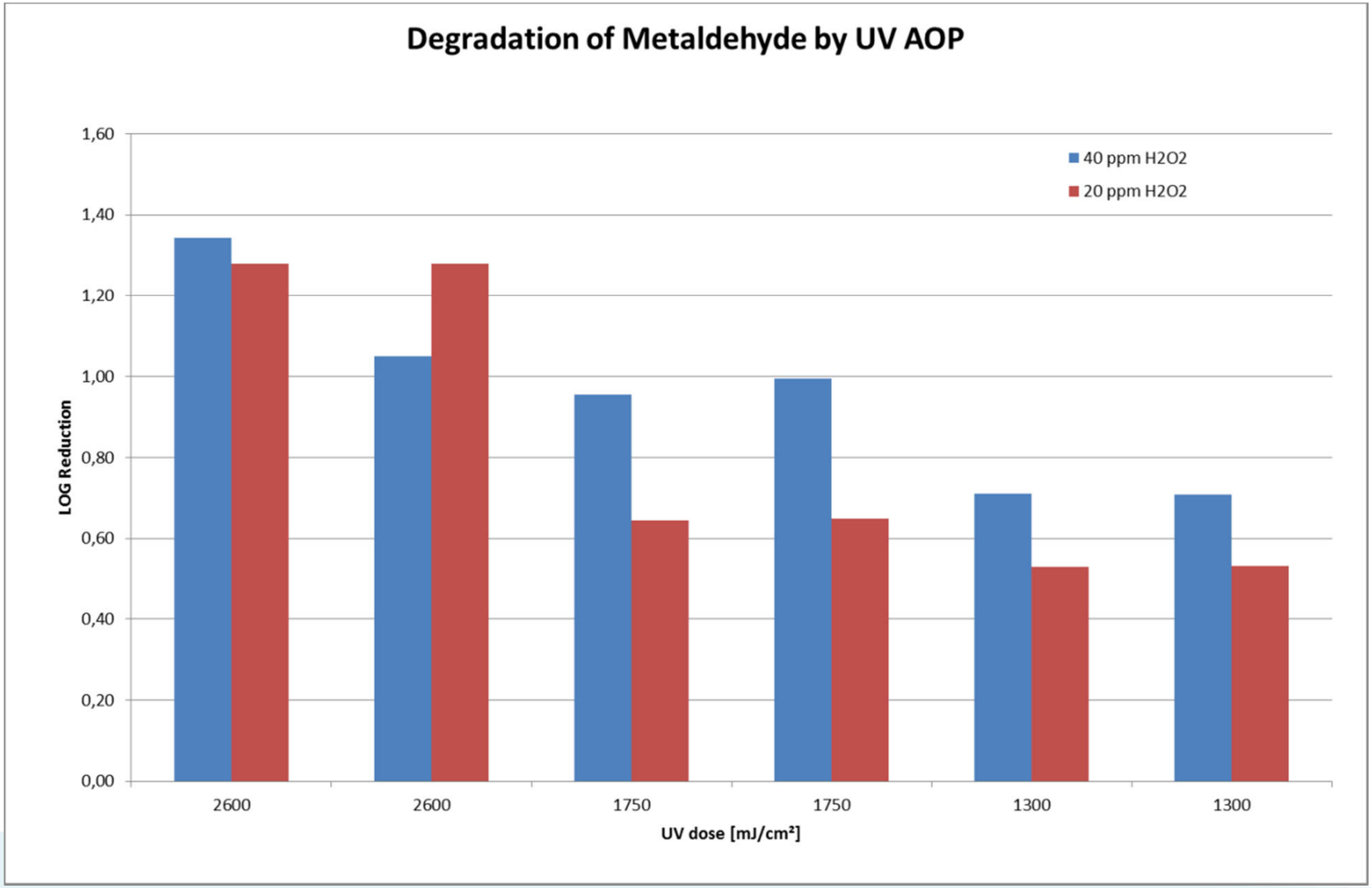
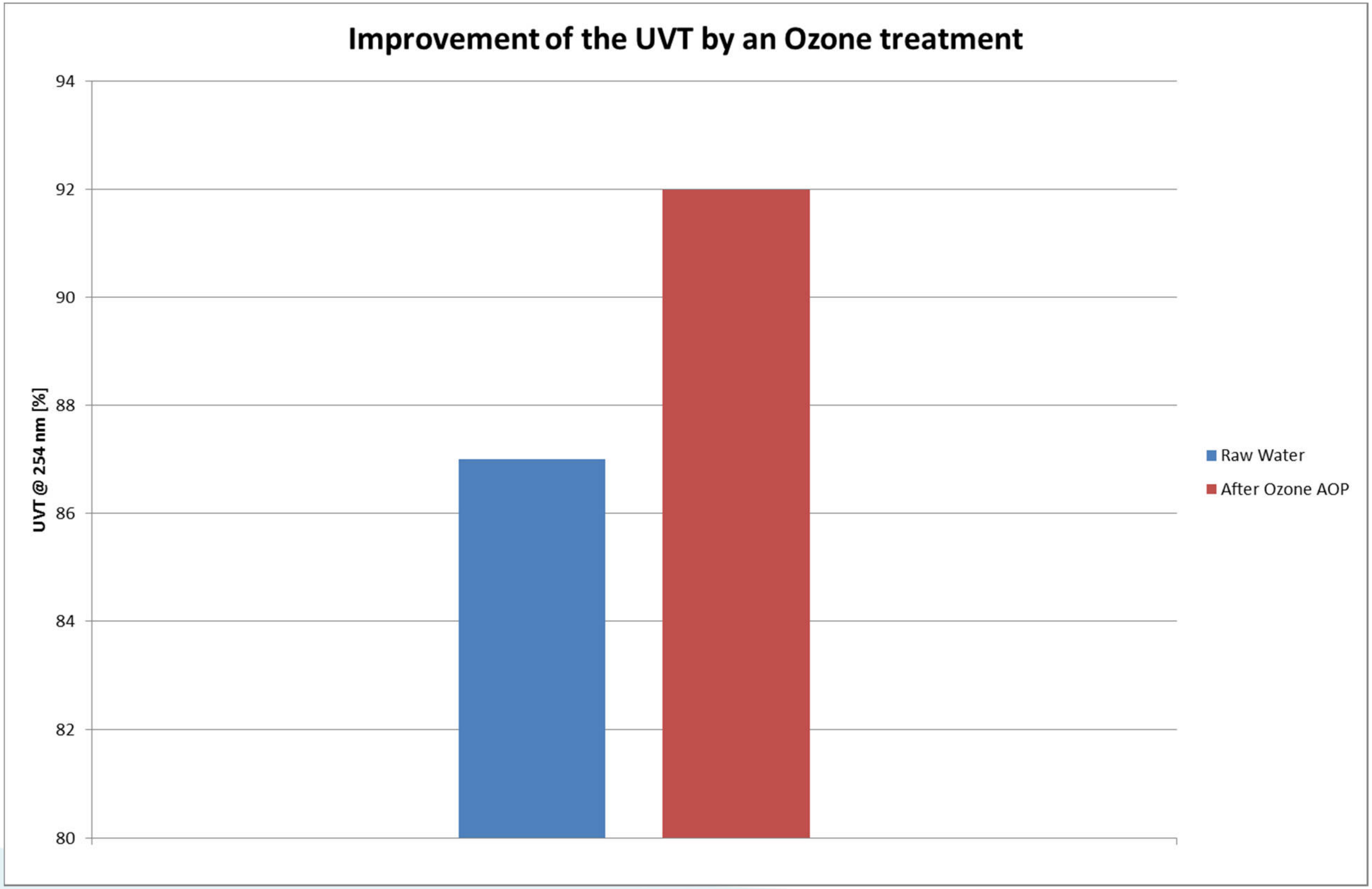
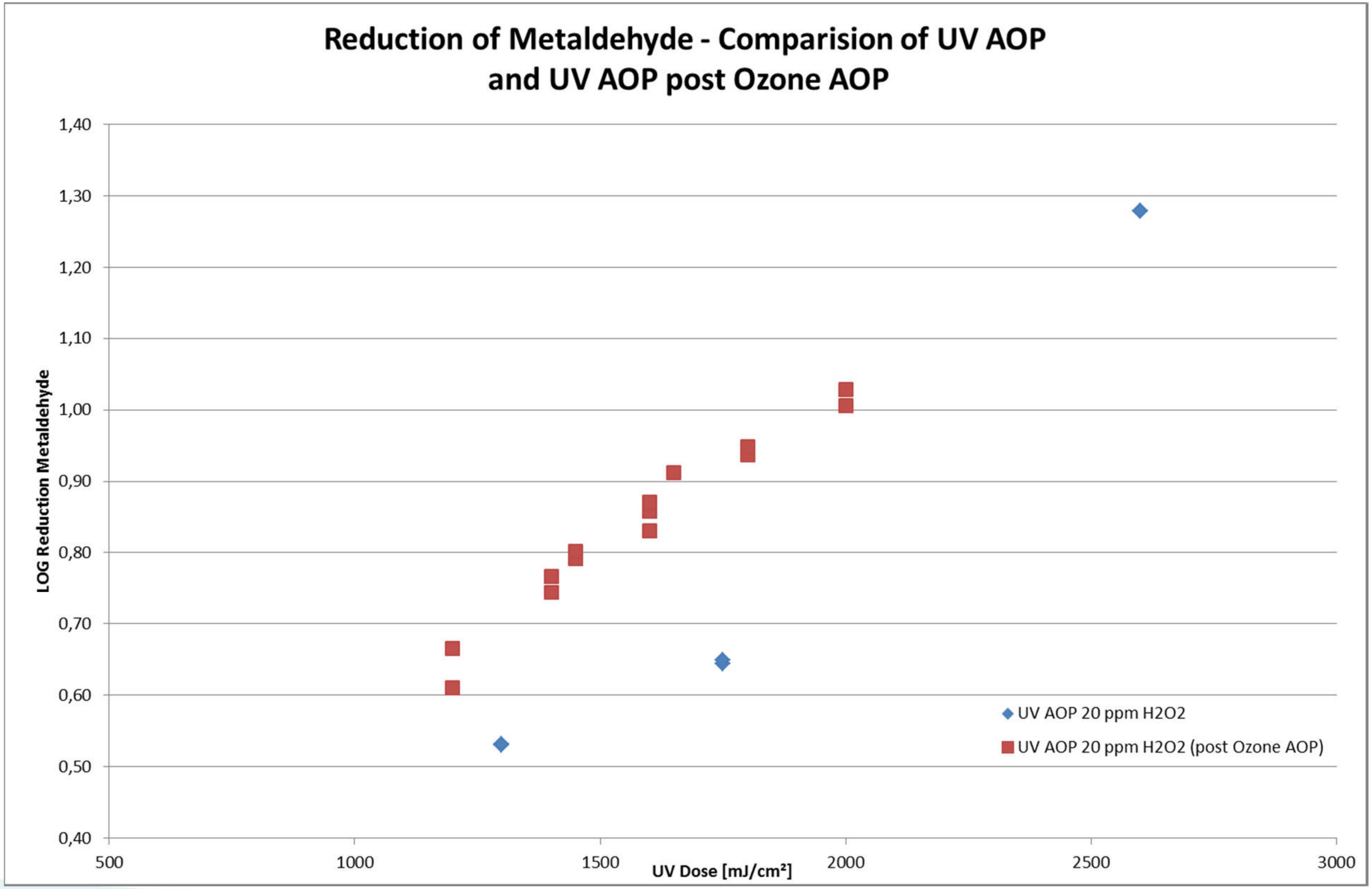
Pesticide Removal



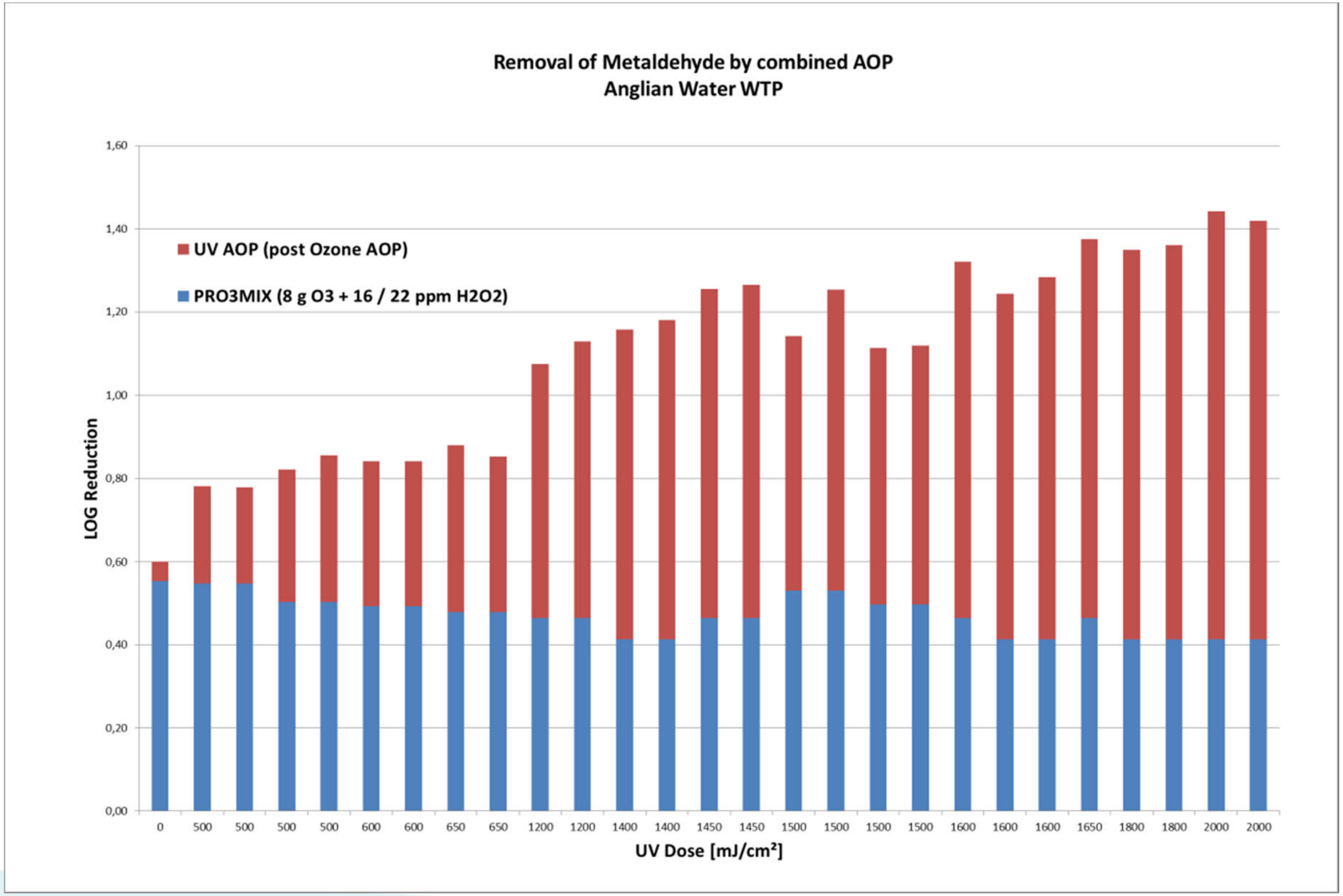
Pesticide Removal



Pesticide Removal



Pesticide Removal



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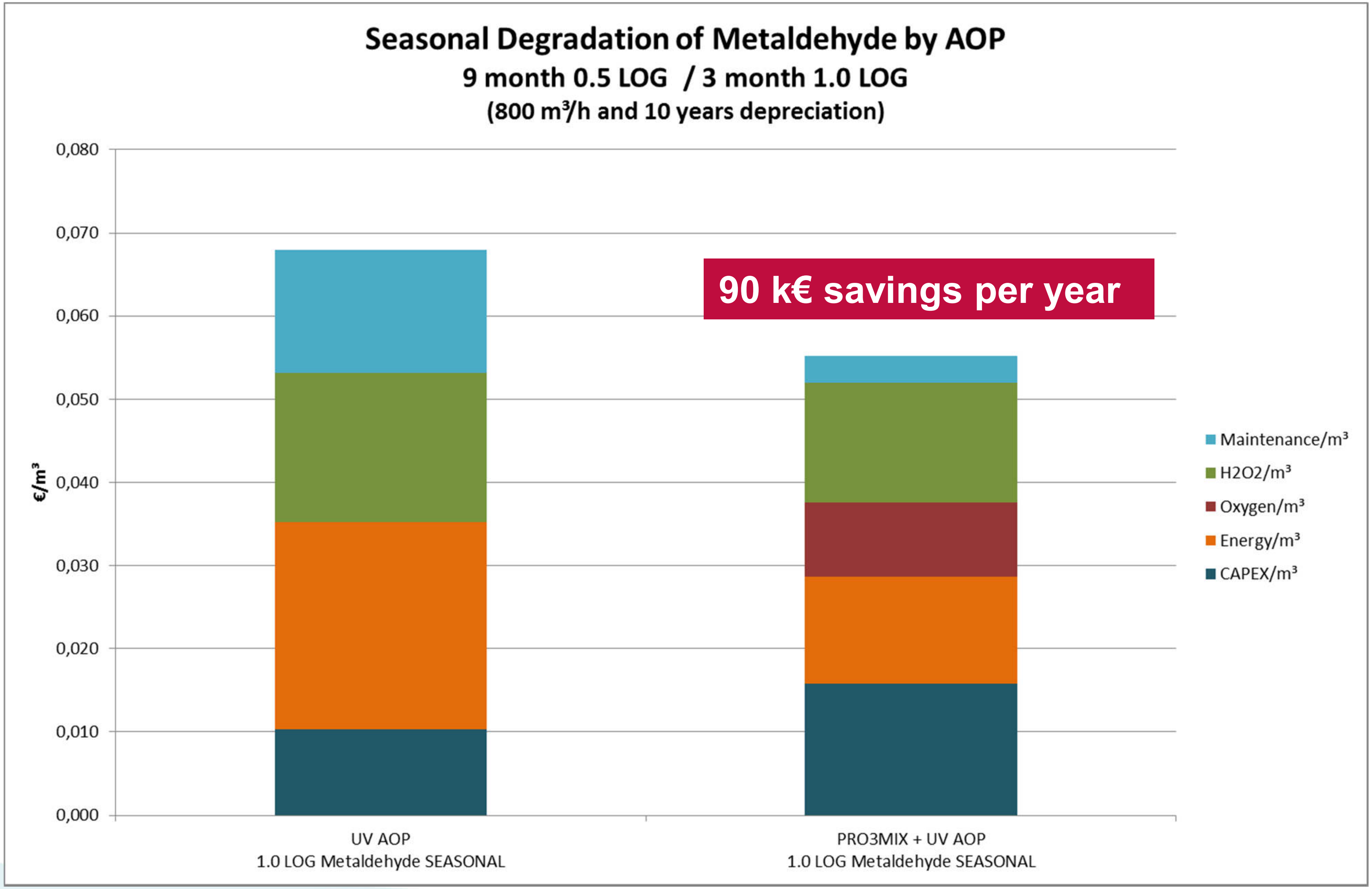
Pesticide Removal



