Theory and Design of UV Disinfection Systems

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Presentation Outline

- Background and Theory

  Darby, J., Emerick, R., Loge, F., and Tchobanoglous, G. (1999) **The Effect of Upstream Treatment Processes on UV Disinfection Performance**, Water Environment Research Foundation, Project 96-CTS-3

- Issues to Consider During Design

- Design Curve Development

  Blatchley, E. R., Emerick, R. W., Hargy, T., Hoyer, O., Hultquist, R. H., Sakaji, R. H., Scheible, O. K., Schmelling, D. C., Soroushian, F., and Tchobanoglous, G. (2000) **Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse**, National Water Research Institute, American Water Works Association Research Foundation

- Design Example

  Emerick, R. W., Salveson, A., Tchobanoglous, G., and Swift, J. (2003) "Is it Good Enough for Reuse?" *Water Environment and Technology*, Vol. 15, No. 3

Background and Theory

Chlorine Disinfection

Advantages

- ~100 years of use
- Basis of health standards
- Easily controllable – can accommodate many different wastewater treatment processes.
- Any degree of pathogen inactivation possible.

Disadvantages

- Disinfection byproducts
- Chemical handling safety concerns
- Need for dechlorination to eliminate aquatic toxicity

UV Disinfection

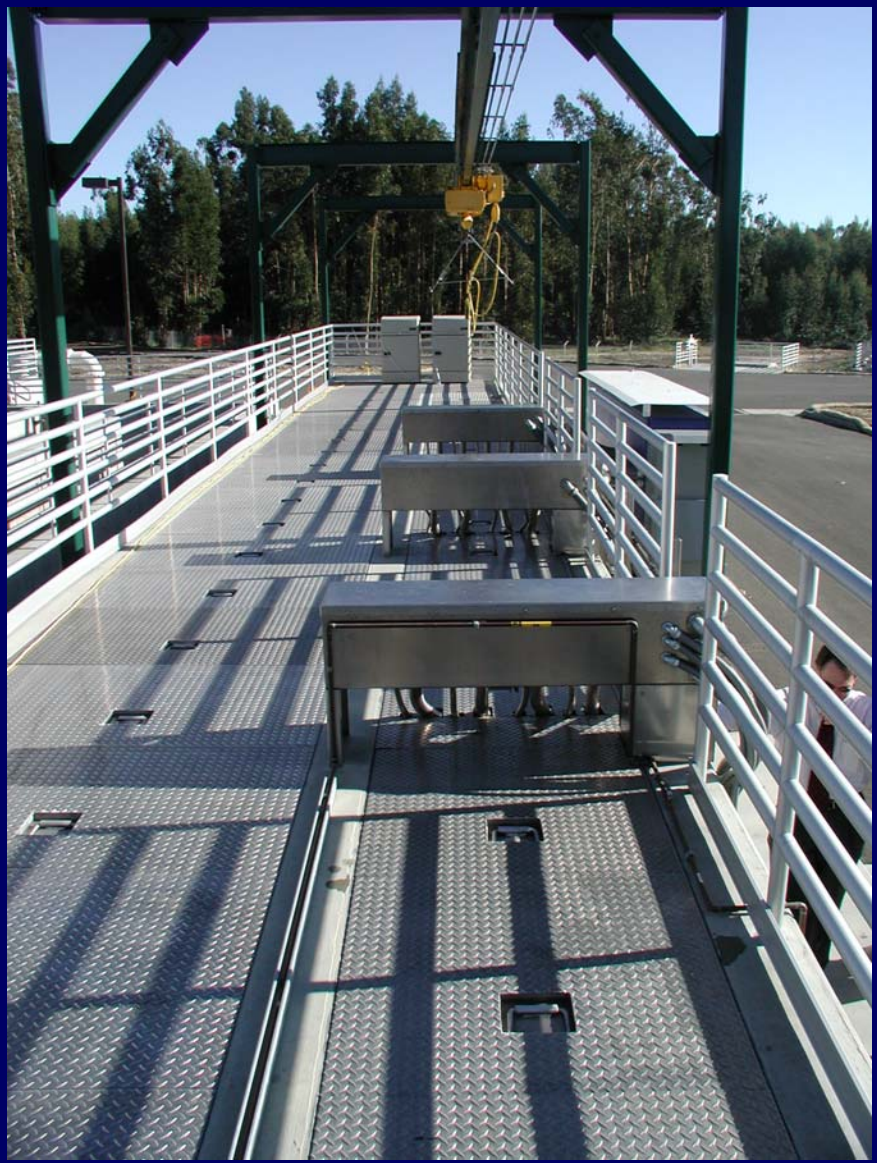
Advantages

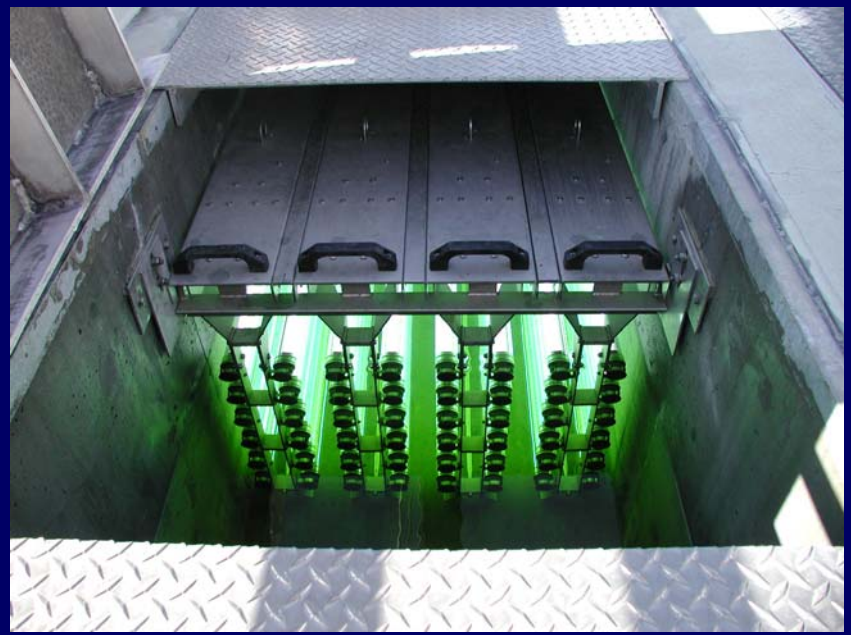
- No disinfection byproducts
- No aquatic life toxicity

Disadvantages

- Deviates from empirical database that underlies health standards
- Limited experience
- Maintenance intensive
- Technology evolving
- Pathogen inactivation limited by WWTP process types.

