CornellEngineering
Civil and Environmental Engineering

CEE 4540

Sustainable municipal drinking water treatment

Topic: Disinfection

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Class #21 11/14/2018 2:55 – 4:10pm

If you can pick only one treatment process, what should it be?

- Membrane Filtration (remove particulate from water)
- Desalination with reverse osmosis membrane
- GAC or Ion Exchange Adsorption for organic contaminant removal (such as TCP, PCB, PFAS, etc.)
- Disinfection
- Advanced Oxidation Process for organic contaminant removal
- Control lead release from piping material
- Remove nitrate from water supply to avoid Blue-Baby syndrome

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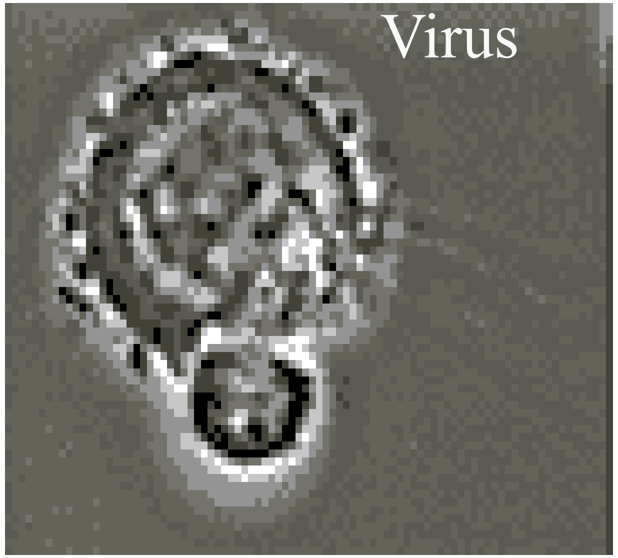
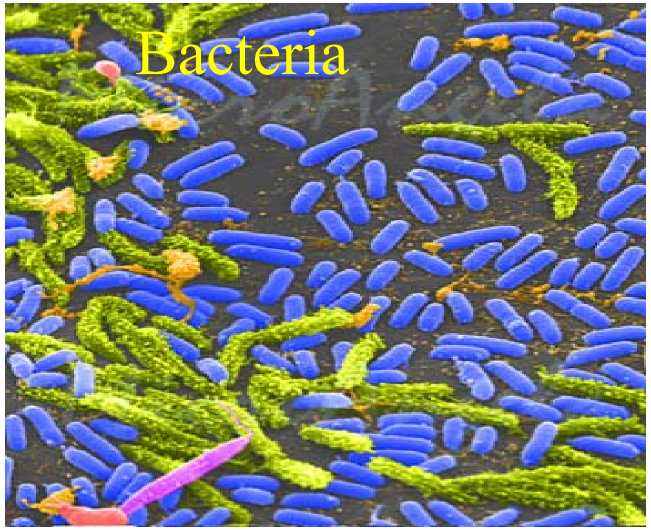
Disinfection Has Been Practiced for Centuries, but….

- Primarily targeting viruses & Bacteria





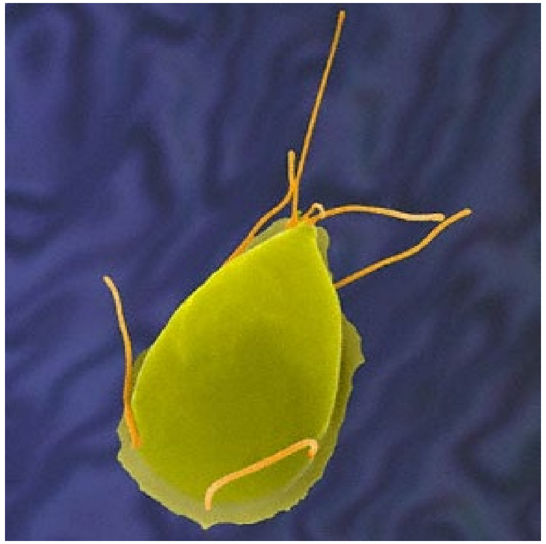
Long-Term 2 Enhanced Surface Water Treatment Rule

– Provides additional health protection from pathogenic microorganisms, especially *Cryptosporidium*