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Pesticide Removal

Technology	LOG	Costs kUSD / 10 y
Ozone AOP	0.5	4.370
UV AOP (LP)	0.5	5.820
UV AOP (LP)	1.0	8.340
Ozone AOP + UV AOP	1.0	7.730

Pesticide Removal

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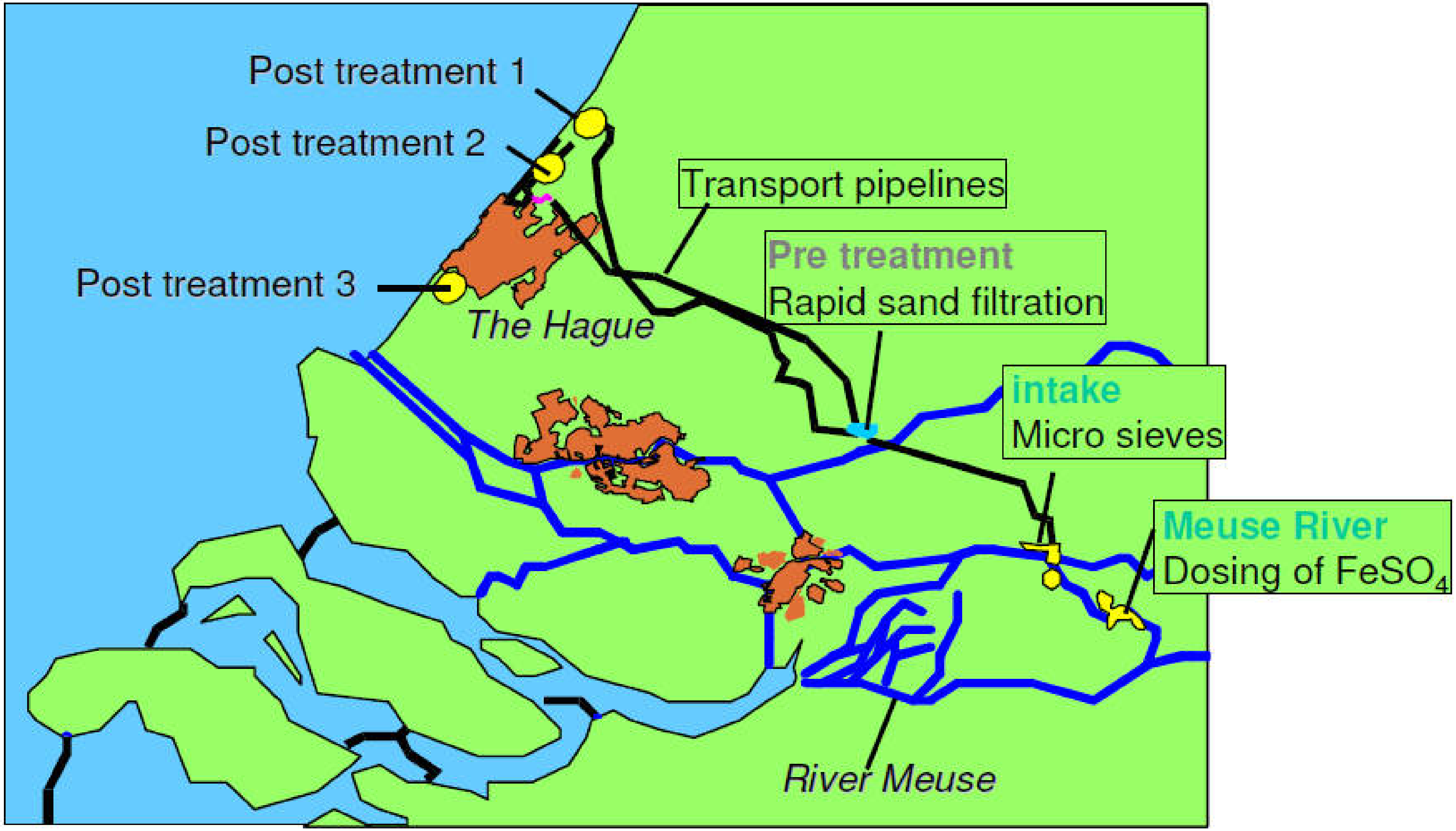
Pesticide Removal

- WTP in the Netherlands
- Flow rate 12,000 m^3/h
- Micro pollutants in the raw water source (Meuse River)
- Elevated Bromide levels 90-170 µg/L
- Very strict Bromate limits (<0.5 µg/L)

Pesticide Removal

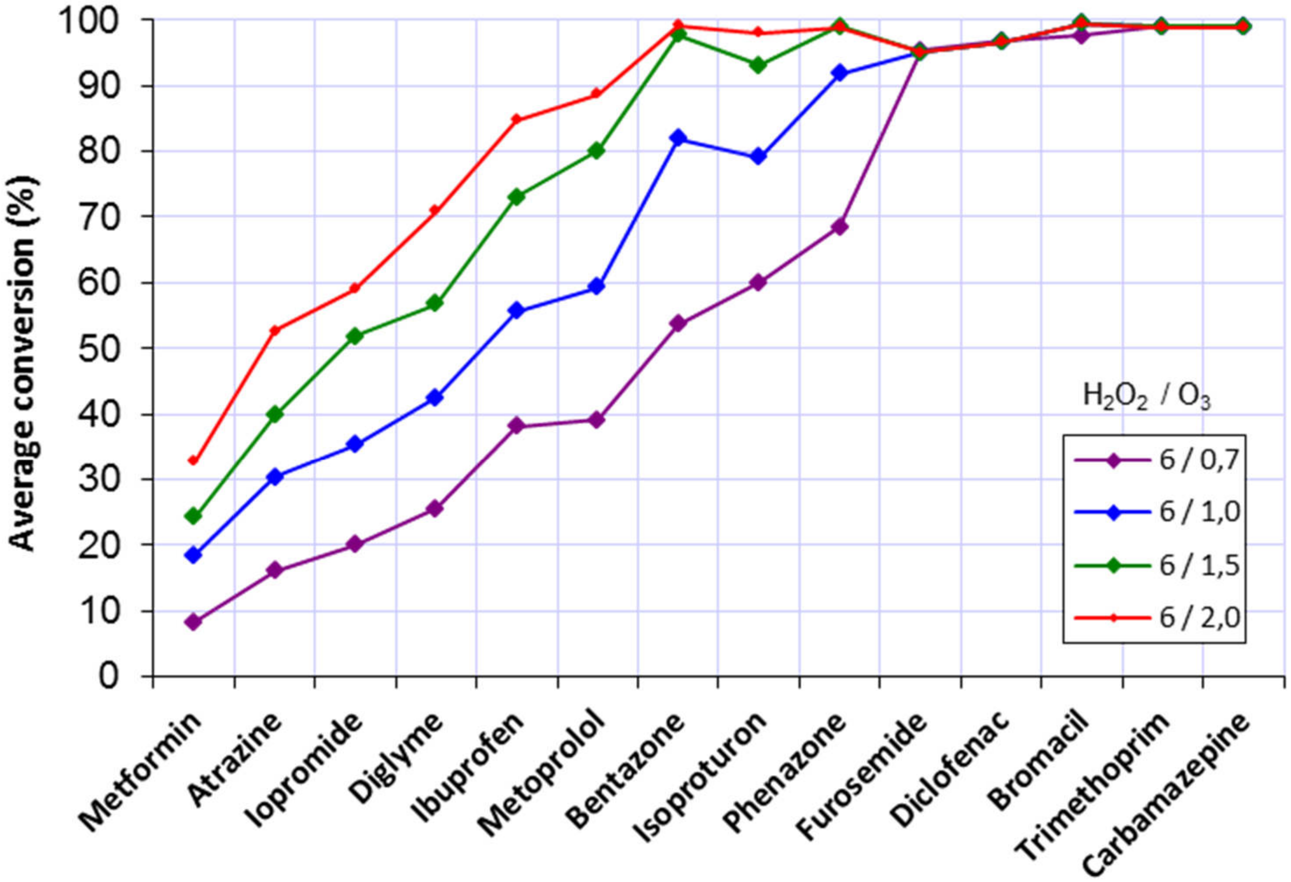


Source: Ton Knol , DUNEA - IOA Berlin 2017

Pesticide Removal

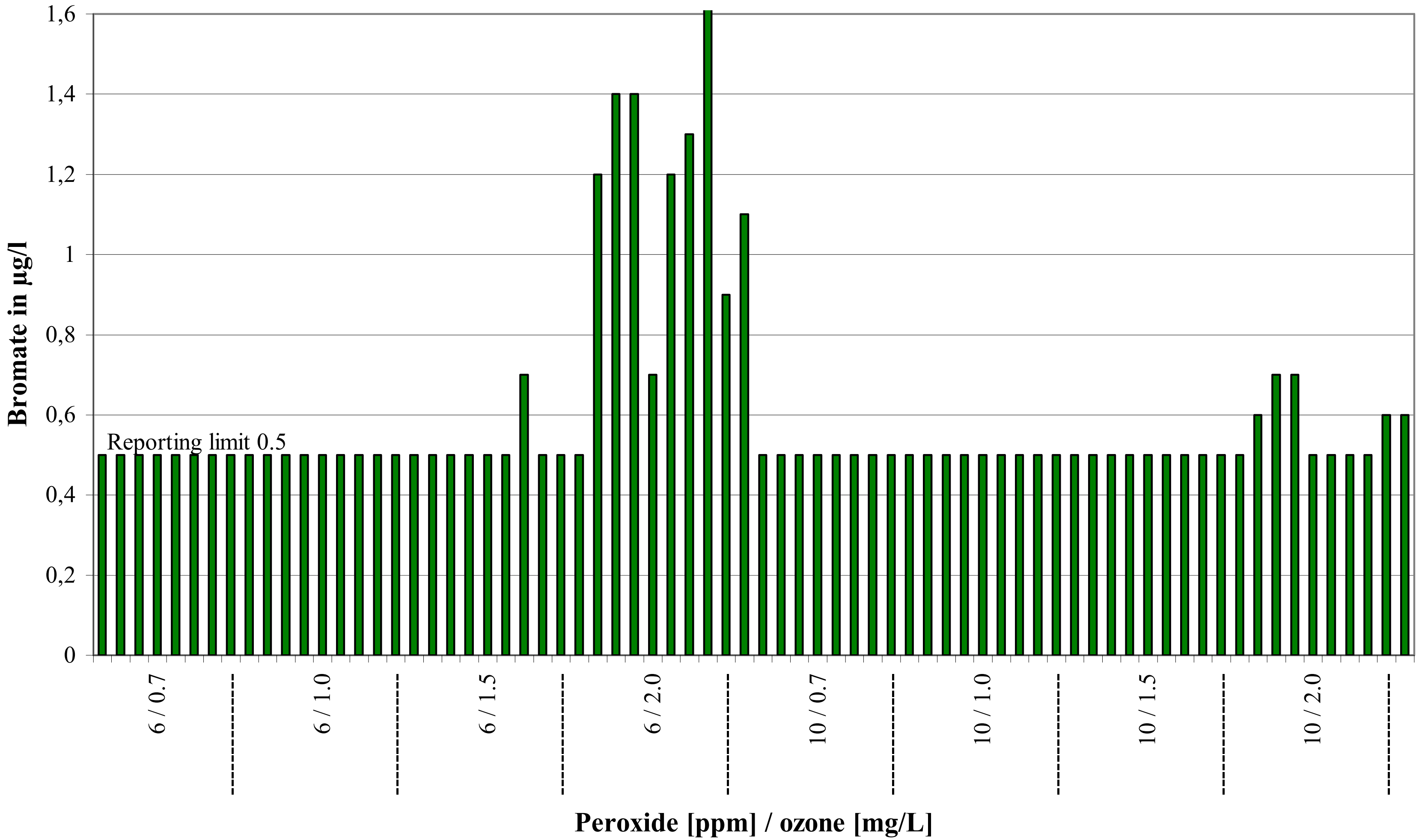
- 8 year research project to evaluate:
    - UV LP AOP
    - UV MP AOP
    - Ozone AOP
    - Ozone + UV LP AOP

Pesticide Removal



Source: Ton Knol et al.

Pesticide Removal



Source: Ton Knol et al.

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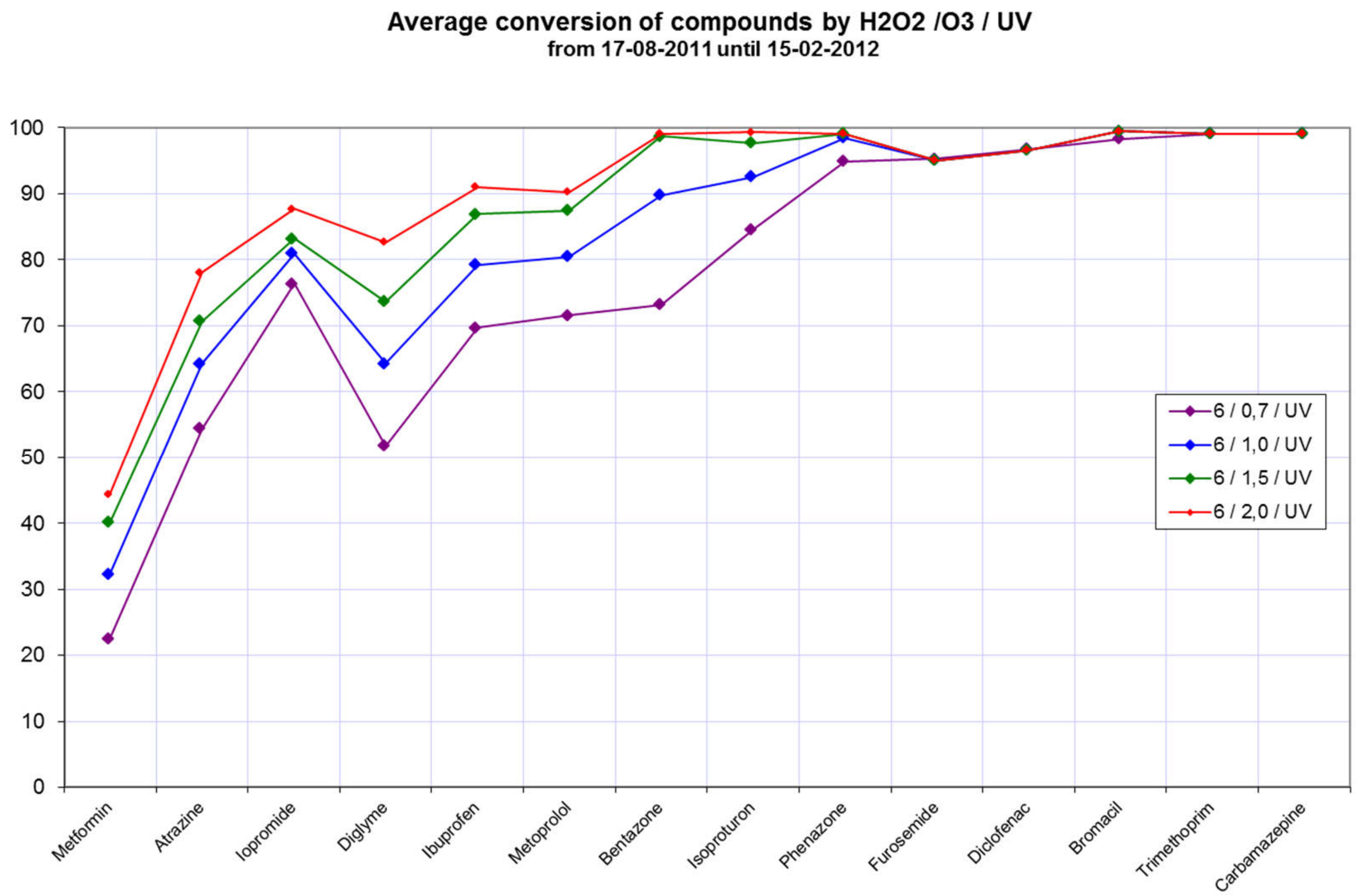
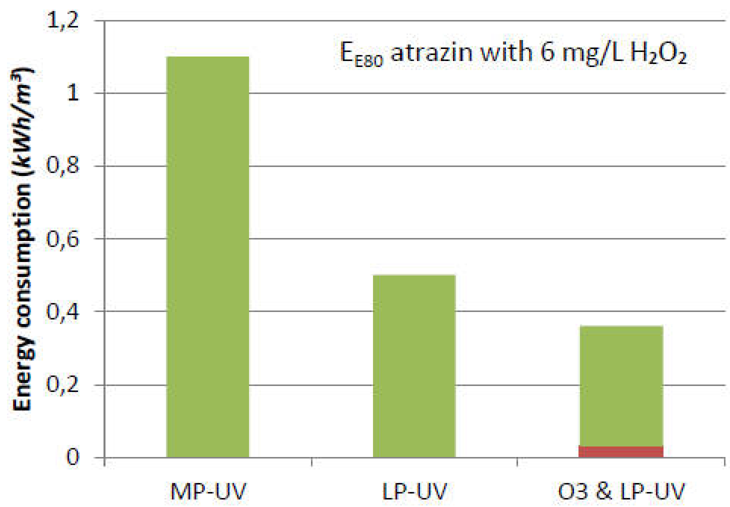
Pesticide Removal

