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Innovative Disinfection Approaches: Status and Future Development

Thursday, March 1, 2018
1:00 – 3:00 p.m. Eastern

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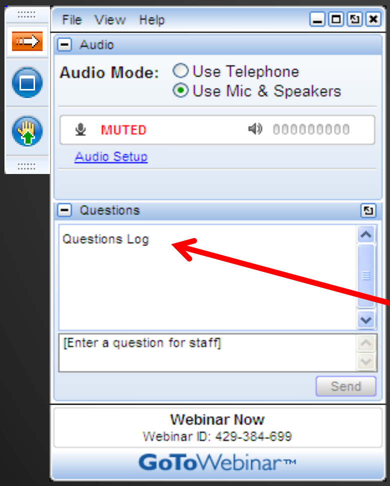
How to Participate Today



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Webinar ID: 429-384-699

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- **A recording will be available for replay shortly after this webcast.**

Today's Moderator

Melanie Holmer

California Region Water Reuse Practice Leader

Stantec

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Today's Speakers

- Kati Bell
  - *Global Practice Leader, Disinfection and Water Reuse, Stantec*
- Jason Assouline
  - *Water Technologist, Jacobs*
- Blair Wisdom
  - *Senior Engineer, Robert W. Hite Treatment Facility*
- Karl G. Linden
  - *Professor, University of Colorado Boulder*

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Next Speaker

Kati Bell, PhD, PE, BCEE

Global Practice Leader, Disinfection and Water Reuse

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Regulations for Wastewater Disinfection and Engineering Challenges

Meeting criteria to protect public health

Presentation outline

- Why we disinfect wastewater
- How are NPDES limits determined for pathogens and what might change
- How we disinfect wastewater
- Disinfection practices and challenges
- Understanding of outcomes

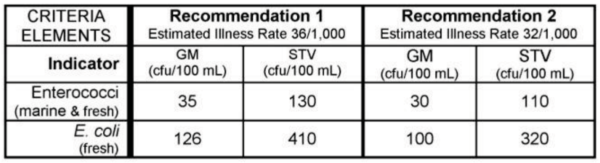
Why we disinfect wastewater

Disinfection is inactivation of pathogenic organisms, to the extent necessary to protect public health

This should be distinguished from “sterilization” which is elimination of all microbial life and is not an objective of wastewater disinfection

Criteria for wastewater disinfection

- CWA addresses microbials to protect human health
  - Surface water for drinking water sources
  - Recreational uses
  - Aquatic food source uses
- EPA 2012 RWQC



CRITERIA ELEMENTS	**Recommendation 1** Estimated Illness Rate 36/1,000		**Recommendation 2** Estimated Illness Rate 32/1,000	
Indicator	GM (cfu/100 mL)	STV (cfu/100 mL)	GM (cfu/100 mL)	STV (cfu/100 mL)
Enterococci (marine & fresh)	35	130	30	110
E. coli (fresh)	126	410	100	320

http://water.epa.gov/scitech/swguidance/standards/criteria/health/recreation/index.cfm

NPDES permits and compliance

- Limits for microbial indicators are typically enforced at the “end-of-pipe”
- This issue is murky because, while EPA in documents such as the Ephraim King Letter (2008) indicated prohibition on mixing zones for bacteria in primary contact recreation waters, the CWA, in fact, allows use of mixing zones.

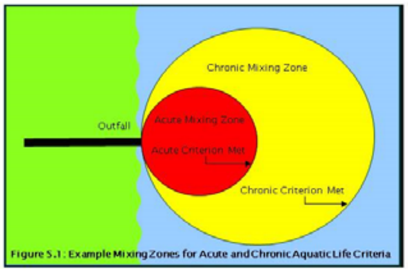
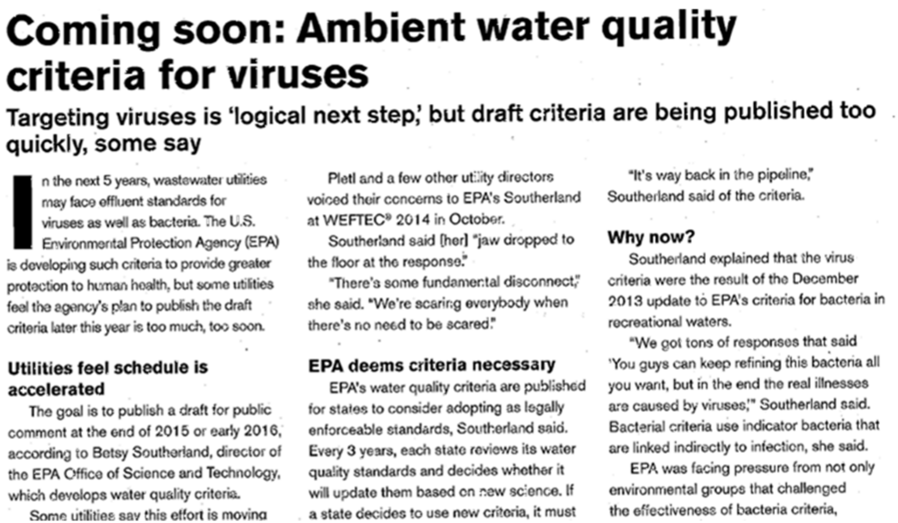


Figure 5.1: Example Mixing Zones for Acute and Chronic Aquatic Life Criteria

http://water.epa.gov/scitech/swguidance/standards/handbook/

What might change, and when?



Coming soon: Ambient water quality criteria for viruses

Targeting viruses is ‘logical next step,’ but draft criteria are being published too quickly, some say

In the next 5 years, wastewater utilities may face effluent standards for viruses as well as bacteria. The U.S. Environmental Protection Agency (EPA) is developing such criteria to provide greater protection to human health, but some utilities feel the agency’s plan to publish the draft criteria later this year is too much, too soon.

Utilities feel schedule is accelerated

The goal is to publish a draft for public comment at the end of 2015 or early 2016, according to Betsy Southerland, director of the EPA Office of Science and Technology, which develops water quality criteria.

Some utilities say this effort is moving

Pletl and a few other utility directors voiced their concerns to EPA’s Southerland at WEFTEC® 2014 in October.

Southerland said [her] “jaw dropped to the floor at the response.”

“There’s some fundamental disconnect,” she said. “We’re scaring everybody when there’s no need to be scared.”

EPA deems criteria necessary

EPA’s water quality criteria are published for states to consider adopting as legally enforceable standards, Southerland said. Every 3 years, each state reviews its water quality standards and decides whether it will update them based on new science. If a state decides to use new criteria, it must

“It’s way back in the pipeline,” Southerland said of the criteria.

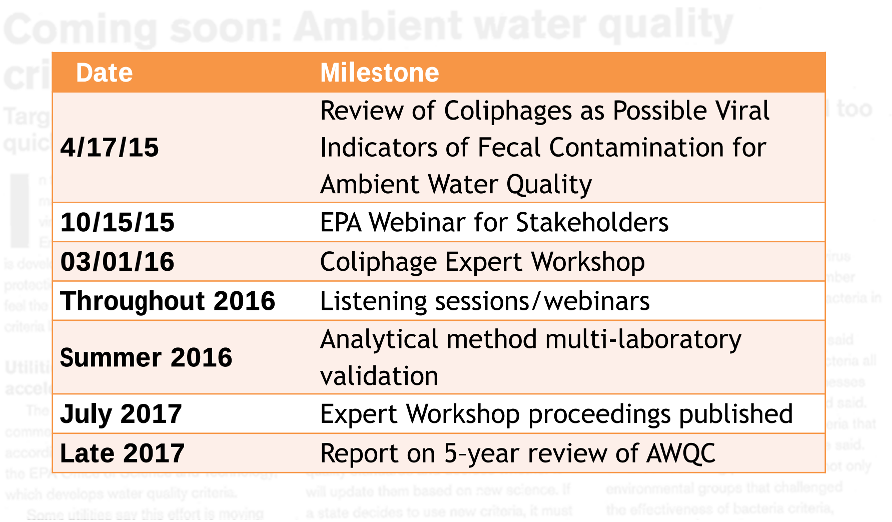
Why now?

Southerland explained that the virus criteria were the result of the December 2013 update to EPA’s criteria for bacteria in recreational waters.

“We got tons of responses that said ‘You guys can keep refining this bacteria all you want, but in the end the real illnesses are caused by viruses,’” Southerland said. Bacterial criteria use indicator bacteria that are linked indirectly to infection, she said.

EPA was facing pressure from not only environmental groups that challenged the effectiveness of bacteria criteria,

What might change, and when?



Coming soon: Ambient water quality

Date	Milestone
4/17/15	Review of Coliphages as Possible Viral Indicators of Fecal Contamination for Ambient Water Quality
10/15/15	EPA Webinar for Stakeholders
03/01/16	Coliphage Expert Workshop
Throughout 2016	Listening sessions/webinars
Summer 2016	Analytical method multi-laboratory validation
July 2017	Expert Workshop proceedings published
Late 2017	Report on 5-year review of AWQC

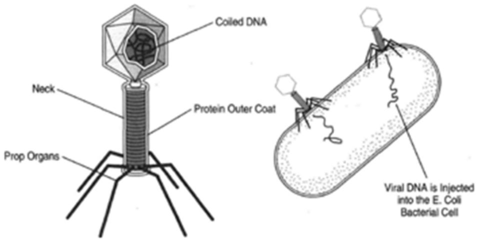
Why is EPA examining virus criteria?

- Laws protect the environment and human health
  - CWA – surface water for drinking water, recreational, and aquatic food source uses
  - SDWA – finished drinking water/protection of source water
- The Acts historically used differing indicators and differing approaches: *"Concerns about future increases in microbial contamination and potential for emergence of new threats have prompted development of a strategy that unites the influence of the two programs."*
- Alignment with FDA (NSSC) and ISSC strategies?

What are bacteriophage?

Bacteriophages are viruses that infect/replicate coliform:

- Male-specific coliphages infect *E. coli* bacteria with physical appendages (pili) used during sexual conjugation
- Somatic coliphages adsorb directly to the cell wall
- Phages infecting *Bacteroides fragilis*



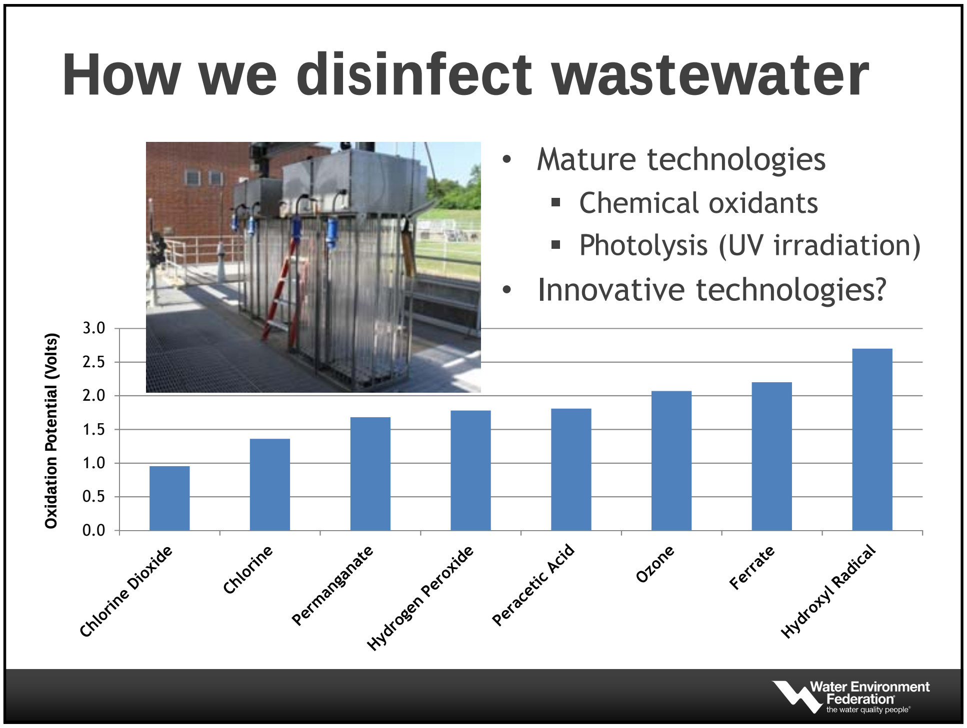
Reproduced from http://www.eplantscience.com/index/introduction_to_botany/t_2_bacteriophage.php

What are FDA and ISSC thinking?

- Noroviruses are most common cause of epidemic gastroenteritis, following consumption of bivalve shellfish contaminated with fecal matter
- NoV can be effectively reduced by wastewater treatment processes such as AS, MBRs, and disinfection
- Most outbreaks associated with shellfish harvested from waters affected by **untreated sewage**
- There are methods for bacteriophage already used for monitoring

EPA wants an “ideal” indicator

- Member of intestinal microflora of warm-blooded animals
- Present with pathogens/absent in uncontaminated water
- Present in greater numbers than the pathogen
- As resistant as the pathogen to environmental factors, and disinfection in water and wastewater treatment
- Do not multiply in the environment
- Detectable by easy, rapid, and inexpensive methods
- Nonpathogenic
- Correlated to health risk
- Specific to fecal source or source of origin



How we disinfect wastewater

- Mature technologies
  - Chemical oxidants
  - Photolysis (UV irradiation)
- Innovative technologies?

