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UV Disinfection for Water and Wastewater Treatment Plants

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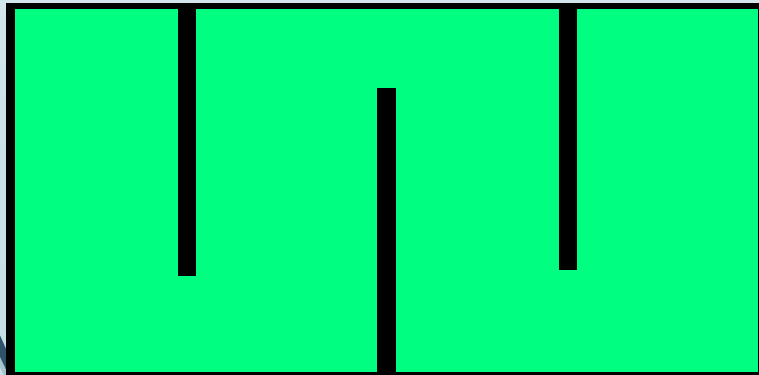
UV Disinfection – Basic Concept

Chemical Disinfection

milligrams*min/Liter

CT

Concentration (mg/L) x
Contact Time (minutes)



UV Disinfection

millijoules/cm²
(mJ/cm²)

IT

Intensity (mW/cm²) x
Contact Time (sec)



History of UV Disinfection

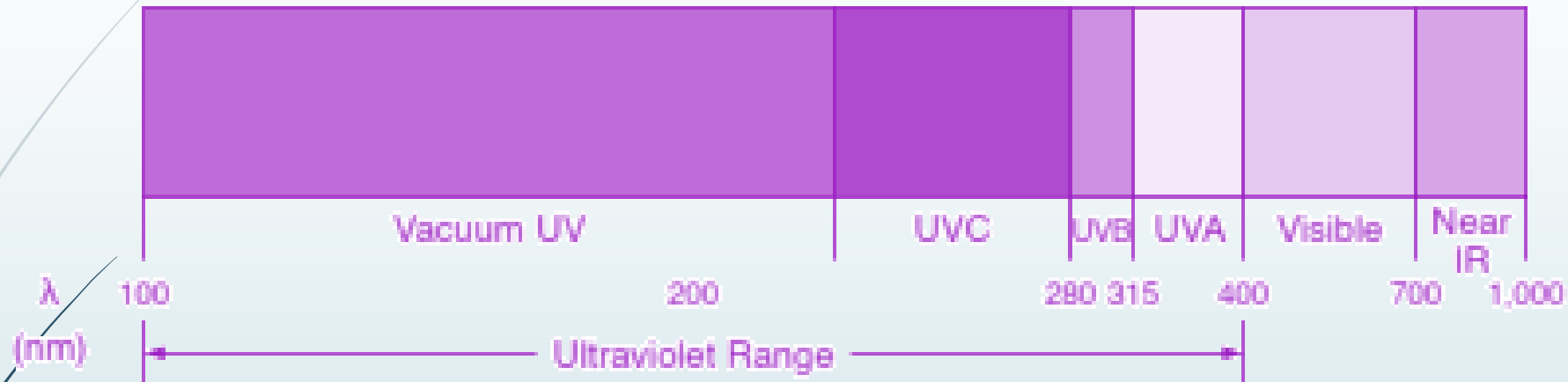
Time	Progress
at least 4000 years ago	Ancient Hindu source written - raw water be boiled, exposed to sunlight , filtered, and then cooled in an earthen vessel.
1887	Germicidal properties of sunlight
1901	Artificial UV light (Mercury lamp) developed
1910	First application in drinking water: Marseilles, France

Fundamentals of UV disinfection

- UV disinfection arises from a photochemical process, in which UV light is absorbed by DNA or RNA in the microorganism, causing a disruption in the structure of the nucleic acid. Therefore, an understanding of UV disinfection requires some background in the fundamentals of UV light, photochemistry, and photobiology

Spectral ranges of UV, visible, and IR light.

The ultraviolet range is 100–400 nm.



The UVC range is sometimes called the germicidal range because it is very effective for inactivating bacteria and viruses. The vacuum ultraviolet (VUV) range is absorbed by almost all substances (including liquid water and oxygen in air). Therefore, it can only be transmitted in a vacuum.