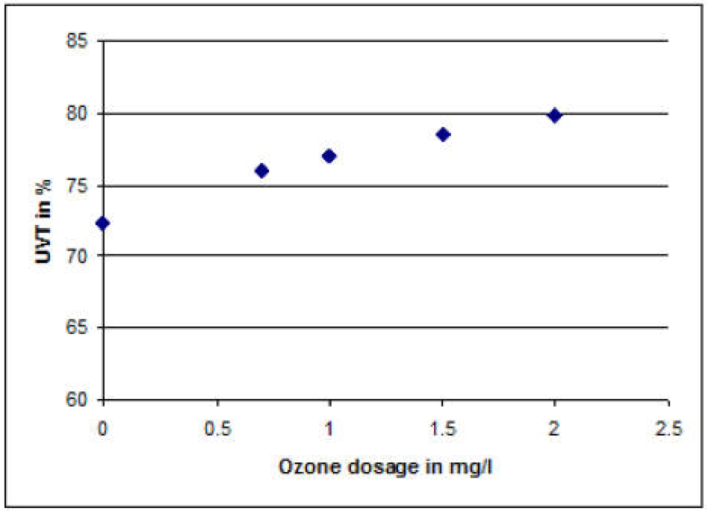


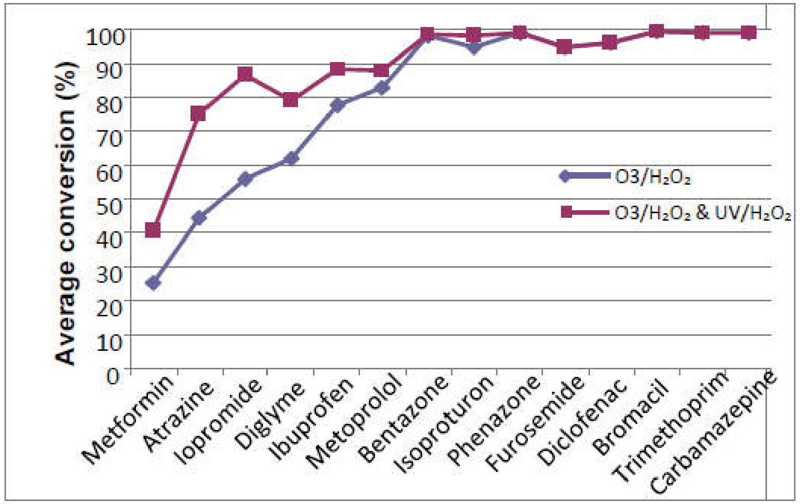
Source: Ton Knol et al.

Benefits serial AOP

- 3 oxidation mechanisms
- Increase UVT by oxidation DOC
- Energy efficient
- Smaller footprint
- Target: 80% conversion of MC at energy consumption of 0.15 kWh/m³







Source: Ton Knol et al. IOA Berlin 2017

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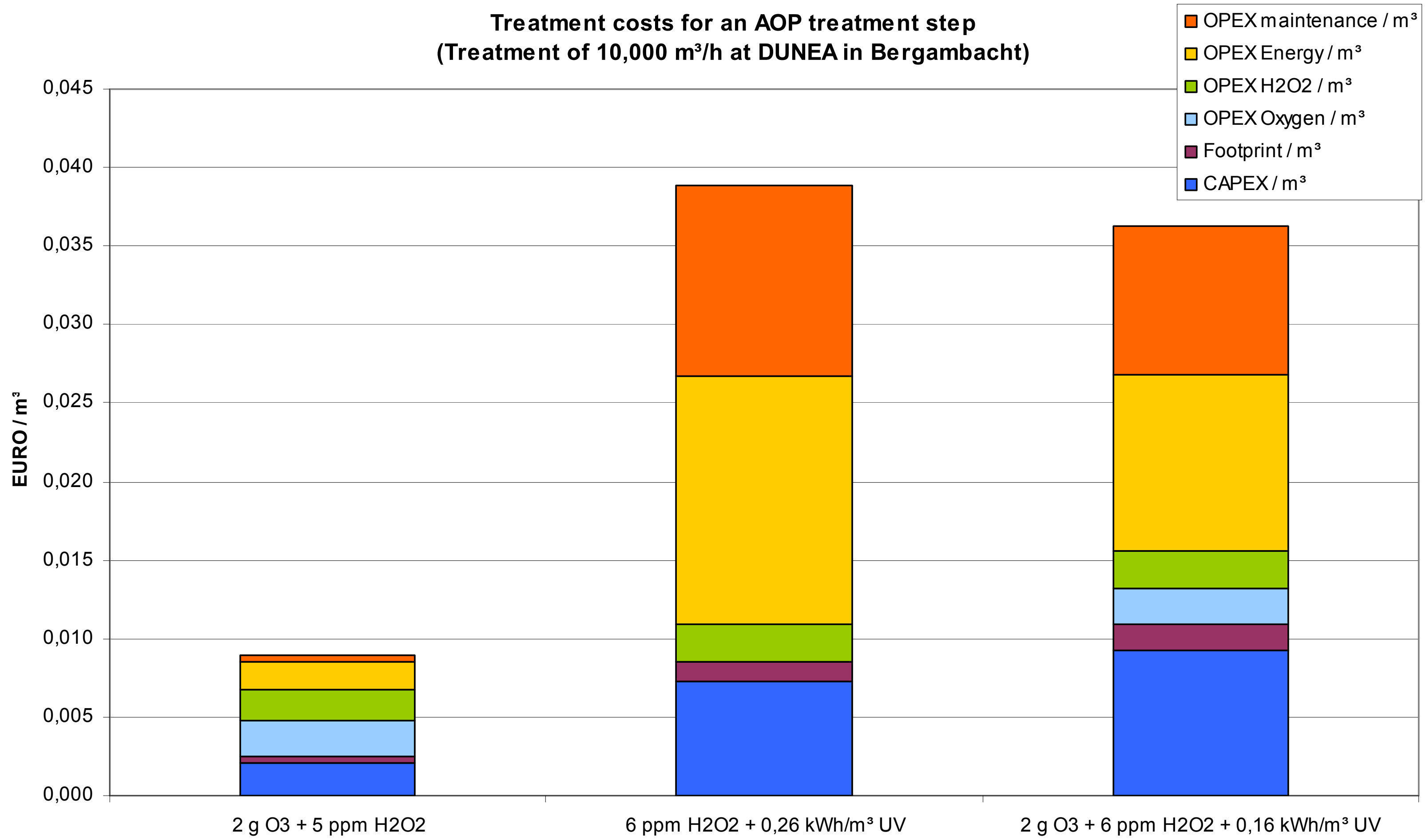
Pesticide Removal



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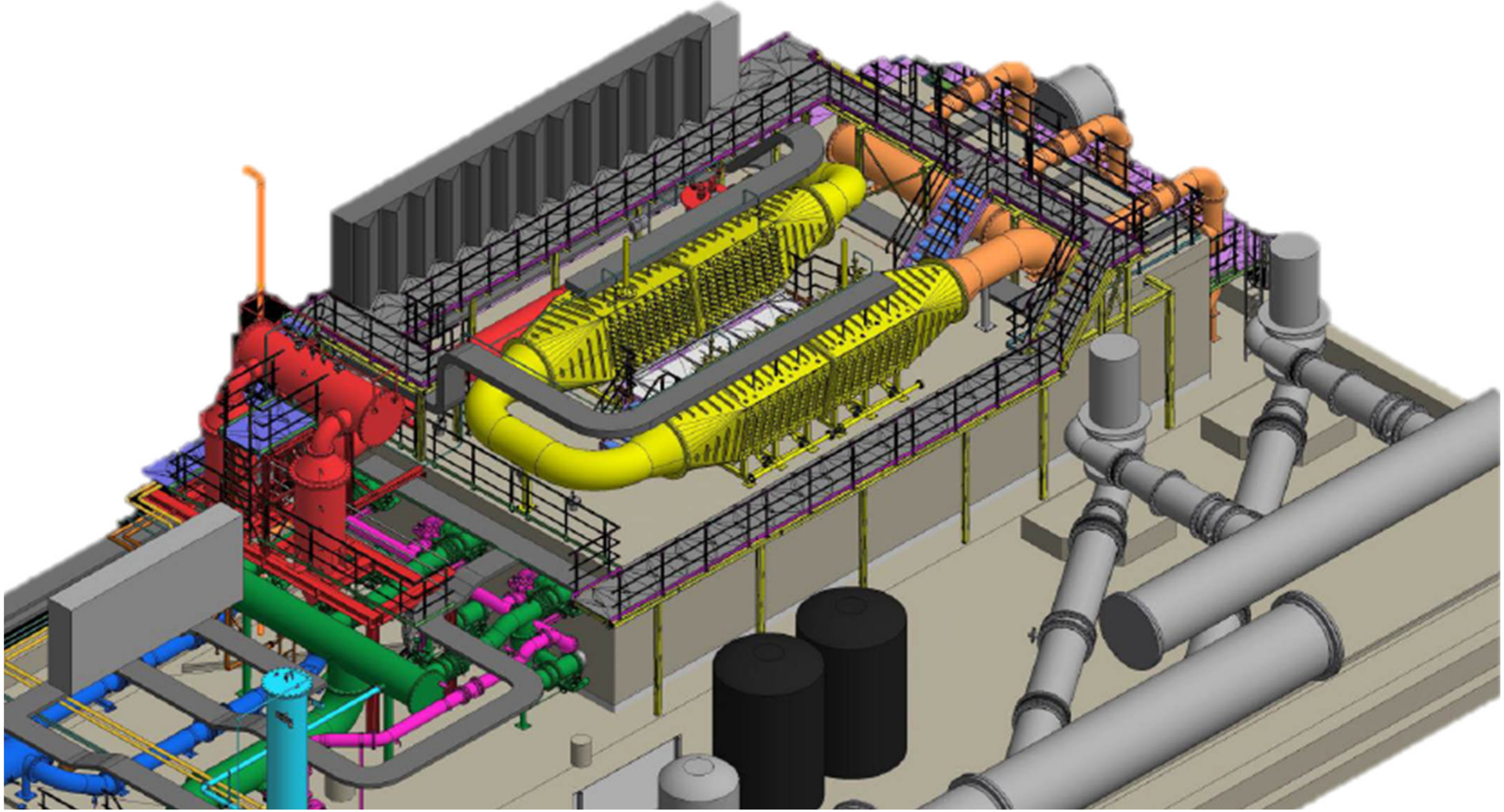
Pesticide Removal



Source: Ton Knol et al. IOA Berlin 2017

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WLL 8000 KG
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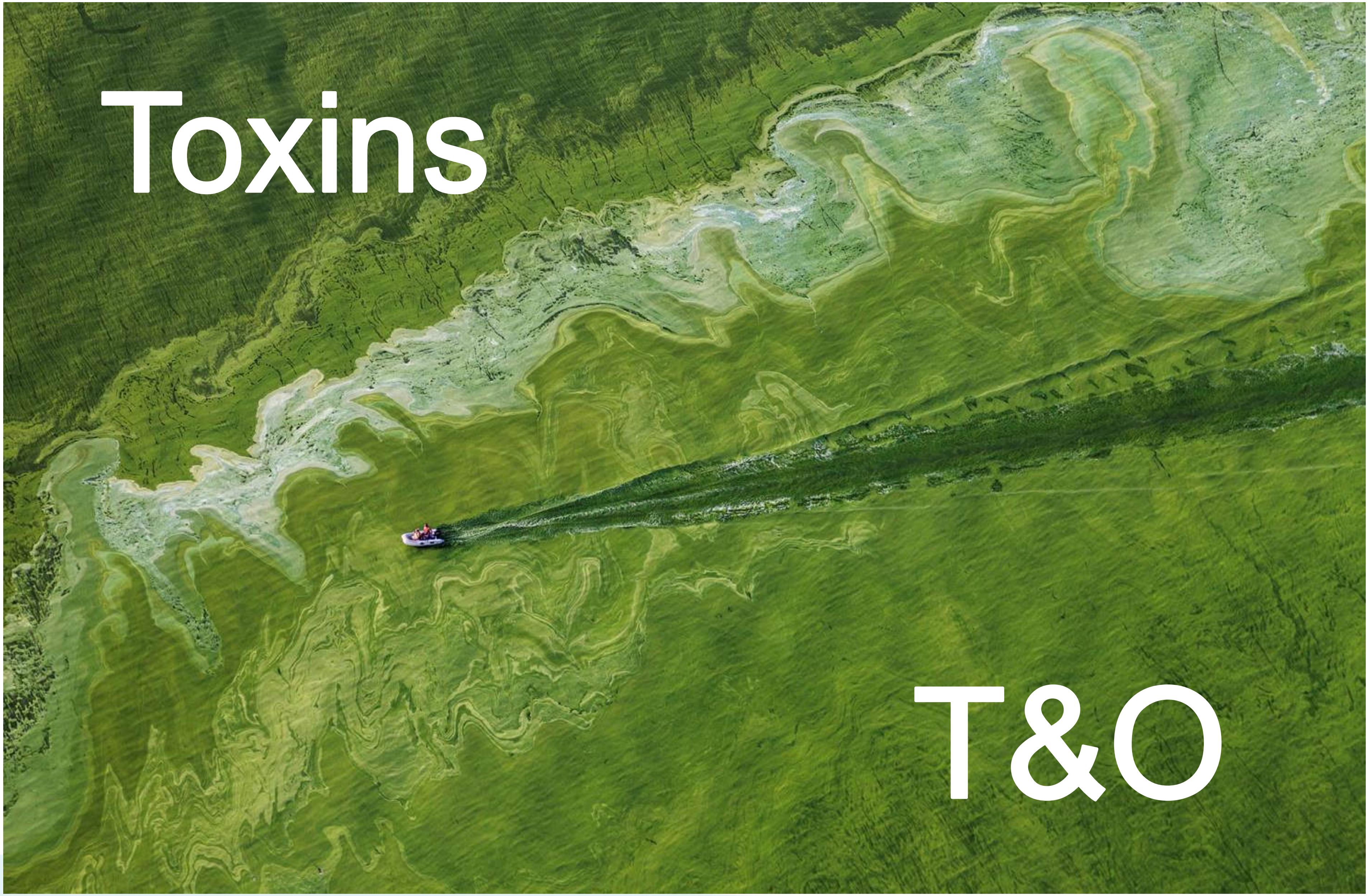
Pesticide Removal Summary

- Ozone improves the UVT and lowers scavenging potential
- Ozone AOP has the lowest OPEX
- When Bromate formation is a concern AOPs can be combined
- Combined AOP‘s can provide lower treatment costs than single UV based AOPs
- Combined treatment steps provide a multiple barrier against a wider range of pollutants and pathogens
- If an upstream ozone treatment is reasonable must be evaluated considering CAPEX and OPEX


HABs



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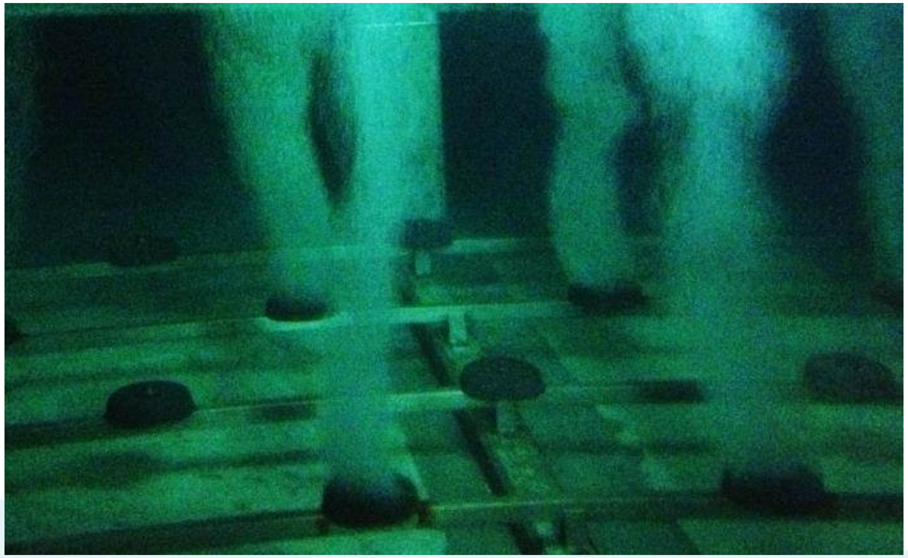
What is T&O?