– Source water monitoring defines extent of *Cryptosporidium* inactivation

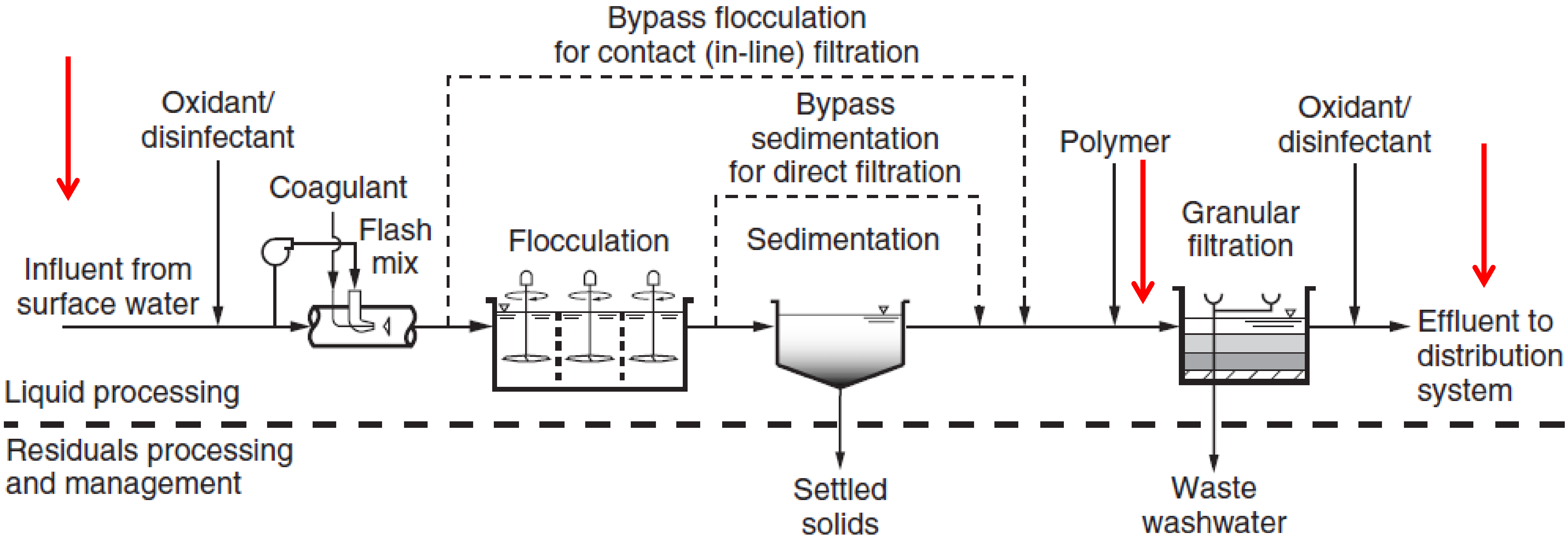
Cryptosporidium

Giardia



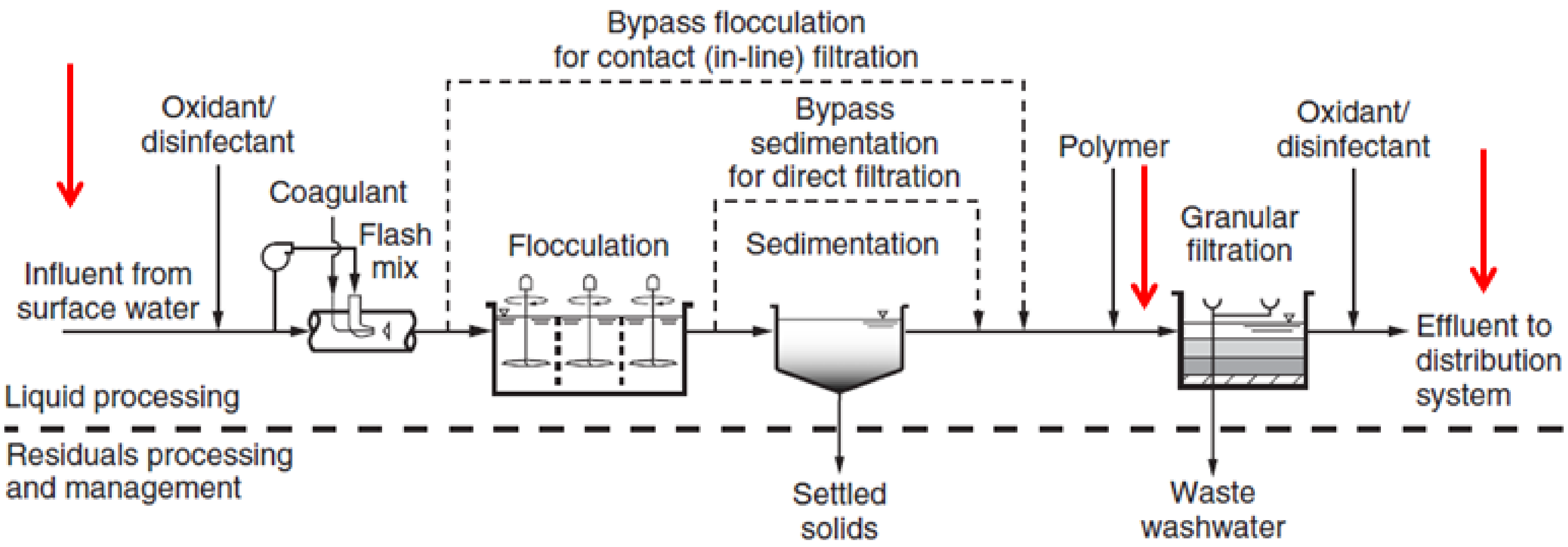
- Supplements existing regulations (SWTR, IESWTR, LT1)
- Inactivation requirement is in addition to *Cryptosporidium* removal credit from the IESWTR

Where is Disinfectant Applied?



Purpose & Function of Various Disinfectant Injection Locations

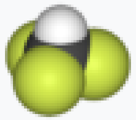
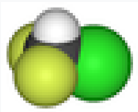
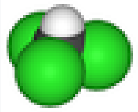
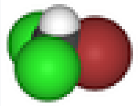
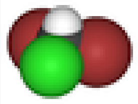
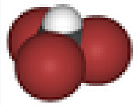
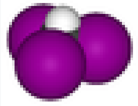
- Intake line: To control on algae growth in the intake line & inside the plant
  - Gain extra CT credits
  - Will increase the formation of disinfection by-products (DBPs)
- Prior to granular filters: To control bio/algae growth inside the filters
  - Gain extra CT credits



Disinfection Byproducts

- Disinfection is an oxidation process and will break larger organic molecules (NOM) to smaller molecules, and react with the organics to form Disinfection Byproducts (DBPs)
- DBPs are known carcinogens and are regulated by USEPA
- Regulated Disinfection Byproducts
  - Thihalomethanes (THM) USEPA Regulations: 80 ppb for TTHM
  - Haloacetic Acids (HAAs): 60 ppb for HAA5

Examples of Trihalomethans

Molecular formula	IUPAC name	CAS registry number	Common name	Other names	Molecule
CHF_3	trifluoromethane	75-46-7	fluoroform	Freon 23, R-23, HFC-23	
$CHClF_2$	chlorodifluoromethane	75-45-6	chlorodifluoromethane	R-22, HCFC-22	
$CHCl_3$	trichloromethane	67-66-3	chloroform	R-20, methyl trichloride	
$CHBrCl_2$	bromodichloromethane	75-27-4	bromodichloromethane	dichlorobromomethane, BDCM	
$CHBr_2Cl$	dibromochloromethane	124-48-1	dibromochloromethane	chlorodibromomethane, CDBM	
$CHBr_3$	tribromomethane	75-25-2	bromoform	methyl tribromide	
CHI_3	triiodomethane	75-47-8	iodoform	methyl triiodide	

Grouping of Haloacetic Acids

- Bromodichloroacetic Acid (BrCl2AA), Dibromochloroacetic Acid (Br2ClAA), and Tribromoacetic Acid (Br3AA) concentrations is known as HAA3.
- The sum of Monochloroacetic Acid (ClAA), Monobromoacetic Acid (BrAA), Dichloroacetic Acid (Cl2AA), Trichloroacetic Acid (Cl3AA), and Dibromoacetic Acid (Br2AA) concentrations are known as HAA5.
- HAA6 refers to the sum of HAA5 and Bromochloroacetic Acid (BrClAA) concentrations.
- HAA6 and HAA3 together make up HAA9

Can These DBPs be Removed?