EMISSION, TRANSMISSION, AND ABSORPTION OF LIGHT

- Various aspects of light are discussed in the context of emission from a UV lamp, transmission through a medium (air, water, etc.), and absorption by a target molecule.

Advantage of UV Disinfection

- Effective disinfectant
- More effective than chlorine in inactivating most viruses, spores, cysts
- No chemical addition required
- No formation of disinfection byproducts
- Water retains its natural flavour and smell
- Microorganism inactivation achieved within seconds
- Max operational safety
- Minimal operating costs

Disadvantage of UV Disinfection

There is no residual disinfectant

The impact of water quality on the efficiency of disinfection

- Buildup of Ca, Mg, Fe scales on the sleeve

- Biofilm formation on the sleeve

- Absorption of UV in water; particle interactions

WHAT HAPPENS WHEN UV LIGHT REACHES ITS INTENDED TARGET

- The absorbed photon energy causes the molecule to rise in energy from its initial ground state to an excited state.
 - ❑ The molecule returns to its ground state with emission of a photon—this is called **fluorescence**.
 - ❑ The excited state can convert to another (usually longer lived) excited state from which photon emission can occur—this is called **intersystem crossing** followed by **phosphorescence**.
 - ❑ The molecule can return to the ground state with the excess energy being lost as heat into the medium—this is called **internal conversion**.