- Two major compounds are responsible for T&O
- **M**ethyl**i**so**b**orneol & Geosmin
- MIB & Geosmin are formed by cyano bacteria during the bloom
- Bloom event is typically seasonal (2-3 month per year)
- Traces (ng/L) of MIB & Geosmin are recognized by humans
- Easy break trough when using GAC
- PAC needs up to 50 ppm for 20 minutes RT

Ozone / Ozone AOP for T&O



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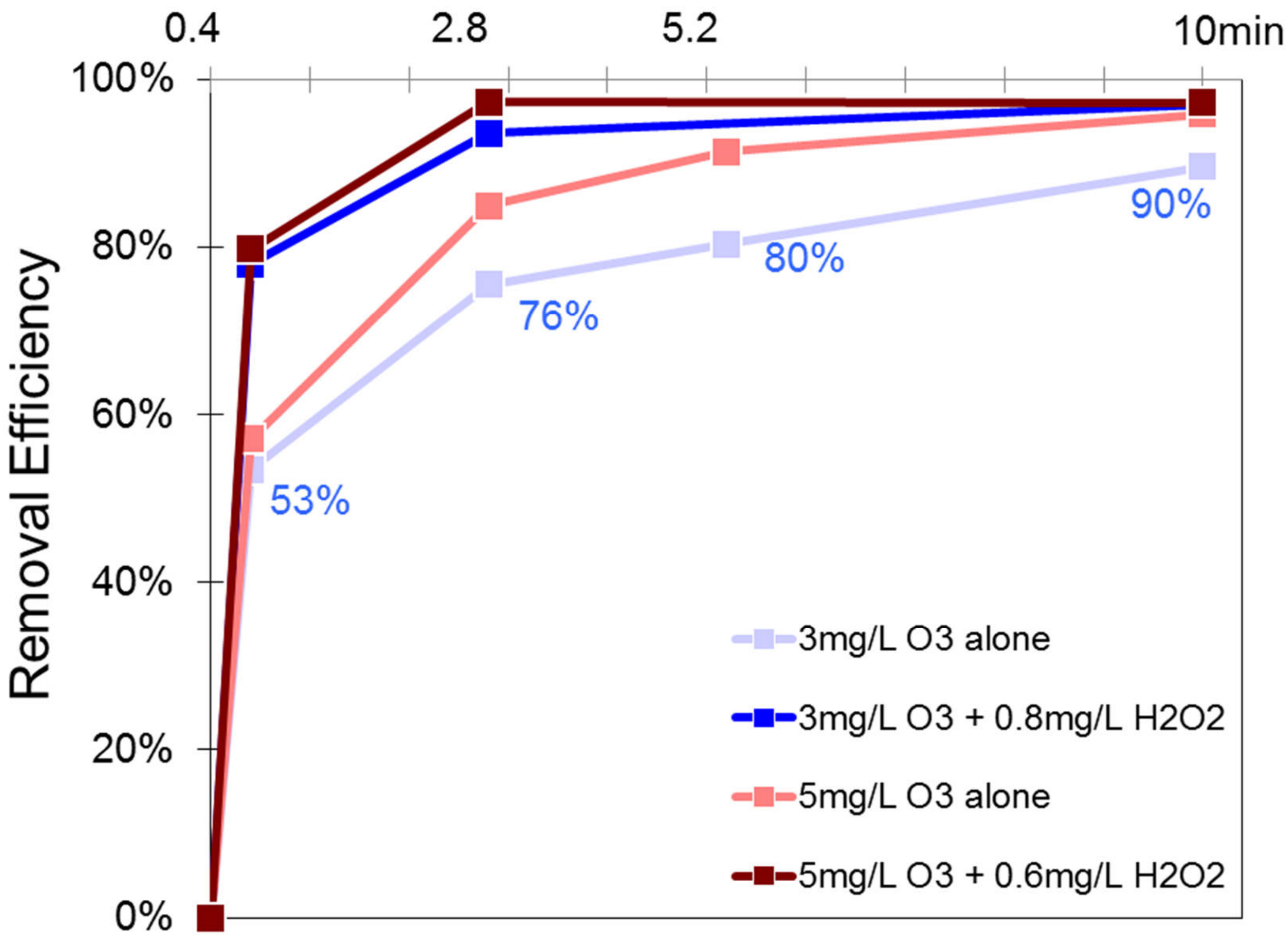
Ozone & Ozone AOP – 2-MIB



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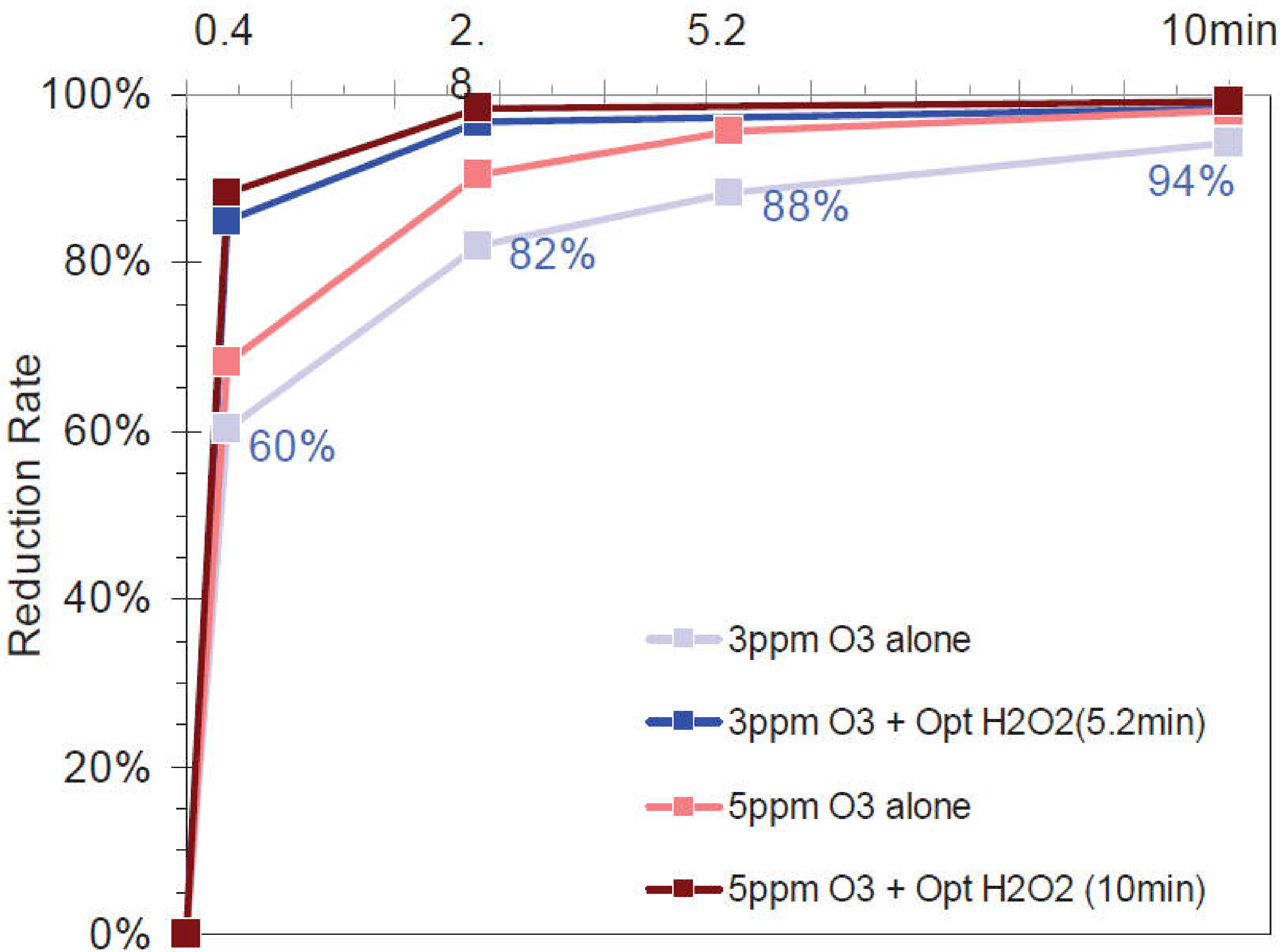
Ozone & Ozone AOP – Geosmin



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Ozone & Ozone AOP

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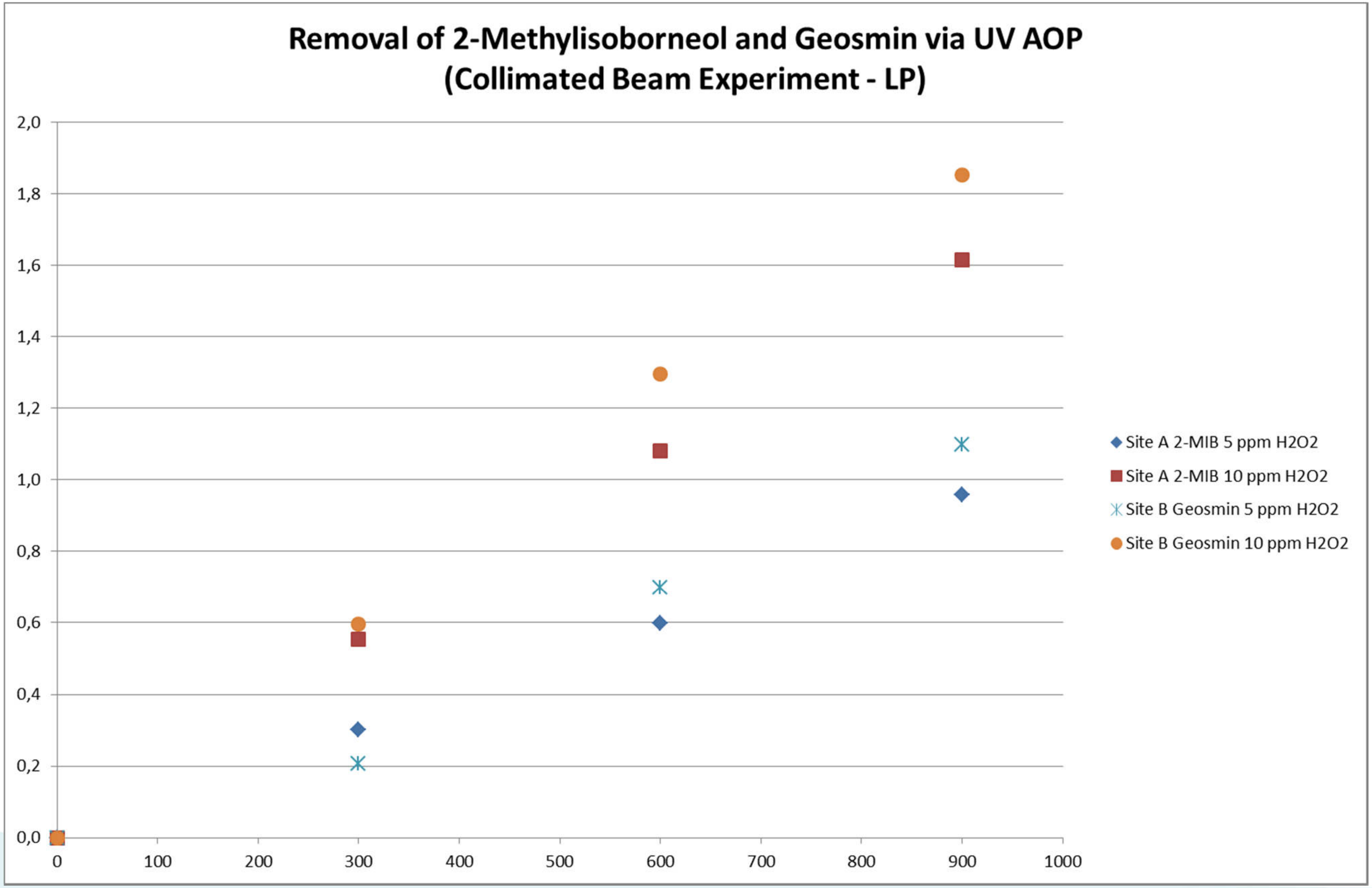
UV AOP for T&O

UV AOP for T&O



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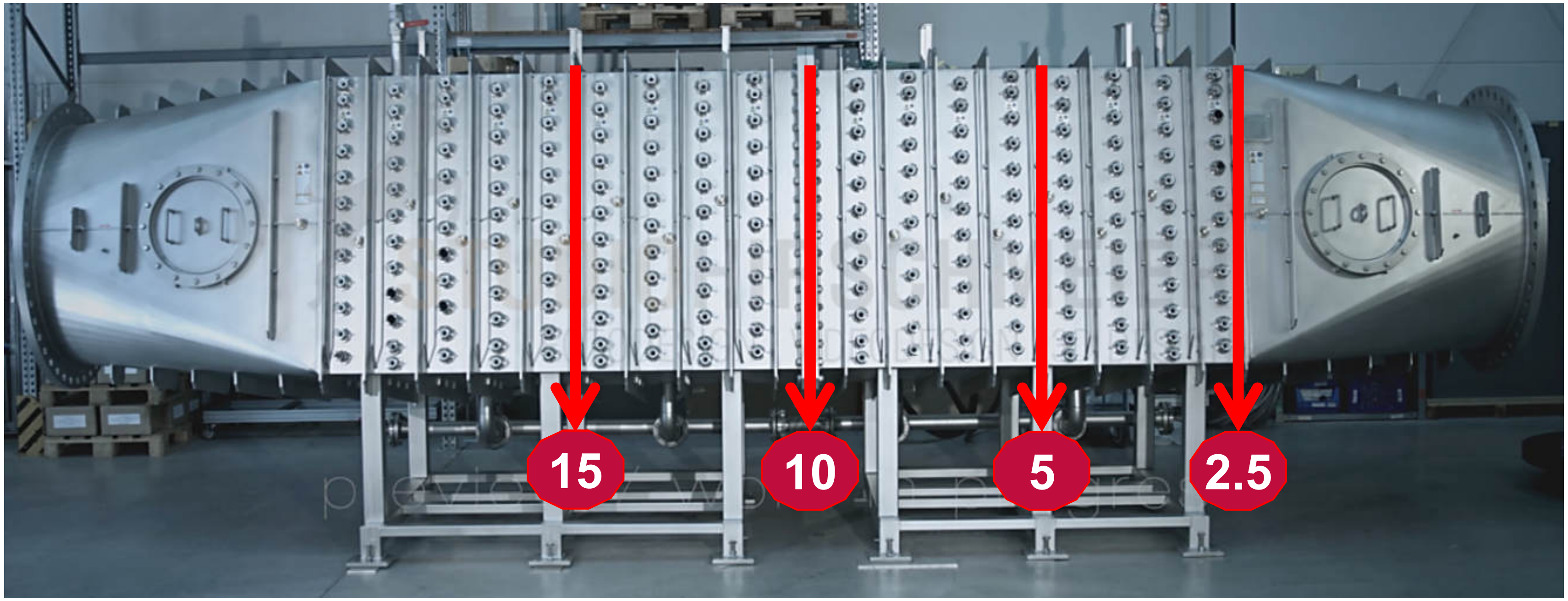
UV AOP for T&O



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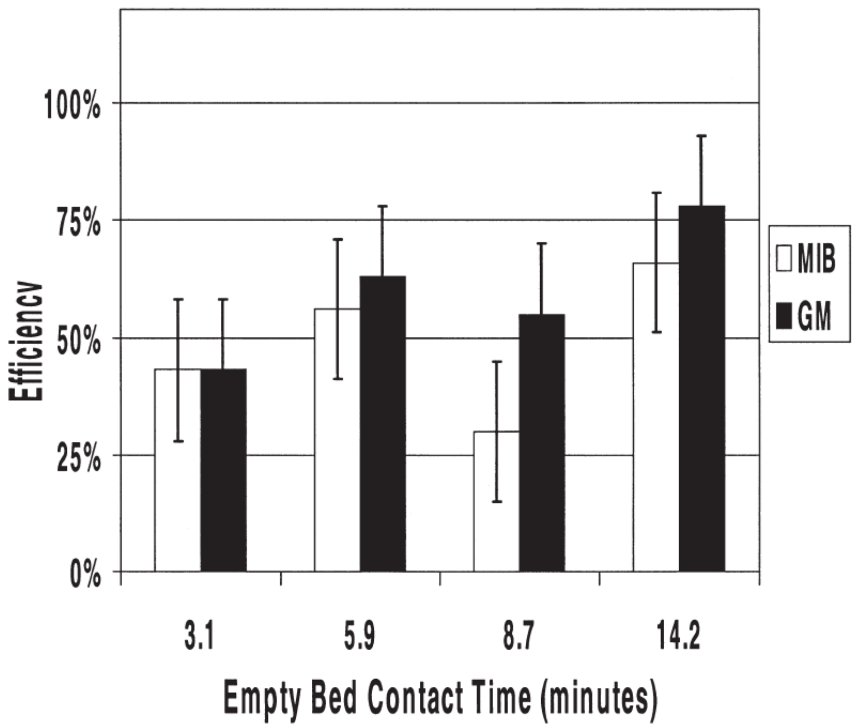
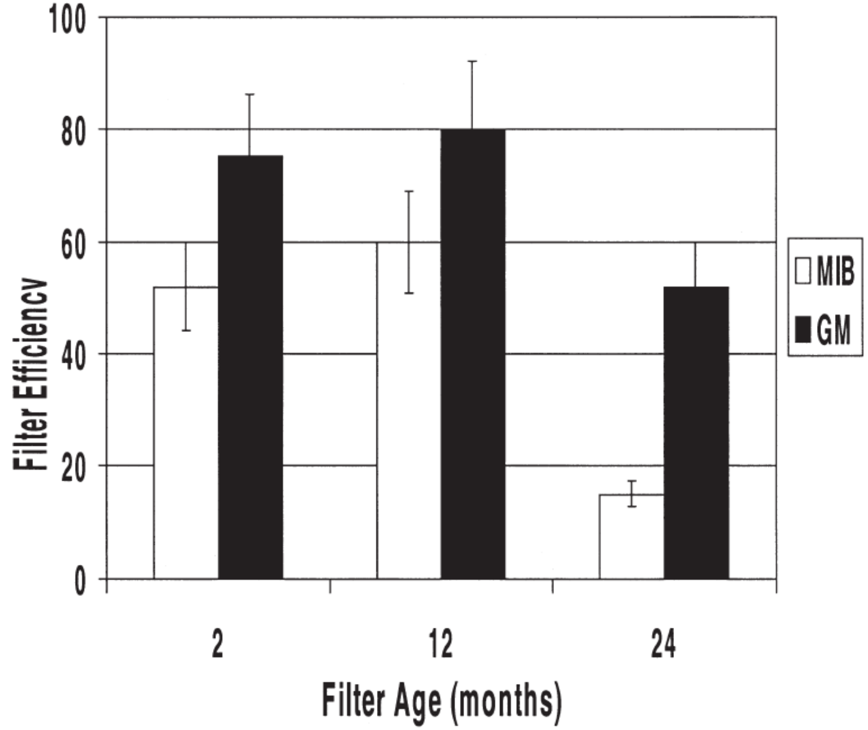
BAF for T&O