Chlorine disinfection and challenges

- Chlorine is still most common method of disinfection
  - Gas has very low cost
  - Same action for all forms
- Chlorine challenges
  - RMP requirements for gas
  - TRC/DBPs
  - Nutrient limits and process control challenges
  - Free versus chloramination

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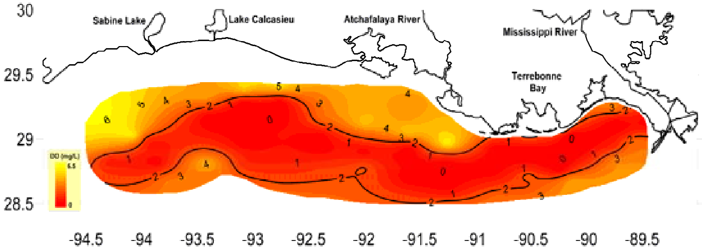
Increasing limits on nutrient discharges due to hypoxia and eutrophication make chlorination more complex



Inactivation Rate	Free Chorine at pH 7.5	Chloramines at pH 8
Giardia cysts (EPA Disinfection Profiling and Benchmarking Guidance Manual, 1999)		
2-log	33	735
3-log	37	1100
Viruses (Keegan, et al., 2012; Black, 2009 and Sirikanchana, 2008)		
2-log	10	2318
3-log	13	3141
4-log	16	3965
E. coli (Taylor et al., 2000)		
3-log	0.09	73

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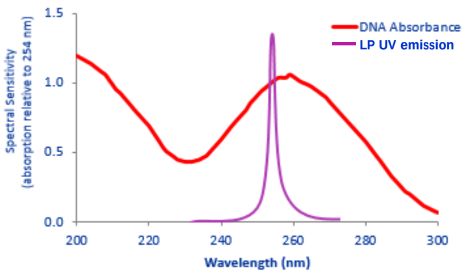
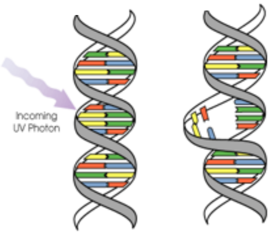
Ozone disinfection challenges

- Ozone can be complex and is unknown to operators
- High levels of TSS, BOD and TOC can require high doses
- Components are proprietary to ozone system suppliers
- Indicator bacteria are more difficult to inactivate than viruses (phage) because mechanism of action is oxidation of cell membrane
  - Crypto requires high CT
  - Enterococci needs high CT

UV (irradiation) disinfection

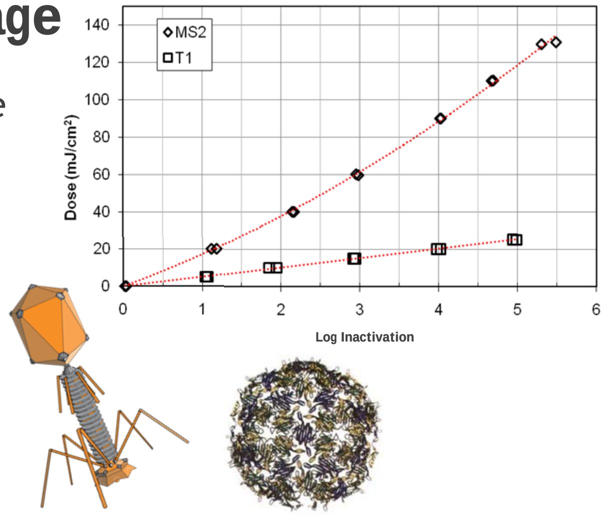




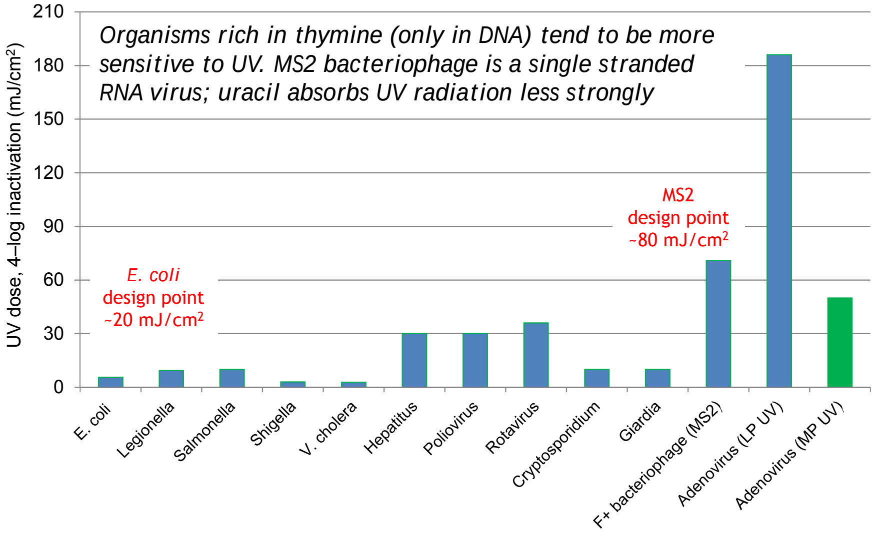
- Germicidal action of UV is photochemical reactions
- Nucleic acid absorption/reactions 10 - 20X > proteins

Dose validation and sizing for UV utilizes phage

- Establishing the UV dose for a reactor is conducted by bioassay validation
- Reduction equivalent "dose" (RED) is tied to the test organism



What does this mean for UV disinfection?



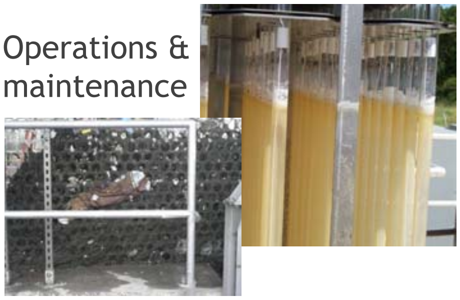
Organisms rich in thymine (only in DNA) tend to be more sensitive to UV. MS2 bacteriophage is a single stranded RNA virus; uracil absorbs UV radiation less strongly

E. coli design point ~20 mJ/cm²

MS2 design point ~80 mJ/cm²

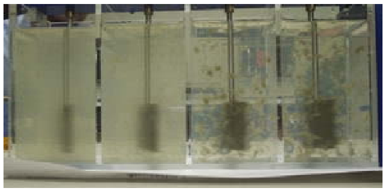
UV and ozone challenges

Operations & maintenance



High demand/low UVT

High TSS events



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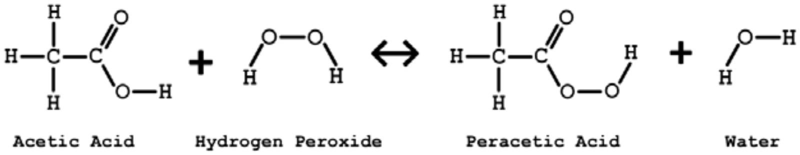
Peracetic acid chemistry



Component	Vigorox WWT II	Proxitane® WW-12
Peracetic Acid (CH_3COOOH)	15%	12%
Hydrogen Peroxide (H_2O_2)	23%	18.5%
Acetic Acid (CH_3COOH)	16%	20%
Sulfuric Acid (H_2SO_4)	<1%	--
Water (free)	45%	balance

Freezing point is approximately -49C (-59F)

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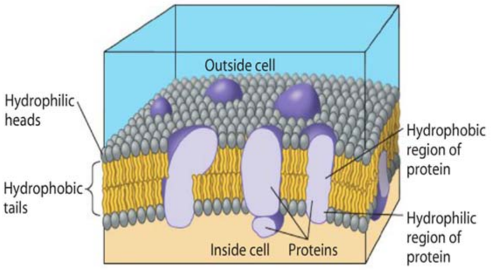
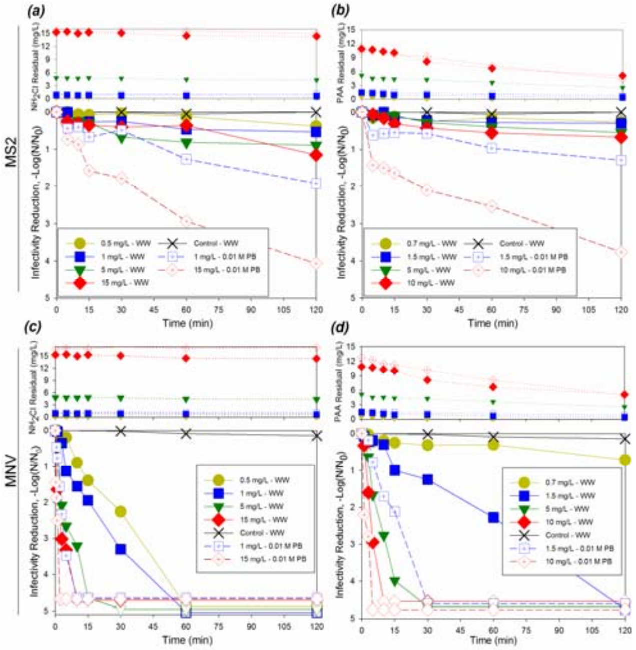
Mechanism of PAA disinfection

Mode of PAA action is oxidation

- "Active oxygen" disrupts sulfhydryl (-SH) and disulfide (S-S) bonds in enzymes and proteins in cell membranes
- Enterococci is more challenging than coliform (*E. coli*) compliance
- PAA reacts with base base pairs in nucleic acids (DNA and RNA)



Kitis, M. (2004). Disinfection of Wastewater with Peracetic Acid: A Review. Environment International, (30):47-55.



Temporal profiles for reduction of viral infectivity in secondary effluent wastewater (WW) and 0.01 M phosphate buffer (PB):

(a) MS2 by NH_2Cl,

(b) MS2 by PAA,

(c) MNV by NH_2Cl

(d) MNV by PAA.

Hollow symbols with no shading or crosses represent viral concentrations below the sensitivity limit of the assay.

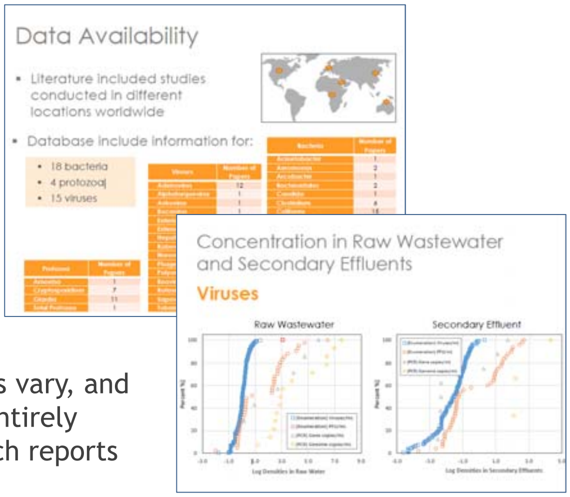
Dunkin et al., *Environ. Sci Technol.* 2017, 51, 2972-2981.

Does a phage criteria improve human health outcomes?

- EPA conducted a review of 8 epidemiological studies
  - 4 studies found significant value in coliphage
    - 3 found FIB to be predictive of illness
    - 1 found coliphage to be a better than FIB; study conducted at slolam course fed partly by wastewater
  - 1 found FIB predictive of illness while coliphage were not (van Asperen, 1998)
  - 3 studies – neither FIB nor coliphages were useful (Von Shirnding, 1992; Abdelzaher, 2011; Dorevitch, 2015)
- Limited data/conflicting findings, indicates more research is needed to establish phage–illness relationship

Phage concentrations in WW

- **Project WERF 14-02**
- Limited data available on concentrations in wastewater
- Description of WWQ operations are lacking in literature
- Data on climate or outbreaks are not well characterized
- Quantification methods vary, and details are often not entirely reported in the research reports



Data Availability

- Literature included studies conducted in different locations worldwide
- Database include information for:
  - 18 bacteria
  - 4 protozoa
  - 15 viruses

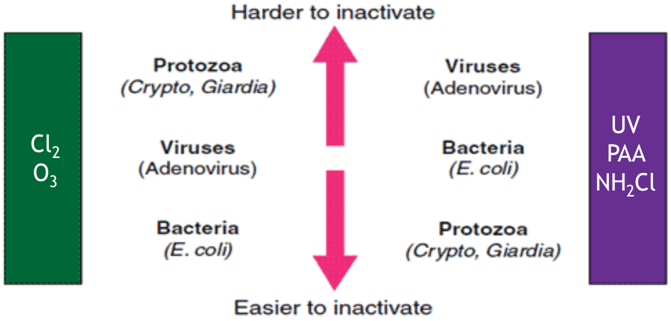
Concentration in Raw Wastewater and Secondary Effluents

Viruses

Summary

“As comprehensive pathogenic virus indices, phages are not very useful because their numbers seldom correlate to pathogenic viruses numbers in water samples …” (Lucena and Jofre, 2010)

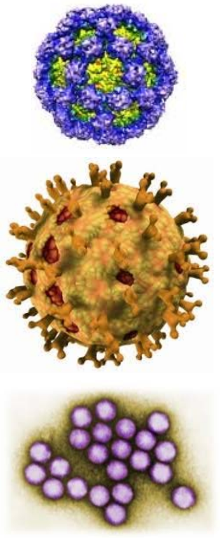
- There is no magic indicator
- There is no magic disinfectant

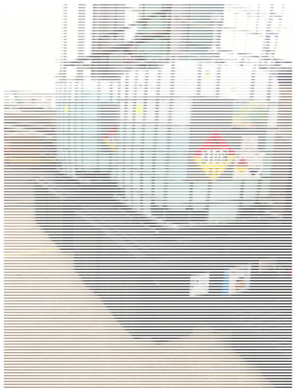

Harder to inactivate

Cl_2 O_3			UV PAA NH_2Cl
	Protozoa *(Crypto, Giardia)*	**Viruses** (Adenovirus)	
	Viruses (Adenovirus)	**Bacteria** *(E. coli)*	
	Bacteria *(E. coli)*	**Protozoa** *(Crypto, Giardia)*	

Easier to inactivate

Contact information





Kati Bell, PhD, PE, BCEE
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Next Speaker

Jason Assouline, P.E.

Water Technologist
Jacobs

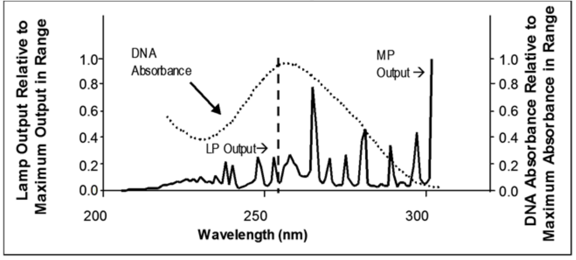
JACOBS

UV ADVANCED OXIDATION PROCESS

Jason Assouline, P.E.

