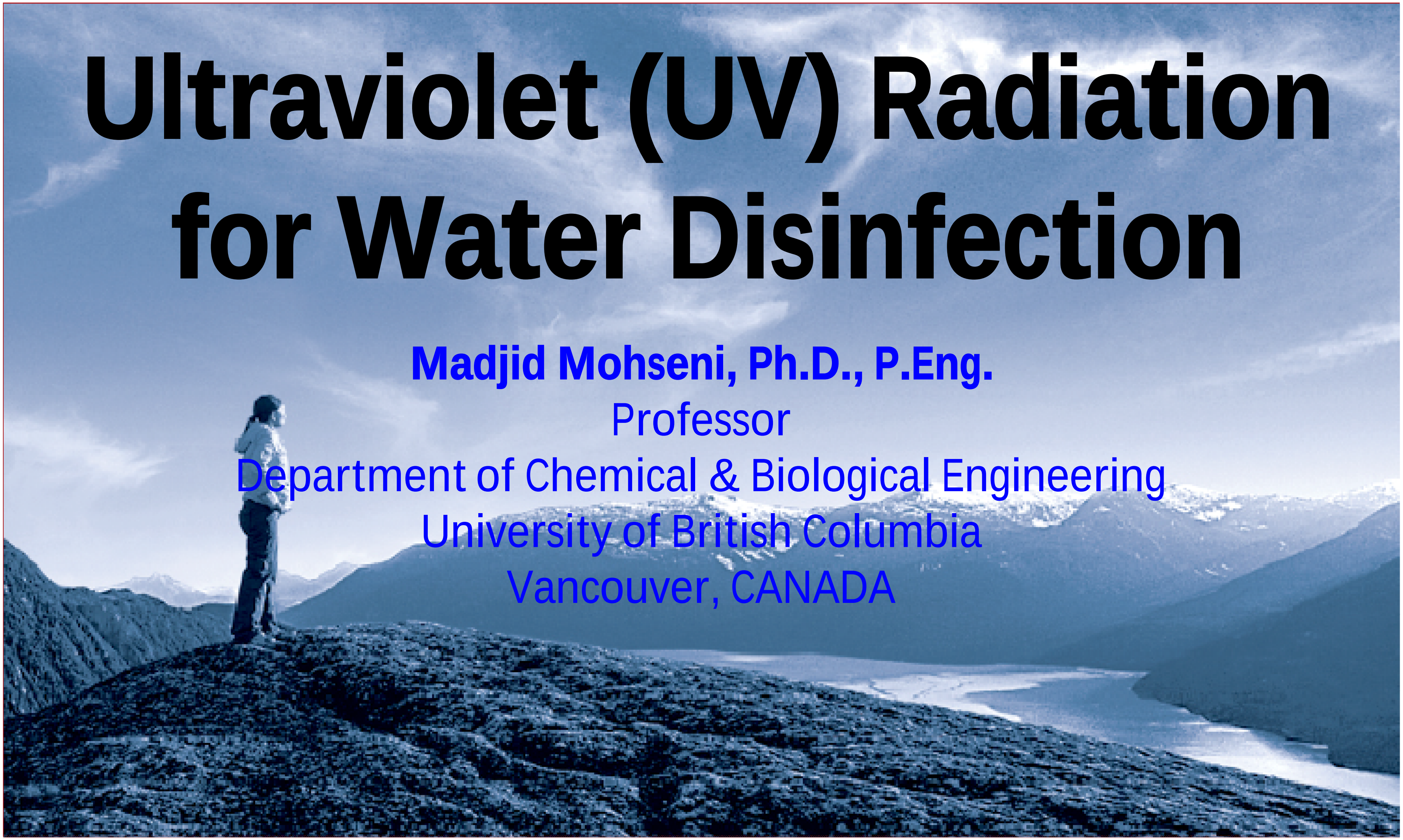

Ultraviolet (UV) Radiation for Water Disinfection

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UBC a place of mind THE UNIVERSITY OF BRITISH COLUMBIA

OSMAHAB Workshop
Dec. 11 & 12, 2011

UV Disinfection

An emerging technology

IS IT REALLY NEW?

Discovery of Ultraviolet (UV)

1801 Ultraviolet radiation was discovered by Johann Wilhelm Ritter, a German electro-chemist

1878 Microbial inactivation with UV from the sun was discovered by Downes & Blunt

1901 Invention of the mercury arc by Cooper-Hewitt

1906 Invention of first intensive UV source

UV Disinfection

- **1910** First full scale UV disinfection system for pre-filtered water from the river Durance (Marseille, France)
- **1916** First full-scale application of UV in the US (Henderson, Kentucky)
- **1940s** With the invention of neon tubes, low pressure Hg lamps became available for UV disinfection
- **1970s** Discovery of DBPs from chemical disinfection, supported and promoted UV disinfection
- **1982** First large scale UV disinfection system in Canada (Tillsonburg, ON)
- **1998** Low UV dose was found effective for the inactivation of *Crypto* and *Giardia*

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UV Disinfection in Canada

1965 Ontario Water Resource Commission evaluated germicidal performance of UV on Humber River

1975 Canada Centre for Inland Waters evaluated UV disinfection as viable alternative

1979 Train derailment in Mississauga and major Cl_2 release increased impetus for alternative disinfectants

1999 More than 100 UV disinfection plants in operation in the province of Ontario

UV Disinfection

Presently

More than 10000 drinking water facilities use UV based disinfection

UV Disinfection Standards and Regulations

1989 The EPA Surface Water Treatment Rule (SWTR) did not indicate UV as Best Available Technology (BAT) for the inactivation of *Giardia*

2000 EPA started evaluating UV as a BAT for surface water disinfection

2006 EPA released the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR)

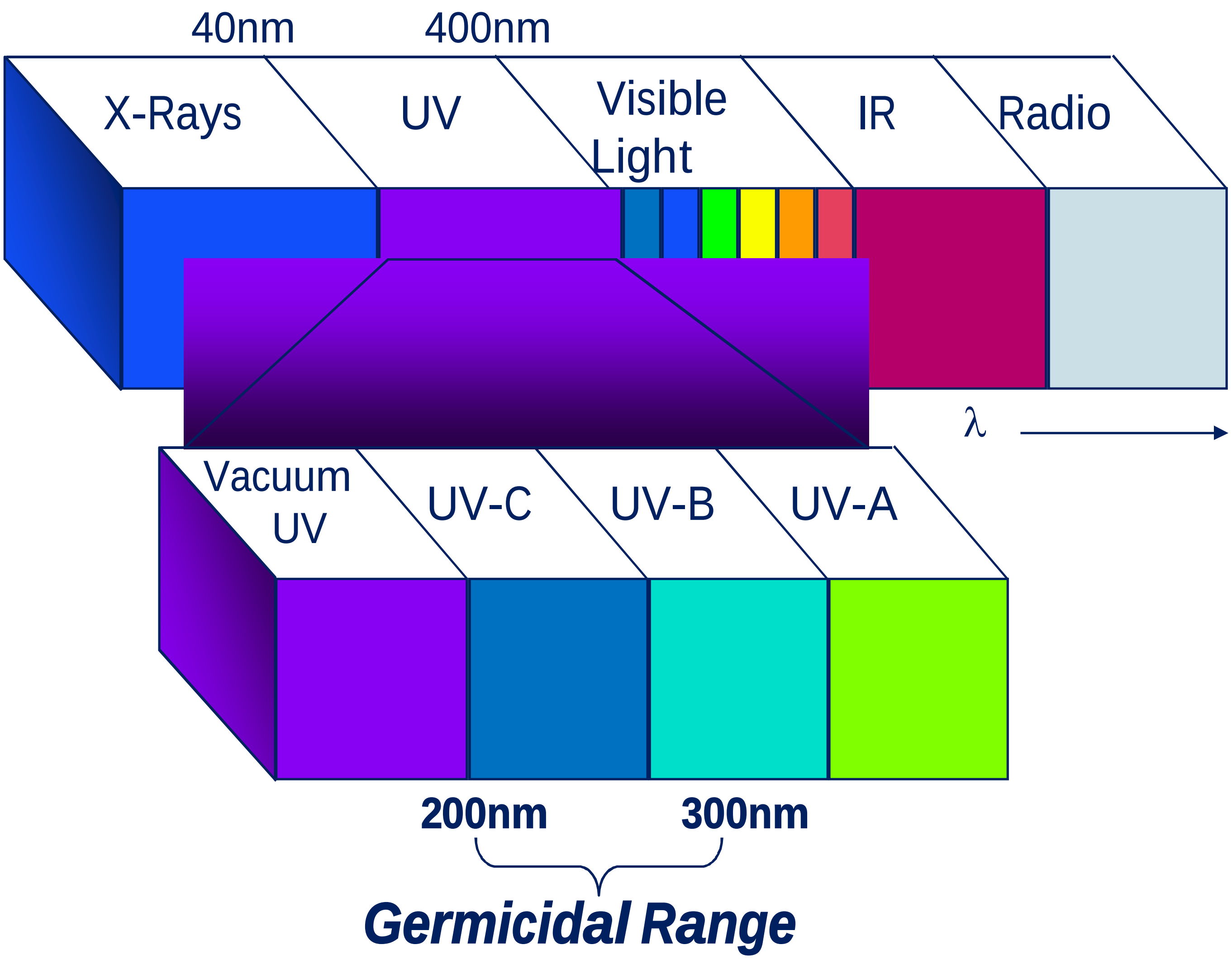
How does UV work

and

What does affect its

performance?