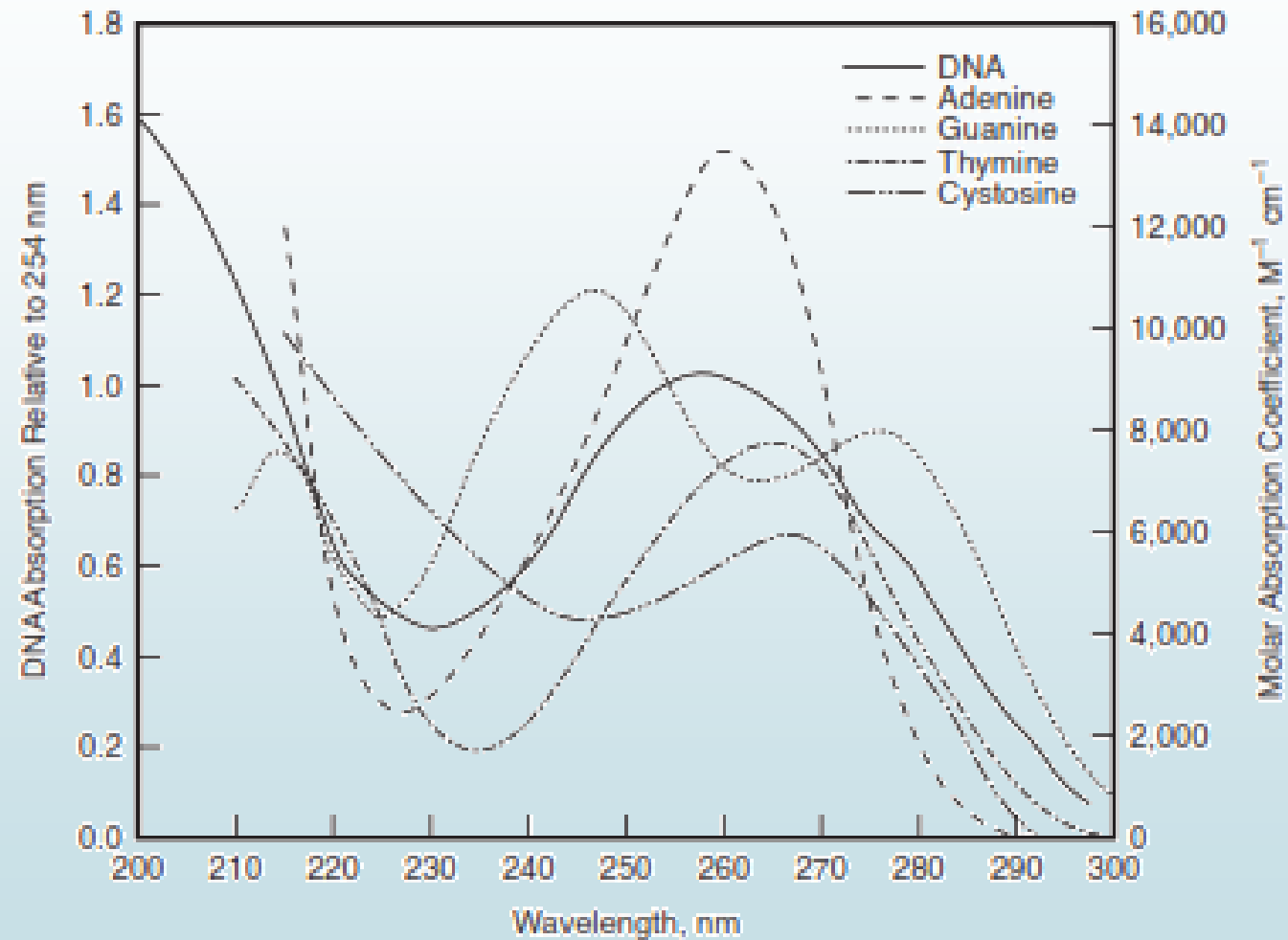
Mechanisms of UV Disinfection

- ❑ UV light inactivates microorganisms by damaging nucleic acids (DNA or RNA) thereby interfering with replication of the microorganisms and therefore incapable of infecting a host

Mechanisms of UV Disinfection

- ❑ Different microorganisms have different degree of susceptibility to UV radiation depending on DNA content
- ❑ Viruses are the most resistant
- ❑ Microbial repair: regain of infectivity

Absorption spectra of nucleotides and of DNA



UV SENSITIVITY OF MICROORGANISMS

- Microorganisms exhibit a wide variation in their sensitivity to UV light.
- The measurement of the UV sensitivity of microorganisms at a specific wavelength, or narrow band of wavelengths, is performed through the determination of a UV dose (fluence)–response curve.

UV Dose

- ❑ The effectiveness of UV disinfection is based on the UV dose to which the microorganisms are exposed
- ❑ UV dose is analogous to Cl_2 dose
 $\text{Cl}_2 \text{ dose} = \text{Cl}_2 \text{ conc.} \times \text{contact time (t)} \text{ or } C \times t$

- ❑ UV dose (D) = $I \times t$ or $\int_0^t I \cdot dt$ if intensity not constant

Where, D = UV dose, mW.s/cm^2 or mJ/cm^2

I = UV intensity, mW/cm^2 & t = exposure time, s

- ❑ UV dose can be varied by varying either the intensity or the contact time

Germicidal Effectiveness of UV Radiation

- **UV light is physical rather than chemical disinfecting agent – penetrates the cell wall and is absorbed by nucleic acids, which either kills cells or prevents replication (RNA interference)**

Variables affecting performance:

- **Characteristics of UV disinfection system**
- **Overall system hydraulics**
- **Presence of particles**
- **Characteristics of the micro-organisms**
- **Chemical characteristics of the wastewater**

photoreactivation

- 1949: Kelner was the first to discover photoreactivation.
- He found that bacteria stored for some time after UV exposure were able to recover; however, the effect was quite variable. On further investigation, he found that exposure of bacteria, previously inactivated by UV light, to visible or near UV light greatly enhanced the ability of the bacteria to recover.

UV dose (fluence) at 254 nm required for 4-log (99.99%) inactivation of various bacteria

Bacterium	UV Dose (Fluence) (mJ cm ⁻²) for 4-log (99.99%) Inactivation	
	Without Photoreactivation	With Photoreactivation [‡]
<i>Aeromonas hydrophila</i>	5	NA
<i>Bacillus anthracis</i> spores [§]	>60	—
<i>Bacillus subtilis</i> spores	80	—
<i>Enterobacter cloacae</i>	10	33
<i>Enterocolitica faecium</i>	17	20
<i>Campylobacter jejuni</i>	4.6	NA
<i>Citrobacter diversus</i>	11.5	NA
<i>Clostridium perfringens</i>	23.5	NA
<i>Corynebacterium diphtheria</i>	6	NA
<i>Coxiella burnetii</i>	3	NA
<i>Escherichia coli</i> ATCC 11229	10	28
<i>Escherichia coli</i> O157:H7	6	25

UV dose (fluence) at 254 nm required for 4-log (99.99%) inactivation of various viruses