Fundamentals of UV disinfection

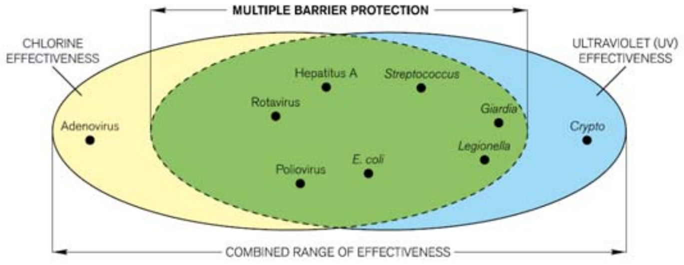
- Physical process
  - Electromagnetic energy prevents the cellular proteins and nucleic acids (i.e., DNA and RNA) from further replication
- Energy absorbed by DNA
- Inhibits replication
- An organism that cannot replicate cannot infect



UVDGM (EPA, 2006)

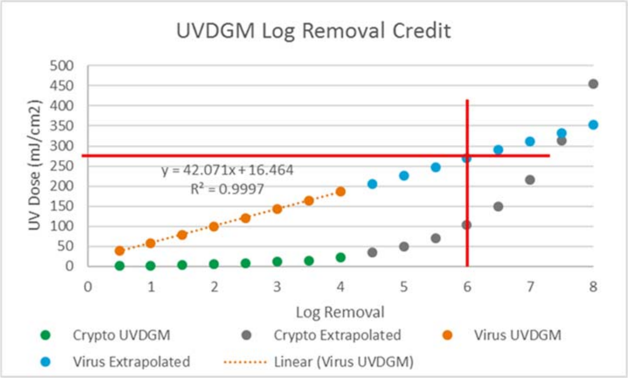
UV Effectiveness for Pathogens

- UV disinfection (10-40 mJ/cm^2) is very effective at pathogen inactivation
- UV more effectively inactivates *Giardia* and *Cryptosporidium* compared to viruses



UV Dose Threshold for 6-log

- Applying UV doses greater than 269 mJ/cm^2 for greater than 6 log virus

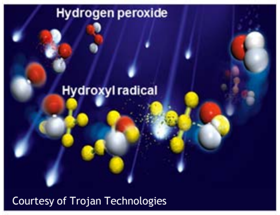


High Dose UV Disinfection

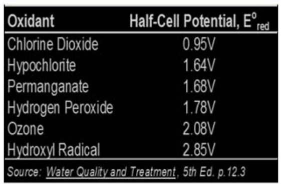
- A UV system designed to provide 6-logs inactivation of virus will also result in provide 6-log *Giardia*, and *Cryptosporidium*
  - A dose of 269 mJ/cm^2 (or higher) will provide this level of disinfection based on extrapolation
- UV-AOP applications typically operate at UV doses greater than 500 mJ/cm^2
- Therefore pathogen inactivation will be excellent in UV-AOP systems

UV-AOP Process Description

- **UV-AOP**
  - Dose of >500 mJ/cm2 with oxidant (typically H_2O_2) addition
  - UV light converts H_2O_2 to $OH\cdot$ radical, which is a very powerful oxidant
  - Strong oxidation and disinfection process
  - Because of high UV dose, high UVT water is required for efficiency and to reduce power costs
- **Other Objectives of UV-AOP**
  - Photolysis of NDMA
  - $\geq$ 0.5-log destruction of 1,4-dioxane by oxidation process (California)
  - UV-AOP can be used to meet both requirements



Courtesy of Trojan Technologies



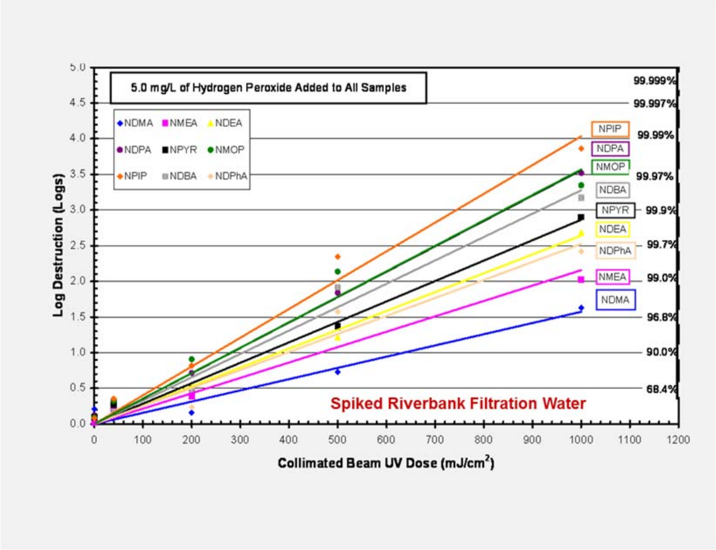
Oxidant	Half-Cell Potential, E^{o}_{red}
Chlorine Dioxide	0.95V
Hypochlorite	1.64V
Permanganate	1.68V
Hydrogen Peroxide	1.78V
Ozone	2.08V
Hydroxyl Radical	2.85V

Source: *Water Quality and Treatment*, 5th Ed. p.12.3

Benefits of UV-AOP

- High level of disinfection (Giardia, Cryptosporidium, viruses)
- Photolysis of nitrosamines (including NDMA)
- Barrier for destruction of trace organics
- Destruction of taste and odor-causing compounds (e.g., MIB and geosmin for drinking water)
- Public acceptance in potable reuse systems

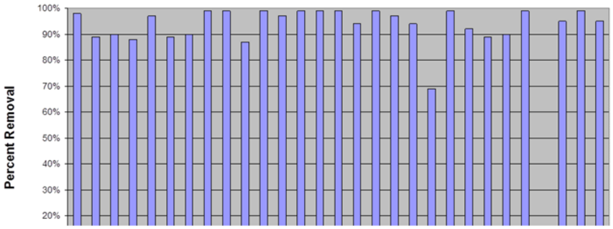
Destruction of Nitrosamines



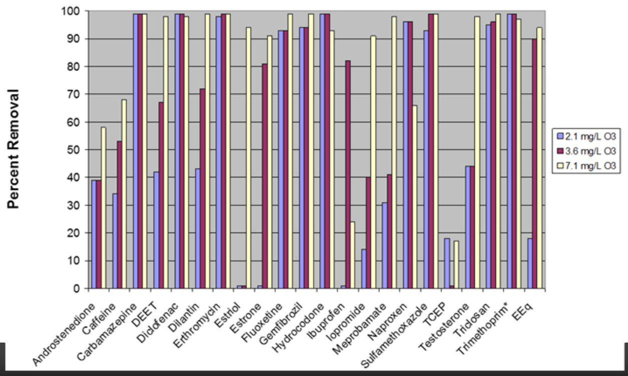
Ozone / UV: Destruction of CECs

- Standard UV disinfection doses are not effective:
  - Most contaminants studied < 20% removal (Snyder 2007)
- UV-AOP is very effective, but requires high UV doses and sufficient H_2O_2
- Ozone:
  - Good removal, even at low doses
  - Fast oxidation: Majority of contaminants will be removed after 2 minute contact time

Removal of Emerging Contaminants by UV-AOP (Snyder et. al 2007)
UV Dose: 671 mJ/cm2 H2O2 Dose: 5 mg/L



Removal of Emerging Contaminants with Ozone



Chlorine as AOP Catalyst

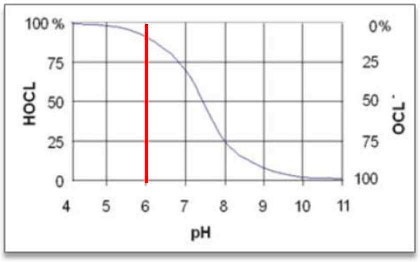
- Most UV-AOP systems use 3-5 ppm of hydrogen peroxide
    - Inefficient photolysis with peroxide
    - Requires quenching of residual peroxide
- Chlorine is an emerging approach for producing comparable trace organic removal at lower cost

Benefits of Hypochlorite

- Hypochlorite readily used at most facilities
- Hypochlorite costs much less than H_2O_2
- Instruments for measuring free chlorine are common

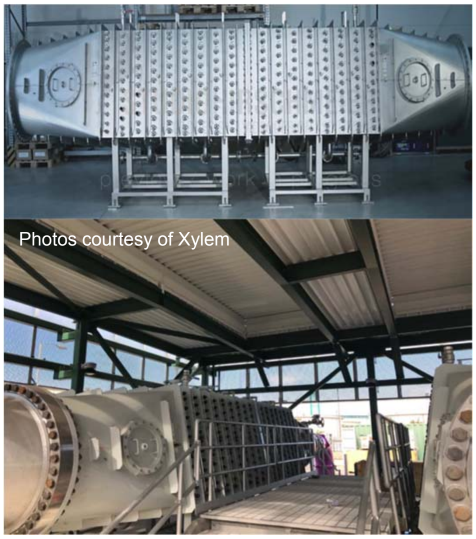
Considerations for Hypochlorite

- Must quench free ammonia and/or chloramines to form a free chlorine residual
- Requires a low pH (less than 6) for efficient AOP
- Most efficient downstream of RO



UV-AOP with Sodium Hypochlorite

- Requirements
  - UV influent pH must be <6.0 for efficient OH· formation
  - Must consider ammonia impacts, DBP formation
- Being implemented at LASAN Terminal Island WRP



Photos courtesy of Xylem

Where has this been implemented?

- LA Sanitation District – Terminal Island WRP
- San Diego – North City Pure Water Facility
- Many others to follow

Implementation

- California LRV approach
  - Groundwater recharge requires 12/10/10 (includes treatment through WWTP)
  - Surface water augmentation requires varying LRVs based on contribution to and retention time in receiving water (could be lower or higher than groundwater recharge)
- Treatment train must consist of at least 3 separate processes, and each separate treatment process may be credited with no more than 6-log reduction

Implementation

- Use of typical drinking water dose tables and validation approaches limited ability to demonstrate 6-log credit.
- Reactors in series to demonstrate up to 6-log credit
- Direct log inactivation validation approaches allow demonstration of higher credit

UV System Control – EED vs. Dose

- EED-based approach adjusts lamp power based on UVT, flow, and water temperature
  - Does not include UV intensity sensors
  - Assumed lamp output based on aging curves
- UV dose is calculated based on measured UV intensity in the reactor and flow
  - Matches approach for drinking water disinfection

Other UV-AOP Future Technology Considerations

- Most municipal UV-AOP applications have used LPHO lamps due to reduced power cost in year-round use
- New developments in more powerful LPHO lamps and reactors
- Calgon’s sizing shows a single 48” MP reactor can meet AOP targets for 10 mgd post-RO
- First small LED lamp applications expected in next few years
- Consider site-specific water quality, system capacity, performance targets, and disinfection credit to determine best fit for each project

Next Speaker

Blair Wisdom, P.E.

Senior Engineer
Robert W. Hite Treatment Facility

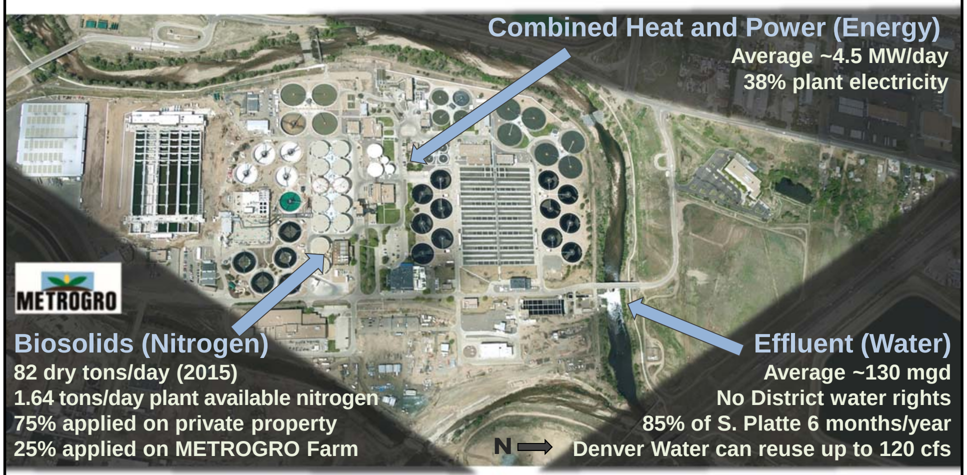
Peracetic Acid Disinfection at the RWHTF

Agenda

- Drivers for Peracetic Acid (PAA) Disinfection at RWHTF
  - Initial Pilot
  - Full-Scale Demonstration
- Demonstration Plan
- Demonstration Data
- Operational Challenges
- Future Work

PAA disinfection system, January 2018

Resource Recovery at the Hite Facility



Combined Heat and Power (Energy)
Average ~4.5 MW/day
38% plant electricity

Biosolids (Nitrogen)
82 dry tons/day (2015)
1.64 tons/day plant available nitrogen
75% applied on private property
25% applied on METROGRO Farm

Effluent (Water)
Average ~130 mgd
No District water rights
85% of S. Platte 6 months/year
Denver Water can reuse up to 120 cfs

Drivers for Peracetic Acid Disinfection

Proven wastewater disinfection technology

Original Interest in PAA

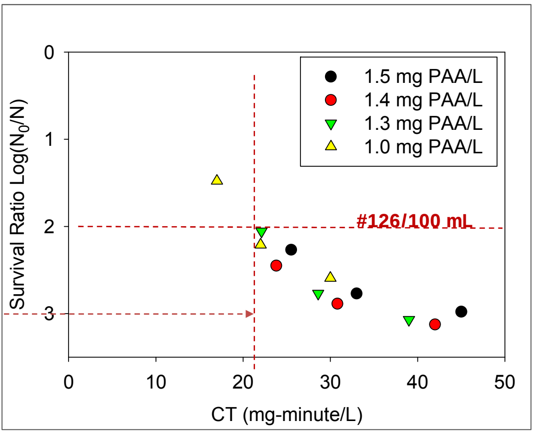
Sodium hypochlorite (SHC) delivery, December 2010

- Re-simplify the disinfection approach
  - Chlorine gas (1980s) with sulfur dioxide (1990s–2000s)
  - Converted to liquid chemical systems (2010–2011)
  - Converted to chloramine disinfection through the addition of ammonia feed (2014)
  - **PAA disinfection would eliminate ammonia feed completely and eliminate need for sodium bisulfite (SBS) most of the time**
- Position for future emerging water quality drivers
  - **Nitrogen and increasingly stringent ammonia limits, salts addition to our low-dilution receiving water**

Pilot Testing Results - Efficacy

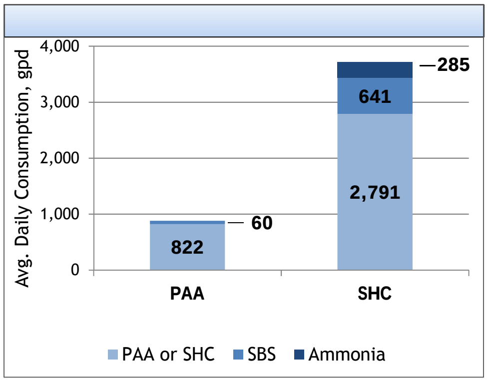
- Conducted pilot scale test in 2016: 6-week duration in NSEC and 6-week duration in SSEC
- Collected data on different doses and detention times

Detention time at 300 mgd



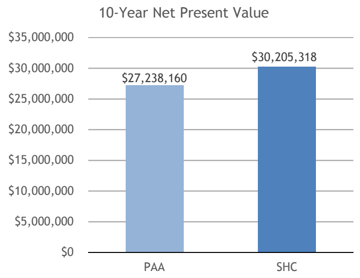
Pilot Testing Results - Chemical Handling

- PAA reduces chemical volume by ~2/3
  - Operator time
  - Storage
  - Transportation/Delivery Logistics
  - Salt addition to receiving water
  - GHG for chemical production and transport