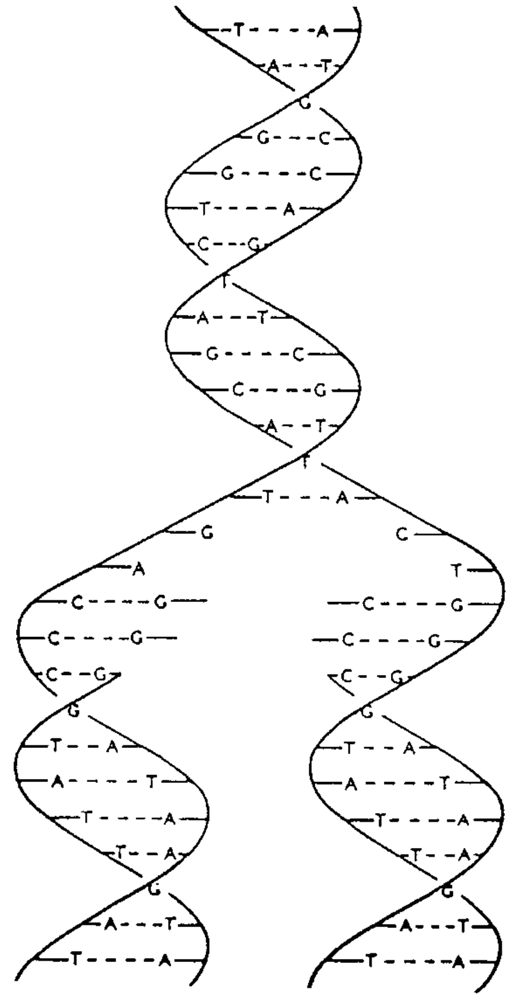
Electromagnetic Spectrum



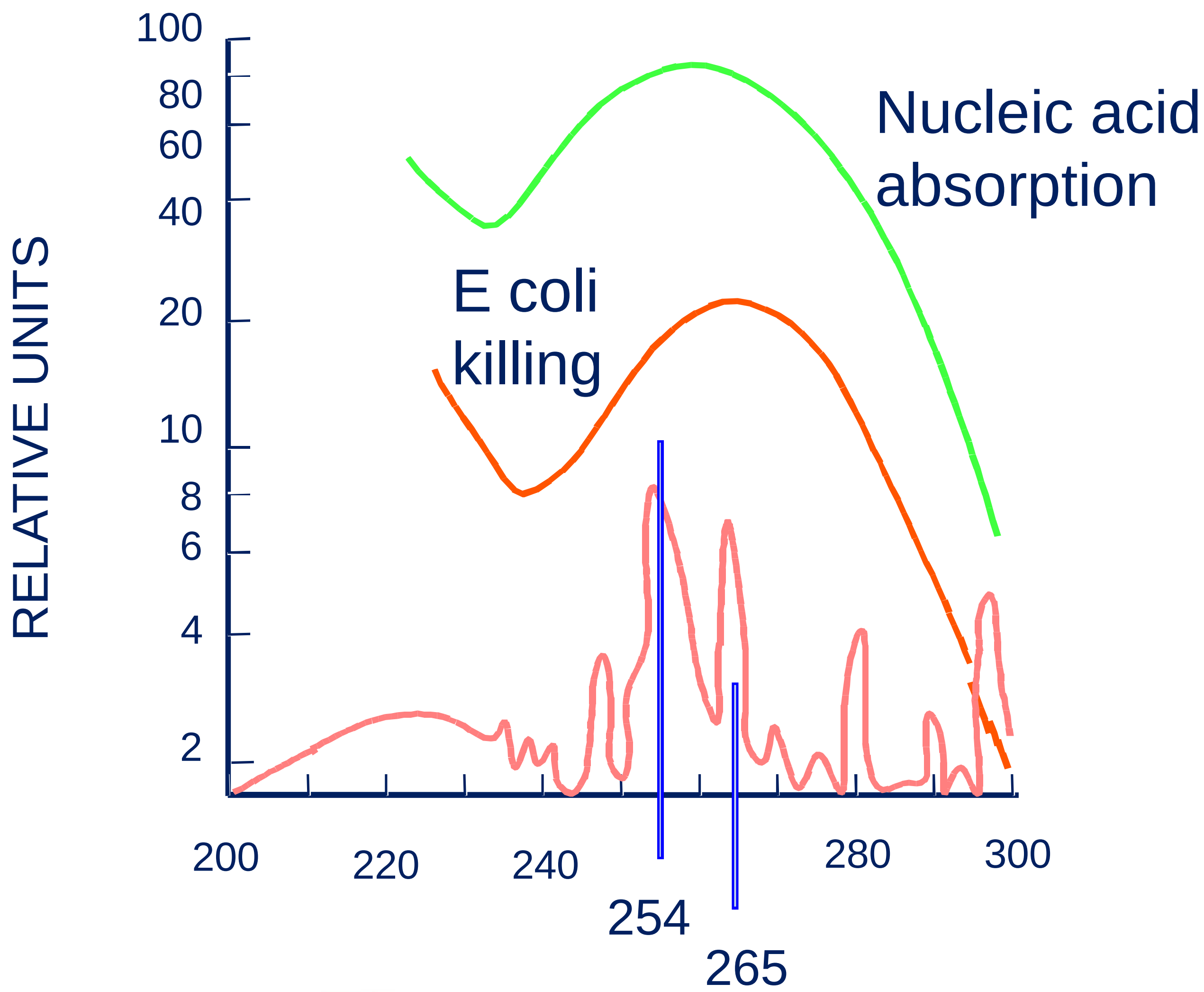
DNA Structure and Replication

Parental DNA strands

Daughter DNA strands

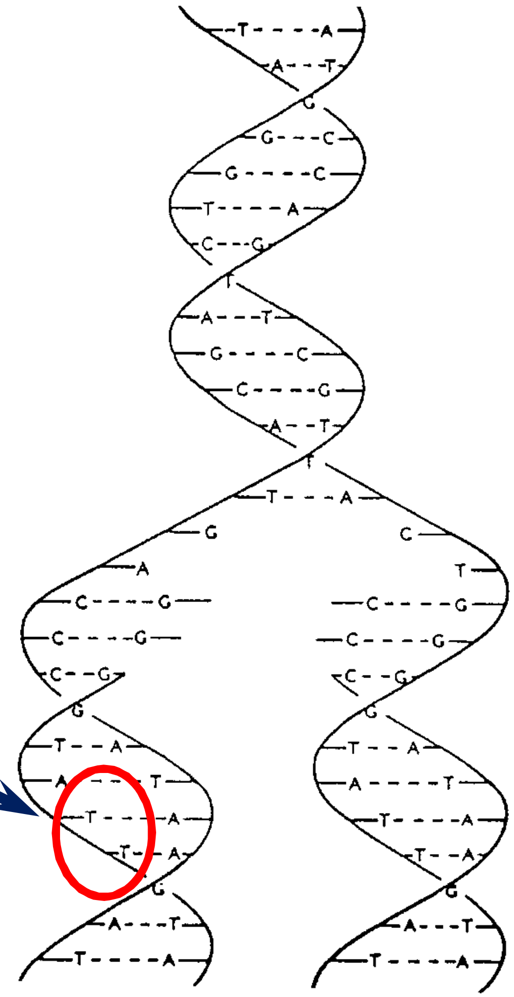


Spectral Output of UV



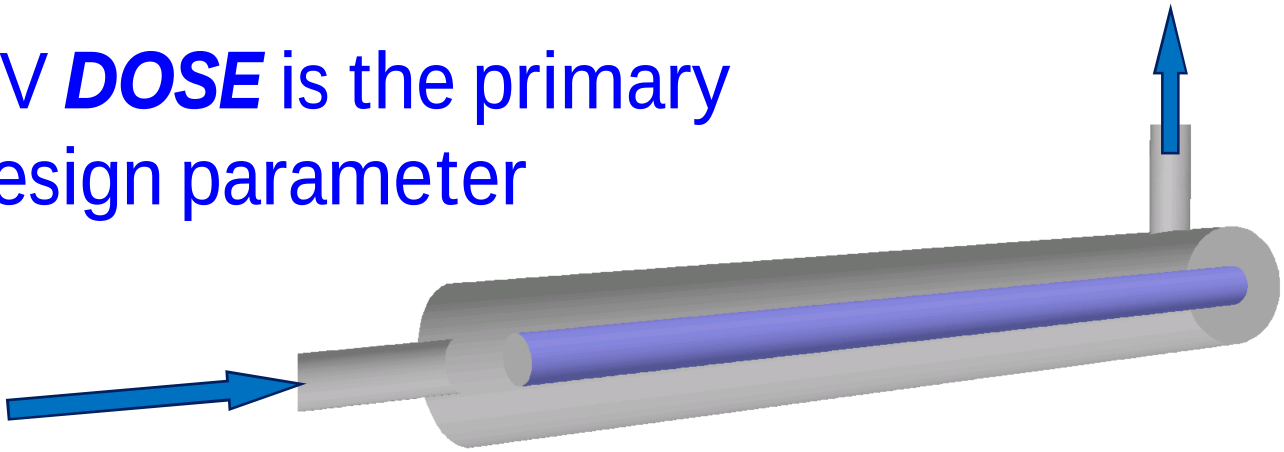
UV Damage to DNA

Dimerization of Thymine nucleotides



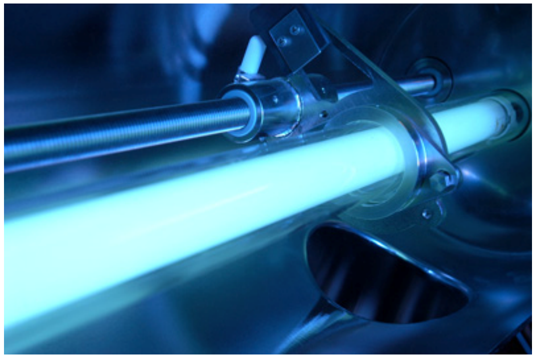
UV Disinfection

UV ***DOSE*** is the primary design parameter

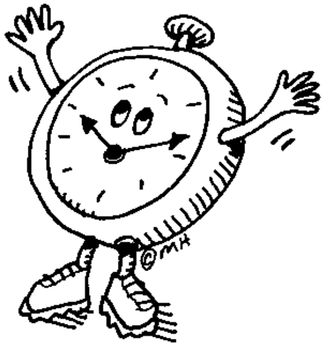


UV ***DOSE*** is a product of Intensity and retention time

Intensity x Retention time = DOSE

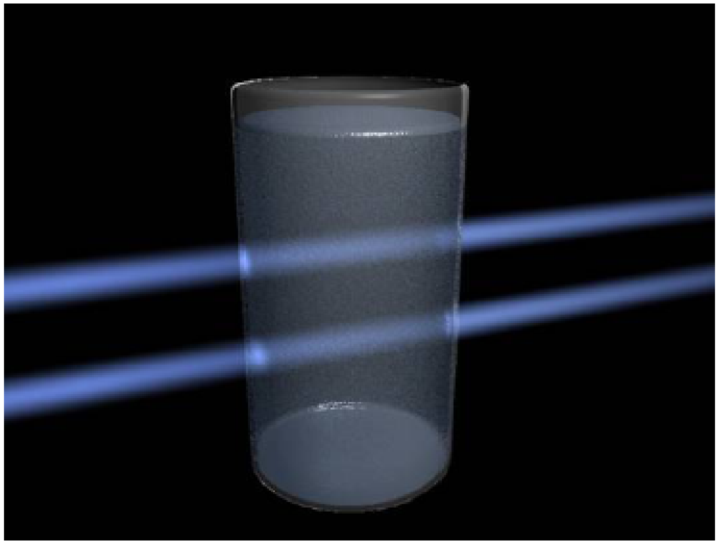


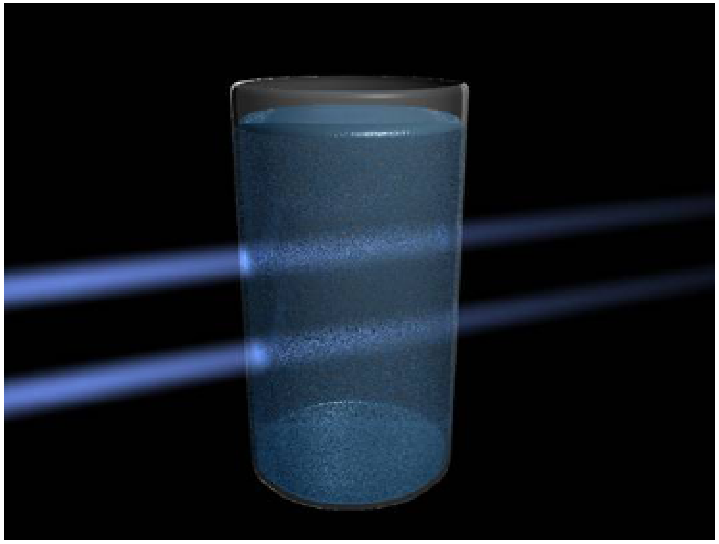
Courtesy of Aquionics ***(www.aquionics.com)***



UV Dose Influencing Factor

Water Clarity
UVT

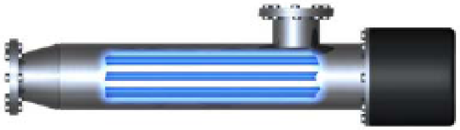




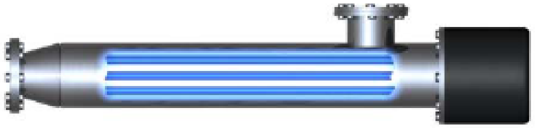
High UVT = High Dose

Low UVT = Low Dose

Flow Rate



Fast Flow = Low Dose



Slow Flow = High Dose

Key Factors in UV Disinfection

- UV lamp type
- Water quality
- Target organisms
- Reactor geometry and configuration