Virus	Classification	UV Dose (Fluence) (mJ cm ⁻²) for 4-log (99.99%) Inactivation	
		Without Photoreactivation	With Photoreactivation [†]
Adenovirus Type 40	dsDNA	124 [§]	—
Adenovirus Type 41	dsDNA	112 [§]	—
B40-8 phage		28	—
Coxsackievirus B5	ssRNA	36	—
Hepatitis A HM175	ssRNA	16	—
Hepatitis A	ssRNA	21	—
MS2 Bacteriophage	ssRNA	62	—
Poliovirus Type 1	ssRNA	27	—
PRD-1 phage		30	—
ΦX174 phage	ssDNA	10	—
Rotavirus SA11	dsRNA	36	—
S. aureus phage A994		38	—

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§ The USEPA has set a 4-log inactivation UV dose of 186 mJ/cm² as the virus limit

UV dose requirements, in mJ cm⁻² (USEPA 2006)

Microorganism	UV Dose for Log Inactivation							
	0.5	1	1.5	2.0	2.5	3.0	3.5	4.0
<i>Giardia</i>	1.6	2.5	3.9	5.8	8.5	12	15	22
<i>Cryptosporidium</i>	1.5	2.1	3.0	5.2	7.7	11	15	22
Viruses	39	58	79	100	121	143	163	186

categories for UV Disinfection Systems

- **Low-pressure low intensity**
- **Low-pressure high intensity**
- **Medium-pressure high intensity**

Mercury Vapor Lamp Operational Advantages

Low-pressure and Low-pressure High-output	Medium-pressure
• Higher germicidal efficiency; nearly all output at 254 nm • Smaller power draw per lamp (less reduction in dose if lamp fails) • Longer lamp life	• Higher power output • Fewer lamps for a given application

Closed Channel & Open Channel Reactors

Drinking Water



**WSSC Laurel, MD UV System
(120 mgd)**

Wastewater



**Racine, WI UV System
(100 mgd peak)**

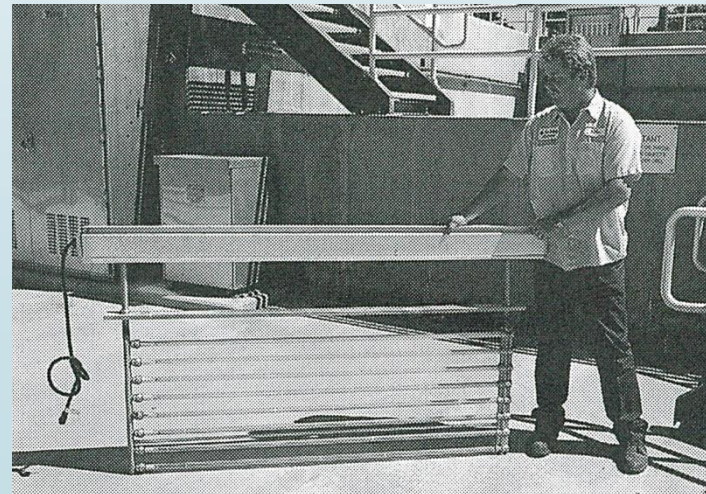
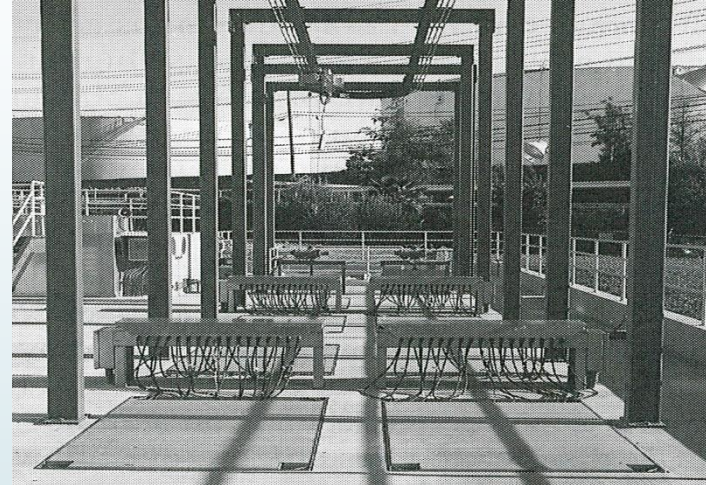
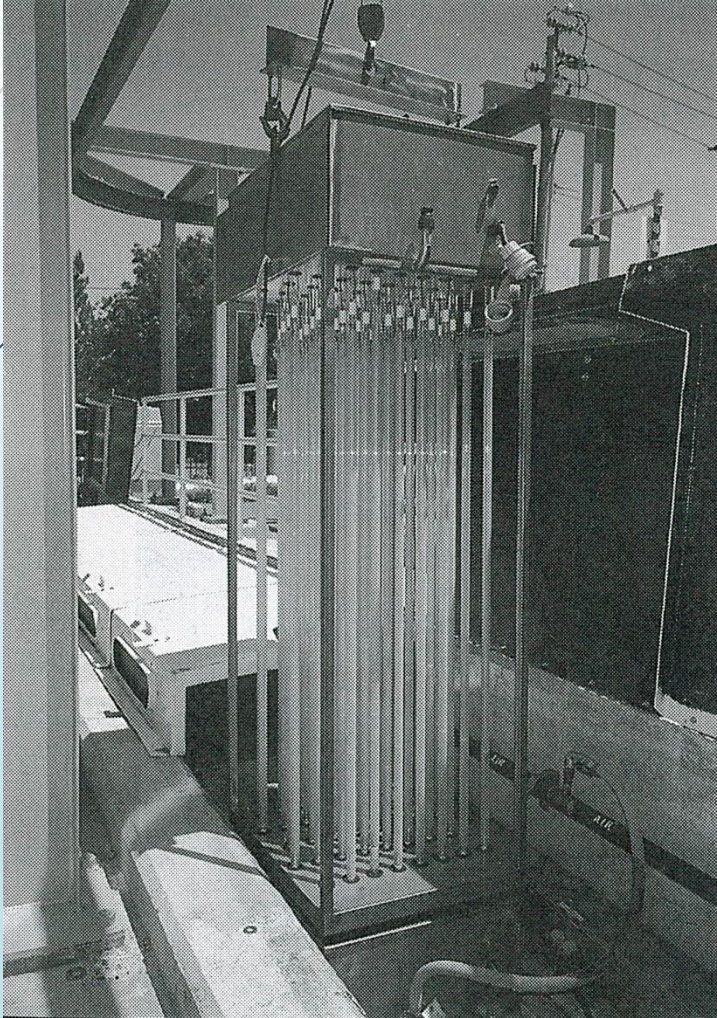
Upstream solids removal process has large impact on UV system sizing and cost