- TTHM
  - Volatile and can be stripped off with aeration
  - Consider using GAC adsorption for off-gassing
- HAA
  - Not volatile so cannot be stripped off by aeration
  - Can be biodegraded, but will require additional biological treatment processes
- As long as there is chlorine and TOC remain in the water, DBPs will continue to form
- Control DBP in distribution system is still a very hot topic

Common Disinfection Processes

Primary Disinfection

- Chlorine (Most common)
- Ozone (Less common, but gaining tractions with biological filtration)
- Chorine Dioxide (not common, due to chlorate regulation & potential T&O)
- UV Disinfection (for Cryptosporidium & Giardia) (Very common, especially for water reuse)

Secondary Disinfection (residual chlorine in distribution system)

- Chlorine (Most common)
- Chloramine (Second to Chlorine)
- Chorine Dioxide (uncommon)

TOC Removal Requirements

– TOC removal requirements for DBP control is based on water quality

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as CaCO3)		
	0 – 60	> 60 – 120	>120 [3]
> 2.0 – 4.0	35.0 %	25.0 %	15.0 %
> 4.0 – 8.0	45.0 %	35.0 %	25.0 %
> 8.0	50.0 %	40.0 %	30.0 %

Concept of CT

- Potency of disinfection is measured by Concentration of Disinfectant x Effective Reaction time; C x T
- USEPA has established CT table for chlorine, chlorine dioxide, and chloramine
- Effective CT required depends on water pH and temperature

CT Values for 4-Log Virus Inactivation by Free Chlorine

CT VALUES* FOR
4- LOG INACTIVATION OF VIRUSES BY FREE CHLORINE

For soften water

	pH	
Temperature (°C)	6-9	10
0.5	12	90
5	8	60
10	6	45
15	4	30
20	3	22
25	2	15

*Although units did not appear in the original tables, units are min-mg/L.

CT Values Required for Giardia Inactivation with ClO2

- Chlorine is NOT effective for Giardia

TABLE B-3

CT VALUES* FOR
3-LOG INACTIVATION OF *GIARDIA* CYSTS
BY CHLORINE DIOXIDE

Temperature (°C)					
< = 1	5	10	15	20	25
63	26	23	19	15	11

*Although units did not appear in the original tables, units are min-mg/L.

CT Values Required for Cryptosporidium Inactivation with ClO2

TABLE IV.D–4.—CT VALUES FOR CRYPTOSPORIDIUM INACTIVATION BY CHLORINE DIOXIDE [1] (MG/L × MIN)

Log credit	Water temperature, °C										
	≤0.5	1	2	3	5	7	10	15	20	25	30
0.25	159	153	140	128	107	90	69	45	29	19	12
0.5	319	305	279	256	214	180	138	89	58	38	24
1.0	637	610	558	511	429	360	277	179	116	75	49
1.5	956	915	838	767	643	539	415	268	174	113	73
2.0	1275	1220	1117	1023	858	719	553	357	232	150	98
2.5	1594	1525	1396	1278	1072	899	691	447	289	188	122
3.0	1912	1830	1675	1534	1286	1079	830	536	347	226	147

CT Requirement for Ozone Disinfection: Cryptosporidium

- Ozone will cost a lot more….

TABLE IV.D–3.—CT VALUES FOR CRYPTOSPORIDIUM INACTIVATION BY OZONE[1] (MG/L × MIN)

Log credit	Water temperature, °C										
	≤0.5	1	2	3	5	7	10	15	20	25	30
0.25	6.0	5.8	5.2	4.8	4.0	3.3	2.5	1.6	1.0	0.6	0.39
0.5	12	12	10	9.5	7.9	6.5	4.9	3.1	2.0	1.2	0.78
1.0	24	23	21	19	16	13	9.9	6.2	3.9	2.5	1.6
1.5	36	35	31	29	24	20	15	9.3	5.9	3.7	2.4
2.0	48	46	42	38	32	26	20	12	7.8	4.9	3.1
2.5	60	58	52	48	40	33	25	16	9.8	6.2	3.9
3.0	72	69	63	57	47	39	30	19	12	7.4	4.7

[1] PWSs may use this equation to determine log credit between the indicated values: Log credit = $(0.0397 \times (1.09757)^{Temp}) \times CT$.