All are important parameters in determining and obtaining the required

MINIMUM UV DOSE

Key Factors in UV Disinfection

- UV lamp type
- Water quality
- Target organisms
- Reactor geometry and configuration

Key Factors in UV Disinfection

Three most common lamp technologies used in water disinfection are:

- Low pressure (LP)
- Low pressure high output (LPHO)
- Medium pressure (MP)

Other UV lamps:

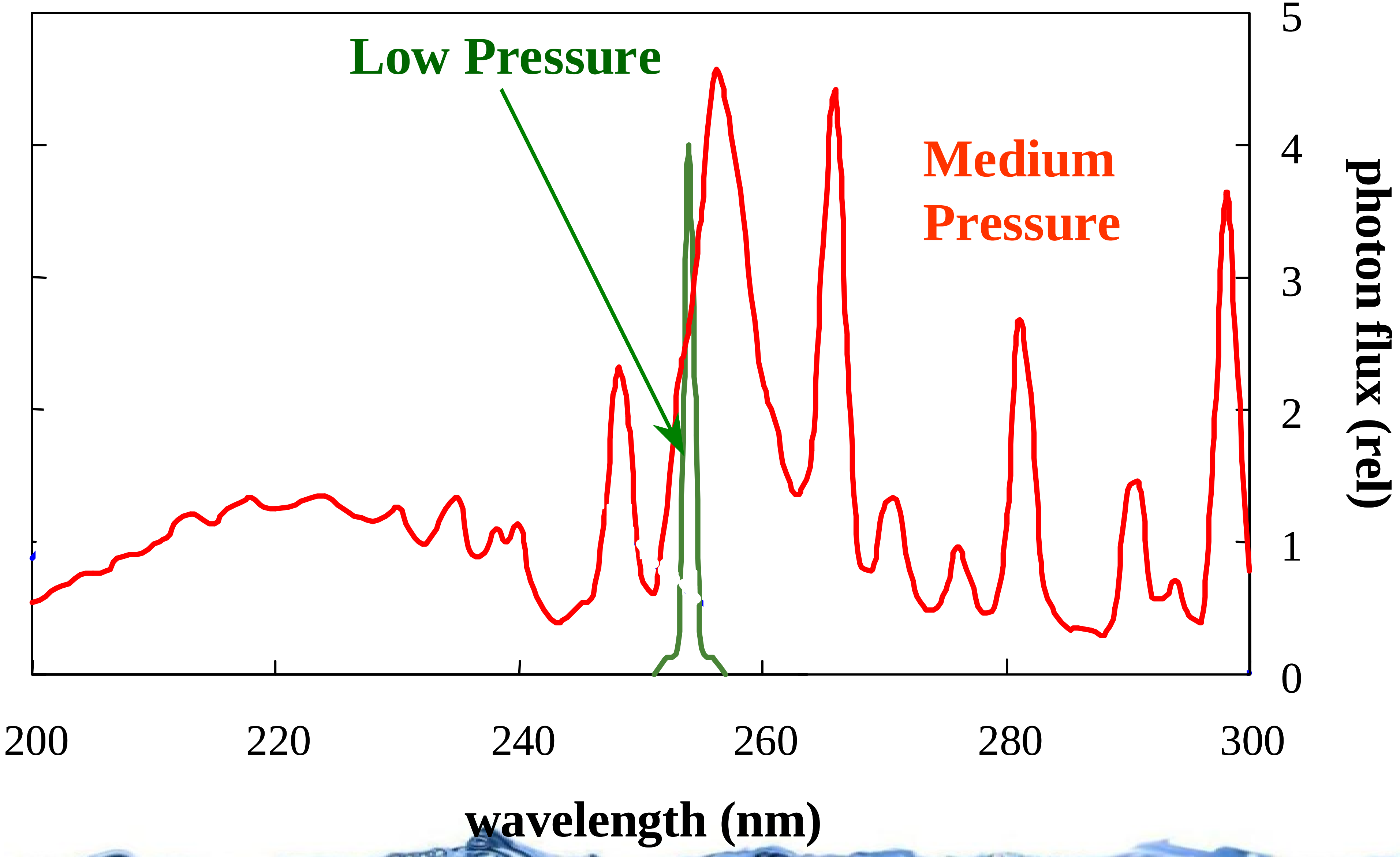
- Electrode less mercury vapor lamp
- LED lamp
- UV lasers
- Pulsed UV

Mercury Vapor UV Lamps

- Emit UV in the germicidal wavelength ranges
- UV is generated by applying a voltage across a gas mixture containing mercury vapor

Vapor pressure	**Temperature**	**UV**
Low (<1 torr)	Moderate (40°C)	Monochromatic (253.7 nm)
High (>300 torr)	High (600-900 °C)	Polychromatic

Mercury Vapour Lamps



Mercury Vapor UV Lamps

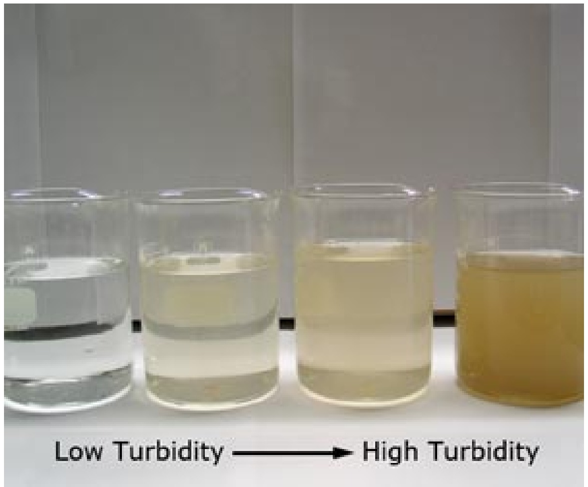
Parameter	LP	LPHO	MP
Germicidal UV	253.7 (nm)	253.7 (nm)	Polychro-matic
Electrical input (W/cm)	0.5	1.5-10	50-250
Efficiency (%)	35-38	30-40	10-20
No. lamps required	High	Intermediate	Low
Complexity	Low	Moderate	Moderate

Source: *EPA's UV Disinfection Guidance Manual*

Key Factors in UV Disinfection

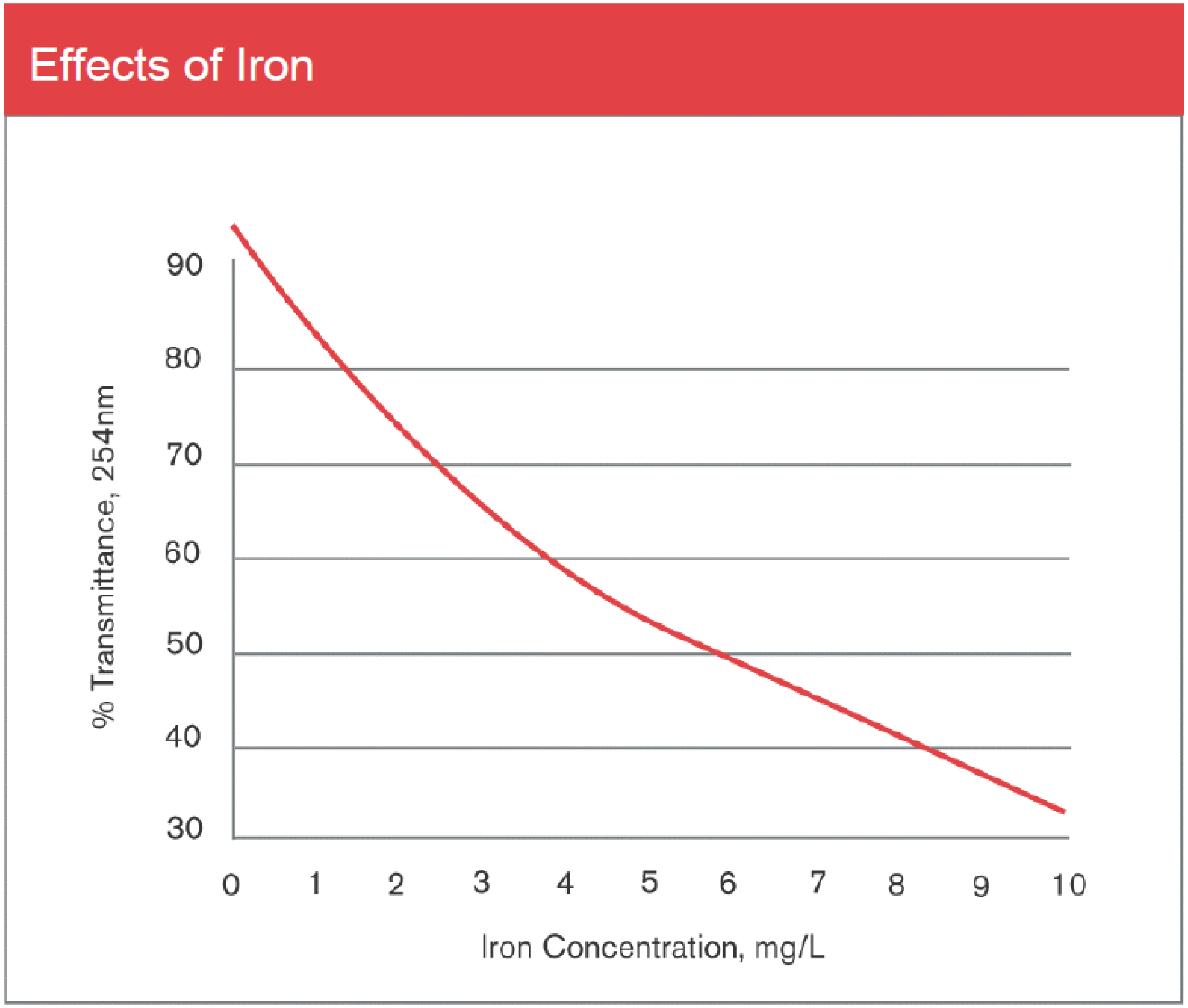
- UV lamp type
- Water quality
- Target organisms
- Reactor geometry and configuration

Water Quality Parameters



- Solids and suspended particles (turbidity and TSS)
- Dissolved organics and inorganic matters (TOC, NOM, iron, Ca, sulfites)
  - block or attenuate UV
  - cause fouling of the quartz and/or UV sensor
- Temperature