Technology evaluation





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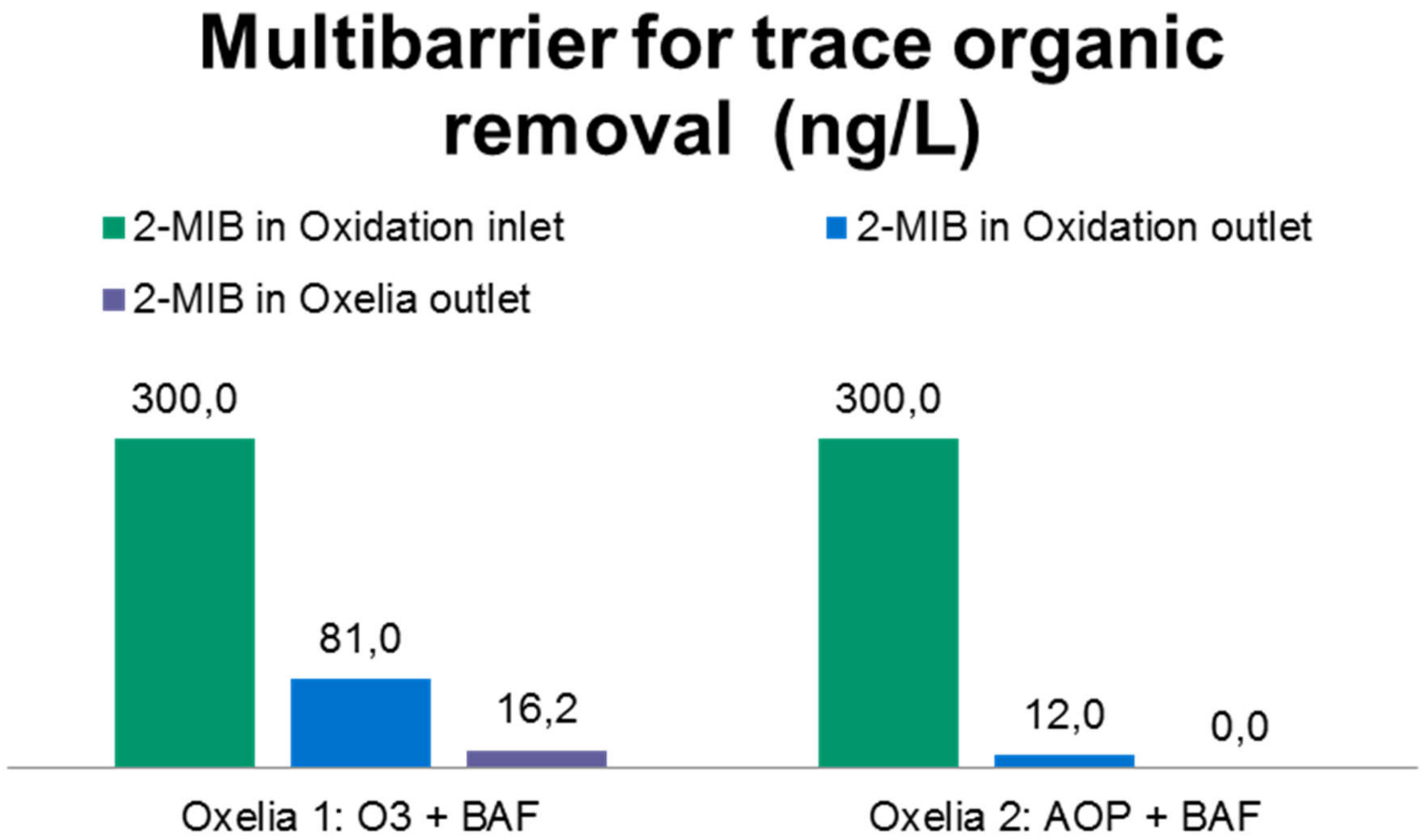
Technology evaluation



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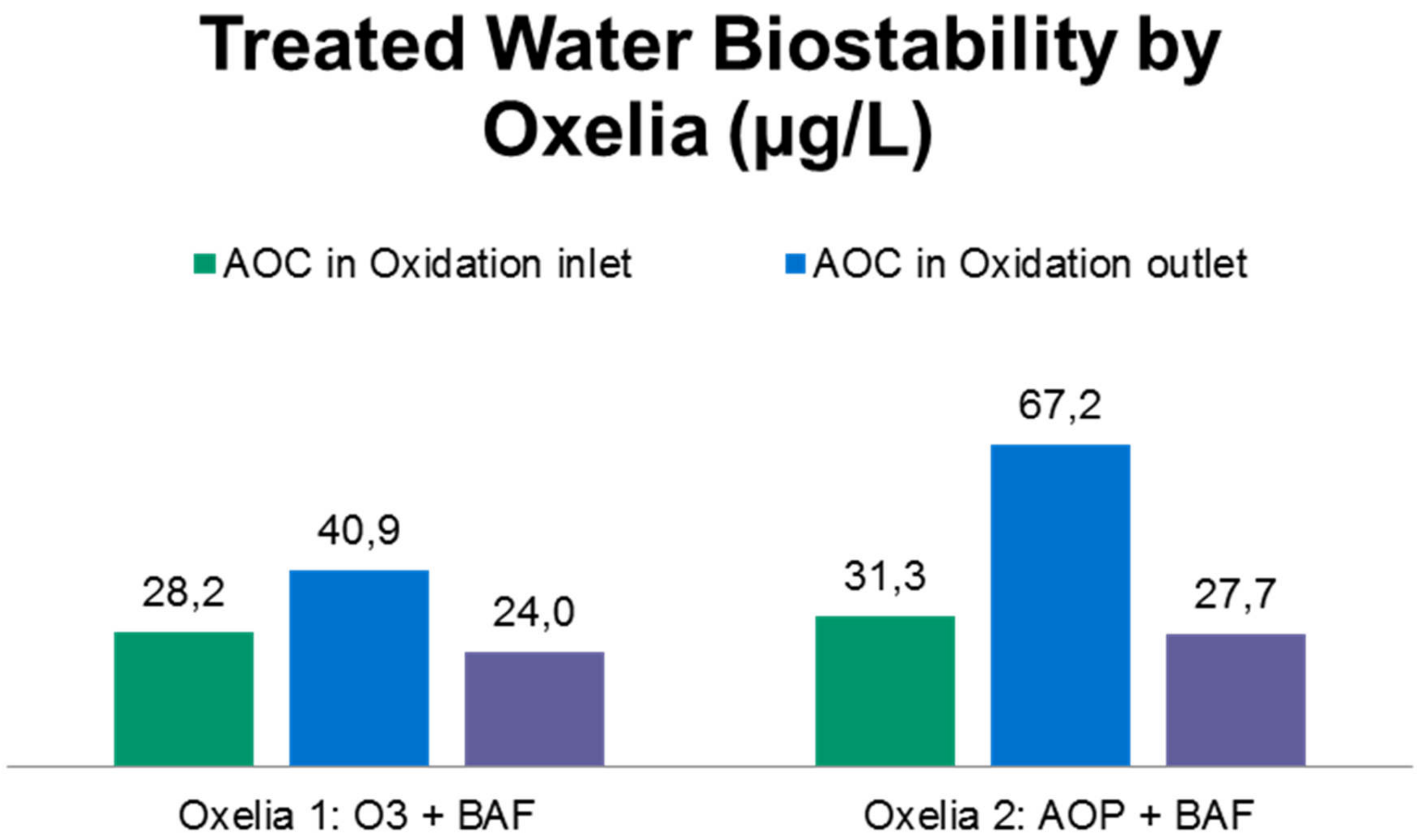
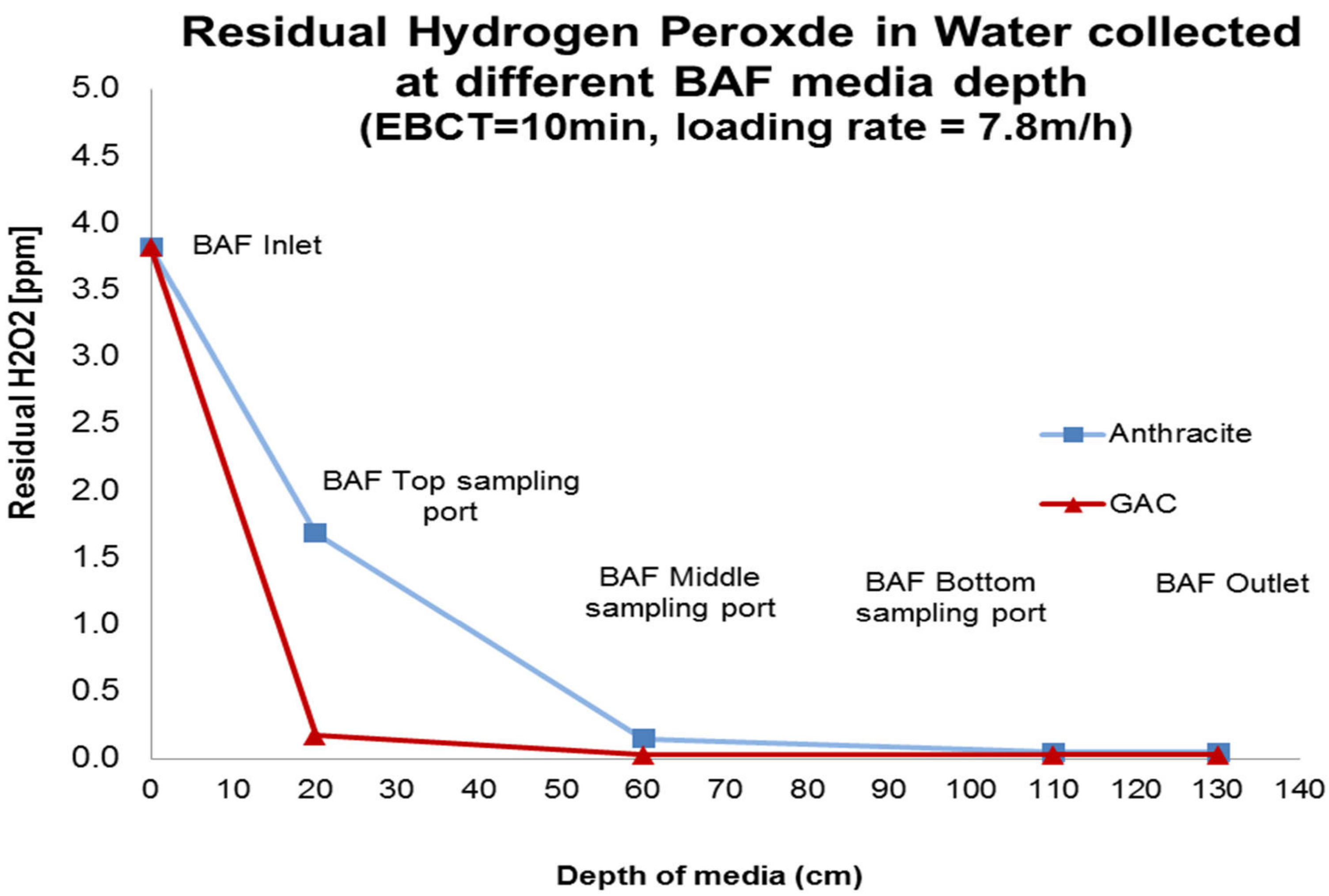
Technology evaluation



Technology evaluation



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Technologies - Selection

- How long is the T&O event
- Flow rate
- Water quality (UVT, TOC, Alkalinity, etc.)
- Existing infrastructure / Available footprint
- Price for oxygen, peroxide, etc.
- Other treatment challenges
- ….

Technologies – Selection: UV LP vs. MP

	low pressure system	medium pressure system
Flow rate	4419 m³/h	4419 m³/h
Number of reactors	3	3
Quantity of lamps	504	48
Lifetime of lamps	14,000 h	9,000 h
Quantity of ballasts	252	48
Average power consumption (AOP mode)	148 kWh (33.5 W/m³)	296 kWh (67 W/m³)
H_2O_2 Dose	10 mg/L	10 mg/L
AOP mode operation	1560 h/a	1560 h/a
Average power consumption (Disinfection mode)	15 kWh	65 kWh
Disinfection mode operation	7200 h/a	7200 h/a
Price 1 kWh	0,08 $	0,08 $
Annual ballast failure rate	2 %	3 %
Years of operation	15	15
Interest rate	3%	3%

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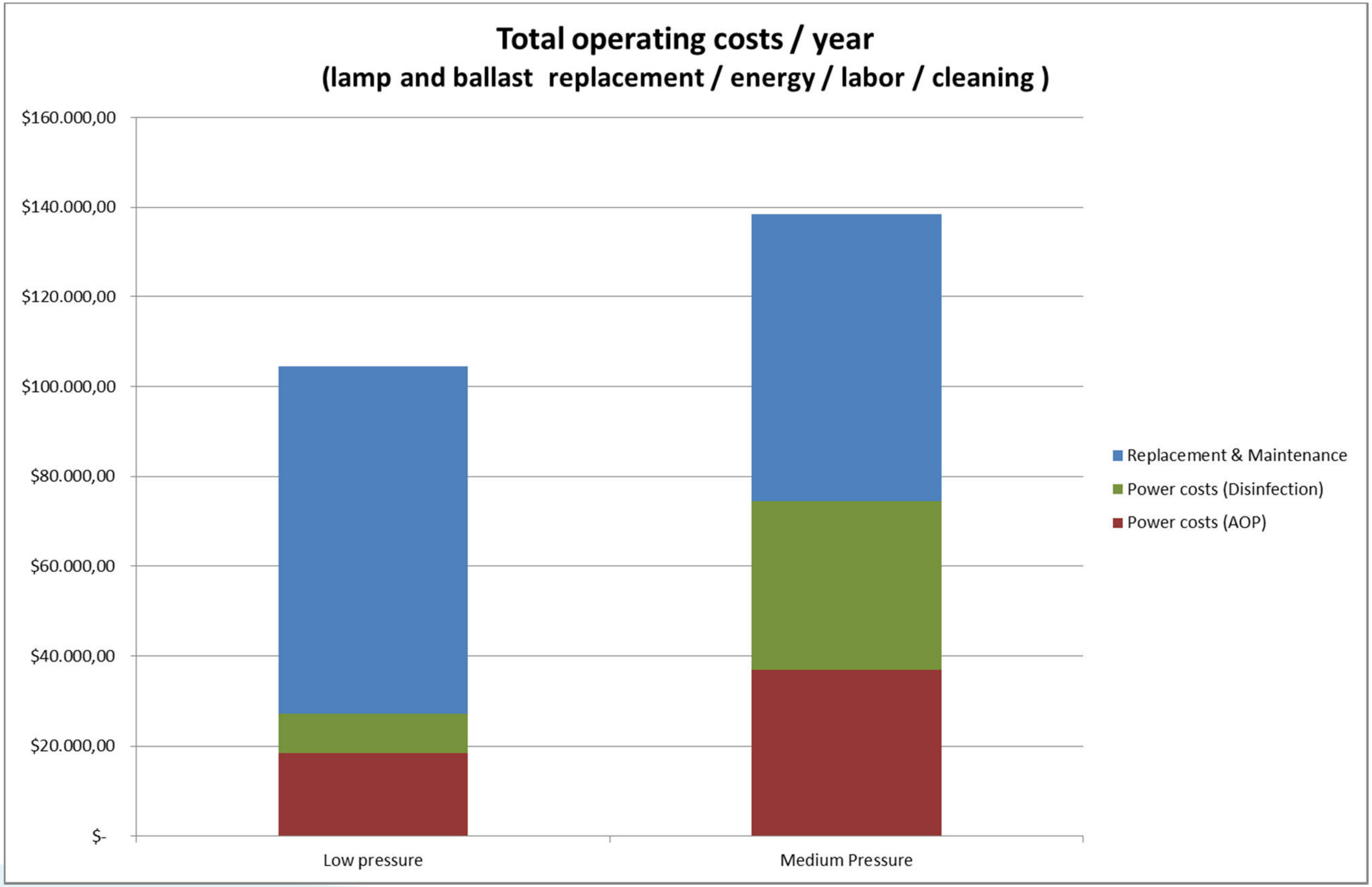
Technologies – Selection UV LP vs. MP



Technologies – Selection UV LP vs. MP

Days of AOP operation	Savings LP vs. MP
30	38,000 USD
60	44,000 USD
90	50,000 USD
120	56,000 USD
360	105,000 USD

Technologies – Selection UV LP vs. MP

- UV LP has become more popular due to higher rated lamps (> 0.5 kW / lamp) → CAPEX savings

- Year around disinfection requirements favor UV LP due to lower energy costs → OPEX savings