PAA Pilot Study at RWHTF

- Results were promising
  - Excellent disinfection performance
  - Environmentally friendly
  - Opportunities for easy process control and optimization
  - Potential for cost-effective approach to meet *E. coli* permit limits
  - 10-year net present value projected to be less than maintaining and operating SHC system
- Recommended a full-scale pilot demonstration

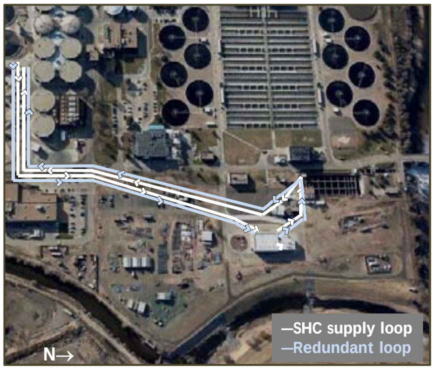


Drivers for Full Scale Demonstration

Reliability, sustainability, cost-effectiveness

Existing SHC Based Disinfection System

- A three-chemical system
  - SHC
  - Aqueous ammonia
  - Sodium bisulfite (SBS)
- Very long SHC pipe loops from Disinfection Building to North and South Dosing Buildings (~7,600 feet)
- Started to experience issues in existing buried and plant installed feed piping - system became unreliable



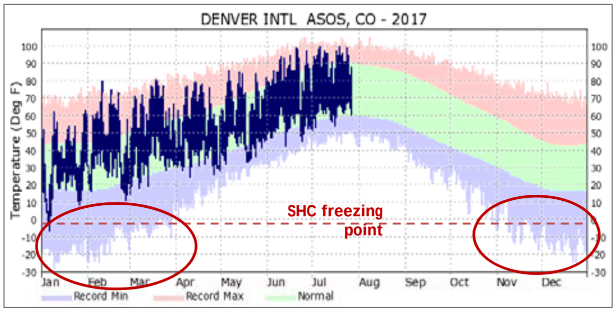
Immediate (Temporary) Response

- SHC supply system piping loops were shut off on May 12, 2017
- Temporary SHC tote system in operation from May 12 through June 14
- At each (North and South) temporary dosing location:
  - Eight 250-gallon totes
  - Two dosing pumps (2 duty, 1 standby) with instrumentation and controls
  - One flow meter

Temporary tote system

Temperature Conditions

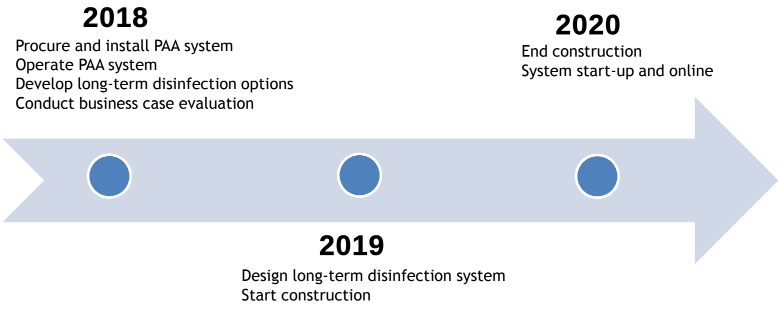
- Freezing Points
  - SHC = –3˚F
  - PAA = –56˚F



Case for Full Scale Demonstration of PAA

- Approved disinfection chemical by Colorado Department of Public Health and Environment
- Does not require freeze protection – less time and capital to install a system ready for winter
- Successful pilot showed efficacy at low doses for our secondary effluent
- Not chlorine-based; eliminates the need for SHC and ammonia (and possibly SBS)
- Does not form regulated disinfection by-products associated with chlorine

Recommended Evaluation Schedule



2018

Procure and install PAA system
Operate PAA system
Develop long-term disinfection options
Conduct business case evaluation

2019

Design long-term disinfection system
Start construction

2020

End construction
System start-up and online

Demonstration Plan

Risk Assessment of Peracetic Acid

Effluent Residual

Current USEPA approved PAA products

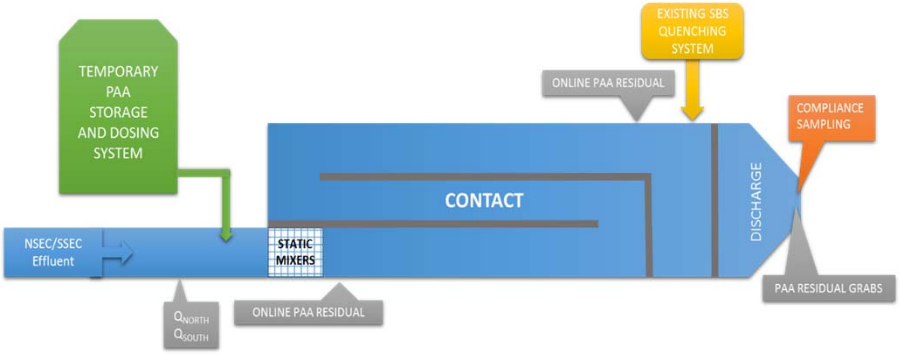
	Proxitane* WW-12	VigorOx® WWT II	BioSide™ HS 15%	Peraclean®15	Peragreen® 22WW
EPA Registration (date of registration)	68660-1 (2013)	65402-3 (2008)	63838-2 (2015)	54289-4 (2015)	63838-20 (2015)
Application Rate and Allowable Residual	0.5 – 10 mg/L <1.0 mg/L	0.5 – 15 ppm <1.0 mg/L, if DF>12, 0.09*DF	0.5 – 10 mg/L <1.0 mg/L	0.5 – 15 ppm <1.0 mg/L	0.5 – 10 mg/L <1.0 mg/L
Peracetic Acid (CH_3COOOH)	12%	15%	15%	15%	22%
Hydrogen Peroxide (H_2O_2)	18.5%	23%	23%	23%	5%
Acetic Acid (CH_3COOH)	20%	16%	16%	16%	45%
Sulfuric Acid (H_2SO_4)	--	<1%	--	<1%	--
Water (free)	balance	45%	45%	45%	balance
Freezing point	-40.3 to -42.0C (-40.5 to -43.6°F)	-49C (-56°F)	-49C (-56°F)	-49C (-56°F)	< -18C (< 0°F)

Effluent Residual

- Colorado does not have a limit for PAA residual
- Target residual will be set at
  - 0.7 mg/L daily maximum and
  - 0.4 monthly average;
  - 1 mg/L instantaneous max
- SBS system will continue to provide means to control effluent residual

RWHTF outfalls, October 2014

System Diagram



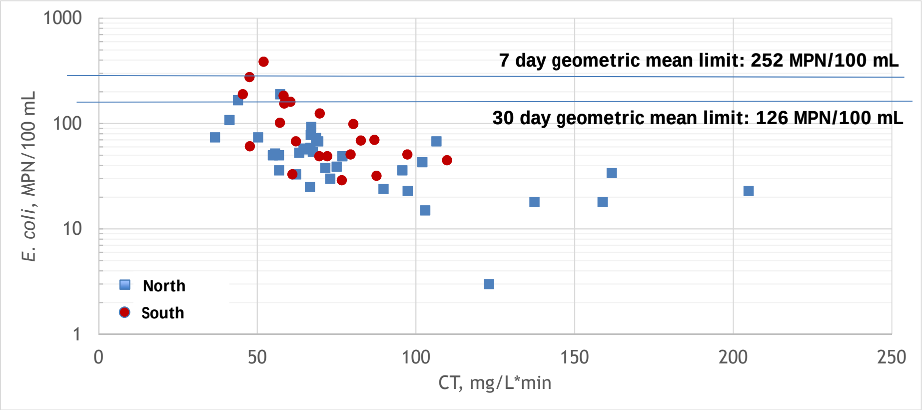
In-Line Instrumentation Trial

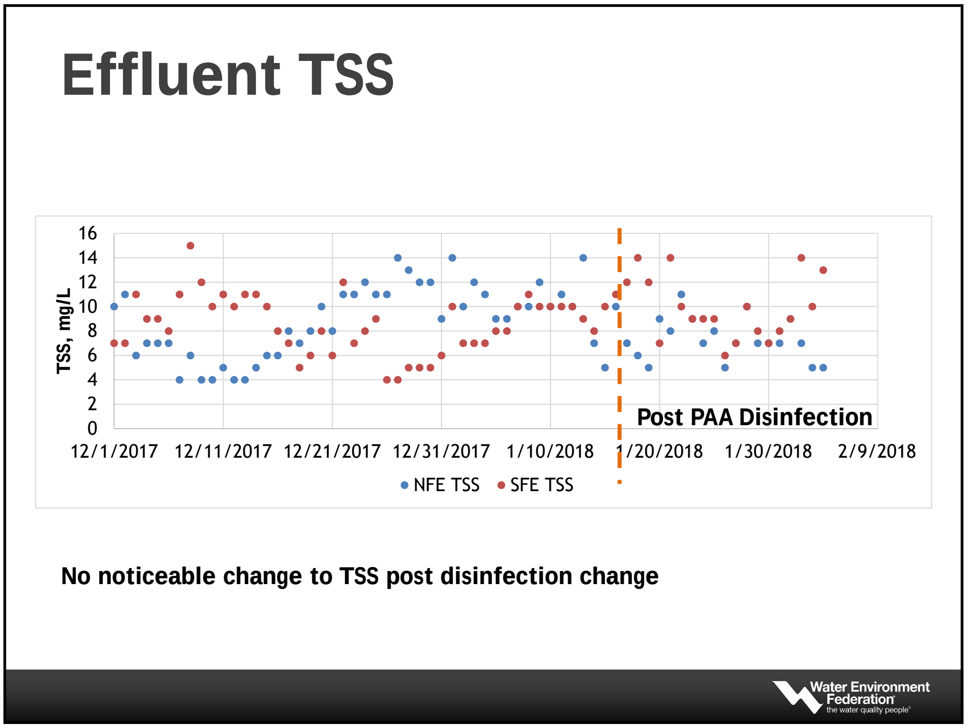
- Currently installed CL-17 devices were being used for chlorine residual monitoring and control
- The District is performing an instrument trial to determine the instrument best fit for monitoring PAA residual
- Trial includes:
  - CL-17
  - Endress + Hauser CCS120 Total Chlorine amperometric sensors
  - ATI amperometric probe
  - Prominent amperometric probe

Demonstration Data

Key Discharge Permit parameters

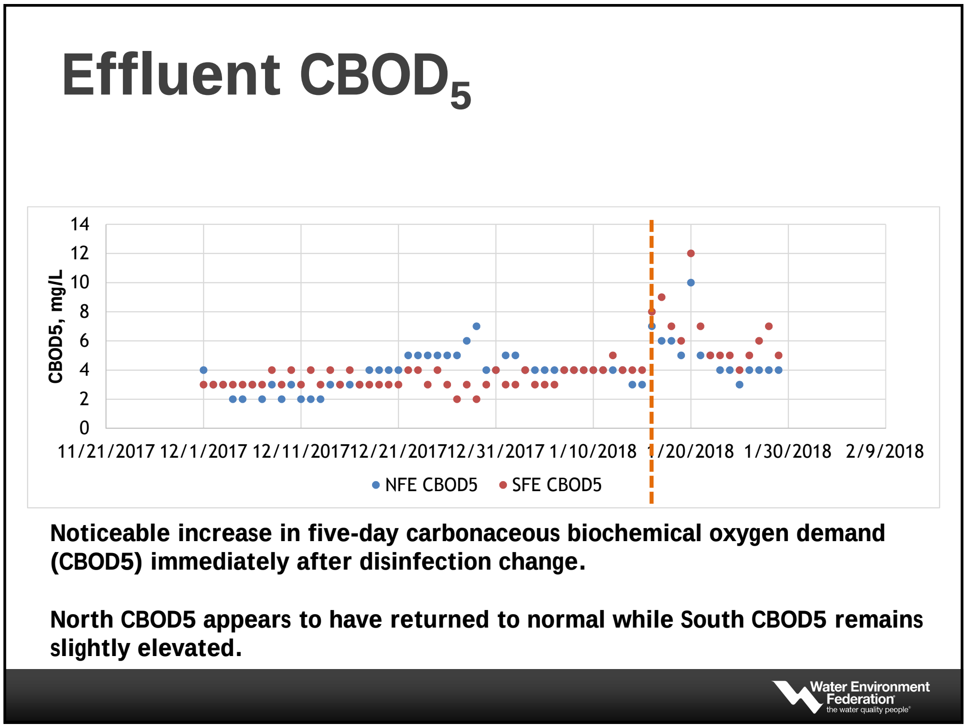
Compliance Testing





Effluent TSS

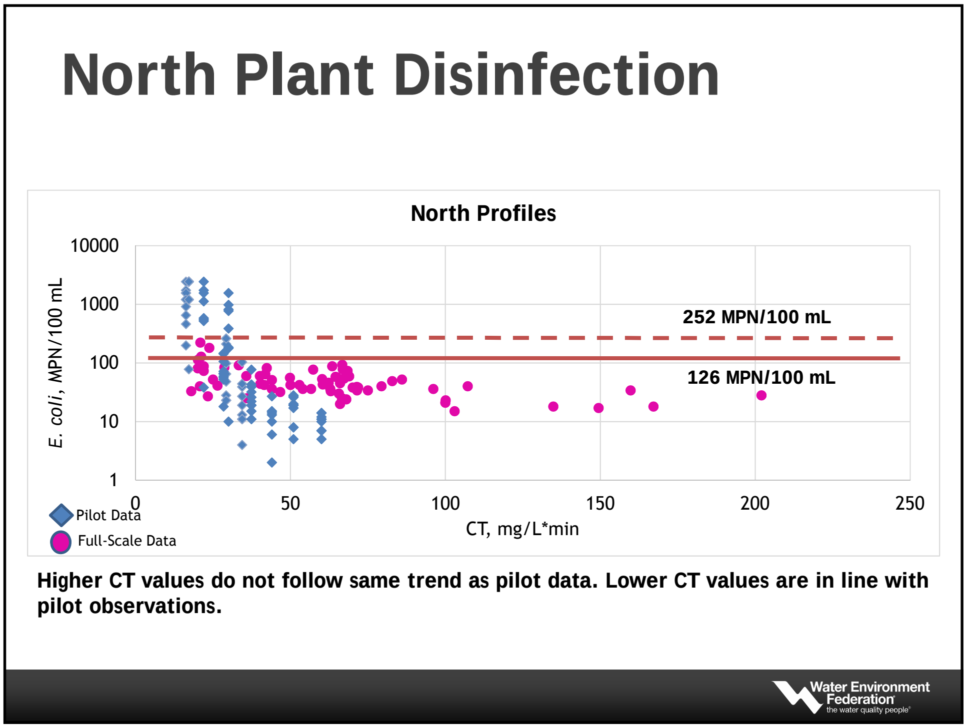
No noticeable change to TSS post disinfection change