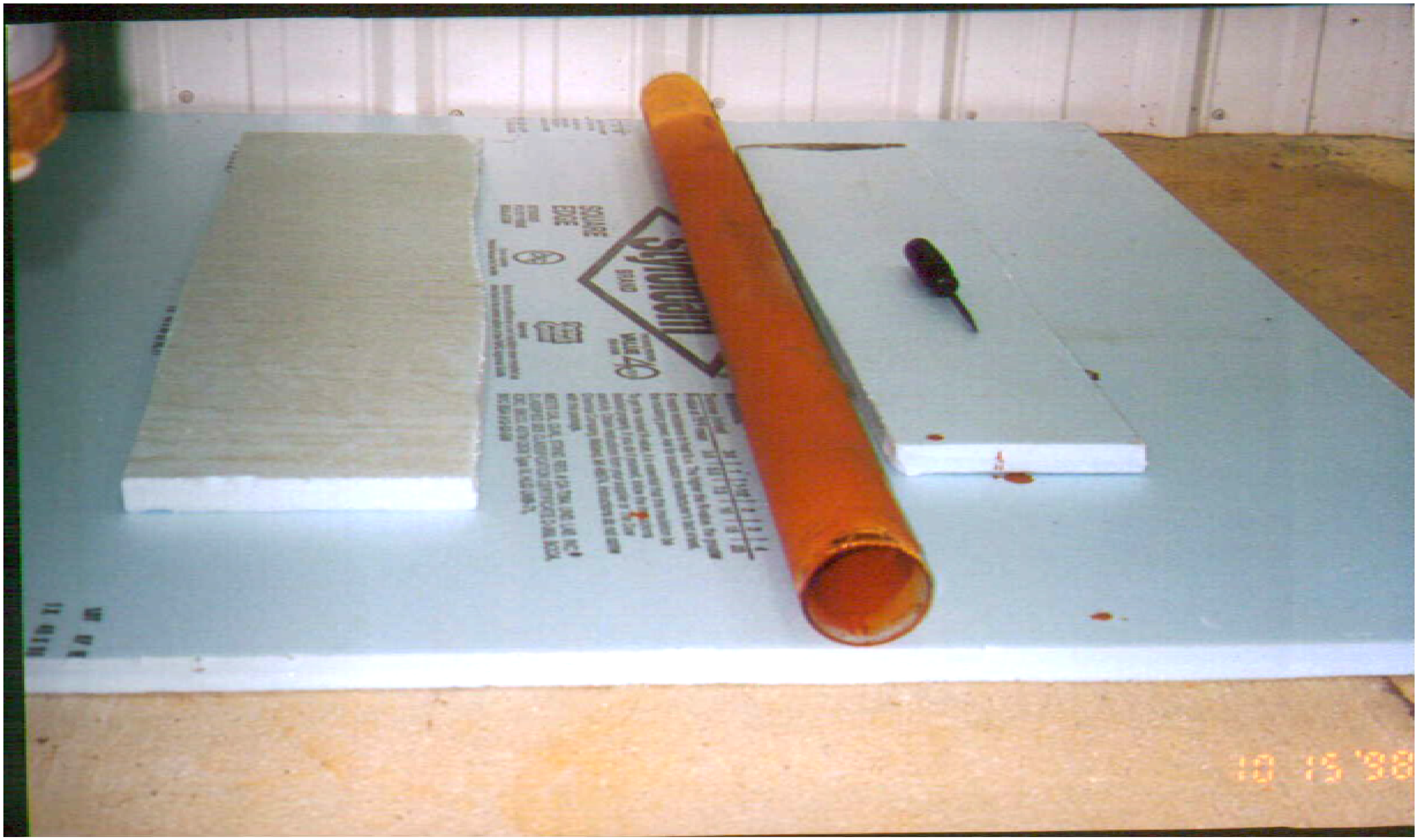
Effect of Iron



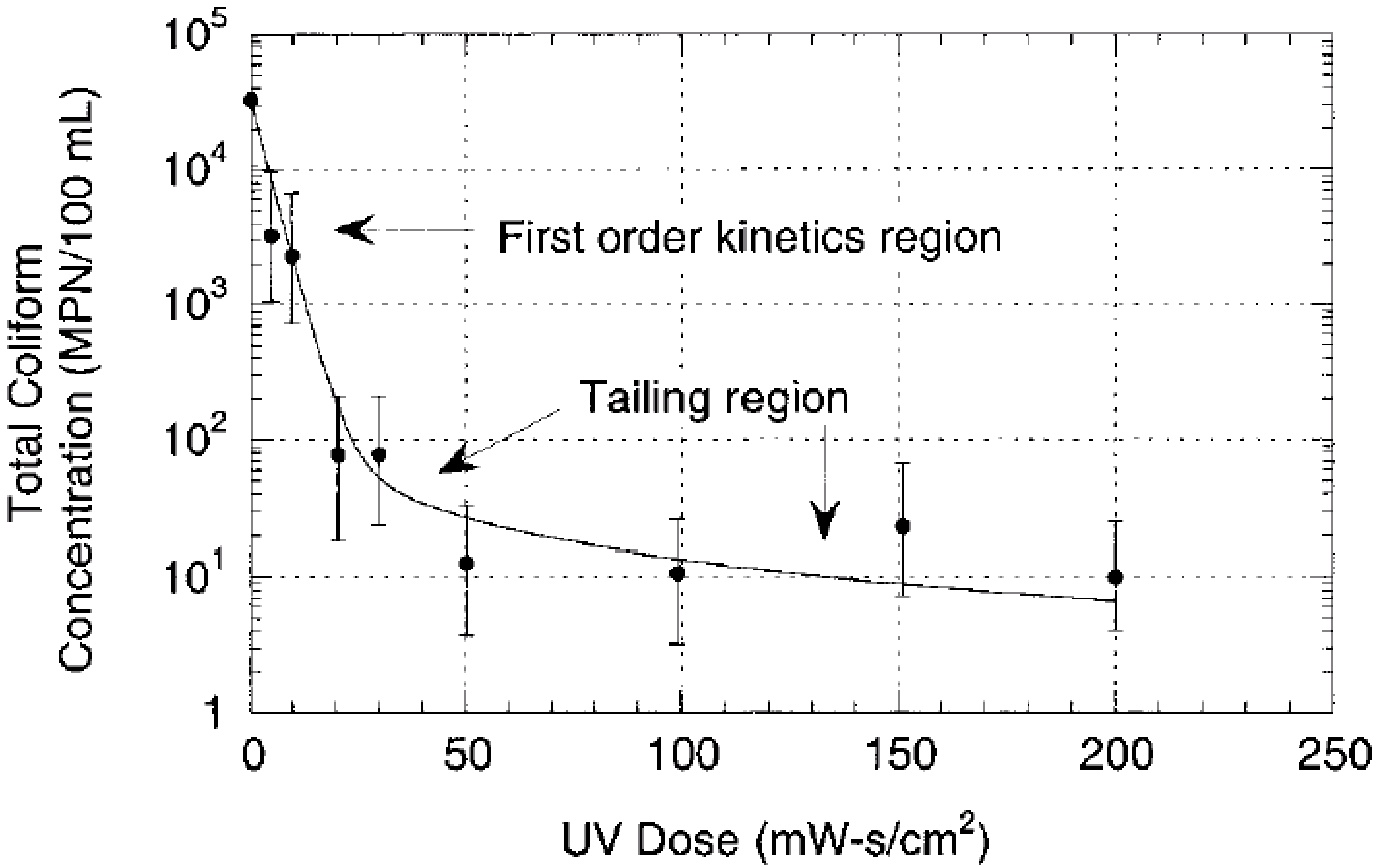
Iron reduces the transmittance of the water

But, more importantly, Iron along with hardness cause fouling of the quartz sleeves

UV Quartz Sleeve Fouling



Effect of Particles



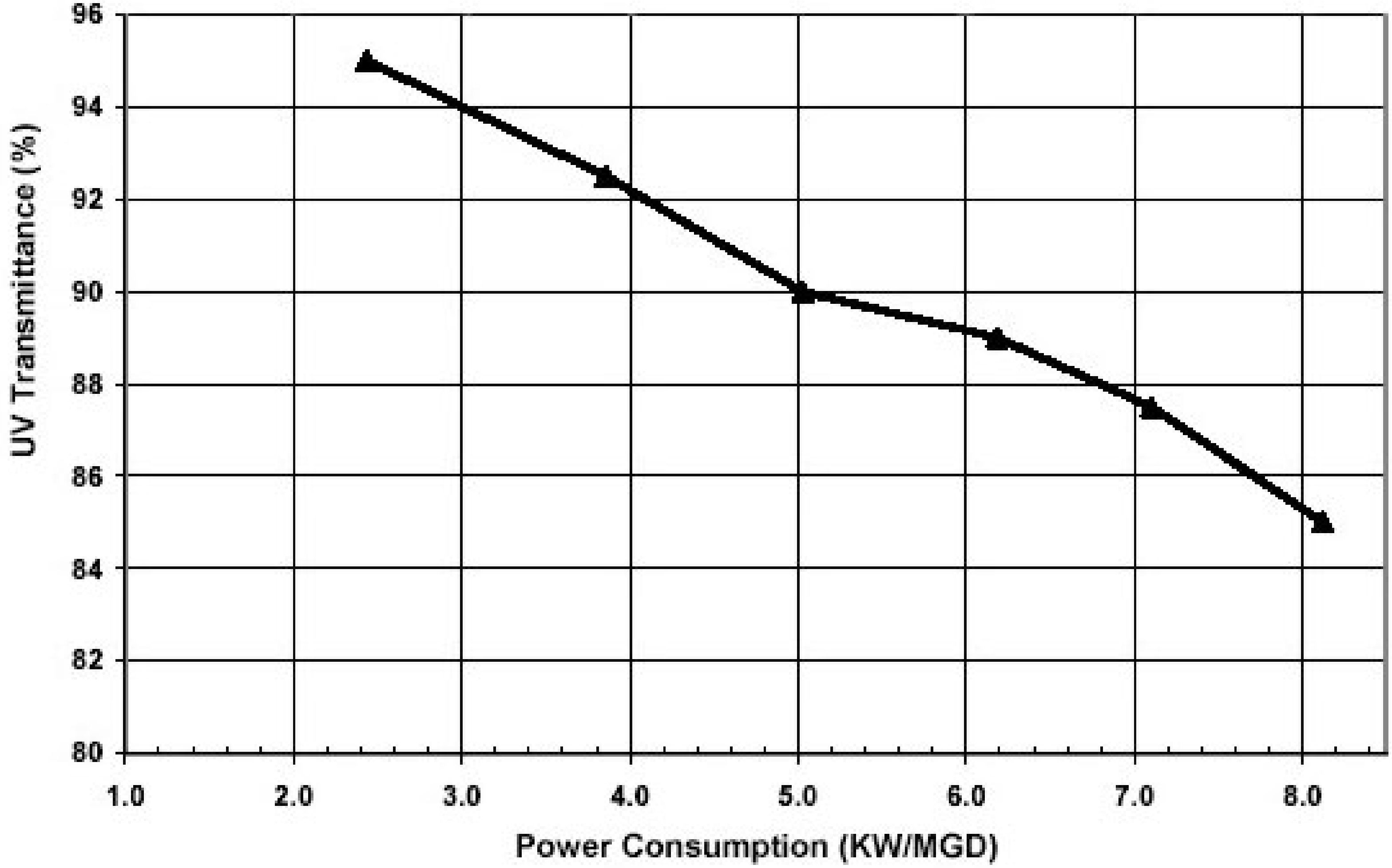
Typical response of Coliform bacteria to UV in wastewater (containing suspended solids)

UV Transmittance

Water	Typical UVT
Unfiltered surface water	70% - 95%
Filtered surface water	75% - 95%
Groundwater	80% - 95%
Membrane treated water	> 95%

- A 5% reduction in UVT translates in nearly doubling the UV reactor size (to maintain the same dose)
- Turbidity of < 5 NTU and TSS of < 10 ppm recommended
- For UVTs less than 85-90%, pretreatment is recommended

Effect of UVT on MPUV Power Consumption



Estimates are based on end of lamp life and include a 20% safety factor

Source: UV Shadow Force Research Laboratory, UNH

Key Factors in UV Disinfection

- UV lamp type
- Water quality
- Target organisms
- Reactor geometry and configuration

Target Organisms

UV germicidal efficiency for different organisms varies based on:

- Content of cytosine relative to thymine in the DNA
  - Quantum yield for thymine dimer formation is different from that of cytosine dimer formation
  - Thymine and cytosine have different absorbance spectra
- Specific characteristics of the DNA repair system
  - Viruses and bacteria have different repair mechanisms