UV Disinfection for Cryptosporidium & Giardia

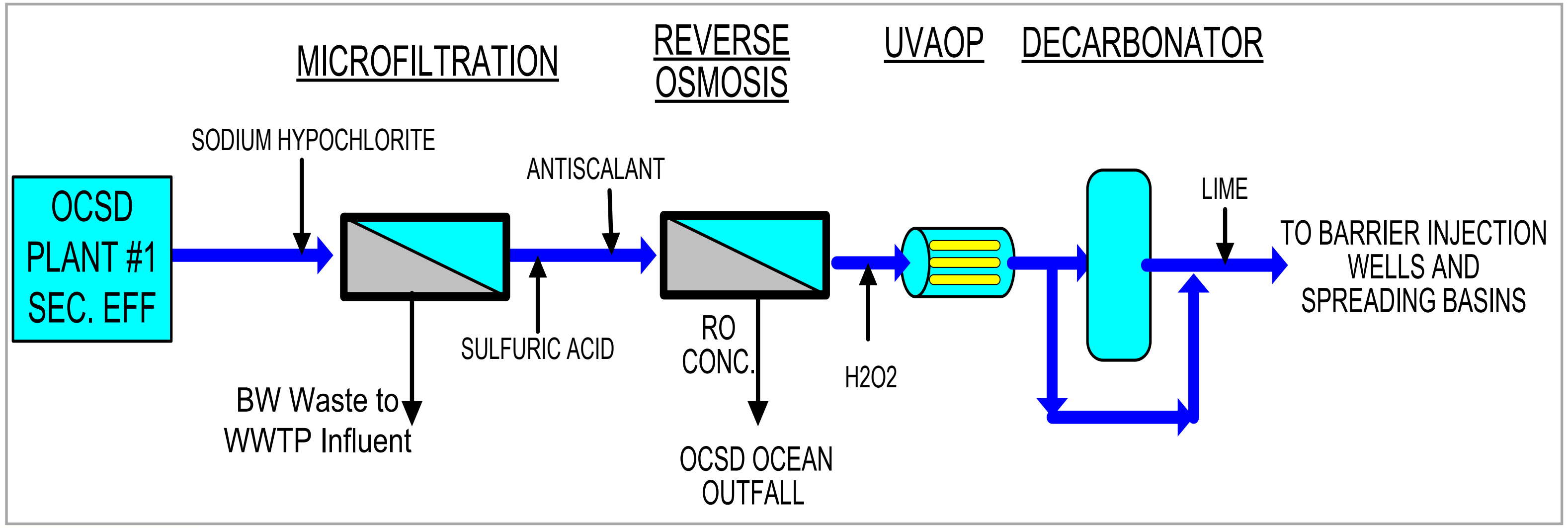
– UV is not very effective for viruses

TABLE IV.D–5.—UV DOSE REQUIREMENTS FOR CRYPTOSPORIDIUM, GIARDIA LAMBLIA, AND VIRUS INACTIVATION CREDIT

Log credit	Cryptosporidium UV dose (mJ/cm^2)	Giardia lamblia UV dose (mJ/cm^2)	Virus UV dose (mJ/cm^2)
0.5	1.6	1.5	39
1.0	2.5	2.1	58
1.5	3.9	3.0	79
2.0	5.8	5.2	100
2.5	8.5	7.7	121
3.0	12	11	143
3.5	15	15	163
4.0	22	22	186

Disinfection in Direct/Indirect Potable Reuse

- IPR/DPR requires full advanced treatment (FAT) consisting of RO and Advanced Oxidation Processes (AOP) to meet Groundwater Recharge and Recovery via subsurface injection
  - MF/UF are used for pretreatment prior to RO
- Very effective; meets all primary and secondary MCLs, notification level chemicals, and other requirements



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Disinfection Credit is the Single Most Important Factor in Potable Water Reuse

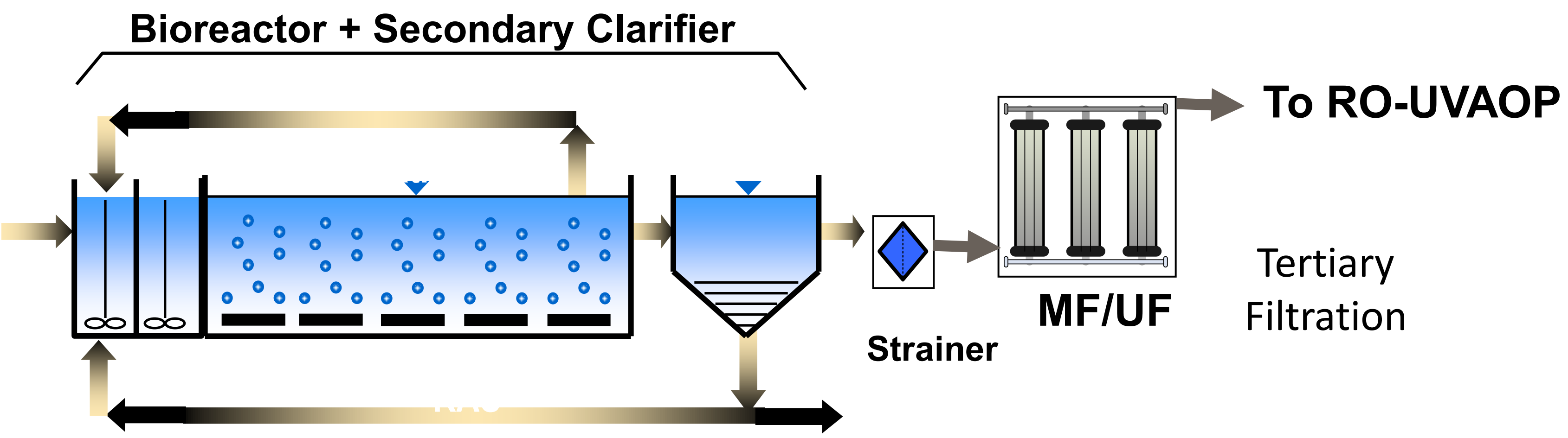
- FAT can reliably meets pathogen removal/inactivation requirements of GWR

	Primary and Secondary Treatment[1]	MF/UF	RO	UVAOP	Free Chlorine	Total	Minimum LRV for GWR via Injection
Crypto	1.2	4	1.5-2	6	0	12.7-13.2	10
Giardia	0.8	4	1.5-2	6	0	12.3-12.8	10
Virus	1.9	0	1.5-2	6	5	14.4-14.9	12