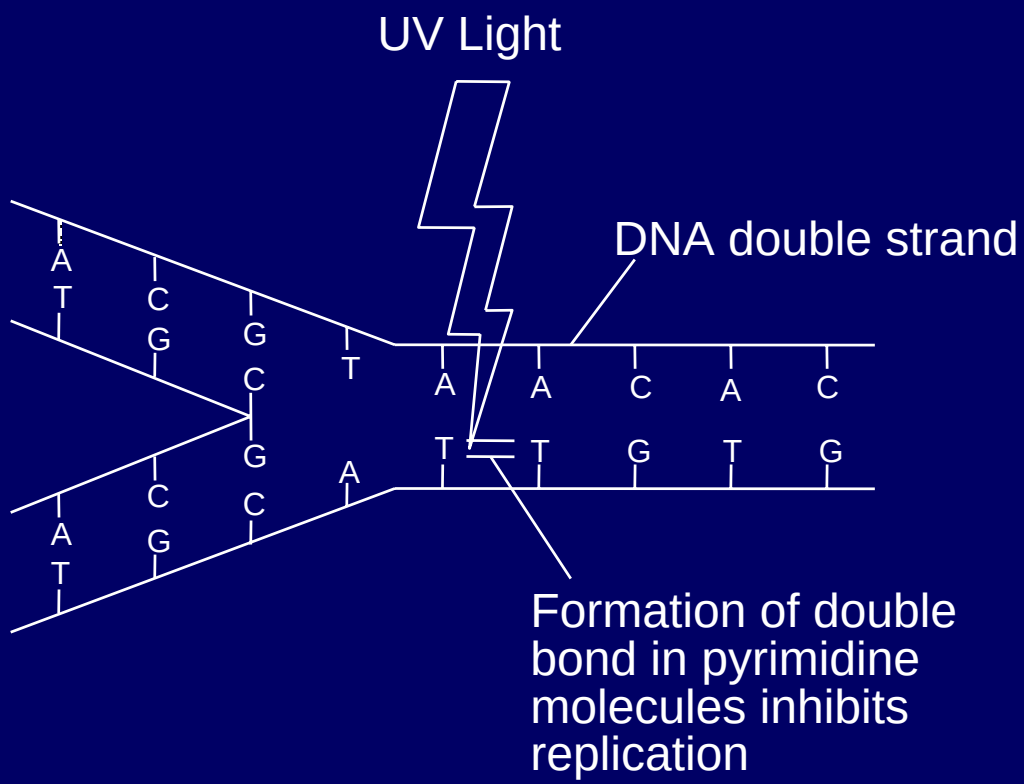
Example Wastewater UV Disinfection System