Effluent CBOD$_5$

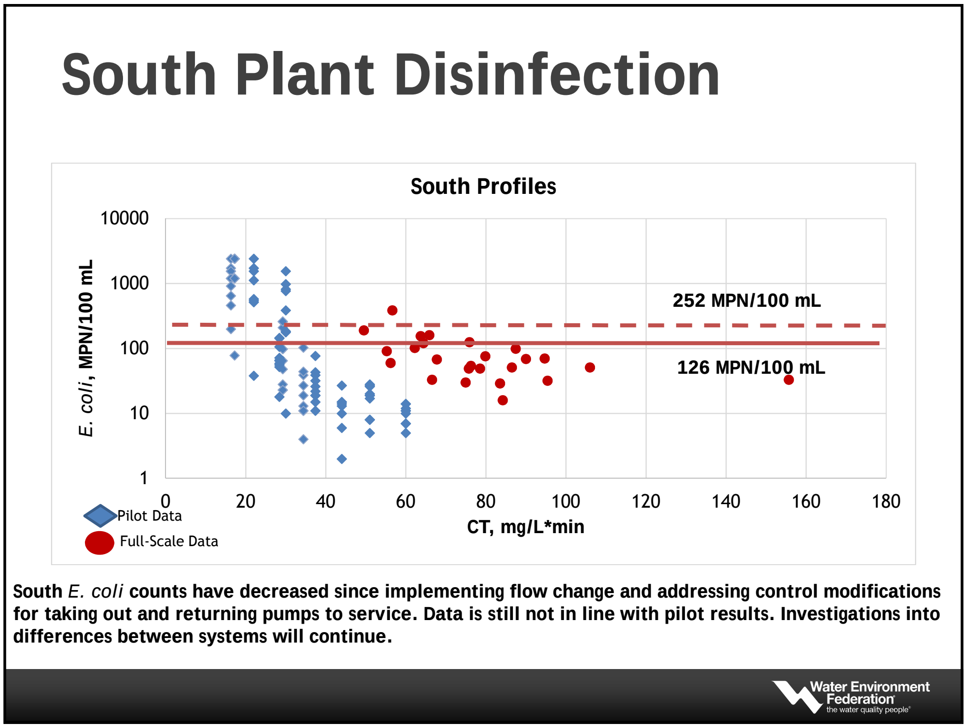
Noticeable increase in five-day carbonaceous biochemical oxygen demand (CBOD5) immediately after disinfection change.

North CBOD5 appears to have returned to normal while South CBOD5 remains slightly elevated.



North Plant Disinfection

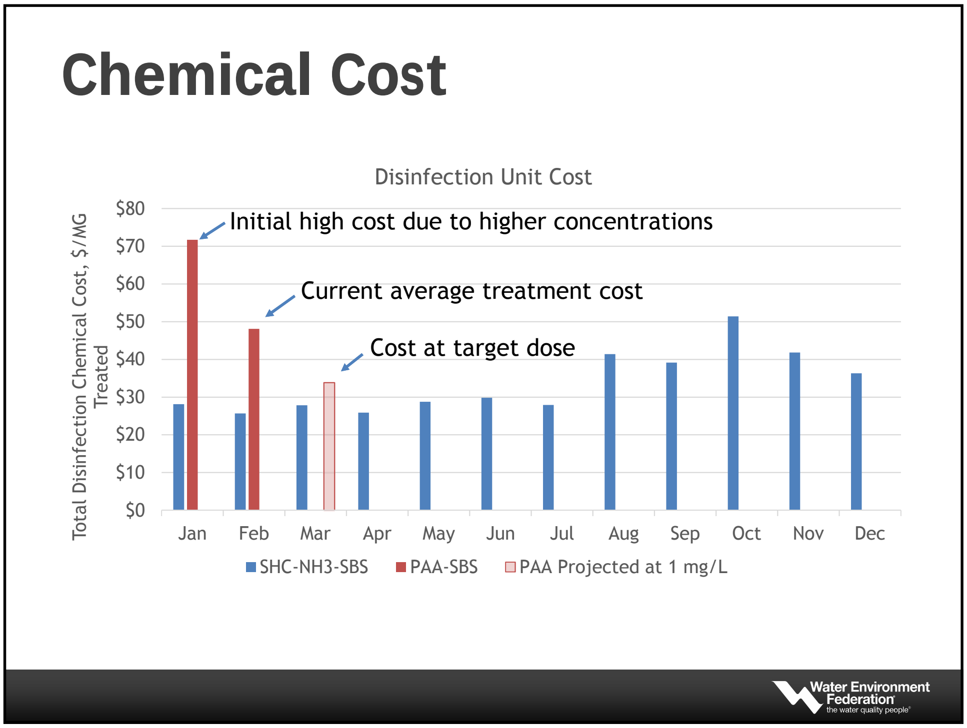
Higher CT values do not follow same trend as pilot data. Lower CT values are in line with pilot observations.



South Plant Disinfection

South *E. coli* counts have decreased since implementing flow change and addressing control modifications for taking out and returning pumps to service. Data is still not in line with pilot results. Investigations into differences between systems will continue.

Chemical Cost



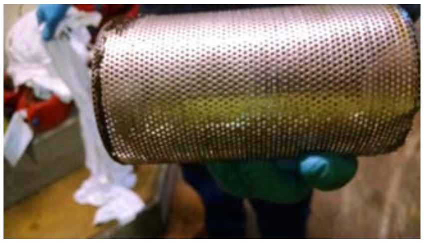
Initial high cost due to higher concentrations

Current average treatment cost

Cost at target dose

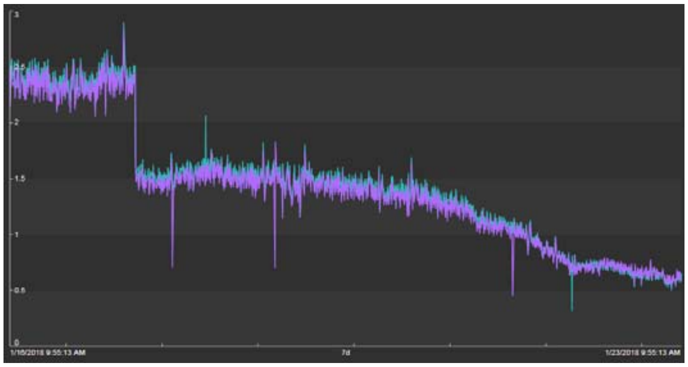
Operational Challenges

Plant Water System



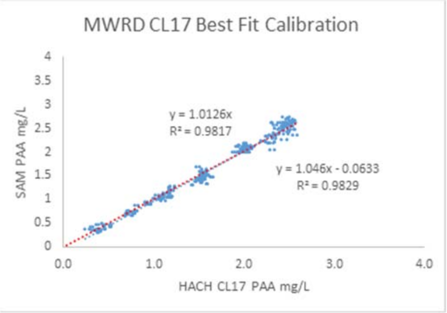
- Significant growth observed in plant water system – concern with blockages at strainers
- Mitigation plan is currently under development

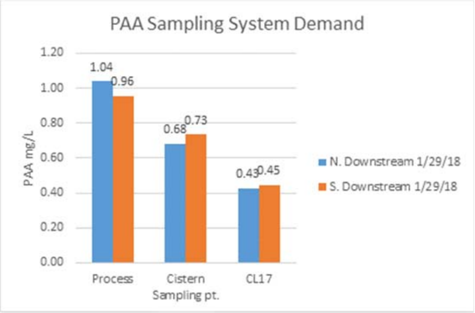
CL-17 Performance



- Significant decay of upstream residual over time observed

CL-17 Performance





- Machine accuracy has been high.
- Further analysis points to degradation due to bio-fouling of sample pipe discharge line and instrument feed lines.
- Mitigation mechanisms will be studied. Analysis of probes is ongoing.

Future Work

Future Work to be Completed

- Continue study on residual monitoring to select instrumentation technology for implementation
- Study and implement plant water system biofilm mitigation
- Continue to optimize PAA dose for average conditions while collecting information regarding *E. coli* degradation through contact basins
- Conduct flow through WET testing
- Collect operating data and estimates for construction in order to perform business case evaluation to guide long-term process decisions
- Investigate non-monetary considerations

Next Speaker

Karl G. Linden, Ph.D.

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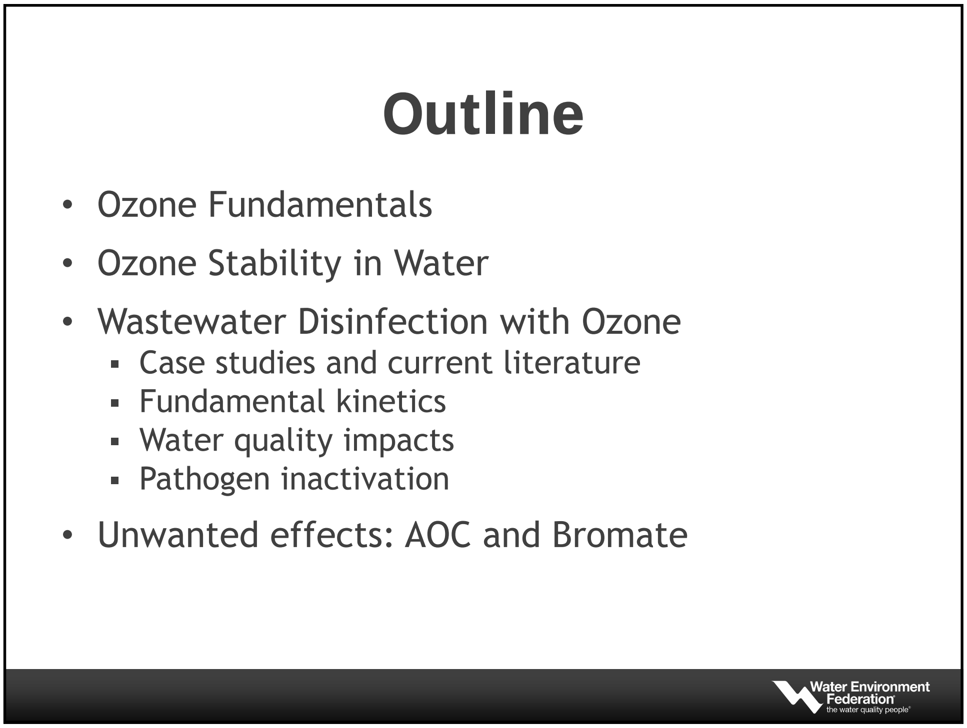
Implementing Ozone Disinfection for Wastewater

Water Environment Federation
the water quality people



Outline

- Ozone Fundamentals
- Ozone Stability in Water
- Wastewater Disinfection with Ozone
  - Case studies and current literature
  - Fundamental kinetics
  - Water quality impacts
  - Pathogen inactivation
- Unwanted effects: AOC and Bromate

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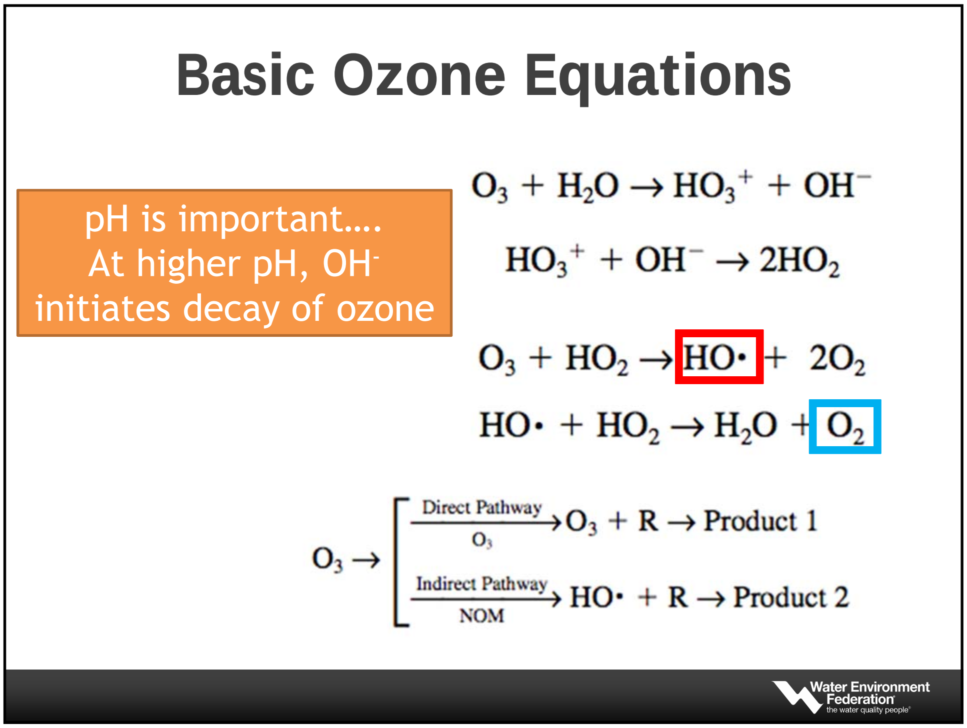