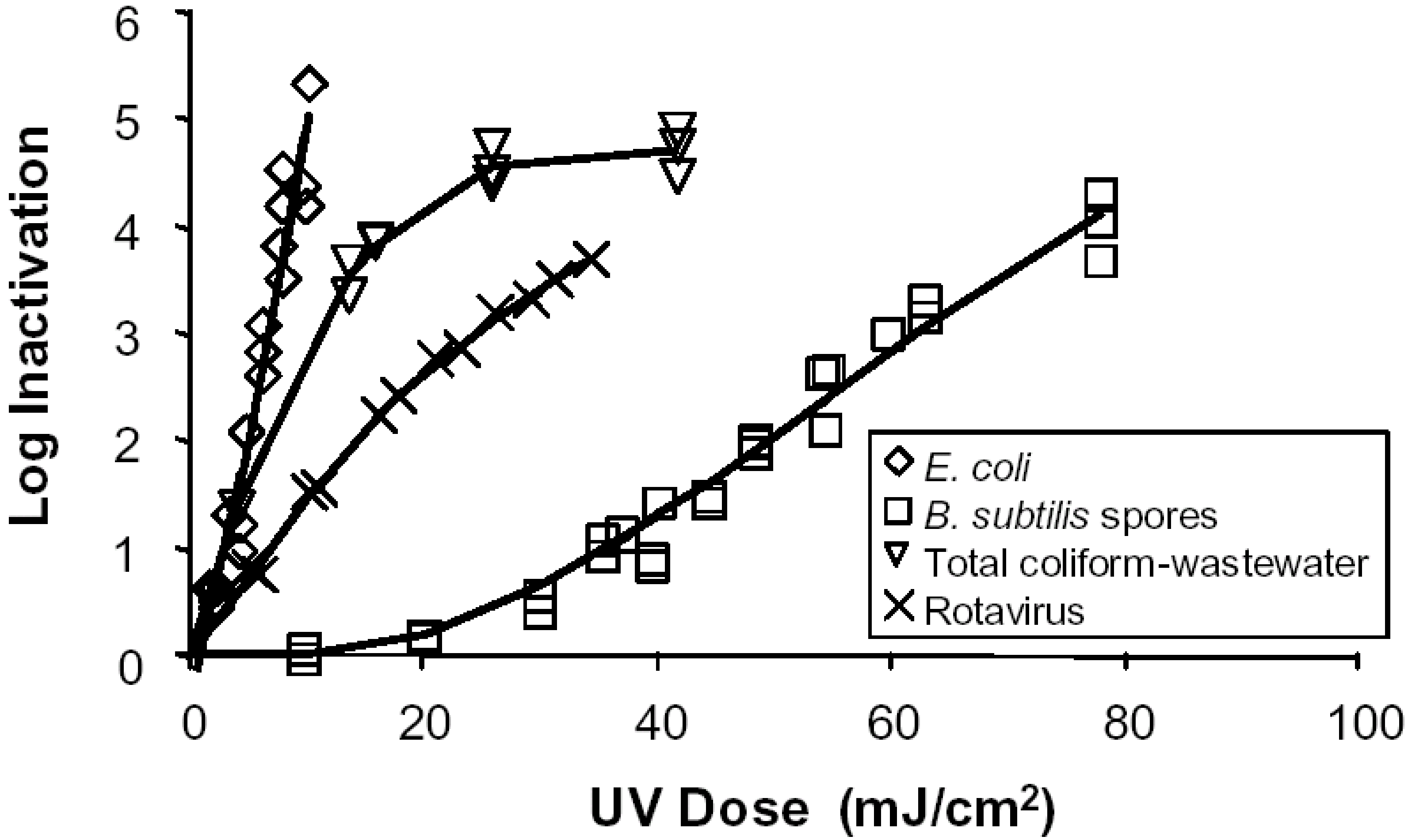
Responses of Different Organisms to UV

Least resistant to UV

Most resistant to UV

Cysts & Oocysts < Bacteria < Viruses < Spores

Effect of Organisms



Source: *Chang et al. 1985*

UV Efficacy - Bacteria

UV doses (mJ/cm^2) for 4-log inactivation

E. coli	8
HPC	11
Total coliform	15
V. chloera	3
S. typhi	7
L. pneumophila	9

UV Inactivation of Various Pathogens

Pathogen	Average UV Dose mJ/cm² Required to Inactivate			
	1LOG	2LOG	3LOG	4LOG
Cryptosporidium paravum oocysts	3.0	4.9	6.4	7.9
Giardia lamblia cysts	NA	<5	<10	<10
Giardia mun's cysts	1.2	4.7	NA	NA
Vibrio cholerae	0.8	1.4	2.2	2.9
Shigella dysenteriae	0.5	1.2	2.0	3.0
Escherichia coli 0157:H7	1.5	2.8	4.1	5.6
Salmonella typhi	1.8 – 2 .7	4.1 - 4.8	5.5 - 6.4	7.1 - 8.2
Shigella sonnei	3.2	4.9	6.5	8.2
Salmonella enteritdis	5	7	9	10
Hepatitis A virus	4.1 - 5.5	8.2 - 14	12 - 22	16 - 30
Poliovirius Type 1	4-6	8.7 - 14	14 - 23	21 - 30
Coxsackie B5 virus	6.9	14	22	30
Rotavirus SA 11	7.1-9.1	15-19	23 - 26	31 - 36

NA – data not available

Key Factors in UV Disinfection

- UV lamp type
- Water quality
- Target organisms
- Reactor geometry and configuration

Reactor Configuration

- UV reactors are designed to optimize dose delivery
- Reactor configuration and hydrodynamics play important roles in design
  - Lamp placements
  - Inlet and outlet configurations
  - Baffles
  - Upstream flow conditions
  - mixers

Inactivation Kinetics

$$\frac{dN}{dt} = -kIN \quad \rightarrow \quad \frac{N}{N_0} = e^{-k\,I\,t_R} = e^{-k\,D_{(avg)}}$$

- Ideal: completely mixed reactor

$$D_{(avg)} = I_{(avg)} \times t_R$$

UV Dose = (UV Intensity) x (Exposure Time)

$[J/M^2]$ = $[W/m^2]$ $[s]$

Is Average Dose meaningful?

$$\frac{N}{N_0} = e^{-k\,I\,t_R} \qquad I(x, y, z, UVT, \ldots) \quad t_R(u, v, w, \ldots)$$

- Real flow through reactor: Dose distribution
  - non-uniform intensity field
  - turbulent flow field

Inactivation Kinetic: Real Reactor

Overall reactor survival:

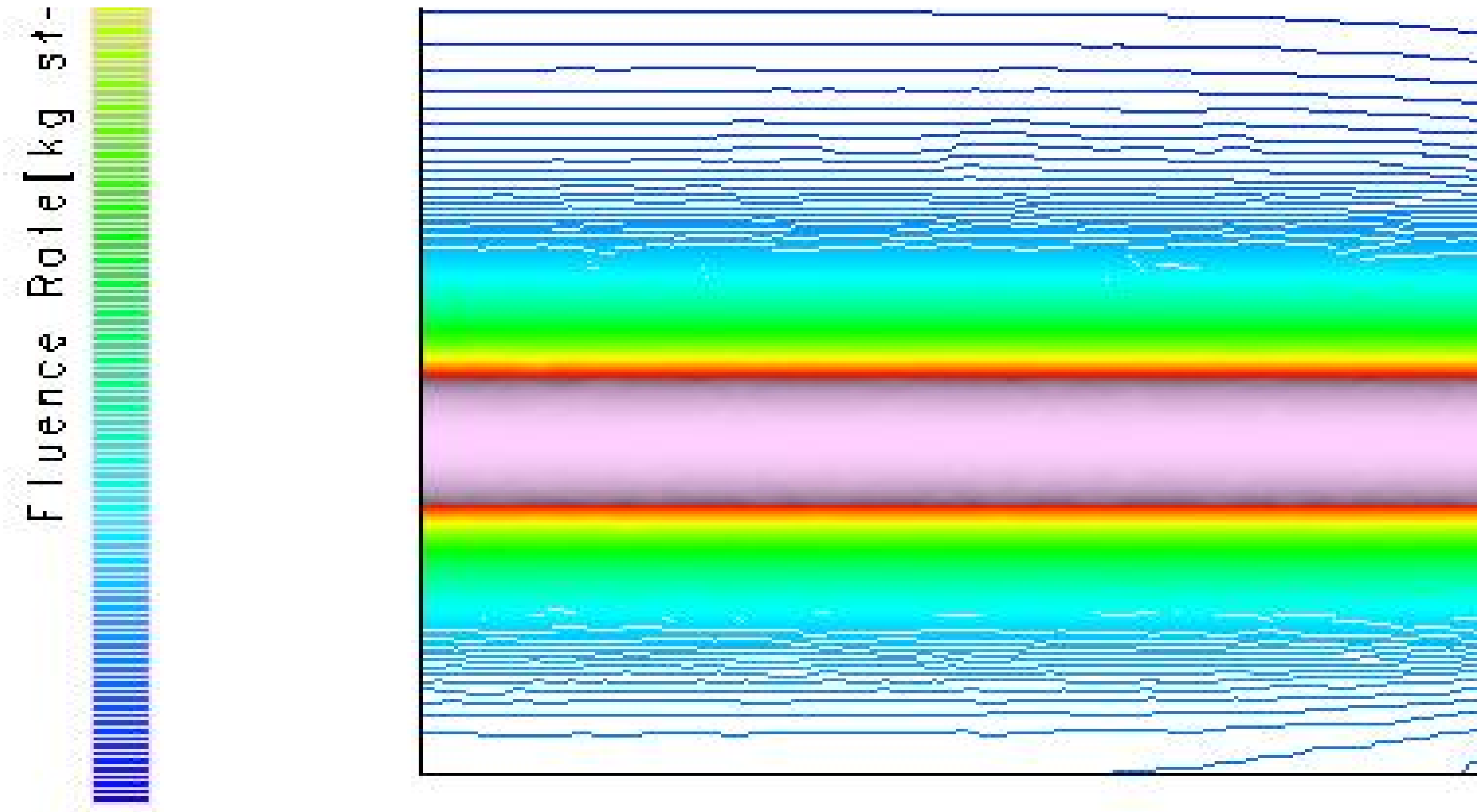
$$\frac{N}{N_0} = \sum_i f_i \times e^{-k\,D_i}$$

Survival population subject to particular dosages:

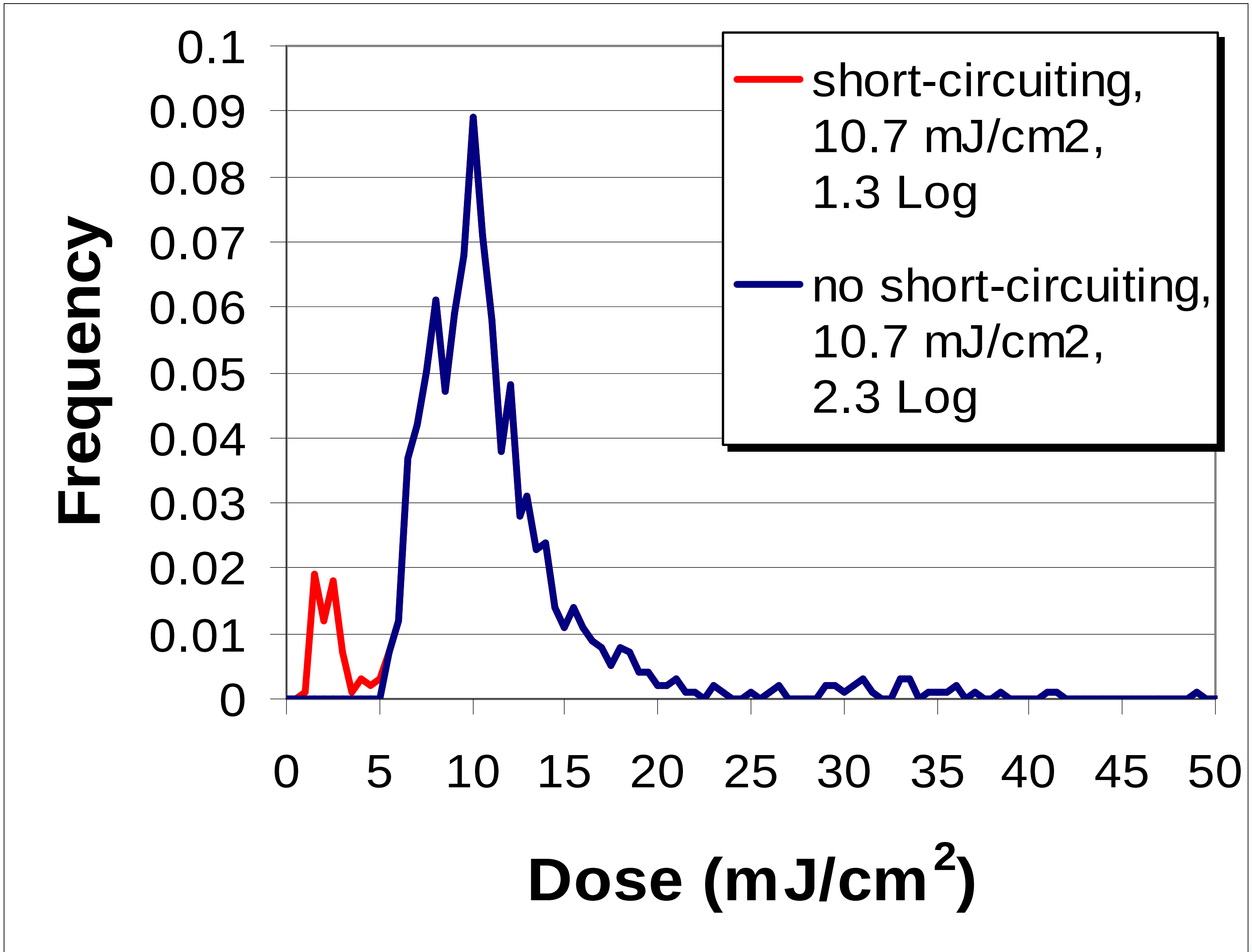
$$\left(\frac{N}{N_0}\right)_i = f_i \times e^{-k\,D_i}$$

f_i is fraction of particles that receiving dose D_i

UV Intensity Field



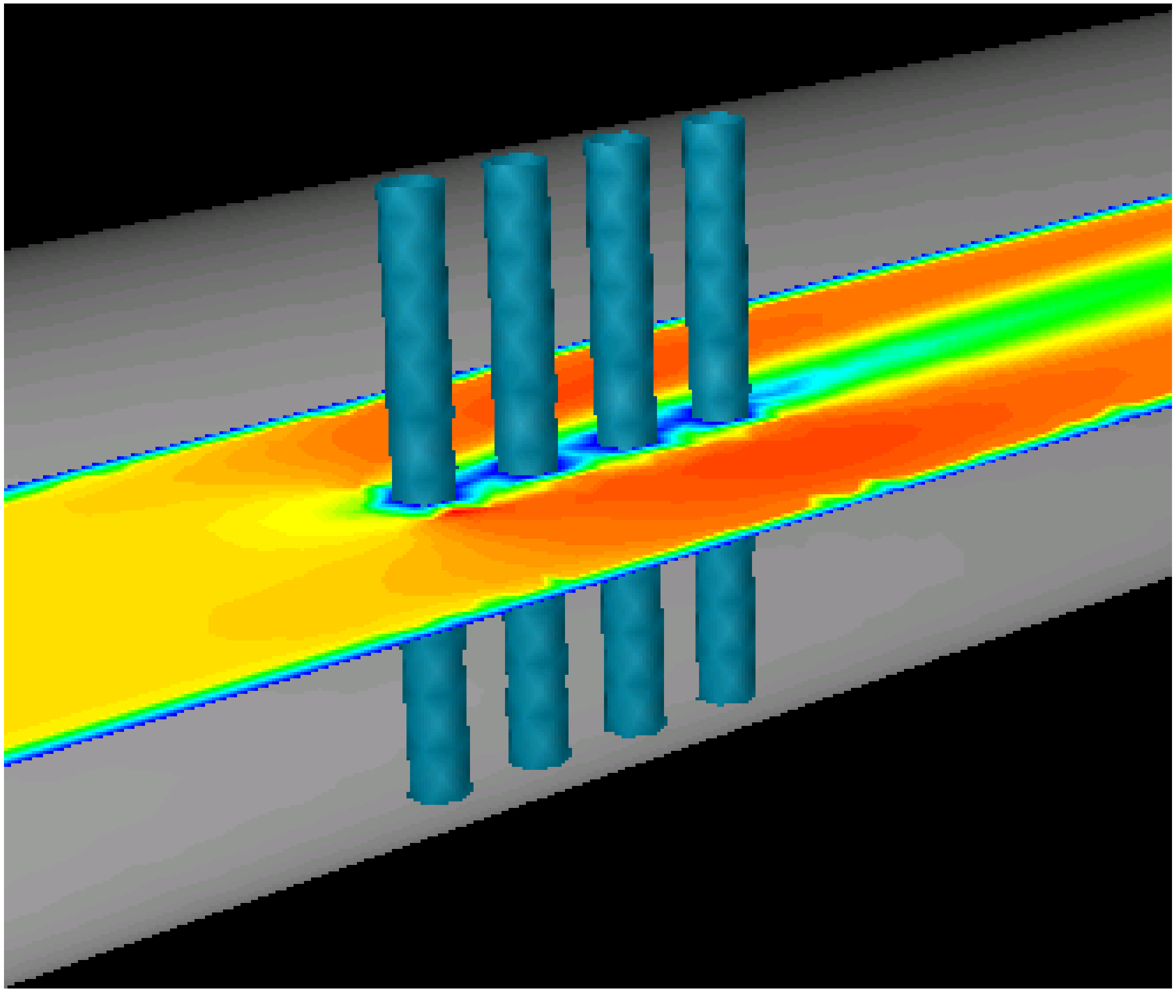
Dose Distribution



Determining UV Dosages in Flowing Reactors

- The only reliable method for pilot & full-scale is bioassay (biodosimetry) method
- Advantages
  - Simultaneously evaluates light intensity distribution (*LID*) and residence time distribution (*RTD)* effects
  - Accounts for water quality matrix interactions
- Disadvantages
  - Time consuming - 24-hr delay in obtaining results
  - Inherent variability in microbiological techniques

Effect of Lamp Position



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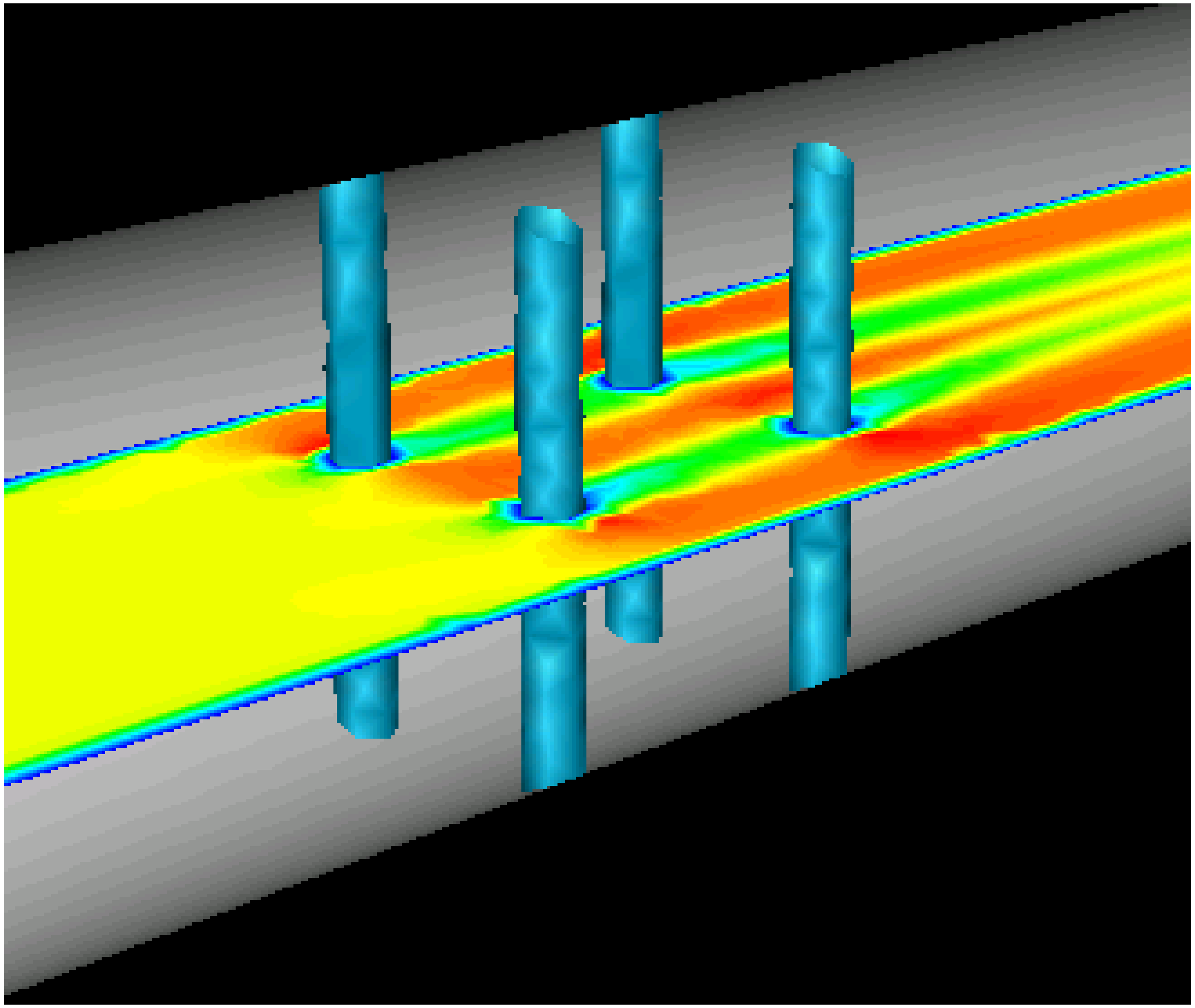