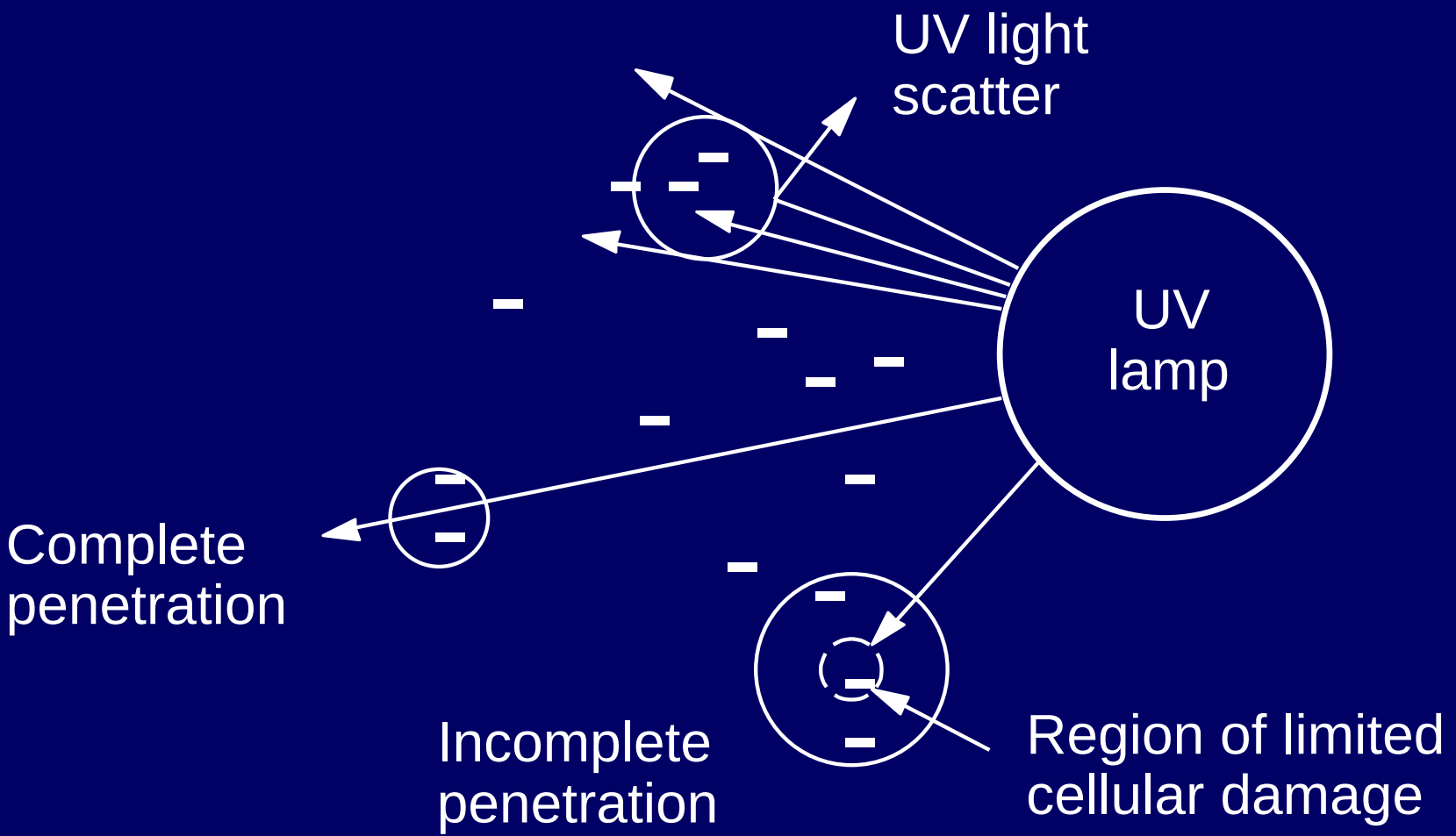


Example Drinking Water UV Disinfection System

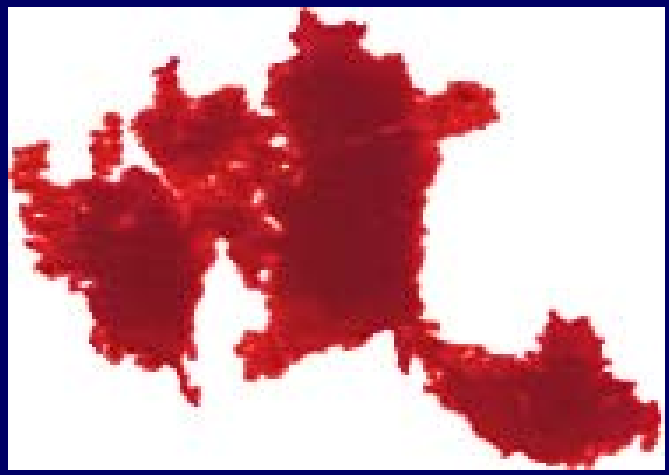
UV Disinfection- How It Works



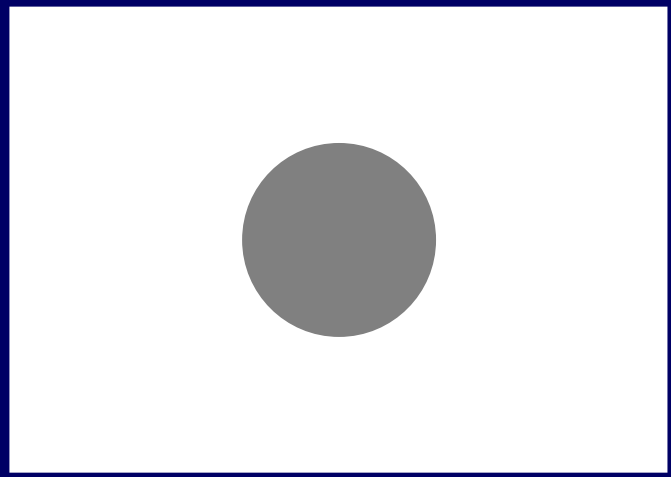
Historical Baggage



Size Distribution of Wastewater Particles