Illustration of How FAT Can be Used in IPR/DPR

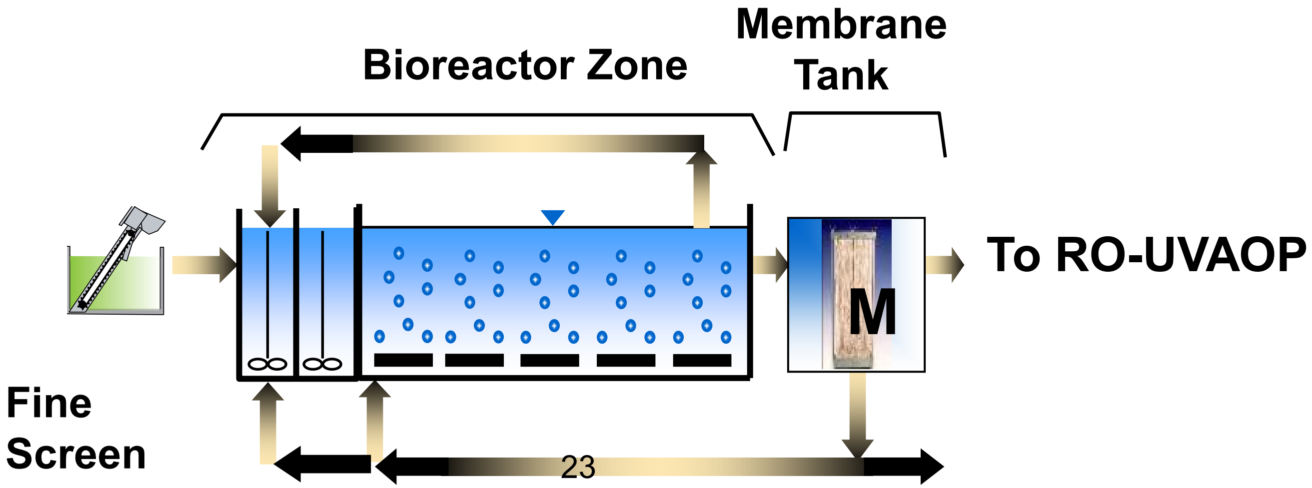
CAS-MF/UF

CAS: Conventional Activated Sludge



MBR

MBR: Membrane Bio Reactor



Demands & Benefits of Using MBR

– Substantial interest in California and other states for replacing MF/UF with MBR in a potable reuse train because MBRs have benefits over CAS/MF-UF systems

- Sludge settling and secondary clarification limitations are no longer an issue with MBR
- Can operate at much higher MLSS than CAS
  - Results in a compact footprint

Additional Benefits of MBR vs. CAS

- For a given activated sludge basin volume, MBR can be operated at longer SRTs than CAS
  - Improves removal efficiencies of bulk (BOD, TOC) and trace organic contaminants (slowly biodegradable org.)

- Mean diameter of MBR flocs are smaller than CAS
  - Improves removal efficiencies of Contaminants of Emerging Concerns (CECs) with logKow≥3 (more hydrophobic), metals (i.e. iron, manganese) and pathogens (MLSS associated)

Do Membranes used in MBR Receive Disinfection Credits?

- To date no pathogen credits have been given to MBR in CA due to lack of approved direct integrity testing or alternative method to assess membrane integrity
- As a result, additional treatment processes or advanced monitoring approaches are needed for MBR trains to meet pathogen requirements in IPR projects
  - Increases CAPEX and O&M costs

No Pathogen Credits Have Been Given to MBRs in CA

	MBR	RO	UVAOP	Free Chlorine	Total	Minimum LRV for GWR via Injection
Cryptosporidium	0	1.5-2	6	0	7.5-8	10
Giardia	0	1.5-2	6	0	7.5-8	10
Virus	0	1.5-2	6	5	12.5-13	12

Could it be a big obstacle for an MBR Based IPR/DPR Train?

New Development in CA

CA State Water Board is considering given following pathogen credits for MBR per WaterVal Protocol (Tier I)

- **Cryptosporidium LRV: 2.0, Giardia LRV=2.0, Virus=1.5**

Parameter	Units	Minimum	Maximum
Bioreactor pH	pH units	6	8
Bioreactor DO	mg/L	1	7
Bioreactor Temperature	C	16	30
Solids Retention Time	d	11	-
Hydraulic Retention Time	h	6	-
Mixed Liquor Suspended Solids	mg/L	3,000	-
Transmembrane Pressure	kPa	3	
Flux	gfd	-	17.6
Turbidity	NTU	-	0.2

Challenges with WaterVal Protocol

- Terms and conditions are not clearly defined
- Conditions (temperature, flux, HRT) may not be met at all time
- SRT and temperature relationship is missing

	MBR	RO	UVAOP	Free Chlorine	Total	Minimum LRV for GWR via Injection
Cryptosporidium	2	1.5-2	6	0	9.5-10	10
Giardia	2	1.5-2	6	0	9.5-10	10
Virus	1.5	1.5-2	6	5	14-14.5	12

What to do under Very Stringent Regulatory Environment?

- To explore cost effective approaches to reliably satisfy Cryptosporidium and Giardia removal requirements, assuming little or no pathogen credit is given to MBR systems

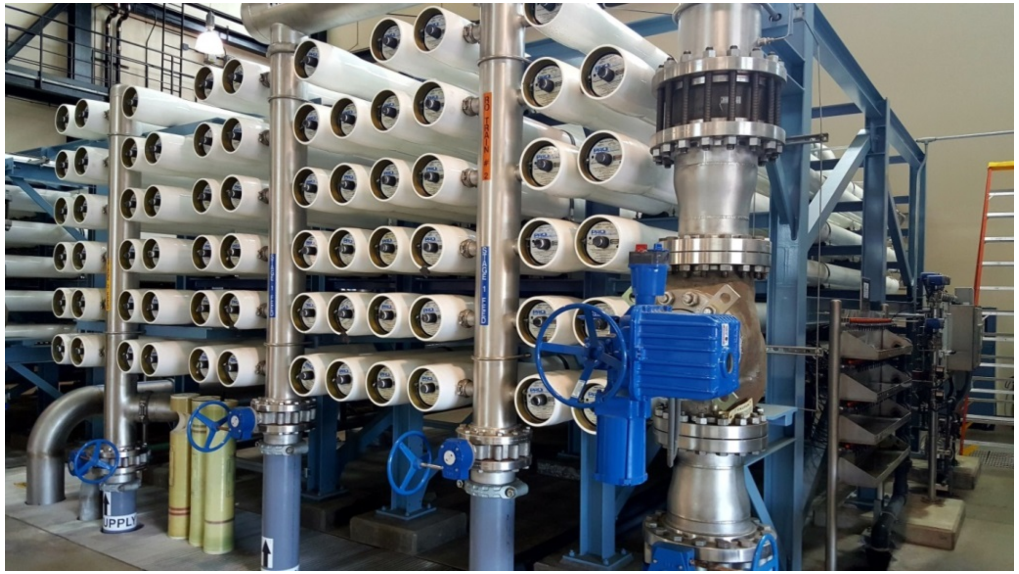
Probably Approaches

1. Get better pathogen credit for RO
2. Get better pathogen credit for UVAOP
3. Consider adding a unit treatment process if the above approaches do not work