Siheung DWTP AOP Project

- UVT : 92.7% ~ 97.3%(Avg. 95.7%)
- Flow : 106,050 m^3/d = 4,419 m^3/h

Treatment Goal

0.5 LOG Removal of 2-MIB

→ **60 days/y**

3.0 LOG Removal of Cryptosporidium

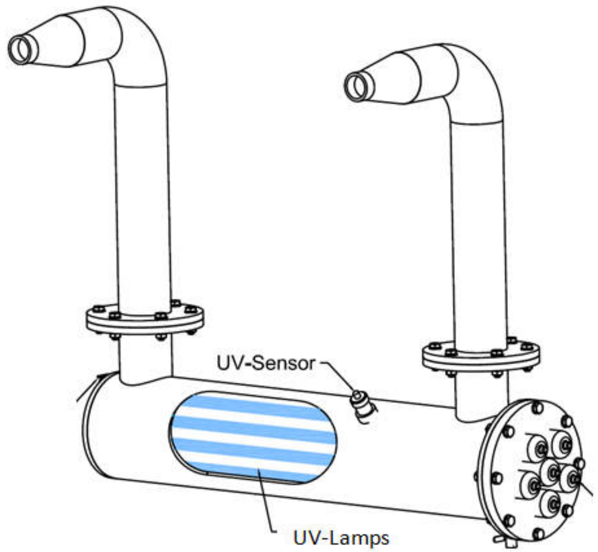
→ **365 days/y**

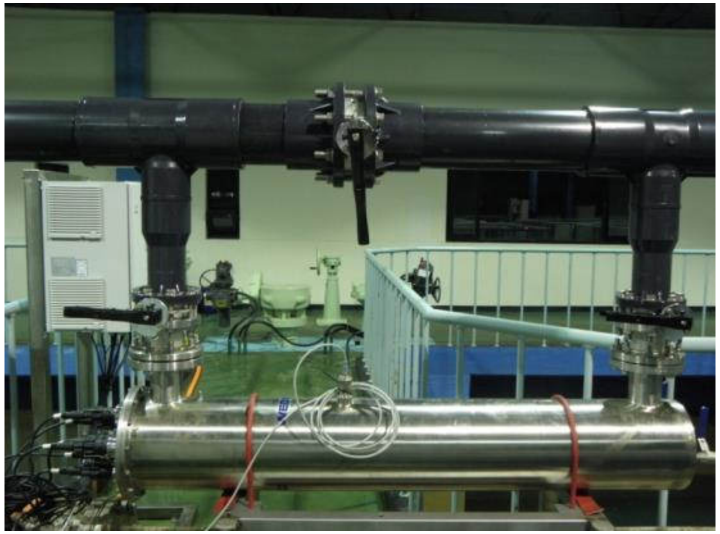
Pilot tests – LP Reactor

Type : WEDECO LBX 120

Flow Rate : 1,000 m³/d

Lamps : 6 Lamp á 360 W incl. Ballasts = 2,16 kW





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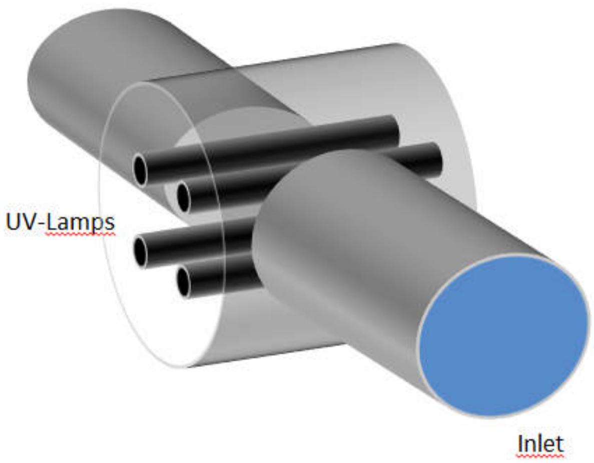
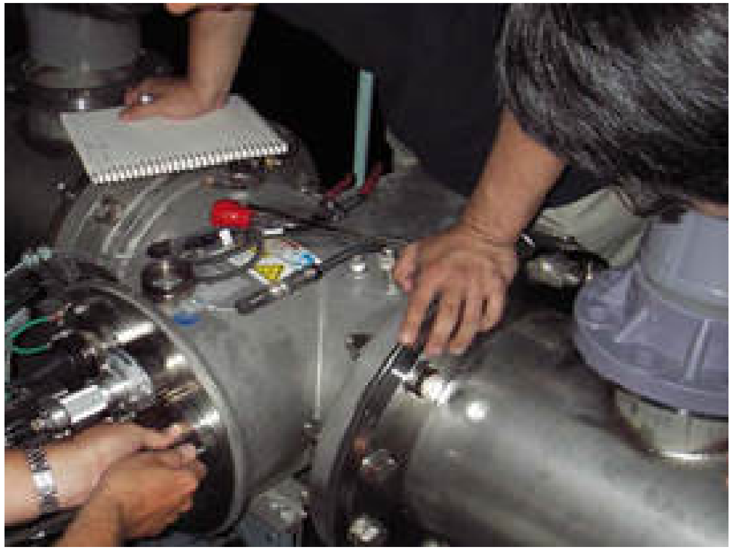
Pilot tests – MP Reactor

Flow Rate : 2,000 m³/d

Lamps : 4 Lamp á 3000 W incl. Ballasts = 12 kW





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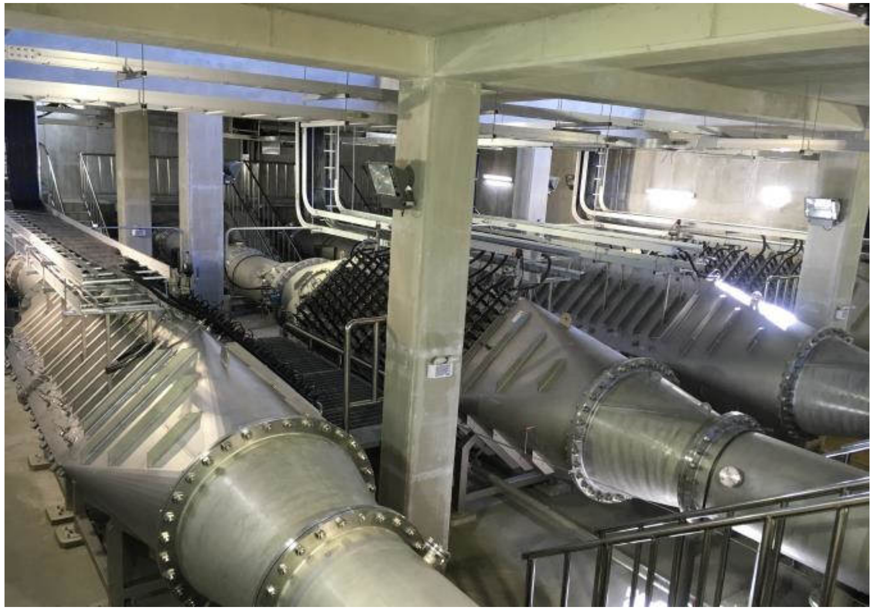
Pilot tests – Summary

Low pressure reactor			Medium pressure reactor		
EED [kW/m³]	H_2O_2 dose [mg/L]	LOG reduction	**EED [kW/m³]**	H_2O_2 dose [mg/L]	LOG reduction
0.07	5	0.58	**0.190**	5	0.50
0.07	10	0.87	**0.144**	10	0.53

→ LP UV AOP needs more than 50% less energy

Siheung DWTP AOP Project



Technology evaluation

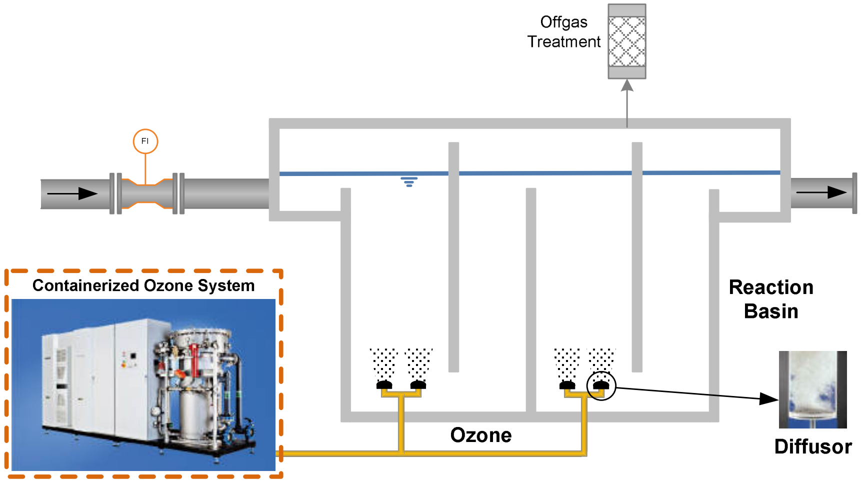
- Surface Water Treatment
- Flow rate 4419 m^3/h
- 60 days T&O removal
- 365 days 3 LOG Crypto
- UVT 93%

AOP

O_3

UV

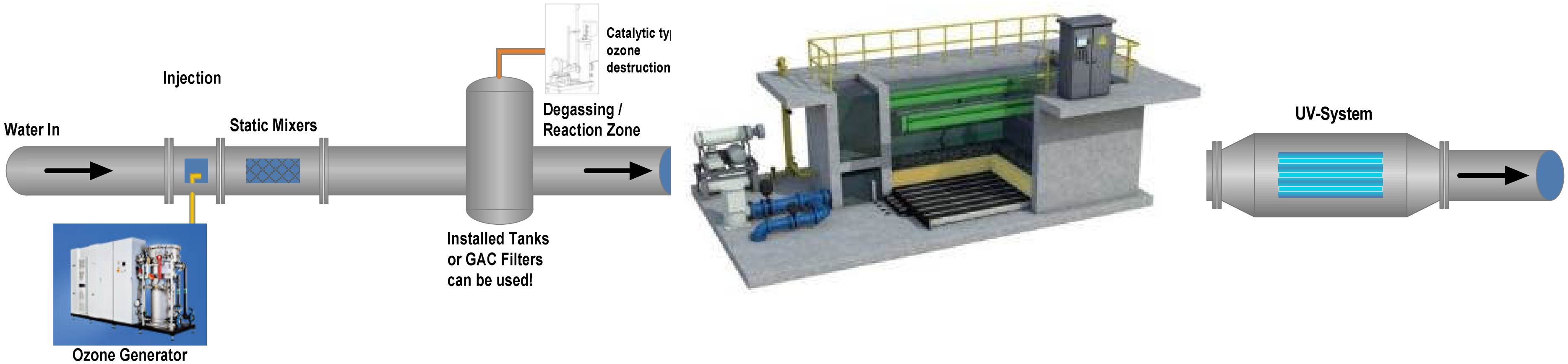
Technology evaluation



- Classic ozone contactor for year round disinfection, color removal, NOM oxidation and seasonal T&O removal by peroxide dosing

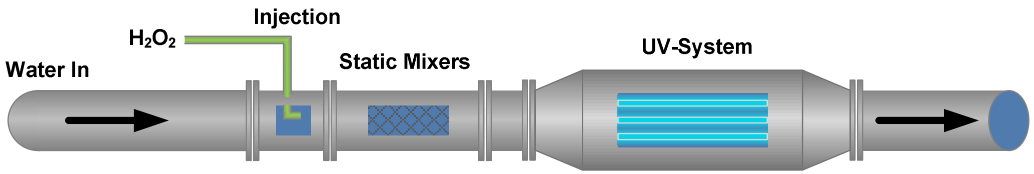
- BAF for peroxide quenching and further NOM / AOC removal

Technology evaluation



- Ozone AOP Reactor for seasonal T&O removal
- BAF for peroxide quenching and further NOM / AOC removal
- UV system for year round disinfection

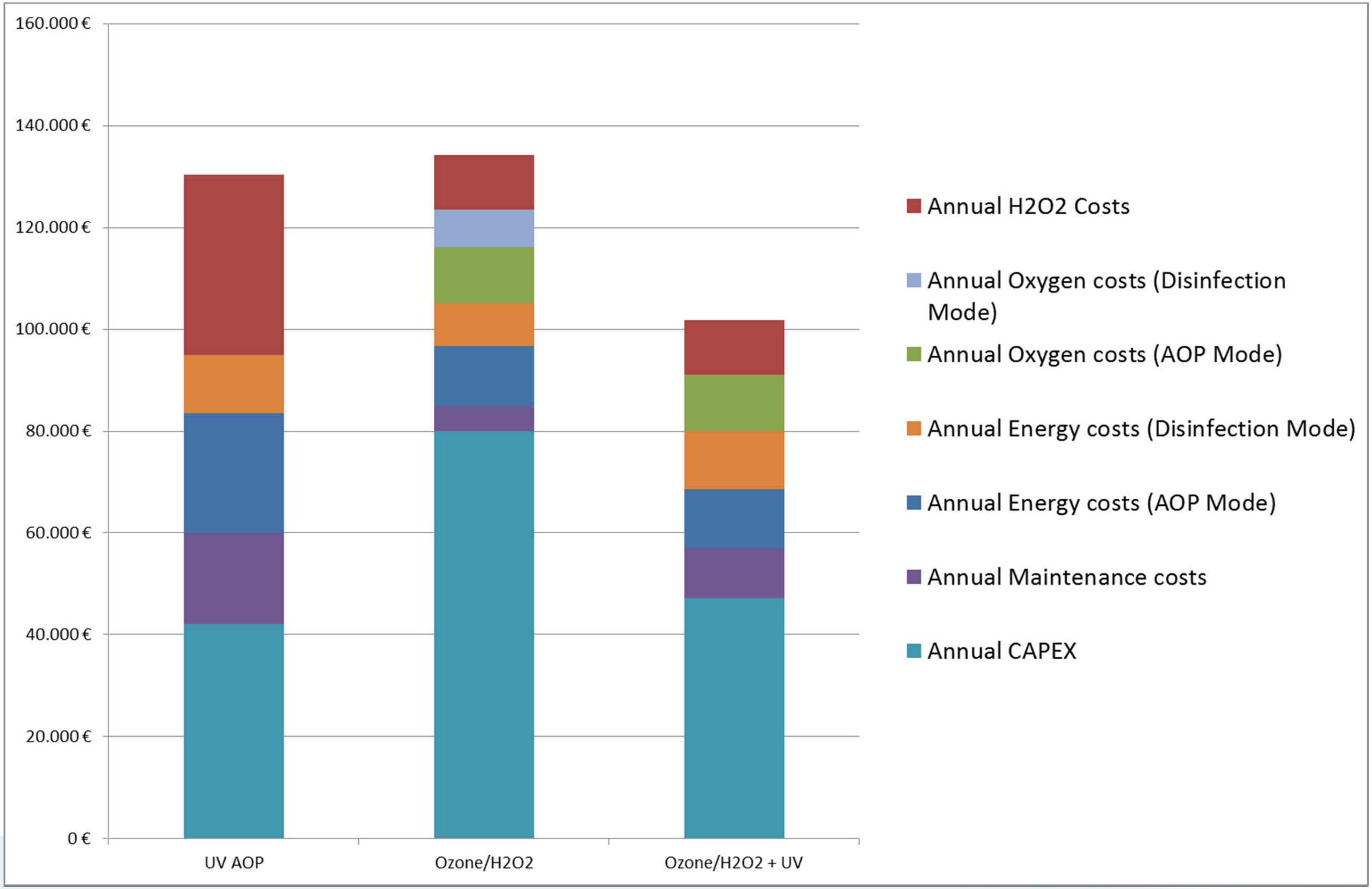
Technology evaluation



- UV AOP system for seasonal T&O removal and year round disinfection

- BAF for peroxide quenching and further NOM / AOC removal

Technology evaluation – 60 days AOP mode



T&O Summary

- LP UV AOP can be an attractive option for seasonal T&O treatment
- LP UV AOP provides significantly lower energy costs compared to UV MP
- Ozone AOP usually provides the lowest OPEX
- Combination with BAF provides a stronger barrier and cost savings for residual peroxide quenching
- Decision which technology is most economical has to be evaluated in each case
- Additional treatment challenges or benefits of certain technology need to be considered

Water Reuse

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Water Reuse


SO WHAT'S THE BIG DEAL? I'VE BEEN DRINKING IT FOR YEARS.
"CITY PLANS RECYCLING TOILET WATER FOR DRINKING"

Water Reuse

Benefits:

- Relieves Water Stress
- Cost-Effective
- Drought-Resistant
- Urbanization means Point of Waste = Point of Use

Challenges:

- Trace Organic Contaminants (TOrCs)
- Pathogens
- Public Perception “The Acceptance Factor”
- Lack of Regulations

Water Reuse

Water Reuse

→ Primary Treatment → Secondary Treatment → Tertiary Filtration → O_3 → **Non-potable reuse (i.e. California T22, irrigation, cooling water, toilet flushing)**

→ Primary Treatment → Secondary Treatment → Tertiary Filtration → O_3 → **UV** → **Non-potable reuse (i.e. California T22, irrigation, cooling water, toilet flushing)**

→ Primary Treatment → Secondary Treatment → Tertiary Filtration → O_3 → **BAF** → SAT → **Indirect potable reuse (i.e. Surface Spreading)**

→ Primary Treatment → Secondary Treatment → MF or UF → Reverse Osmosis → O_3-AOP → **California Draft Groundwater Recharge Regulations (i.e. 1,4-Dioxane)**

→ Primary Treatment → Secondary Treatment → MF or UF → O_3 → **BAF** → **UV** → **WRRF 11-02 (i.e. DPR)**

→ Primary Treatment → Secondary Treatment → O_3 → MF or UF → RO → **UV-AOP** → **WRRF 11-02 (i.e. DPR)**

→ Primary Treatment → Secondary Treatment → O_3 → **BAF** → MF or UF → RO → **UV-AOP** → **San Diego DPR**

Water Reuse

- **The use of Ozone for reuse is primarily driven by the need to:**
  - Remove emerging contaminants due to both public perception and regulatory uncertainty along with known adverse environmental impacts
  - Improve aesthetic impacts of reclaimed water such as color and odor that readily important to customers
  - Enhance multiple-barrier treatment train approaches for indirect and direct potable reuse
  - Address challenges posed by use of membranes such a brine residual management and membrane fouling