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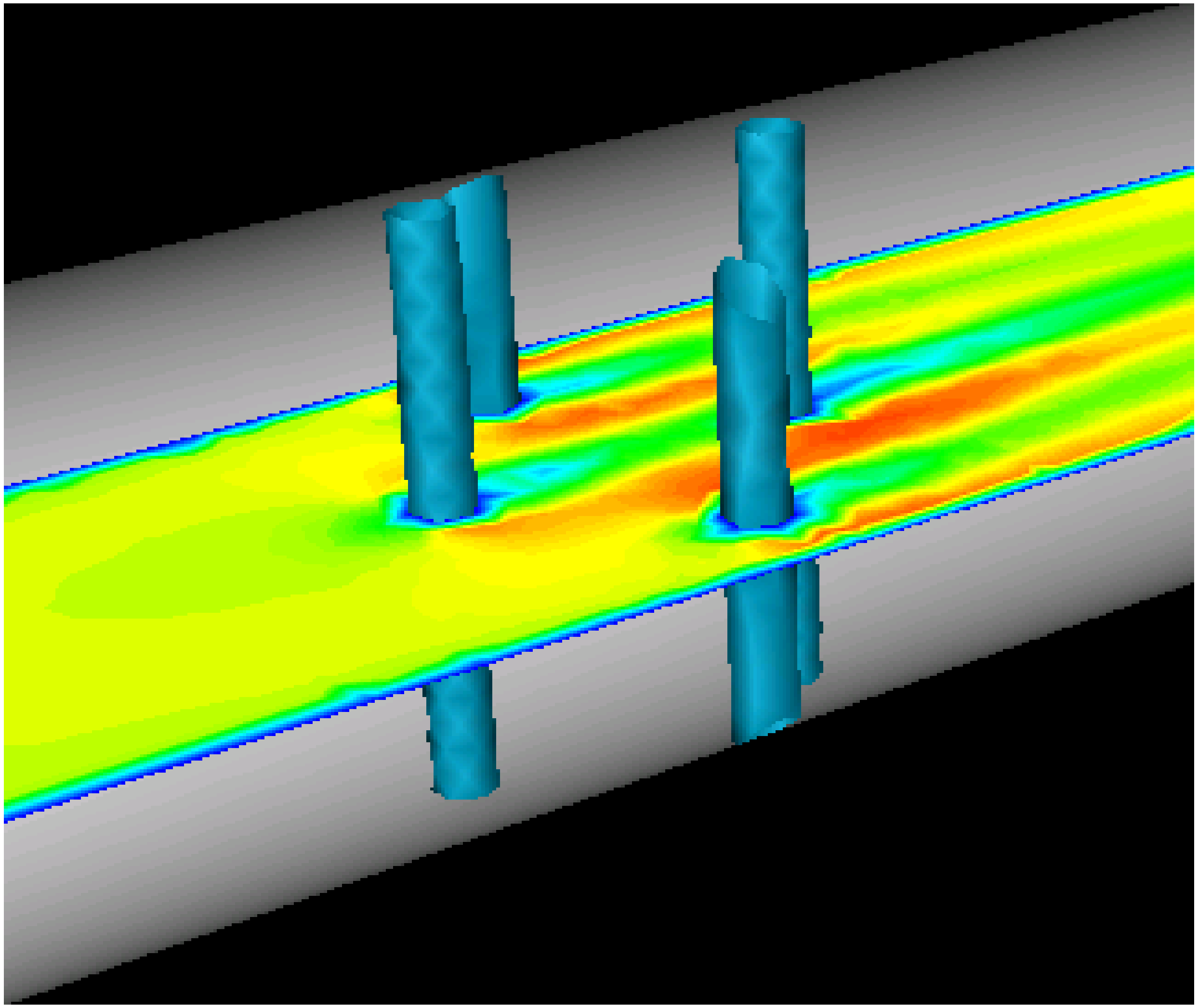

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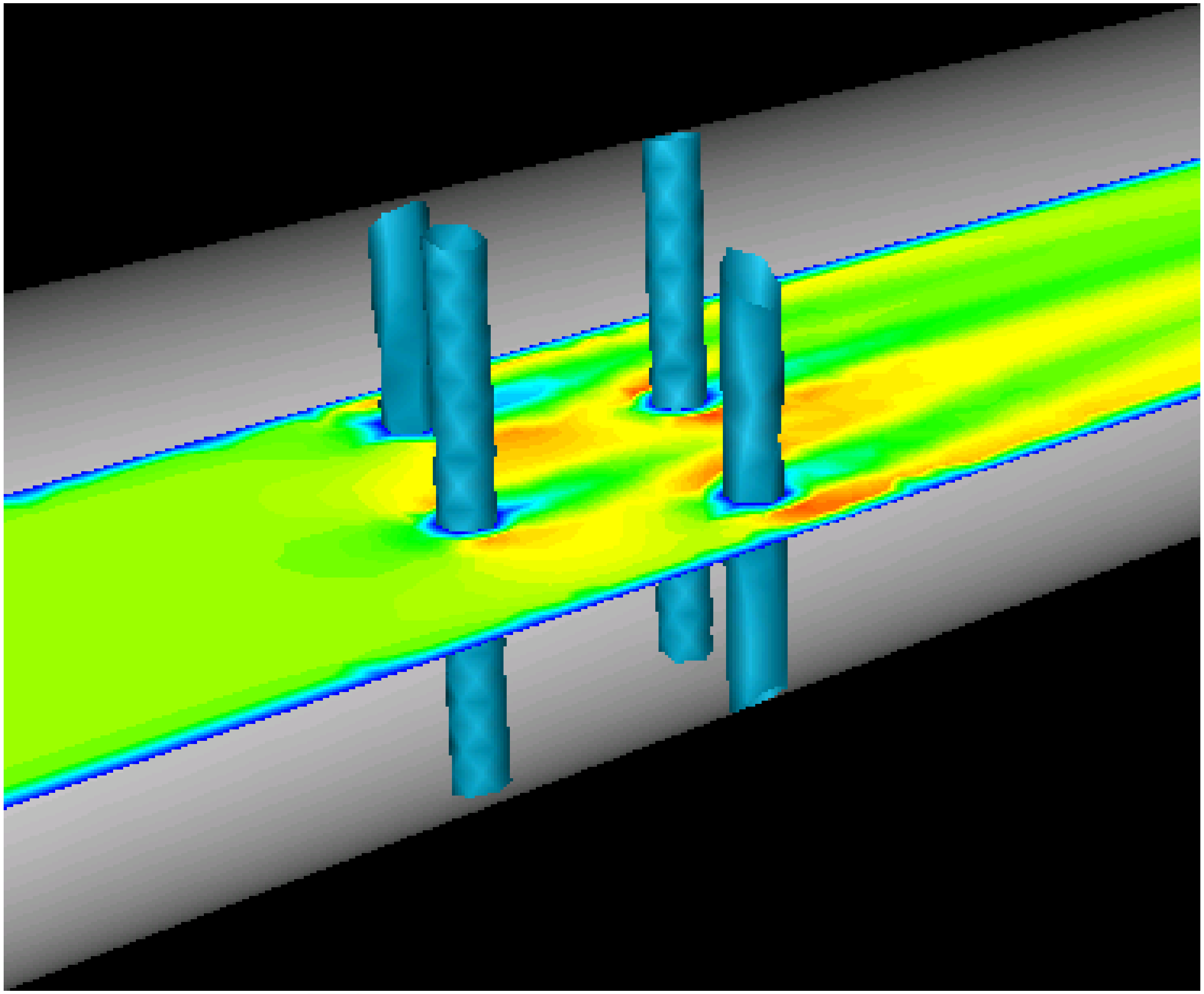


UV Reactors

UV8000™ (courtesy of Trojan Technologies)

UV Disinfection Systems

UV disinfection drinking water facility in Victoria
(Trojan Technologies)

UV Disinfection Systems

UV disinfection drinking water facility in Helsinki, Finland (Wedeco)

Design Criteria

- *Flow rate:* Peak flow vs. average flow
- *Water quality:* UVT, turbidity, Iron, Hardness, colour
- Application: Target organism, Disinfection limit
- Upstream treatment processes
- Chemicals used during the upstream processes
- *Installation configuration:* available footprint and headloss
- Redundancy requirement

Design Guideline
(Section 4.6.2.2)

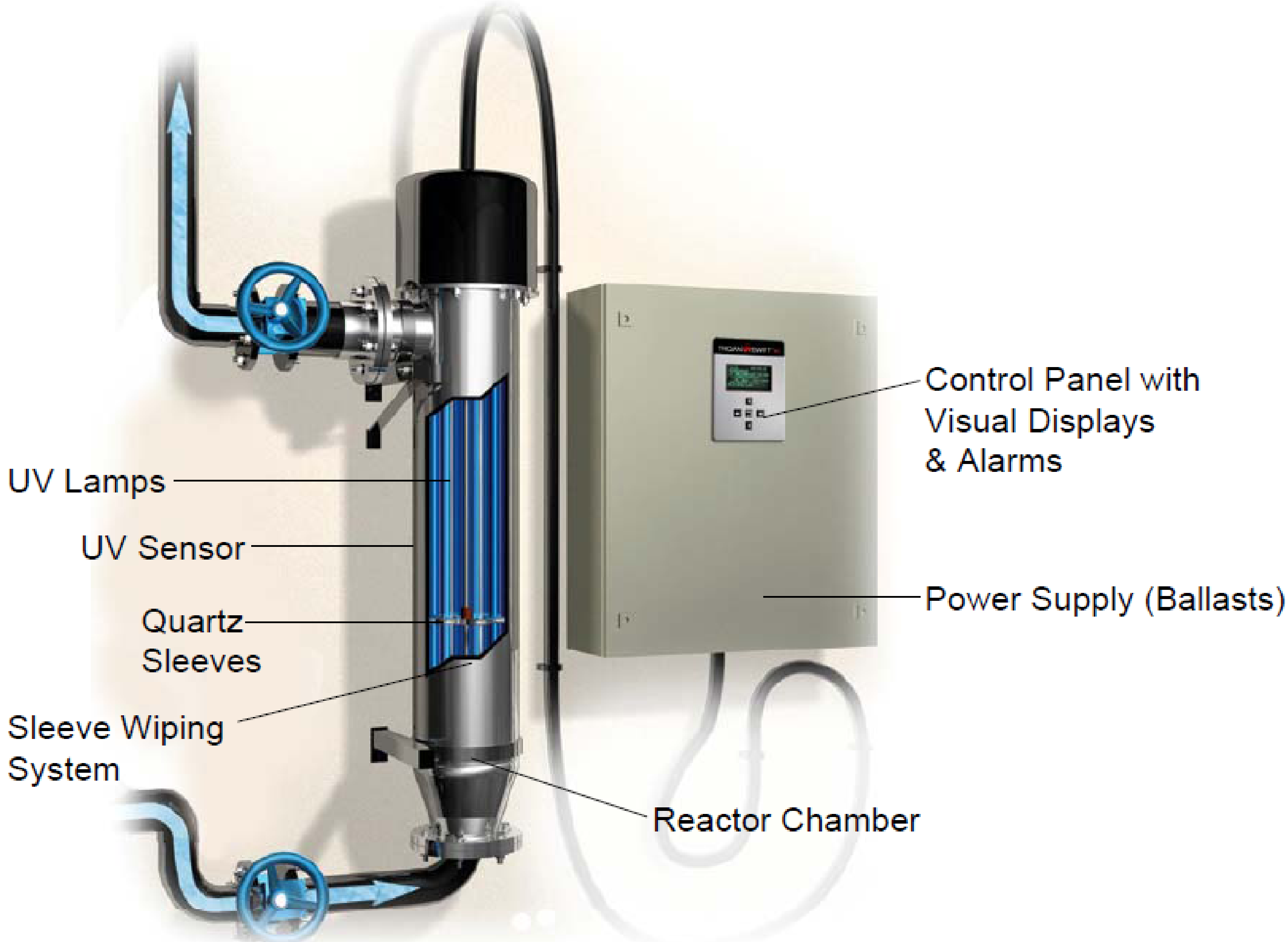
A number of considerations should be made when designing UV systems, among them being:

- The lowest transmittance of the supply to provide pathogen inactivation consistent with regulation
- A minimum 3 log inactivation of *Giardia*, *Cryptosporidium*, and *Viruses*
- A minimum of 50% redundancy
- Based on peak flow and end of lamp life
- Pretreatment for turbidity reduction
- Confirmation of reactor validation

Design Considerations

- **Location/Space Requirements**
  - Low-pressure systems require significantly more space than medium pressure
  - Ancillary equipment takes space (piping, valves, etc.)
  - Retrofit vs. new stand-alone facilities
  - Frequently driven by flexibility of existing piping and associated tie-ins

UV System Key Components



UV Intensity Sensor

The sensor continually monitors the UV intensity to ensure proper disinfection and goes into alarm if the conditions fall below the operating range

UV Control Panel

A *user interface*, generally including:

- Elapsed time meter, giving the user how long the lamp has been in service
- Audio and visual alarms, providing the costumer feedback if there is a problem
- Service reminder, letting the costumer know when it is time to change the lamp or maintain the system

Operational Considerations

Although UV is considered a *plug & play* system, some regular monitoring and maintenance are required:

- Proper O&M ensures the system operate according to specifications
- O&M requirements vary according to the system and manufacturer
- Visual inspection always provides much needed information

Sleeve and Sensor Fouling

By far, the most significant operational issue of the UV systems

Sleeve fouling can affect UVT and disinfection performance

- Many parameters contribute to sleeve fouling (Lamp technology, water quality, flow, etc.)
  - e.g., iron content is often a significant factor in fouling
  - Hardness causes scaling on sleeve

Sleeve and Sensor Fouling

Cleaning can be done through chemical or mechanical wiping

- If automatic wipers are available, ensure they operate properly (e.g., check wiper cleaning fluid)
- For manual cleanings, manually clean sleeves and UV sensors

Sleeve Fouling & Cleaning

Even if system is equipped with a mechanical cleaning system, manual chemical cleaning will still be required.