Basic Ozone Equations

pH is important….
At higher pH, OH^-
initiates decay of ozone

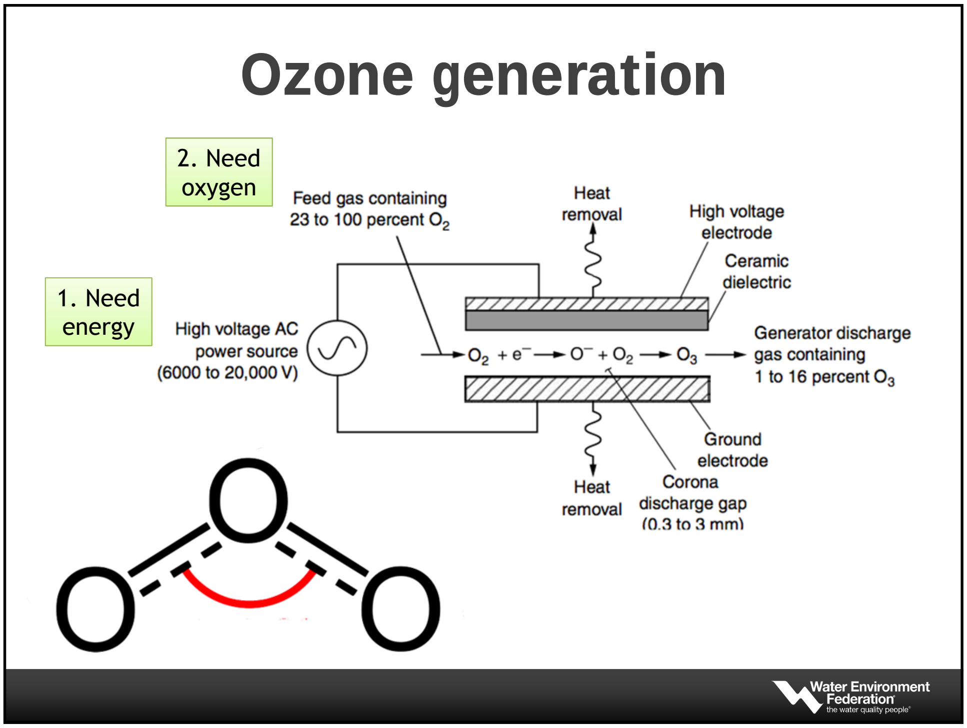
$$O_3 + H_2O \rightarrow HO_3^+ + OH^-$$

$$HO_3^+ + OH^- \rightarrow 2HO_2$$

$$O_3 + HO_2 \rightarrow \boxed{HO\cdot} + 2O_2$$

$$HO\cdot + HO_2 \rightarrow H_2O + \boxed{O_2}$$

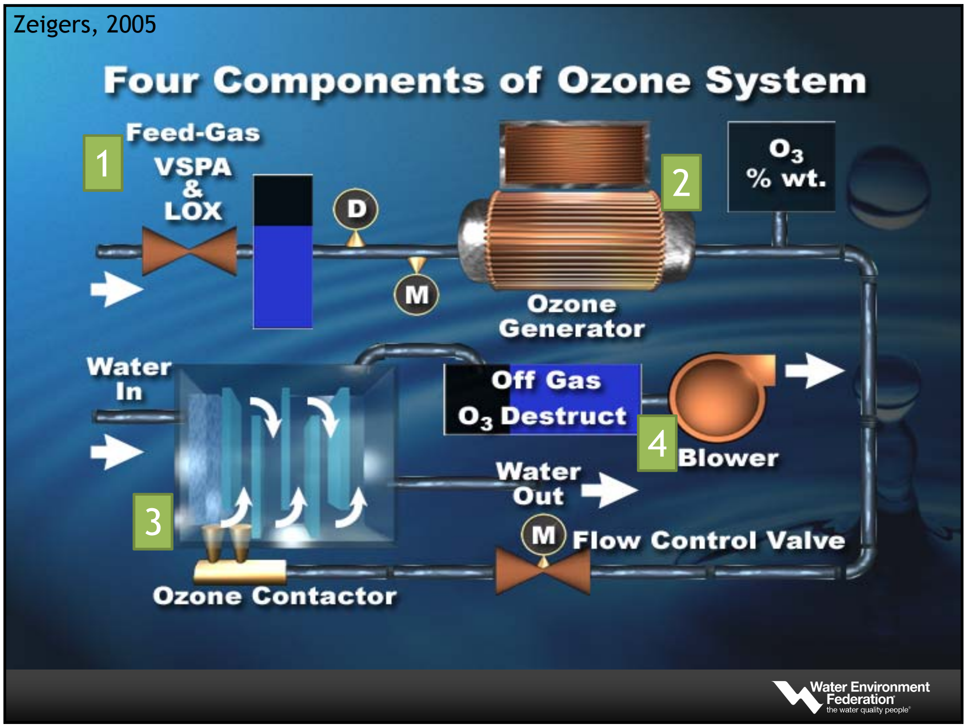
$$O_3 \rightarrow \left[\begin{array}{l} \xrightarrow[O_3]{\text{Direct Pathway}} O_3 + R \rightarrow \text{Product 1} \\ \xrightarrow[\text{NOM}]{\text{Indirect Pathway}} HO\cdot + R \rightarrow \text{Product 2} \end{array} \right.$$



Ozone generation

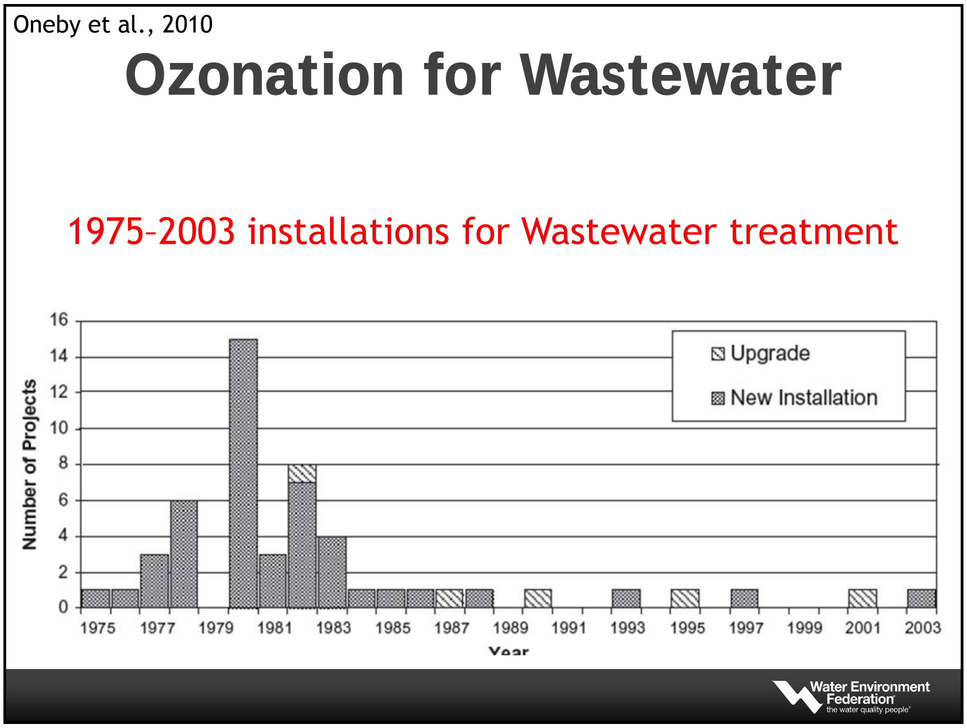
2. Need oxygen

1. Need energy



Zeigers, 2005

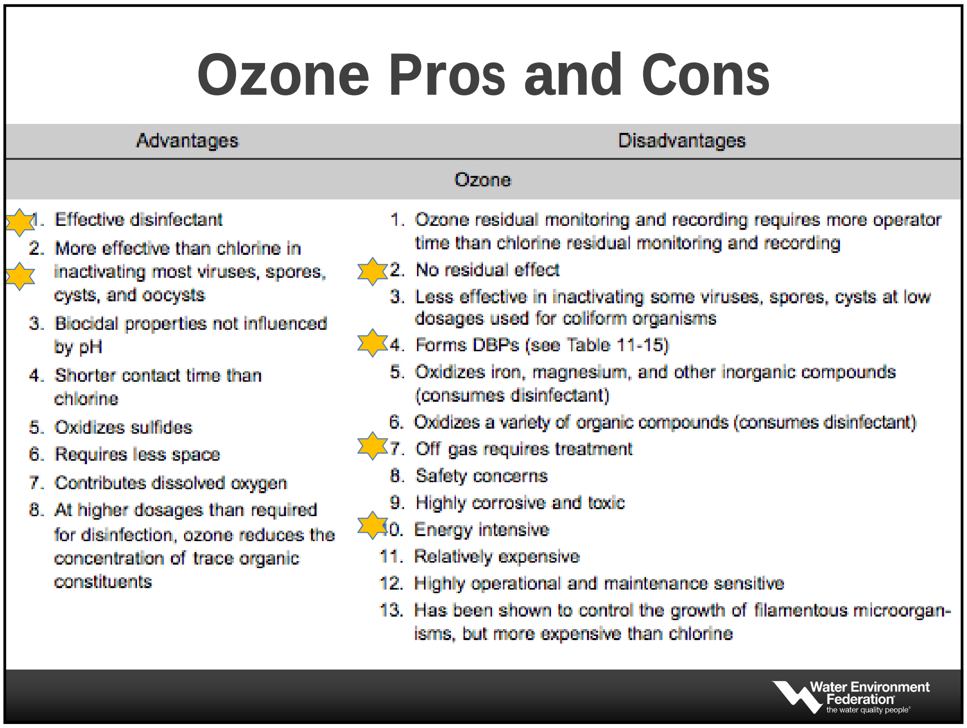
Four Components of Ozone System



Oneby et al., 2010

Ozonation for Wastewater

1975–2003 installations for Wastewater treatment



Ozone Pros and Cons

Advantages	Disadvantages
Ozone	
★1. Effective disinfectant ★2. More effective than chlorine in inactivating most viruses, spores, cysts, and oocysts 3. Biocidal properties not influenced by pH 4. Shorter contact time than chlorine 5. Oxidizes sulfides 6. Requires less space 7. Contributes dissolved oxygen 8. At higher dosages than required for disinfection, ozone reduces the concentration of trace organic constituents	1. Ozone residual monitoring and recording requires more operator time than chlorine residual monitoring and recording ★2. No residual effect 3. Less effective in inactivating some viruses, spores, cysts at low dosages used for coliform organisms ★4. Forms DBPs (see Table 11-15) 5. Oxidizes iron, magnesium, and other inorganic compounds (consumes disinfectant) 6. Oxidizes a variety of organic compounds (consumes disinfectant) ★7. Off gas requires treatment 8. Safety concerns 9. Highly corrosive and toxic ★10. Energy intensive 11. Relatively expensive 12. Highly operational and maintenance sensitive 13. Has been shown to control the growth of filamentous microorganisms, but more expensive than chlorine

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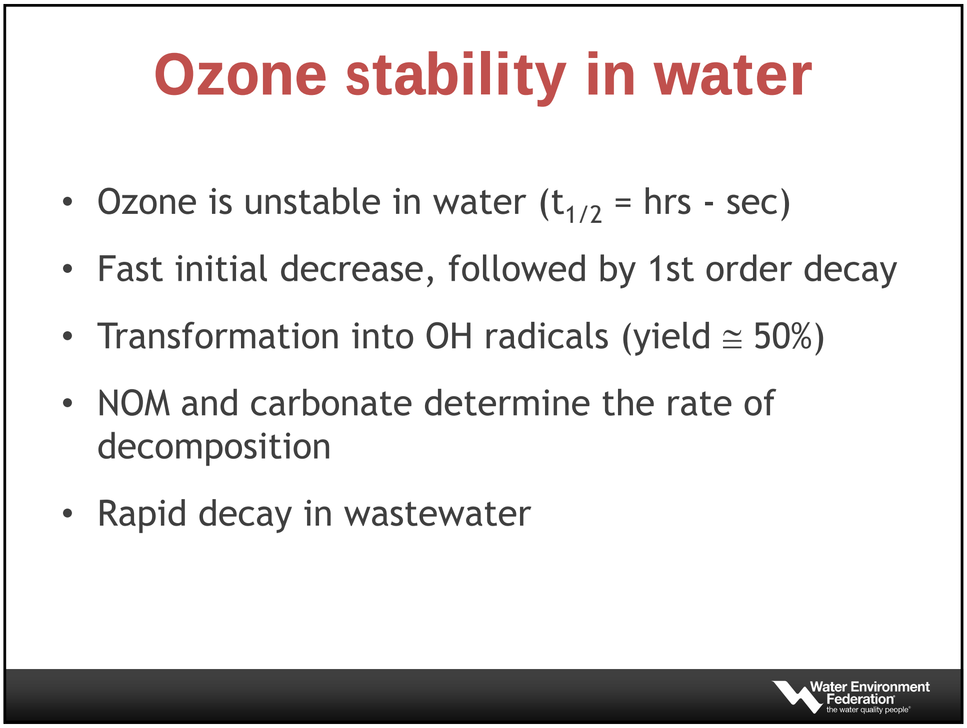

Ozone stability in water

- Ozone is unstable in water ($t_{1/2}$ = hrs - sec)
- Fast initial decrease, followed by 1st order decay
- Transformation into OH radicals (yield ≅ 50%)
- NOM and carbonate determine the rate of decomposition
- Rapid decay in wastewater

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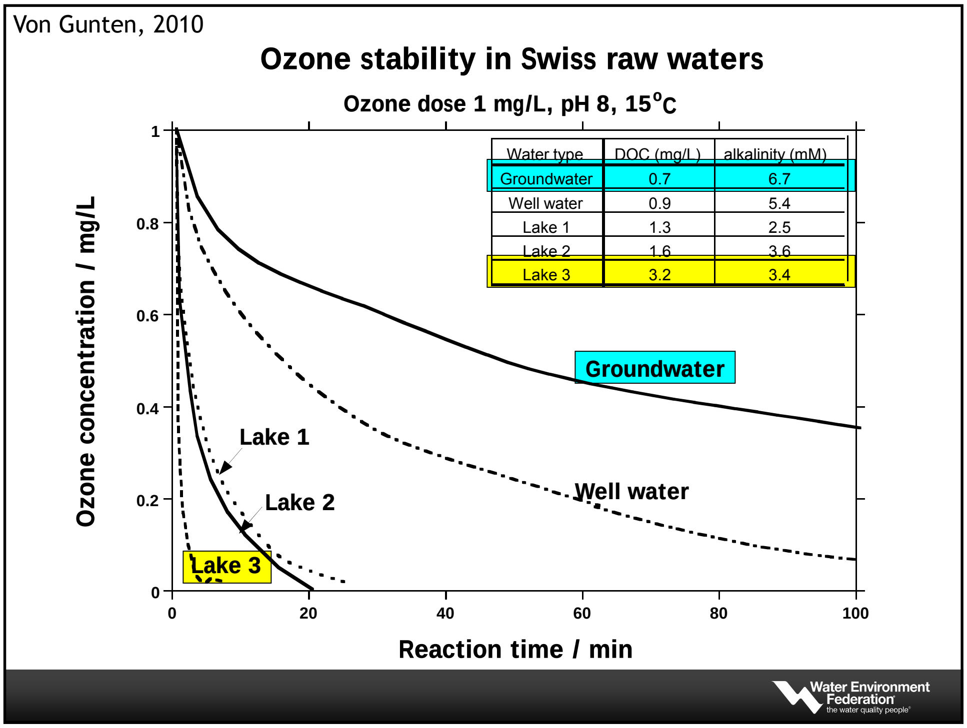
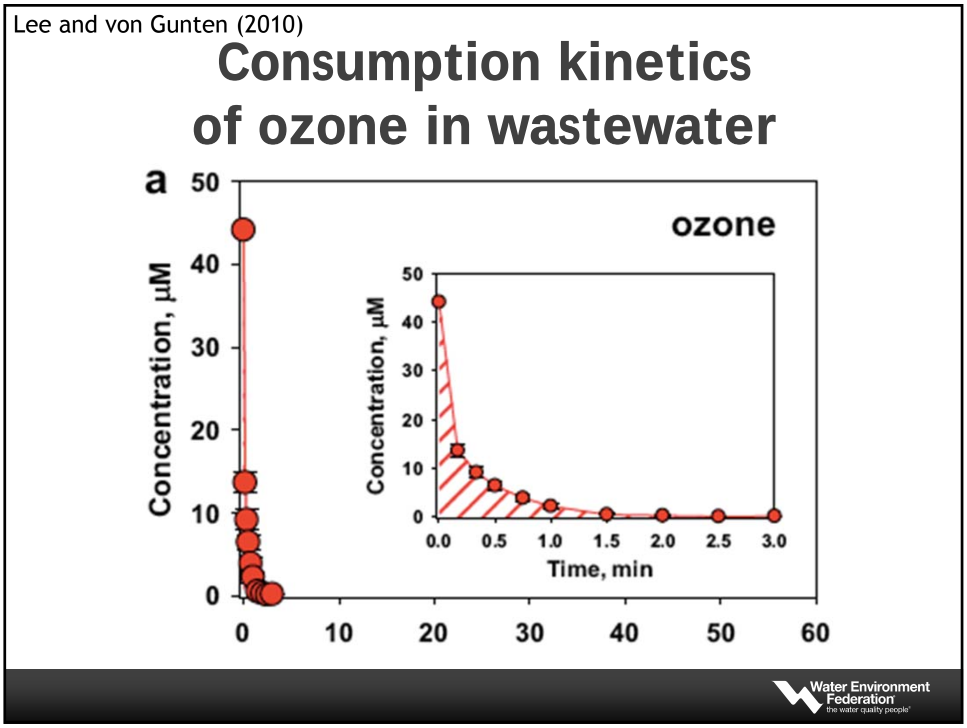