Water Reuse

Ozone-Oxidation

- Disinfects (i.e. virus inactivation)
- Removes color and odor
- Reduces trace organic contaminants
- Increases biodegradability of recalcitrant organic carbon
- Supersaturates water with dissolved oxygen

Ozone-BAF

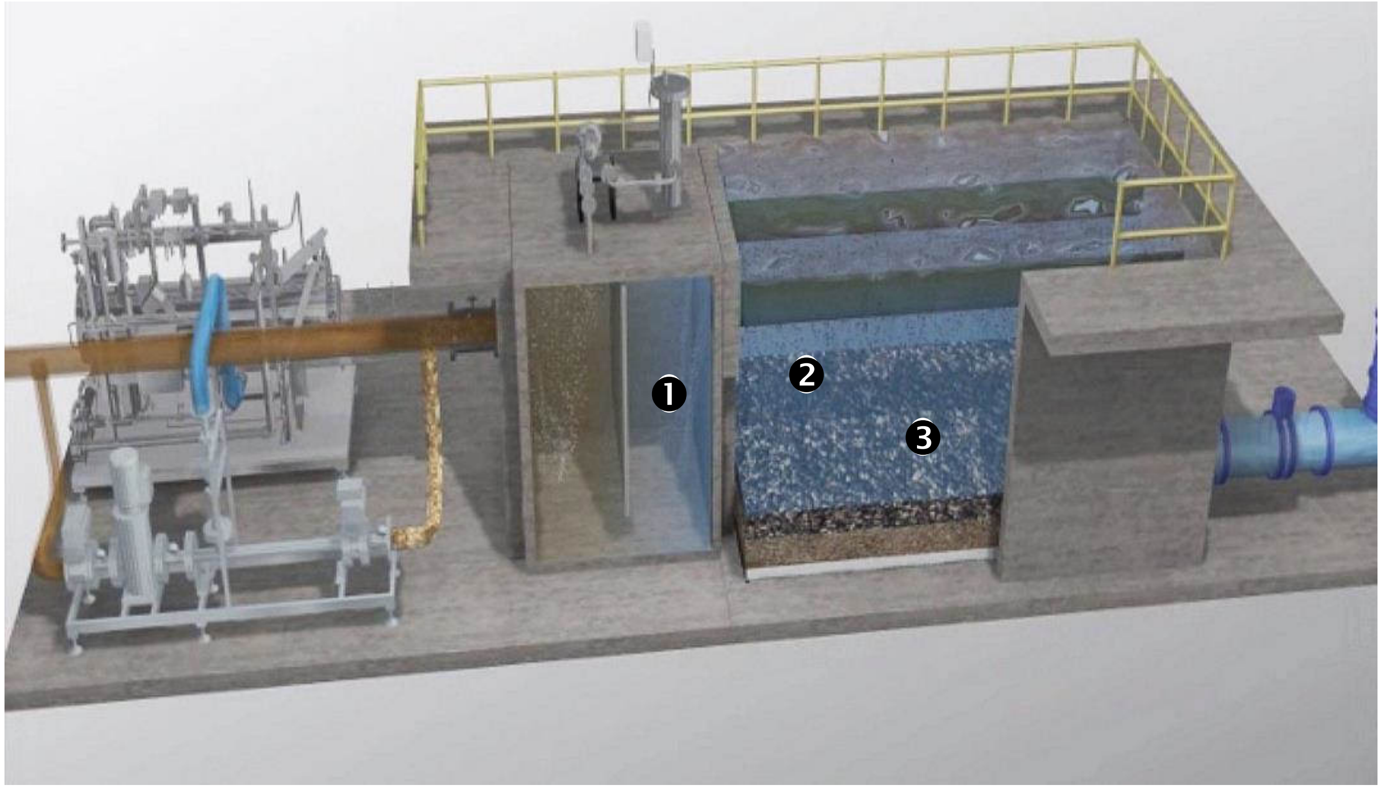
- “Free” biology
- Destroys recalcitrant organic carbon
- Generates biologically stable effluent
- Eliminates toxicity
- Increases UVT
- Provides multiple-barrier

BAF

- Removes ammonia
- Removes TSS
- Reduces trace organic contaminants including NDMA
- Reduces oxidation by-products

Water Reuse

1. Oxidation → 2. Filtration → 3. Biological Treatment



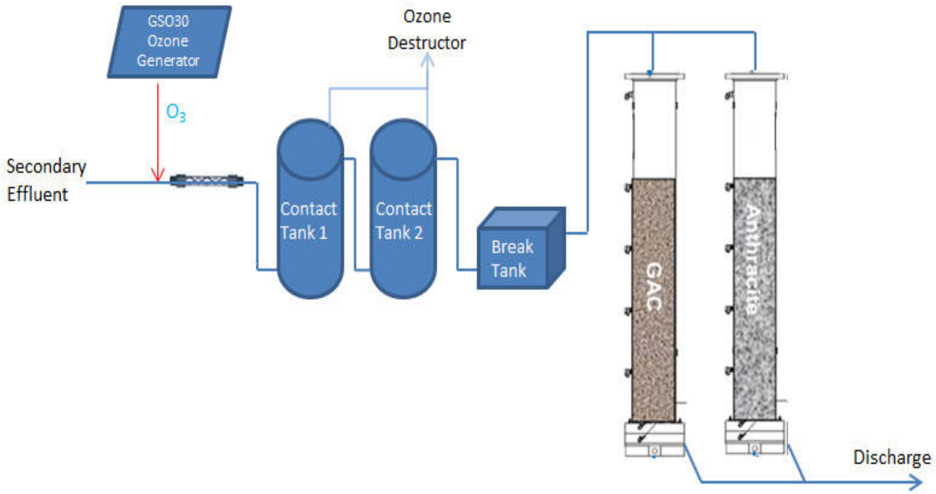
❶ **Inactivation of Pathogens & Oxidation of Organics** ❷ **Removal of TSS and Turbidity** ❸ **Destruction/Removal of TOC, CECs, and DBPs**

Water Reuse

Comparison of O3-BAF to RO for Indirect Potable Reuse

	MF-Ozone-BAF	MF-RO-AOP
Installed capital cost	~ 40% lower	High
Annual operation and maintenance cost	~ 50% lower	High
Energy	Low	High
Consumables	Low (GAC does not need to be replaced)	No (RO membranes must be replaced)
Residual Management	Minimal	Yes
TDS/Salinity Removal	No (use partial RO treatment if needed)	Yes
Destroys TOrCs and TOC	Yes	No (creates a residual waste stream)

Water Reuse – OXELIA Pilots (WWTP Zelienople)



Flowrate	5 – 25 GPM
Ozone Generation System	PSA O2 on-site concentrator + WEDECO GSO system
Ozone Dose	0 or 2 -25 ppm
Ozone Contact tank	2 × 300 gallon
Filter Size	2'(L)× 2'(W)× 17'(H) (Full size filter)
Filter Media	6' of Spent GAC (ES 0.95mm, UC 1.7) 6' of Anthracite (ES 0.95mm, UC 1.7)

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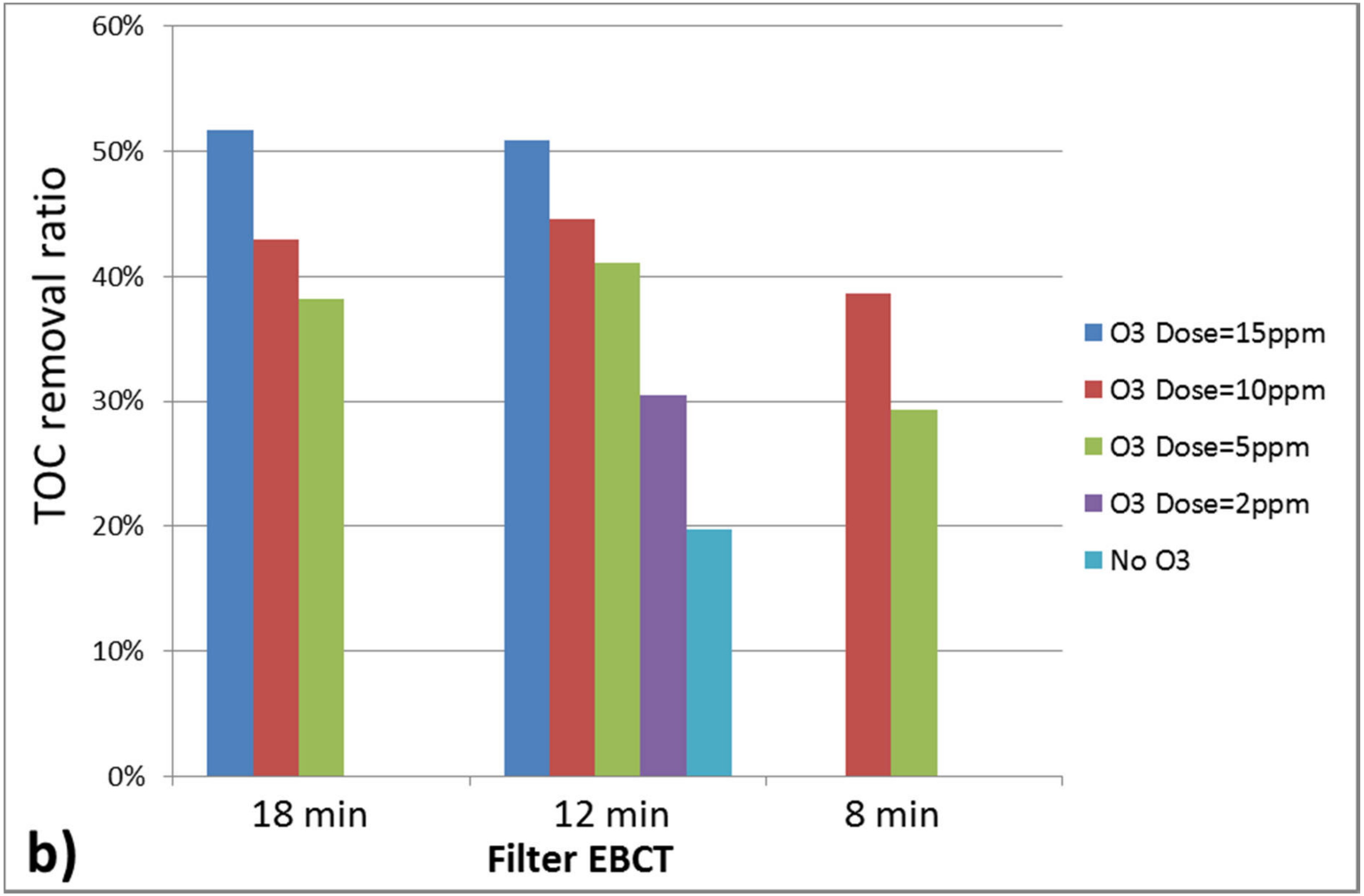
Water Reuse – OXELIA Pilots (WWTP Zelienople)



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Water Reuse – OXELIA Pilots (WWTP Zelienople)

	Secondary Treated Effluent	Ozonated water/ Filter inlet	Filter Outlet
COD	21 – 33 mg/L	Not Measured	10 - 20 mg/L
TOC	4.8 – 7.0 mg/L	Not Measured	3.0 - 5.5 mg/L
UVT	58% – 72%	65% - 82%	70% - 89%
Turbidity	7 – 10 NTU	Not Measured	0.2 – 3.0 NTU
TSS	Not Measured	5 – 10 mg/L	0.2 – 2.4 mg/L
TKN	2.8 mg/L	2.1 mg/L	1.4 mg/L

Water Reuse – San Diego Pure

- O_3 + BAF + MF + RO + UV AOP
- 165 m³/h
- Ozone capacity of 4 kg/h
- 15 min EBCT Gravity GAC Filters
- Base of design for a 5677 m³/h Reuse plant

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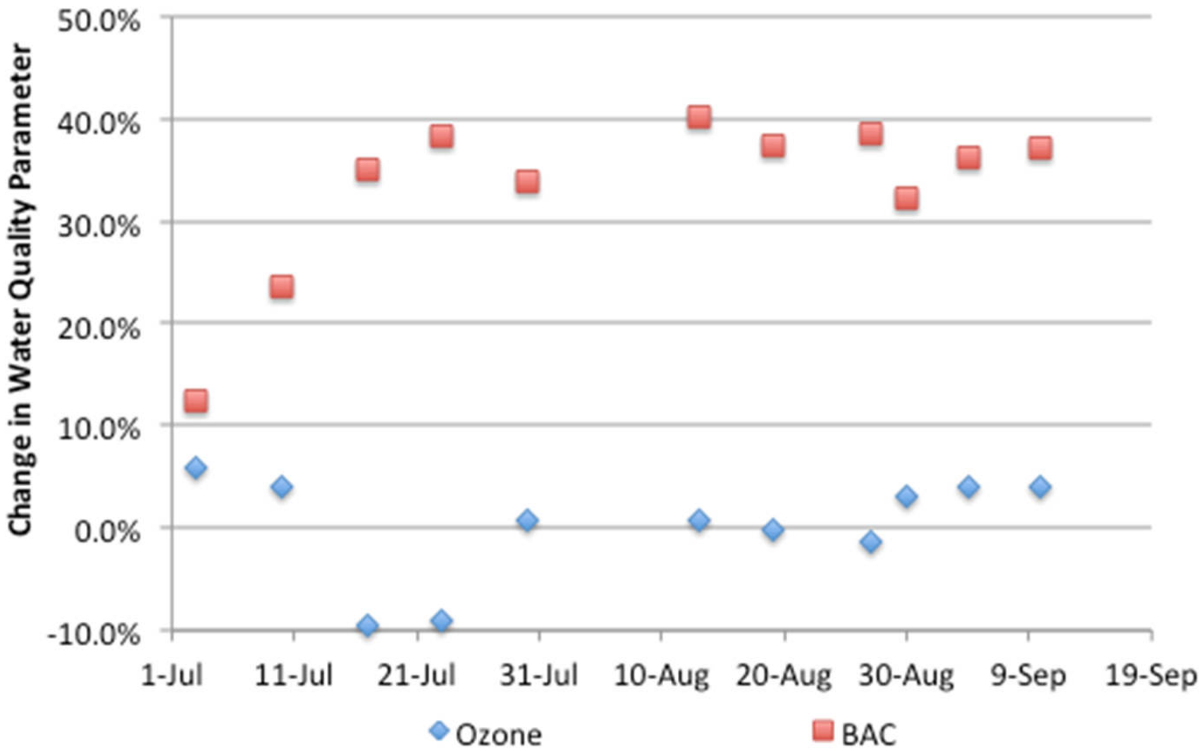
Water Reuse – San Diego Pure

Key Observations

- ~40% TOC removal across O3-BAC system
- Ozone excellent at removing a majority of CECs
- BAC (after ozone) provides additional barrier for most challenging CECs and oxidation byproducts
- O3-BAC significantly reduces organic fouling of UF membranes
- O3-BAC improves quality of RO concentrate
- O3-BAC satisfied California criteria for AOP

Water Reuse – WRRF 11-02



- TOC removal approached steady-state after 4-6 weeks of operation
- Utilize exhausted GAC for study to eliminate adsorption impacts
- Increased UV Transmittance from ~76% to ~89%