Clean Sleeve

Fouled Sleeve

Mechanical Wiper (without chemicals)

Mechanical / Chemical Cleaning

What is the cost of UV disinfection?

Cost Factors

- UV reactors are minor component of total treatment costs
- Other cost factors include:
  - Piping, valves and flow meters adjacent to reactors
  - Tie-ins and interconnecting piping
  - Building costs

Case Study

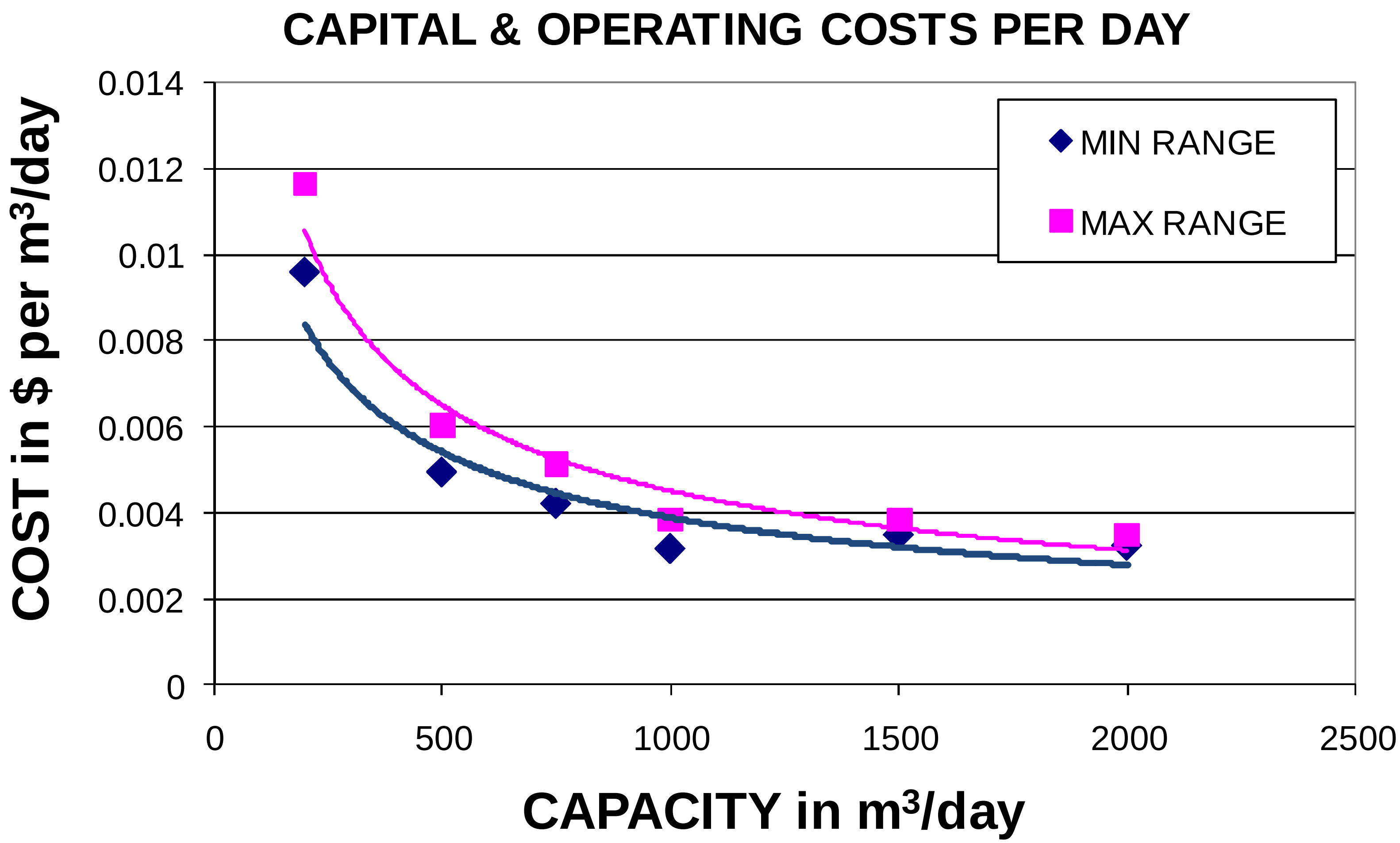
UVSWIFT®

by Trojan Technologies

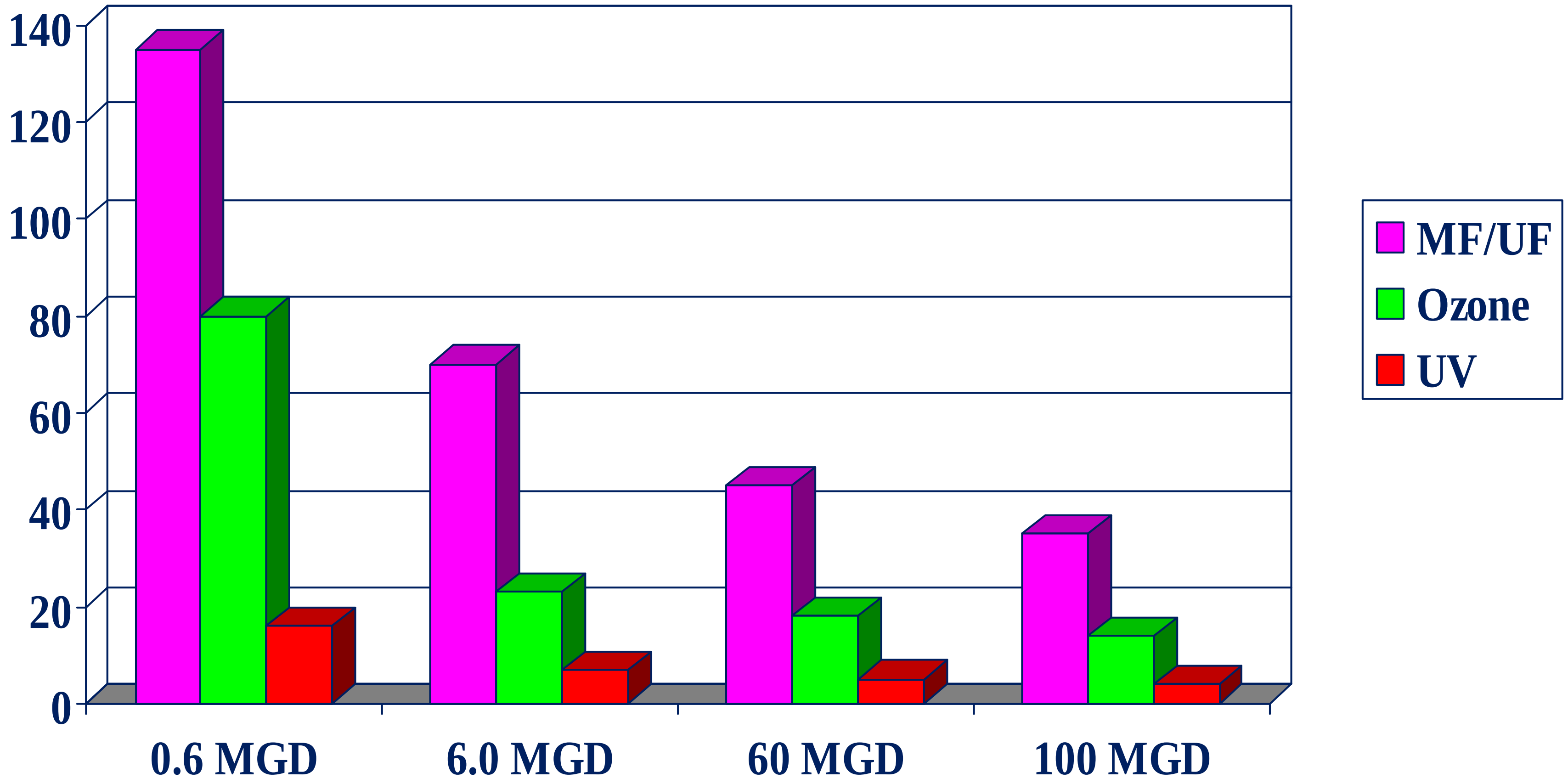
Trojan UVSWIFT®

- UVSWIFT will inactivate bacteria and protozoa, with a dose of 40 mJ/cm^2
- For some source waters, UV may be sufficient (e.g., City of Victoria)
  - However, if turbidity is high settling and/or filtration and coagulation may also be needed

Trojan UVSWIFT®



Comparison of Technology Costs



Source: USEPA-UV Guidance Document, 2001

Case Study: Henderson, NV (Design Criteria – year 2000)

- Design Flowrate = 2360 m^3/h
- UV Transmittance = 88% per cm
- Lamp Fouling = Clean every few hours
- Design Safety Factor = 70 percent of clean, new lamp output
- Level of Redundancy = 1 standby reactor
- UV Dose = 40 mJ/cm^2 (at end of lamp life, peak flow)

Source: CH2M HIll

Case Study: Henderson, NV (Example Cost Factors)

- Initial equipment cost
- Replacement costs for lamps, sensors, sleeves, ballasts, cleaning parts, control system components
- Guaranteed component lifetimes
- Costs for sensor calibration, cleaning, other O&M activities
- Power consumption
- Building space, headloss, expansion, ancillary component sizes

Source: CH2M HIll

Case Study: Henderson, NV (Capital and Operating Costs)

- **Construction Cost:**
  - ***Henderson's 2360 m^3/h - $2.5 million***

- **O&M Costs:**
  - power, labor, and parts (lamps, sleeves, ballasts, sensor checks, sensor calibration, sensor replacement)
  - **$0.006 per m^3 produced**

Source: CH2M HIll

Average UV Cost
(based on various installations in the US)

- **Construction:** \$2.60 to \$4.00 per m^3 (per day basis)

- **O&M:** \$0.003 to \$0.01 / m^3
  - Labor not included

Source: CH2M HIll

SUMMAY

UV Disinfection

Advantages of UV Disinfection

- No disinfection by-products formed
- No biotic toxic residuals
- Effective against bacteria, viruses, and protozoan pathogens
- Easy maintenance, operation, and handling

Issues with UV Disinfection

- No residual disinfection for water supply distribution
- Lamp fouling
- Difficult to monitor on-line
- Not suitable for high turbidity water
- Reactor validation is not performed in many places

Thank You !

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a place of mind
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