1. Get a Better Pathogen Credit for RO

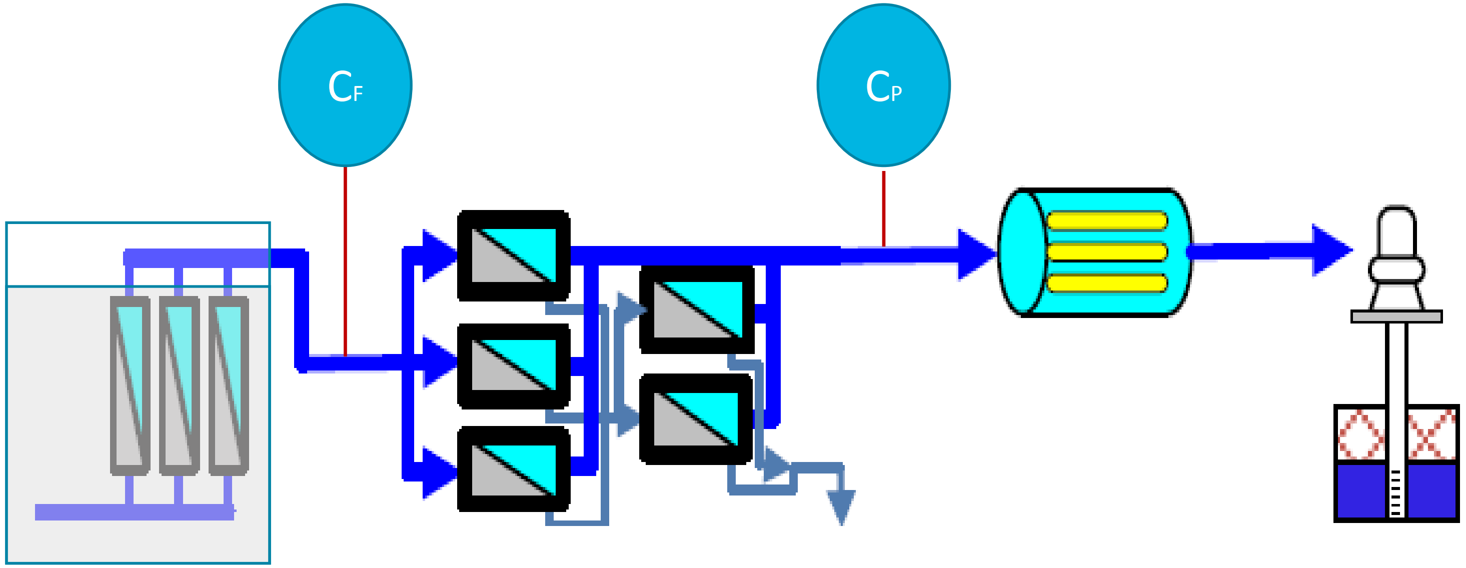
RO integrity may be compromised due to:

- Interconnector and end connector O-ring defects/leaks
- Membrane element glue line leakages
- Surface scratches
- Oxidation of membranes
- Currently RO receives 2 log Credit



Why Are We Getting Only ~2-log LRV for RO?

- Conductivity monitoring is widely used method to assess RO performance (i.e. salt passage)
- Easy to implement with a relatively low cost
- However, resolution of this method is low (up to 2-log)



LRV RO=$\log(C_F/C_P)$

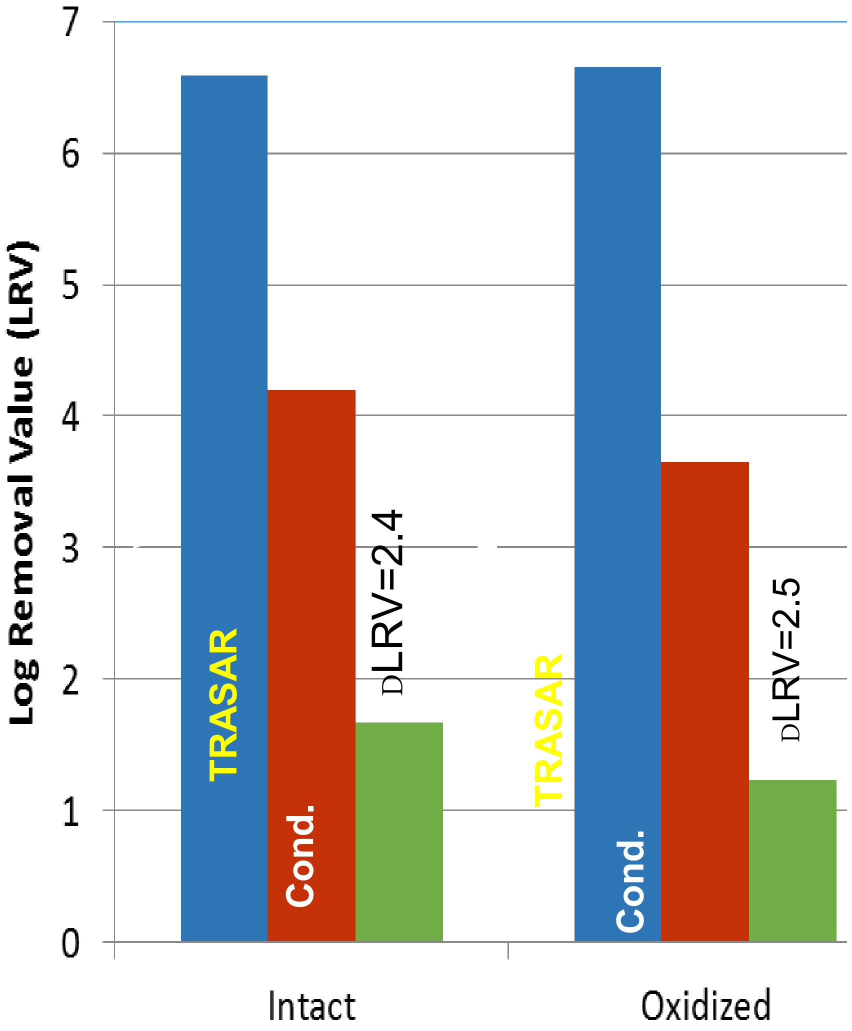
Are There Other Monitoring Methods?