Von Gunten, 2010

Ozone stability in Swiss raw waters

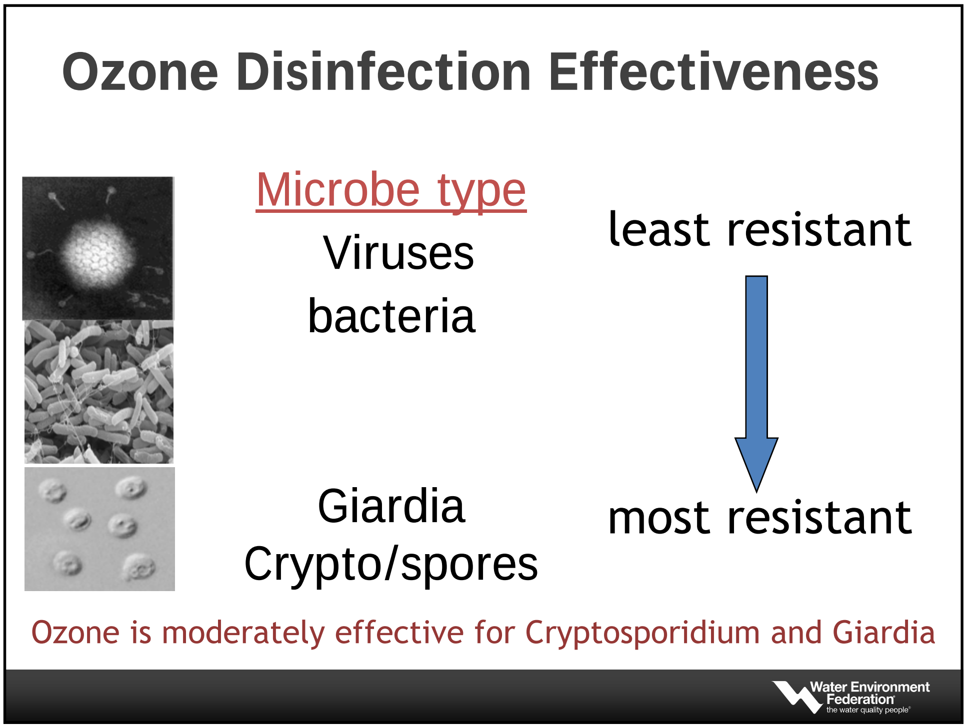
Ozone dose 1 mg/L, pH 8, 15°C

Water type	DOC (mg/L)	alkalinity (mM)
Groundwater	0.7	6.7
Well water	0.9	5.4
Lake 1	1.3	2.5
Lake 2	1.6	3.6
Lake 3	3.2	3.4



Lee and von Gunten (2010)

Consumption kinetics of ozone in wastewater



Ozone Disinfection Effectiveness

Microbe type	
Viruses	least resistant
bacteria	
Giardia	
Crypto/spores	most resistant

Ozone is moderately effective for Cryptosporidium and Giardia

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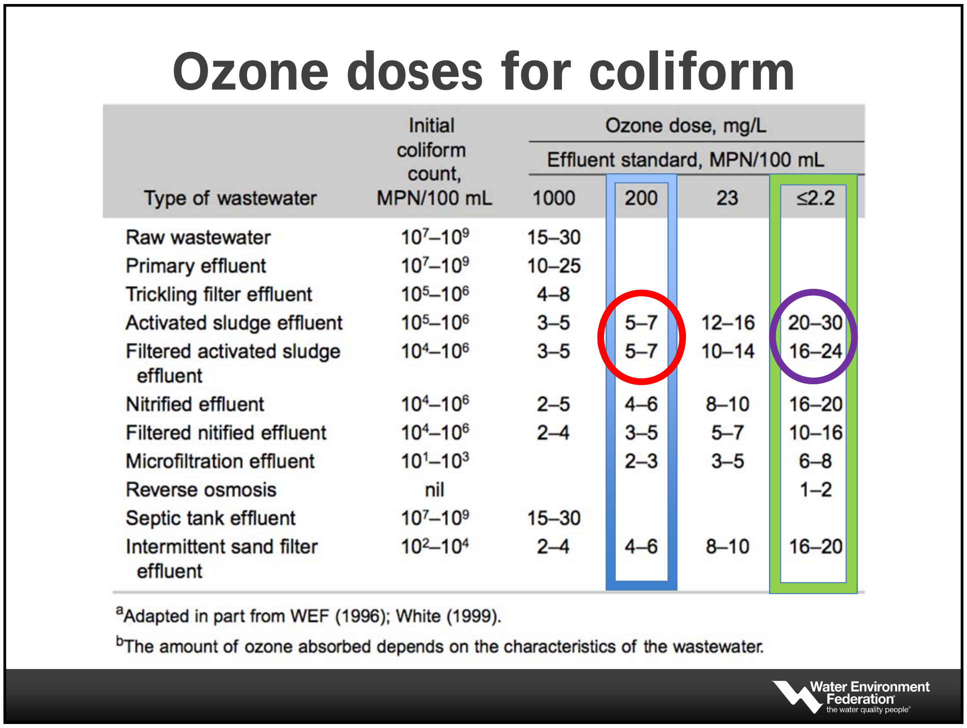

Ozone doses for coliform

Type of wastewater	Initial coliform count, MPN/100 mL	Ozone dose, mg/L			
		Effluent standard, MPN/100 mL			
		1000	200	23	≤2.2
Raw wastewater	10^7–10^9	15–30			
Primary effluent	10^7–10^9	10–25			
Trickling filter effluent	10^5–10^6	4–8			
Activated sludge effluent	10^5–10^6	3–5	5–7	12–16	20–30
Filtered activated sludge effluent	10^4–10^6	3–5	5–7	10–14	16–24
Nitrified effluent	10^4–10^6	2–5	4–6	8–10	16–20
Filtered nitified effluent	10^4–10^6	2–4	3–5	5–7	10–16
Microfiltration effluent	10^1–10^3		2–3	3–5	6–8
Reverse osmosis	nil				1–2
Septic tank effluent	10^7–10^9	15–30			
Intermittent sand filter effluent	10^2–10^4	2–4	4–6	8–10	16–20

[a] Adapted in part from WEF (1996); White (1999).

[b] The amount of ozone absorbed depends on the characteristics of the wastewater.

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Ishida et al., 2008

Ozonation of filtered wastewater: coliform

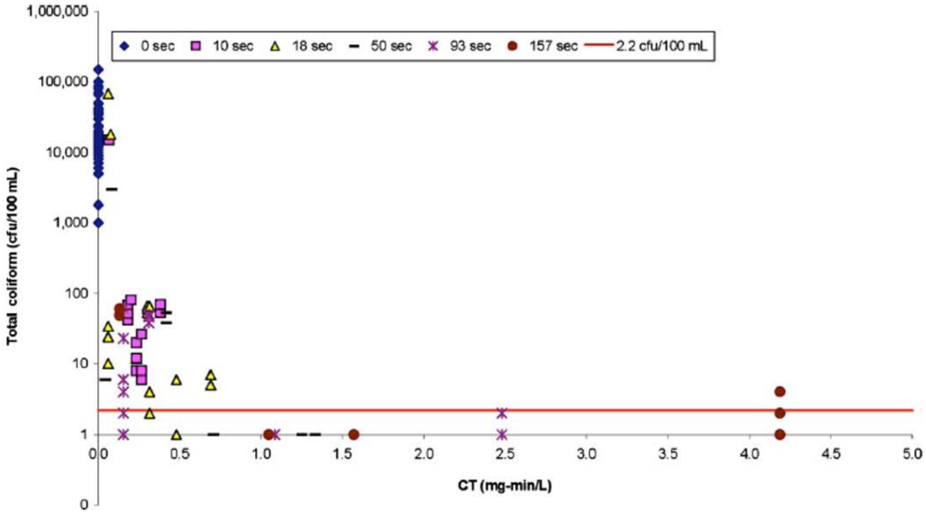
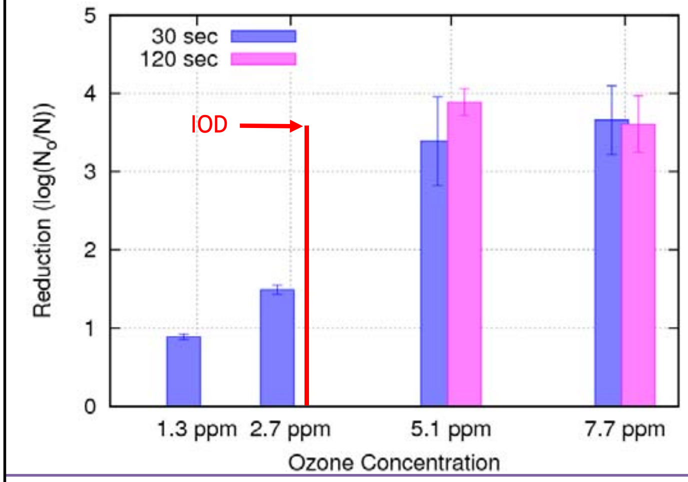


Figure 6 | Total coliform versus CT (ozone residual [mg/L] times contact time [min]) for media filtered water.

Linden et al., 2011

Total Coliform disinfection: Contact time, IOD

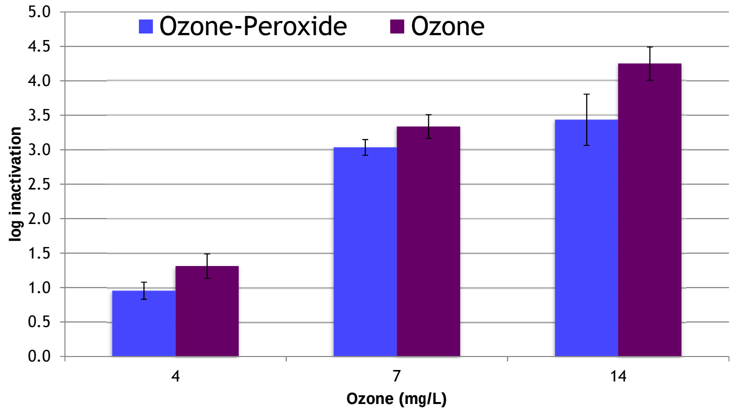


IOD: Initial Ozone Demand

- Concentration is more important than time
- Some disinfection takes place prior to formation of ozone residual

Linden et al., 2011

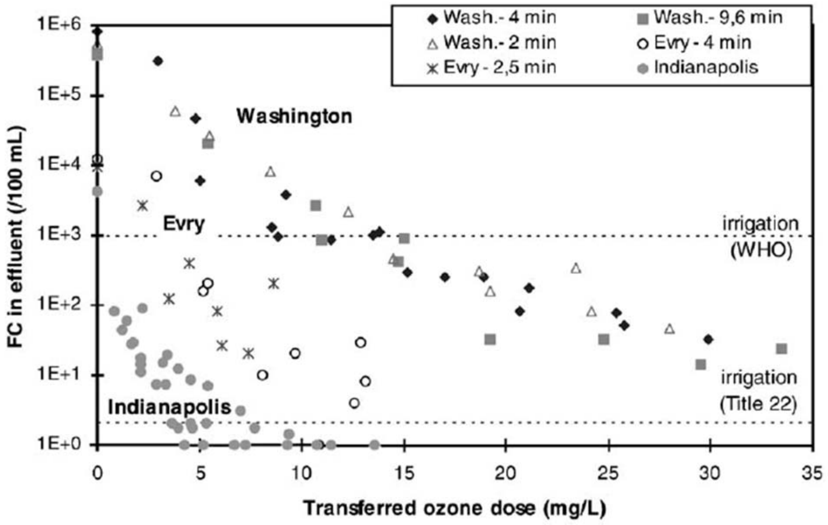
Total Coliform disinfection: O_3 vs O_3/H_2O_2