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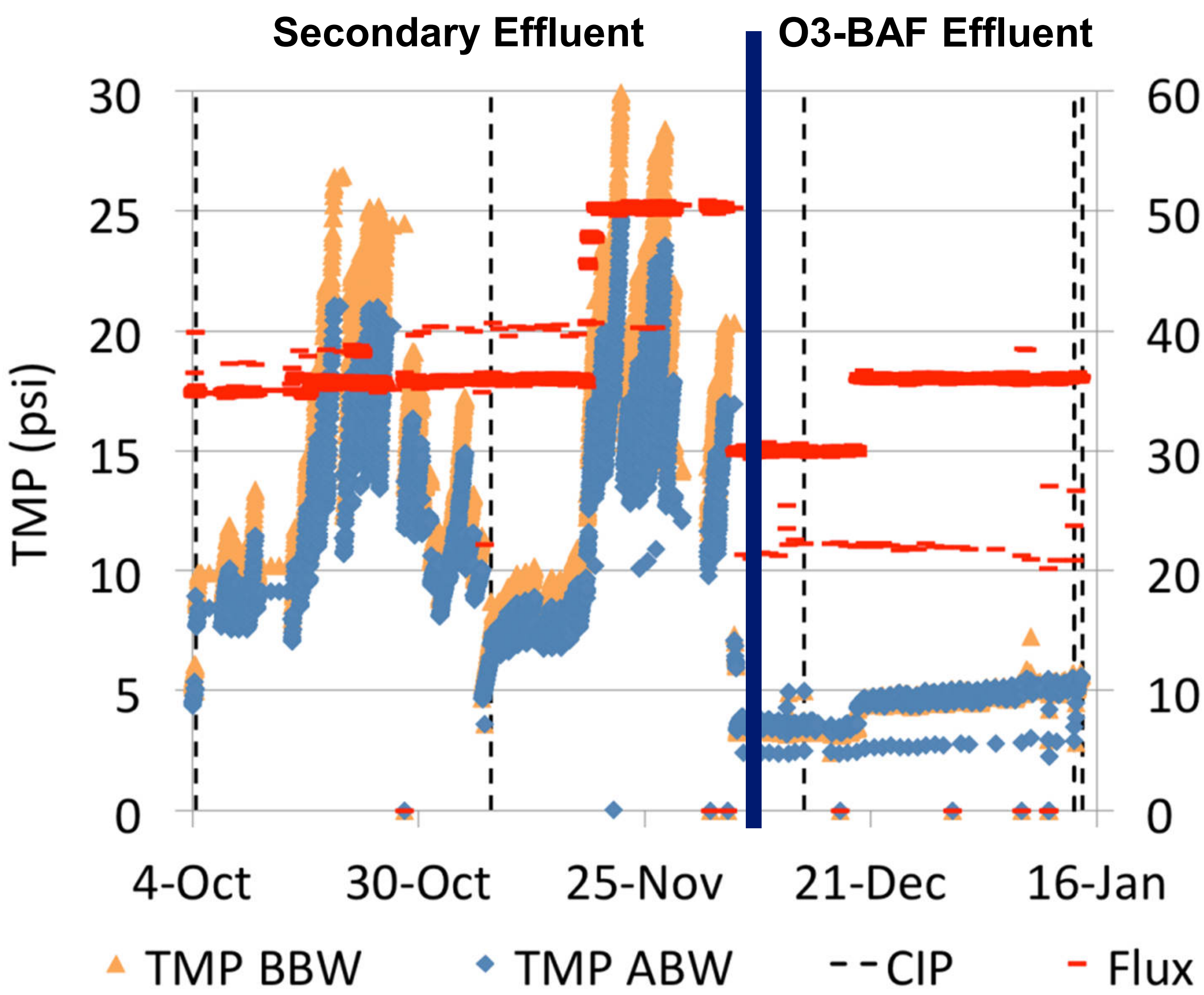
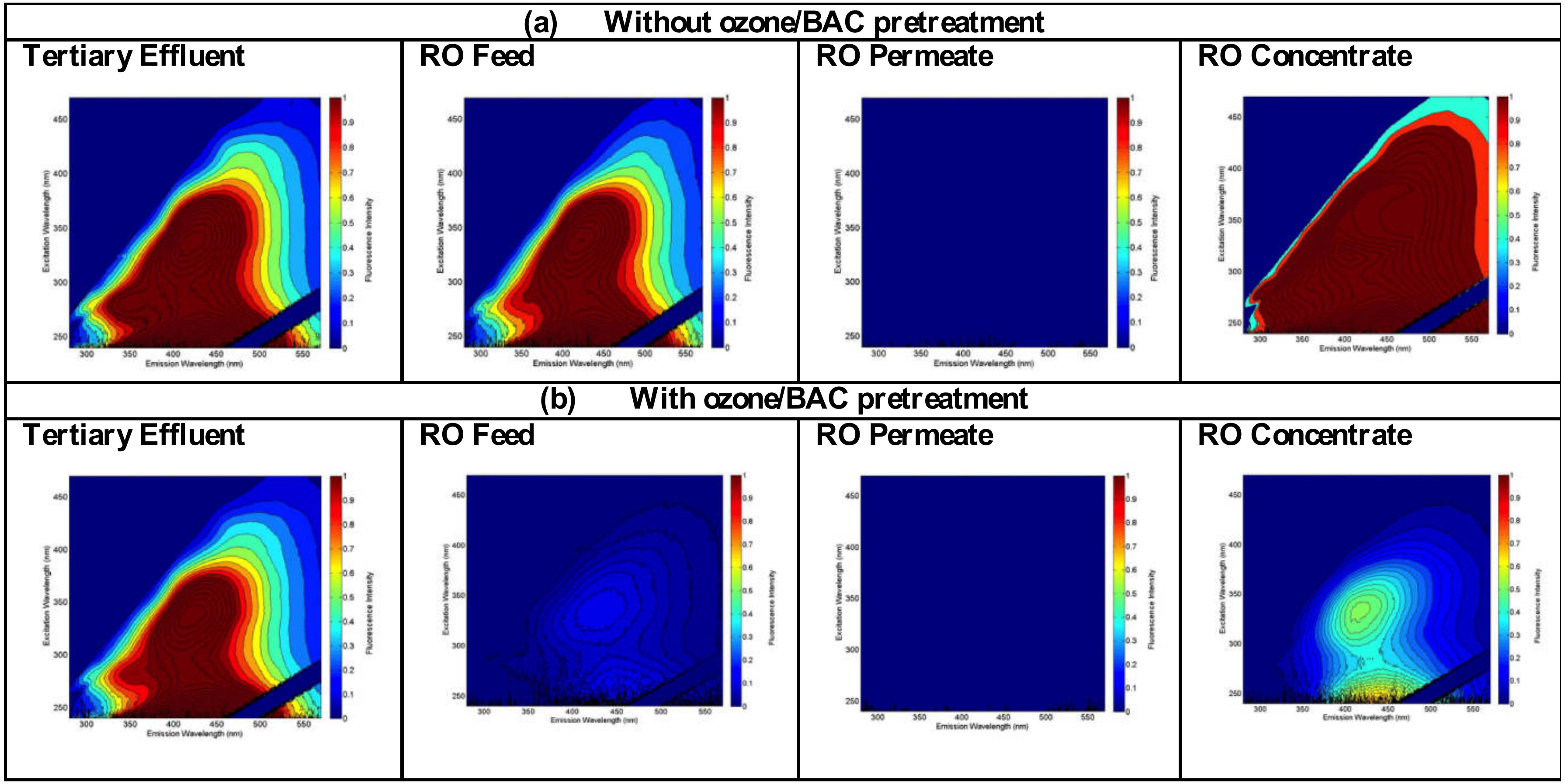
Water Reuse – WRRF 11-02



Ref: WRRF 11-02 Pilot Project

- O3-BAF reduces organic fouling of membranes
- ~ 3x reduction in Transmembrane Pressure Drop
- Reduces energy costs, CIP, and improves overall performance

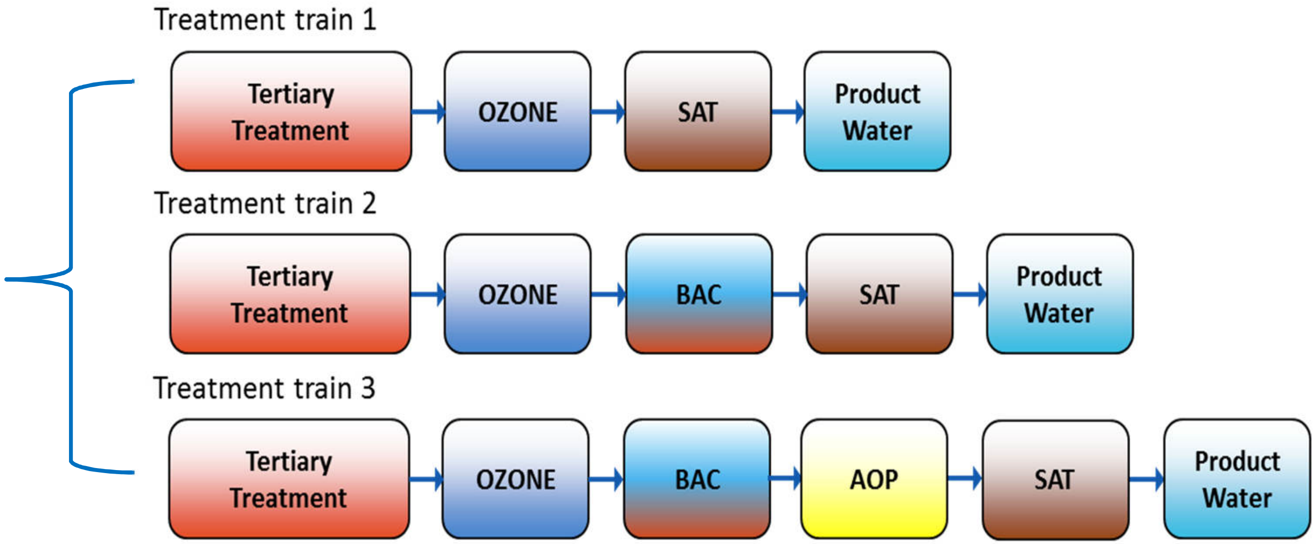
Water Reuse



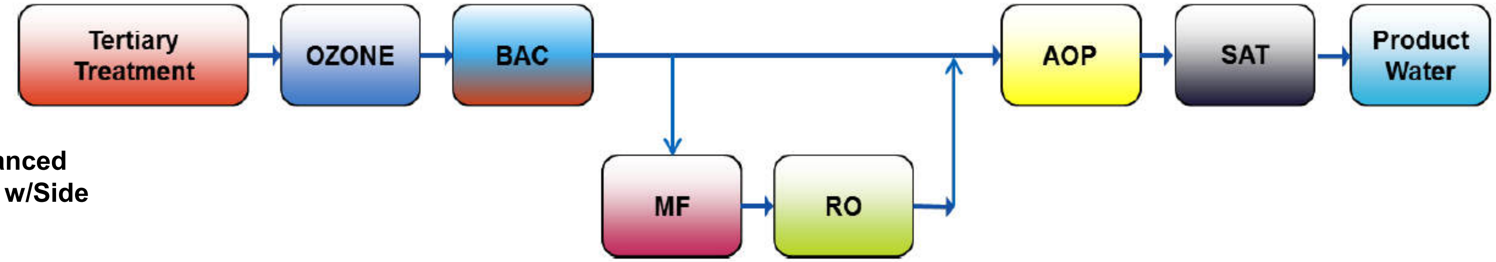
Ref: Trussell Technologies IOA-PAG Dallas 2015

Water Reuse – DCTWRP AWPF Pilot Project

Alternative Advanced Treatment Train



Limited side stream treatment from RO evaluated for the scenario where it is deemed necessary for meeting TDS or chloride limits:



Alternative Advanced Treatment Train w/Side stream from RO

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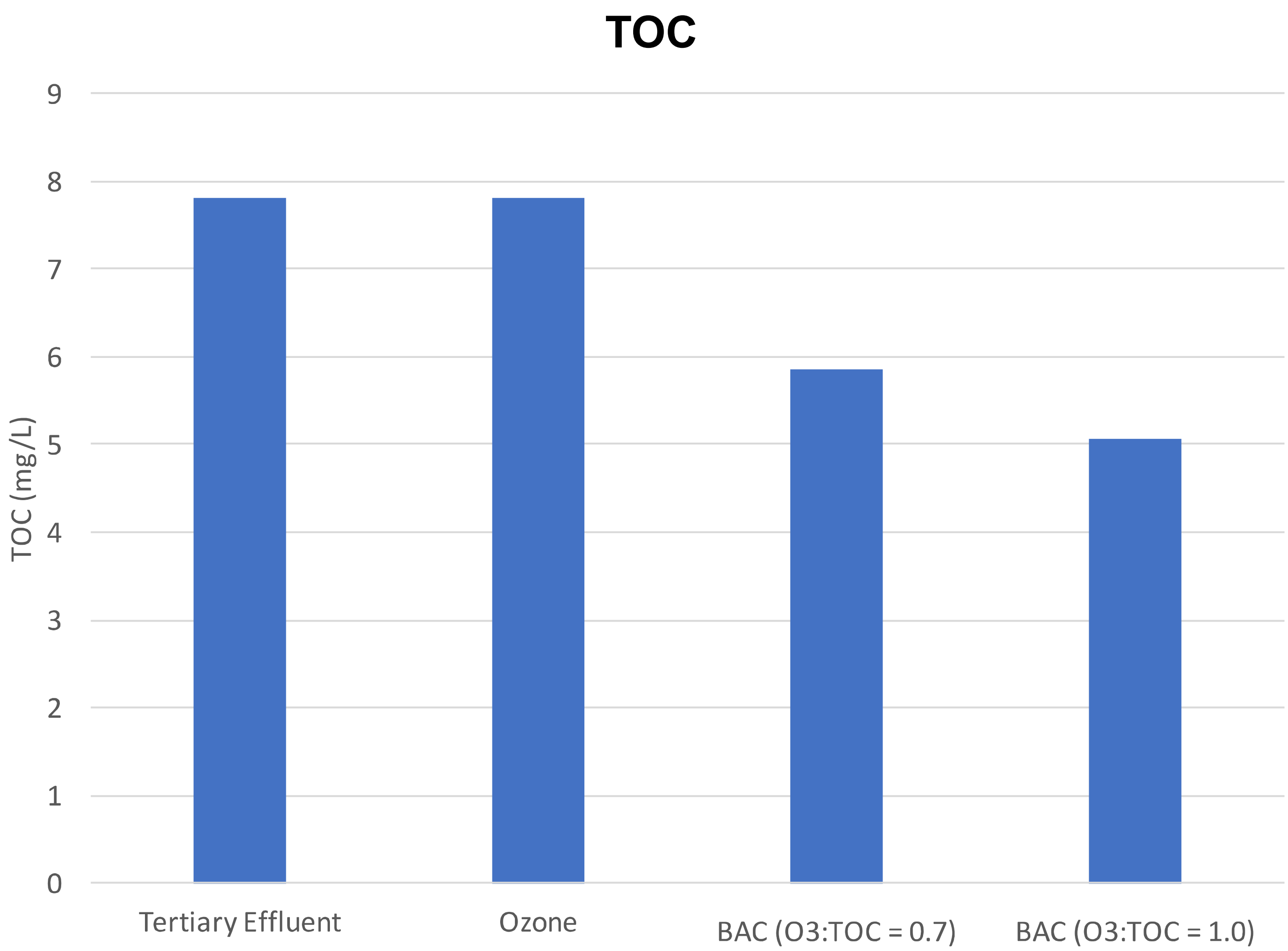
Water Reuse – DCTWRP AWPF Pilot Project



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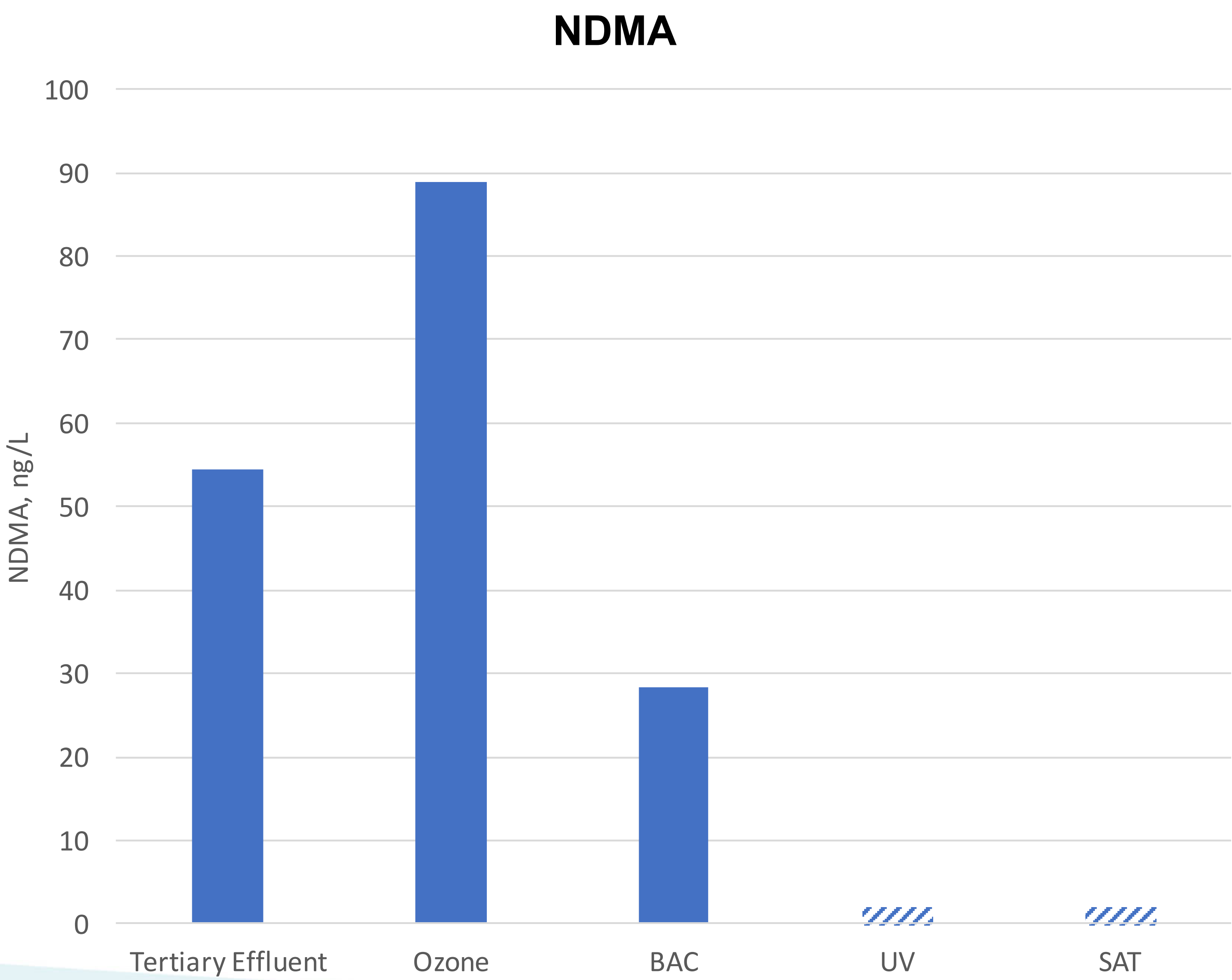
Water Reuse – DCTWRP AWPF Pilot Project



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Water Reuse - Summary

- **TOC removal across O3-BAF System approached steady-state after 4-6 weeks of operation**
  - Measured true acclimatization of biology by beginning pilot with “exhausted” GAC
- **The UV Transmittance of the water increased from ~76% to ~89% across the O3-BAF System**
  - Surrogate for TOC removal, overall performance
  - Significantly reduces size of downstream UV System
- **NDMA formed by Ozone is removed by BAF**
  - Ozone formation of NDMA will vary from site to site
  - Changes in EBCT appear to impact NDMA removal
  - Conceptual treatment train accounts for potential NDMA issues by using UV as final polish
- **Achieving 3-4 day run times in between backwashes, but could be longer if triggered by head loss**
- **Ozone and O3-BAF significantly reduce organic fouling of membranes**
- **Ozone-Enhanced Biologically Active Filtration enables the implementation of cost-effective alternatives to RO-based treatment trains**

Thank You!

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Let's Solve Water