	Sulfate	TOC	Rhodamine WT	TRASAR
RO LRV Demonstrated	~3-3.5	~3	~3	~4
Pros/Cons	Good resolution High investment cost.	Good resolution (0.1 µg/L) High CAPEX and Maintenance Cost	Very high resolution (10 ng/L) but 10µg/L limit in drinking water	Very high resolution (1 mg/L), successfully demonstrated in pilot tests in CA, received NSF approval; single supplier
Net Improvement Over Conductivity Based Monitoring	1.5-2.0	1.0-1.5	1.0-1.5	2.0-2.5

TRASAR

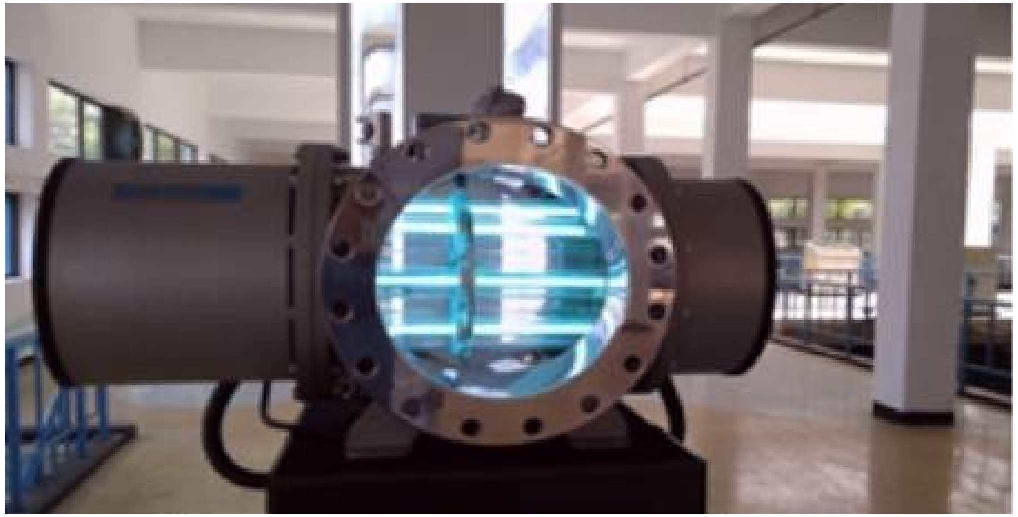
- Utilize fluorescence-embedded RO antiscalant
- Detect trace level of antiscalant

- TRASAR dye dosage in RO feed=40 –100 ppb
- TRASAR dye in permeate=0.001 –0.05 ppb
- 3.5-4.0 LRV can be reliably demonstrated with TRASAR



2. Explore Better Pathogen Credits for UVAOP

- H2O2 is added to UV Reactor to create Hydroxyl Radicals OH•
- Hydroxyl radical is a very strong oxidant



Orange County WD

AECOM

Current Regulatory Status in CA

§60320.108. Pathogenic Microorganism Control.

(a) A project sponsor shall design and operate a GRRP such that the recycled municipal wastewater used as recharge water for a GRRP receives treatment that achieves at least 12-log enteric virus reduction, 10-log Giardia cyst reduction, and 10-log Cryptosporidium oocyst reduction. The treatment train shall consist of at least three separate treatment processes. Except as provided in subsection (c), for each pathogen (i.e., virus, Giardia cyst, or Cryptosporidium oocyst), a separate treatment process may be credited with no more than 6-log reduction, with at least three processes each being credited with no less than 1.0-log reduction.

- Given that UVAOP gets 6-log credit for V/G/C

UVAOP Design in CA

- Adds peroxide or chlorine to create OH* radicals that indiscriminately react with trace organics and oxidize them
- Minimum 0.5-log 1,4-dioxane removal
- UV doses >850 mJ/cm^2 are needed for 0.5-log 1,4-diaxone removal
- Multiple reactors/banks are operated in series to deliver the target UV dose
- Each reactor/bank is operated and mo

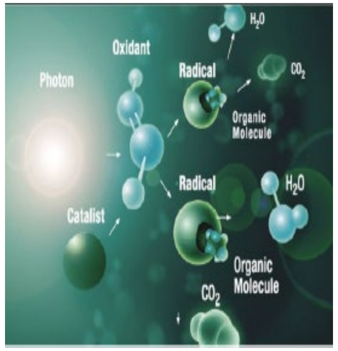


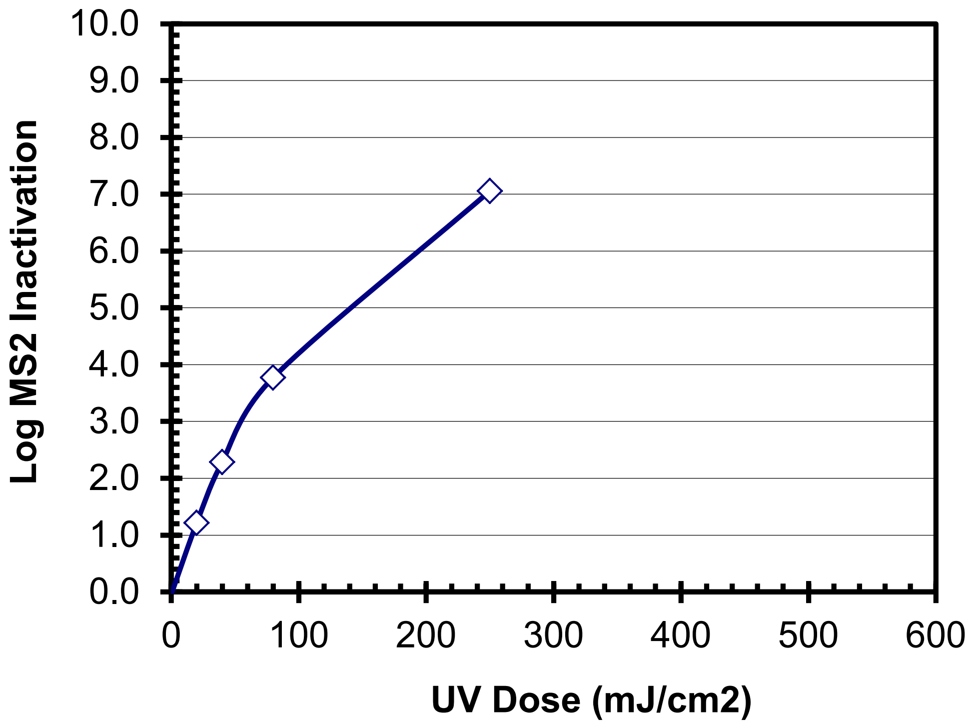
Table 1.4. UV Dose Requirements – millijoules per centimeter squared (mJ/cm^2) [1]