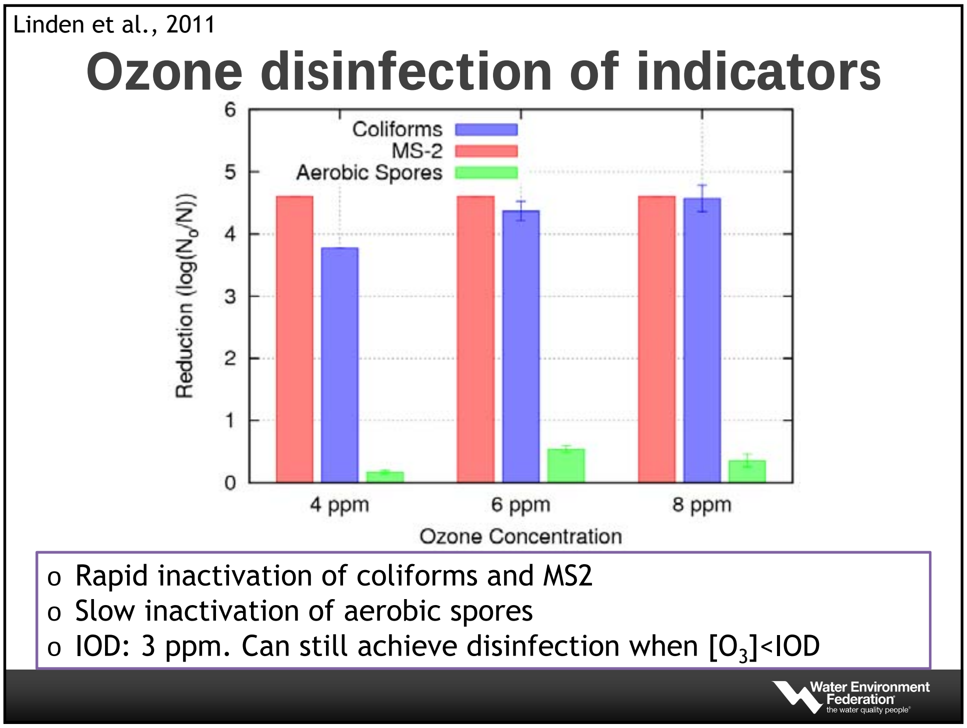


H_2O_2 appears to slightly reduce O_3 disinfection capacity

Xu et al. 2002

Disinfection of fecal coliform in WW

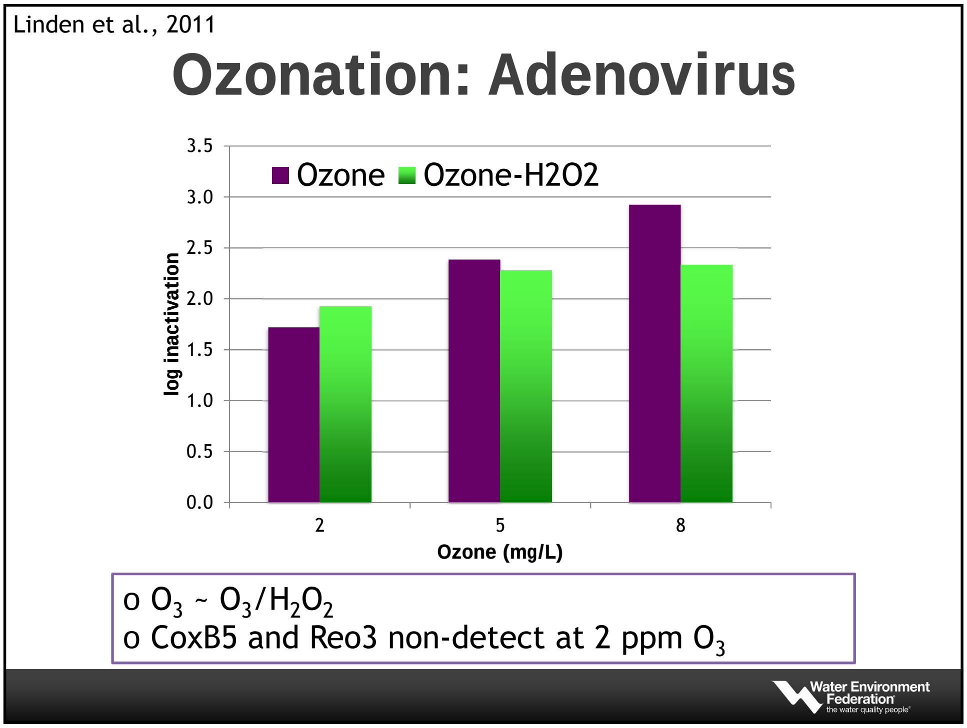




Linden et al., 2011

Ozone disinfection of indicators

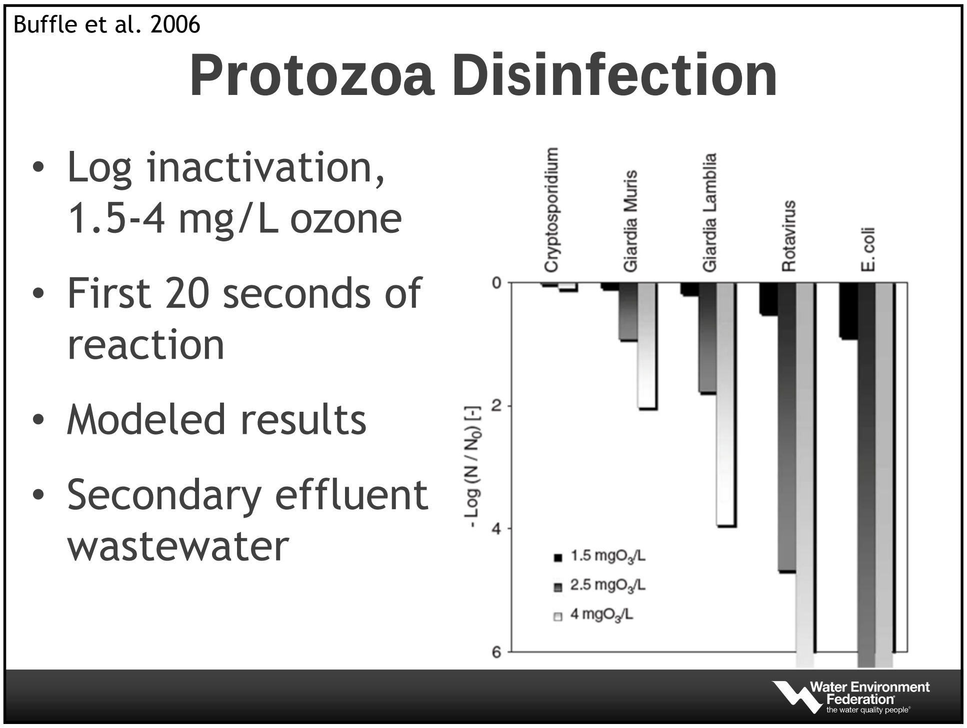
- Rapid inactivation of coliforms and MS2
- Slow inactivation of aerobic spores
- IOD: 3 ppm. Can still achieve disinfection when [O_3]<IOD



Linden et al., 2011

Ozonation: Adenovirus

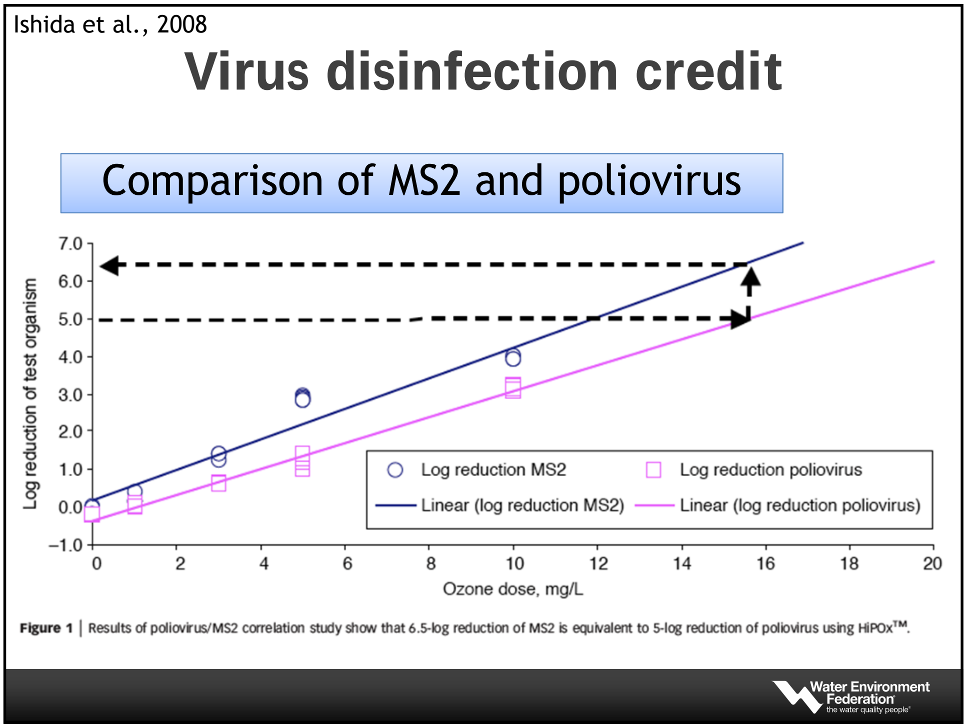
- O_3 ~ O_3/H_2O_2
- CoxB5 and Reo3 non-detect at 2 ppm O_3



Buffle et al. 2006

Protozoa Disinfection

- Log inactivation, 1.5-4 mg/L ozone
- First 20 seconds of reaction
- Modeled results
- Secondary effluent wastewater



Ishida et al., 2008

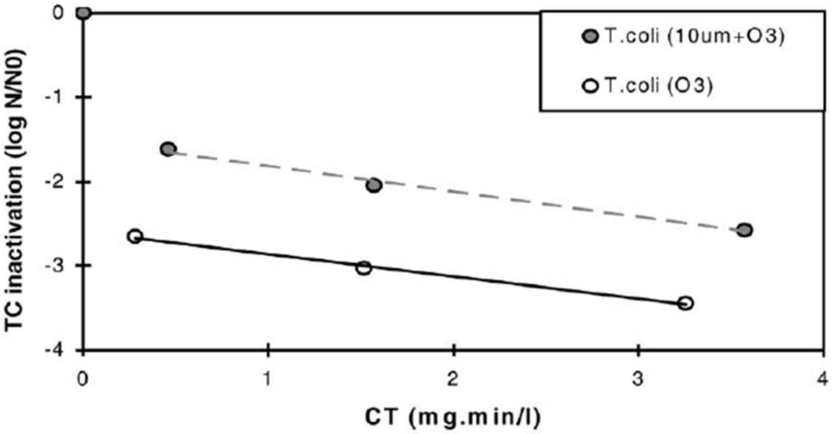
Virus disinfection credit

Comparison of MS2 and poliovirus

Figure 1 | Results of poliovirus/MS2 correlation study show that 6.5-log reduction of MS2 is equivalent to 5-log reduction of poliovirus using HiPOx™.

Xu et al. 2002

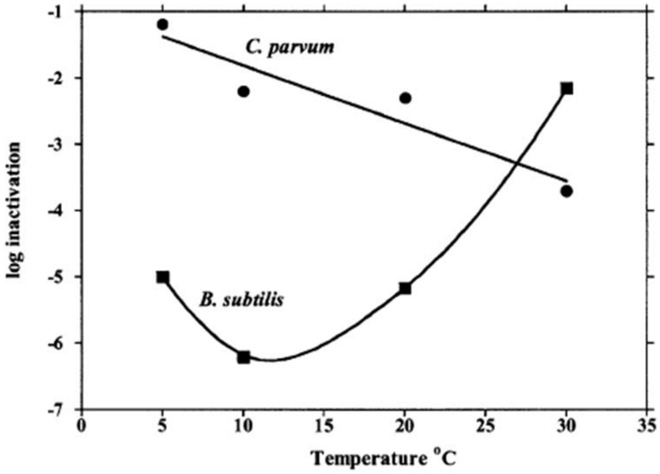
Impact of particles on coliform inactivation



10 micron pre-filtration improves disinfection performance

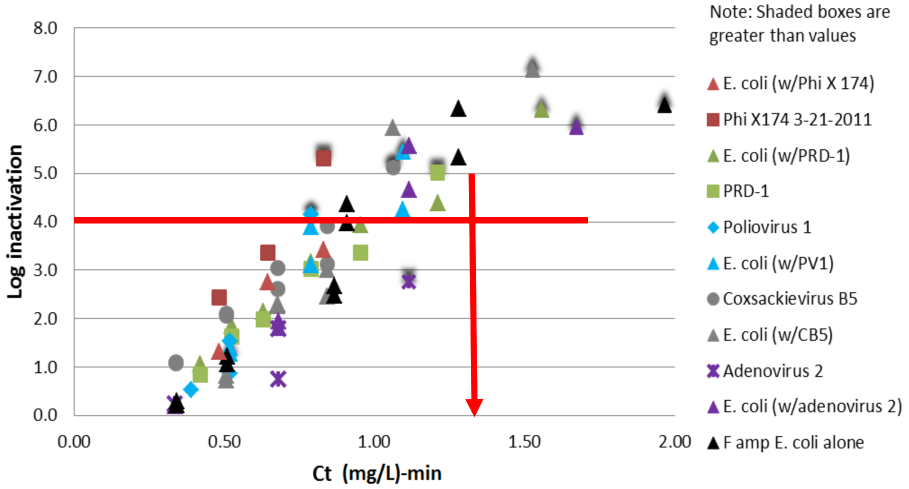
Von Gunten, 2003b

Temperature dependence of ozone disinfection



Sigmon et al., 2016

Inactivation kinetics of pathogens



Note: Shaded boxes are greater than values

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Sigmon et al., 2016

Summary Kinetics compared to E.coli

E. coli is a conservative indicator for virus disinfection with ozone

Normalized Ct requirements for specified log inactivation levels of viruses and surrogates in wastewater (pH=7.96, 16°C)

	E. coli-normalized Ct for wastewater (mg/L)-min			
log inactivation	**1**	**2**	**3**	**4**
E. coli	0.483	0.650	0.816	0.983
Coxsackievirus B5	0.321	0.513	0.705	0.897
Poliovirus 1	0.474	0.577	0.679	0.781
Adenovirus 2	0.590	0.918	1.115*	NA
φX174	0.330	0.450	0.570	0.690
PRD-1	0.428	0.627	0.826	1.025

* 1.115 (mg-min)/L gave >2.76 log inactivation of adenovirus 2

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Some Issues with Ozonation

- Formation of assimilable organic carbon (AOC)
  - Issue with water, wastewater reuse
- Bromate - disinfection byproduct
  - Issue with water, wastewater reuse

Adapted from Von Gunten, 2010

Increase of AOC after ozonation

- Problems in distribution systems after introduction of ozone (1970s)
  - Initial content of DOC important
  - Type of DOC important
- Introduction of combination O_3/BAC (Mühlheim process)
- Combination O_3/BAC/slow sand filtration
  - Zürich: no final disinfection required (AOC very low)
    - True of many European drinking waters
  - Can control AOC in wastewater reuse as well

Zeigers, 2005

Bromate and Disinfection

- 0.75-log inactivation Cryptosporidium
  - Bromate < 5 ppb
- 1.0-log inactivation
  - Bromate < 10 ppb
- >2.0-log inactivation
  - High bromate formation potential
    - Need chemical addition for bromate control less than 5 or 10 ppb
      - Ammonia or Ammonia/Chlorine may meet goal

Conclusions

- Ozone is a proven disinfectant
- Slower inactivation of protozoa
- Ozone residual is unstable in Wastewater
- Can achieve disinfection before measuring a residual
- *E. coli* is a conservative indicator for virus inactivation
- May need to control for some unwanted effects

Questions?

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