Increasing Filtration Cost

Upstream Solids Removal Process	Design UVT (%)	Design UV Dose (mJ/cm ²)
Granular Media	55	100
MF/UF membranes	65	80
RO	90	50

Increasing UV Cost

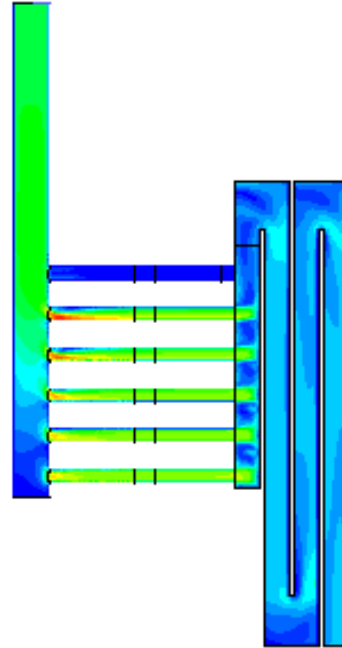
UV Open Channel Systems



Open-Channel Disinfection System

- ❑ Lamp placement : horizontal and parallel to flow (a)
- ❑ : vertical and perpendicular to flow (b)
- ❑ Flows equally divided into number of channels
- ❑ Each channel - two or more banks of UV lamps in series
- ❑ Each bank - number of modules (racks of UV lamps)
- ❑ Each module: number of UV lamps (2, 4, 8, 12 or 16)

UV Closed Systems



- ❑ Mostly flow perpendicular to UV lamp
- ❑ Mechanical wiping: clean quartz sleeves