Target Pathogens	Log Inactivation							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	15	22
Giardia	1.5	2.1	3.0	5.2	7.7	11	15	22
Virus	39	58	79	100	121	143	163	186

[1] 40 CFR 141.720(d)(1)

UVAOP Validation Studies- Oxnard

- UVAOP was designed to meet
  - Minimum 1.2-log NDMA removal (2007 Regs)
  - Minimum 4-log MS-2 Inactivation
- Three chambers in series each has two reactors, (6 reactors, one is standby), each reactor has 72 lamps
- At MS-2 RED Dose of 115 mJ/cm2, each reactor can achieve 4-log MS2 inactivation
  - >4-log Crypto and Giardia removal at an assumed validation factor of 3
- Five reactors in series could achieve >20-log Crypto and Giardia inactivation



3. Tired? Add a UV Disinfection System

UV Dose Requirements for Pathogen Inactivation

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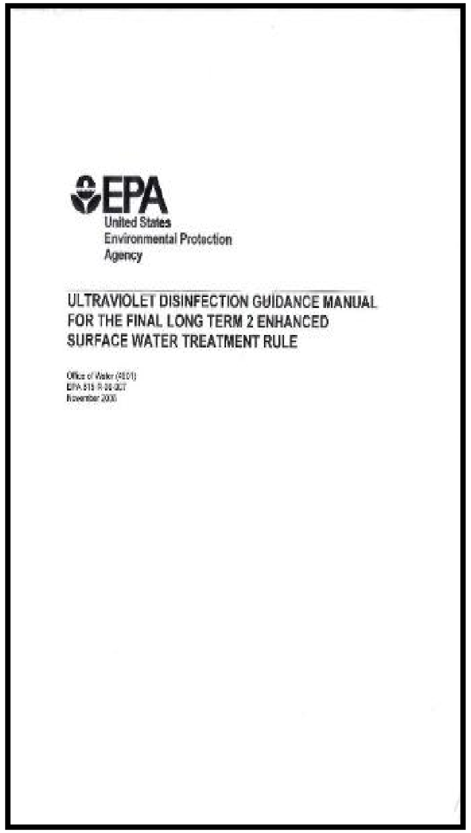

EPA
United States
Environmental Protection
Agency

ULTRAVIOLET DISINFECTION GUIDANCE MANUAL
FOR THE FINAL LONG TERM 2 ENHANCED
SURFACE WATER TREATMENT RULE

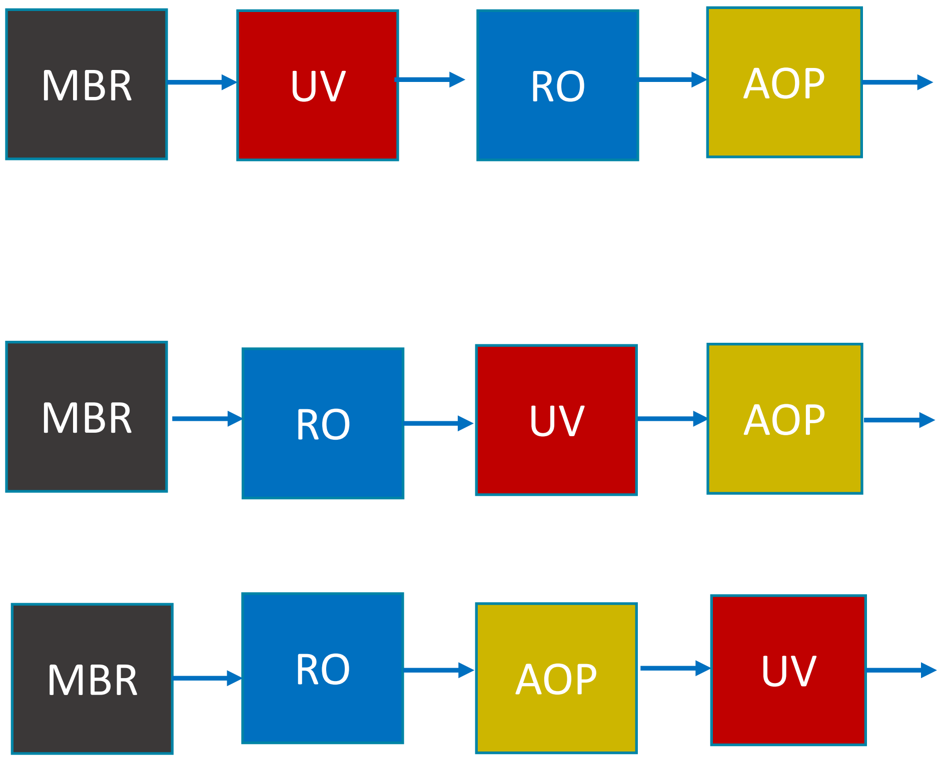
Where Can We Put UV Disinfection?

After MBR (Before RO)

- Lower UVT (typically 70-78%)
- Without chlorine residual it does not provide effective biological fouling control for RO

After RO

- Higher UVT (typically 95-98%)
- Lower hardness
- Reduces both CAPEX and O&M Costs



Summary on Getting Credits Needed for IPR/DPR

- Using TRASAR, or sulfate may provide 1.5-2.0-log additional pathogen credits for RO systems over conductivity based monitoring
  - This will be enough to reliably meet minimum 10 log C/G requirements, if some credits are given to MBR
- A UV dose of 22 mJ/cm^2 can provide 4-log Crypto and Giardia inactivation
  - Putting UV downstream of RO is advantages due to higher UVT

Final Thoughts on Disinfection Credits…..

- Disinfection processes in series each may get up to 6 log pathogen credit (up to 12-log total)
- For systems with multiple UVAOP reactors in series, may <u>deserve credit for each reactor</u> if all the monitoring requirements are met?

- UVAOP + Free Chlorine
- Ozone + UV
- Ozone + UVAOP
- UVAOP+ Low Dose UV
- Chlorine + UVAOP

Questions: Are these disinfection processes in series different than UVAOP reactors in series?

Homework & Reading

- Provide a Disinfection Process Design to achieve enough disinfection credits for a Direct Potable Reuse Project in California. The process should include disinfectants inside distribution system. Make your assumptions on chlorine demand inside distribution system.