Problems with UV Applications

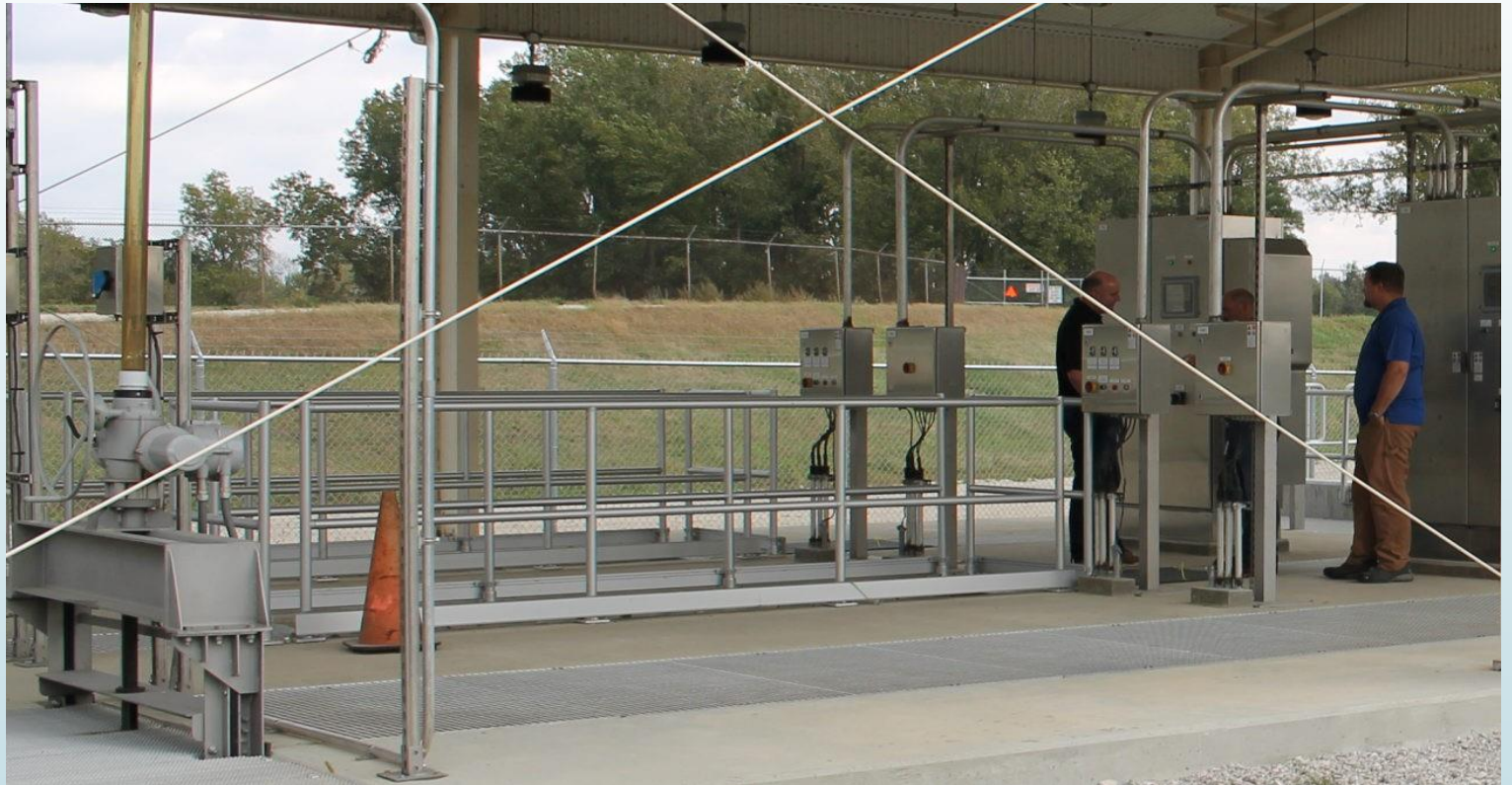
- **Inaccurate knowledge of the UV intensity.**
- **Exposure time associated with all of the pathogens passing through a UV disinfection system.**
- **Open channels – achieving a uniform velocity field in the approach and exit channel. Especially difficult is when UV is retrofitted into existing open channel (converted chlorine contact chambers).**

Typical Mercury Vapor Lamp Characteristics

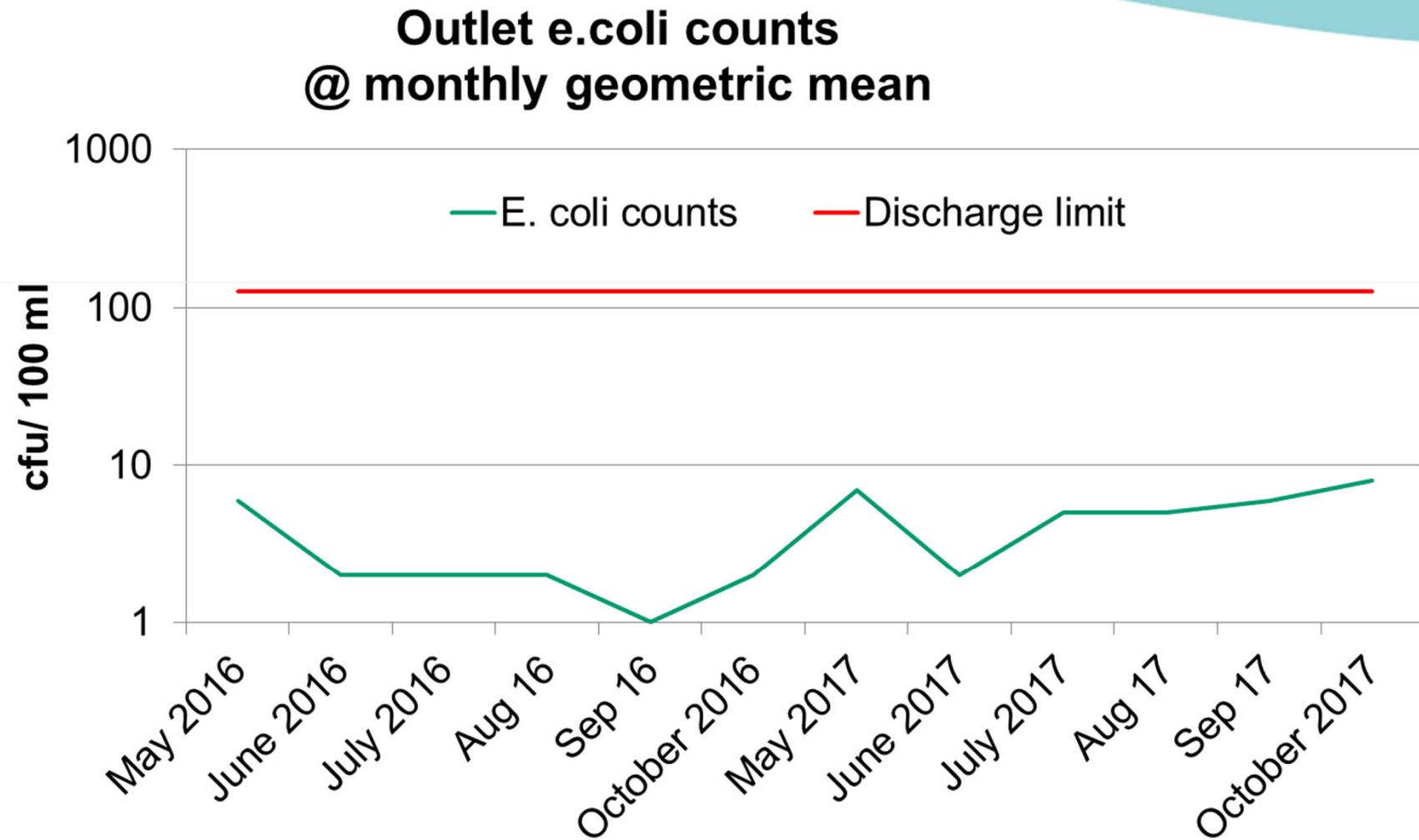
Parameter	Low-pressure	Low-pressure High-output	Medium-pressure
Germicidal UV Light	Monochromatic at 254 nm	Monochromatic at 254 nm	Polychromatic, including germicidal range (200 – 300 nm)
Mercury Vapor Pressure (Pa)	Approximately 0.93 (1.35×10^{-4} psi)	0.18 – 1.6 (2.6×10^{-5} – 2.3×10^{-4} psi)	40,000 – 4,000,000 (5.80 – 580 psi)
Operating Temperature (°C)	Approximately 40	60 – 100	600 – 900
Electrical Input [watts per centimeter (W/cm)]	0.5	1.5 – 10	50 – 250
Germicidal UV Output (W/cm)	0.2	0.5 – 3.5	5 – 30
Electrical to Germicidal UV Conversion Efficiency (%)	35 – 38	30 – 35	10 – 20
Arc Length (cm)	10 – 150	10 – 150	5 – 120
Relative Number of Lamps Needed for a Given Dose	High	Intermediate	Low
Lifetime [hour (hr)]	8,000 – 10,000	8,000 – 12,000	4,000 – 8,000

Performance Evaluation

- Wedeco Duron UV System
- 2 channels
- 3 banks each
- 12 lamps/ bank



Performance Evaluation



Components of UV Disinfection System

1. UV lamps
2. Quartz sleeves: to house and protect lamp
3. supporting structures for lamps and sleeves
4. Ballasts to supply regulated power to UV lamps
5. Power supply
6. Sleeve wiper – to clean the deposit from sleeves

Dose-monitoring Approaches – Key Characteristics

Dose-monitoring Strategy	Parameter Used as the Operational Setpoint	Parameters Monitored During Operations to Confirm Dose Delivery
UV Intensity Setpoint Approach	UV Intensity	Flow rate Lamp status UV intensity
Calculated Dose Approach	Calculated or Validated dose ¹	Flow rate Lamp status UV intensity UVT

¹ As noted in Section 3.4.1, the calculated dose is estimated using a dose-monitoring equation. For the Calculated Dose Approach, the validated dose is equal to the calculated dose divided by a Validation Factor, which accounts for biases and experimental uncertainty.

UV system maintenance comparing to Chlorination system

For Chlorination system

- Unloading Sodium hypochlorite and Sodium bisulfite
- Adjusting pump speeds
- Collecting and analyzing samples in order to adjust dosage of both hypo and bisulfite
- Repairing diaphragms in pumps
- Fixing air lock issues in pumps
- Fixing air lock issues in feed lines
- Fixing issues in winter with lines freezing
- Repairing/ replacing bisulfite pumps

Recommended operations and maintenance tasks

For UV system

Equipment	Frequency	Task
UV reactors	Daily	• Perform overall visual inspection of the UV reactors. • Confirm that system is on automatic mode (if applicable). • Check control panel display for status of system components and alarm status and history. • Review 24-hour monitoring data to confirm that the reactor has been operating within validated limits during that period.
	Monthly	• Check reactor housing, sleeves, and wiper seals for leaks and replace any damaged components.
UV lamps	Monthly	• Check lamp run-time values. Consider changing lamps if operating hours exceed design life.
	Bimonthly	• Check intensity of UV lamps. If UV sensors monitor more than one lamp, verify that the lamp with the lowest intensity value is closest to the UV sensor by replacing the lamp closest to the UV sensor with one-fourth of the lamps in each row/bank (minimum of three). Place the lowest intensity lamp next to UV sensor.
	Quarterly (LP and LPHO lamps)	
	Lamp/manufacture specific	• Replace lamps when any one of the following occurs: – Initiation of low UV intensity or low validated UV dose alarm (UV intensity or validated UV dose equal to or less than setpoint value) after verifying that this condition is caused by low lamp output. – Initiation of lamp failure alarm after verifying it is not a nuisance alarm.

Recommended operations and maintenance tasks

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For UV system

	When lamps are replaced	• Send spent lamps to a mercury recycling facility or back to the manufacturer.
Ballasts	Daily	• Verify that ballast cooling fans are operational and that ballasts are not overheated.
	Semi-annually	• Check ballast cooling fans for unusual noise.
	Manufacturer's recommended frequency	• Check the ballast cooling fans for dust buildup and damage. Replace if necessary. Replace air filters (if applicable).
UV lamp sleeves	Sleeve/manufacturer specific	• Replace sleeve when damage, cracks, or irreversible fouling significantly decreases UV intensity of an otherwise acceptable lamp to the minimum validated intensity (or UV dose) level. Inspect sleeves per the cleaning system inspection frequency below for damage and cracks. Adjust the replacement frequency based on operational experience.

Please visit the below links for full articles, Handbooks related to this session

<https://www.cedengineering.com/userfiles/UV%20Disinfection%20Options%20for%20WTP-R1.pdf>

<https://www.cedengineering.com/userfiles/UV%20Disinfection%20Systems%20for%20Drinking%20Water%20-%20Overview-R1.pdf>

<https://www.cedengineering.com/userfiles/UV%20Disinfection%20Systems%20for%20Drinking%20Water%20Planning%20and%20Design-R1.pdf>

http://pha.poli.usp.br/LeArq.aspx?id_arq=1120

Thanks for listening