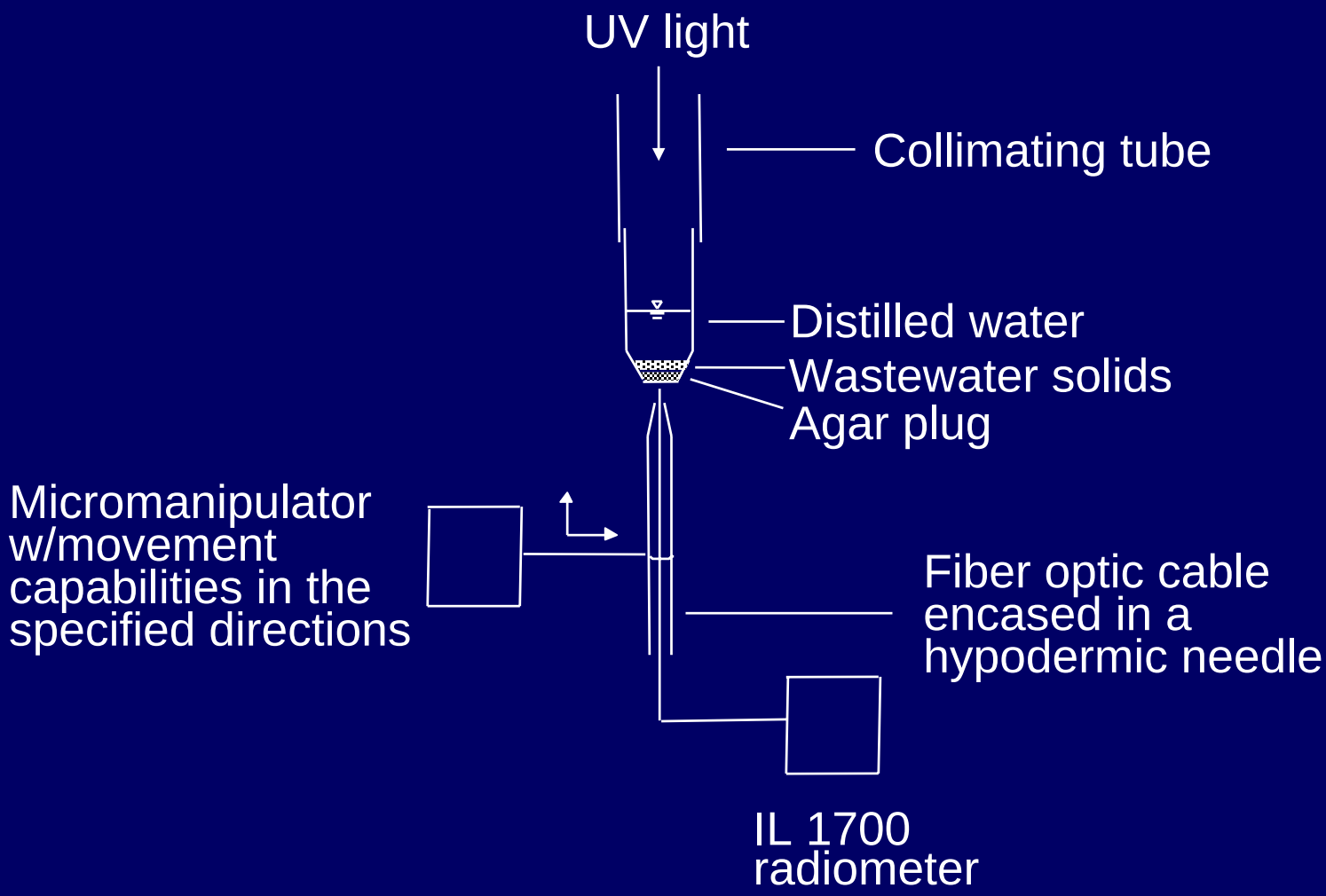


Particle as measured using computer aided image analysis



Particle as measured using electronic particle counters

Fiber Optic Microelectrode Apparatus



Absorbance of Wastewater Solids Collected From Selected WWTPs

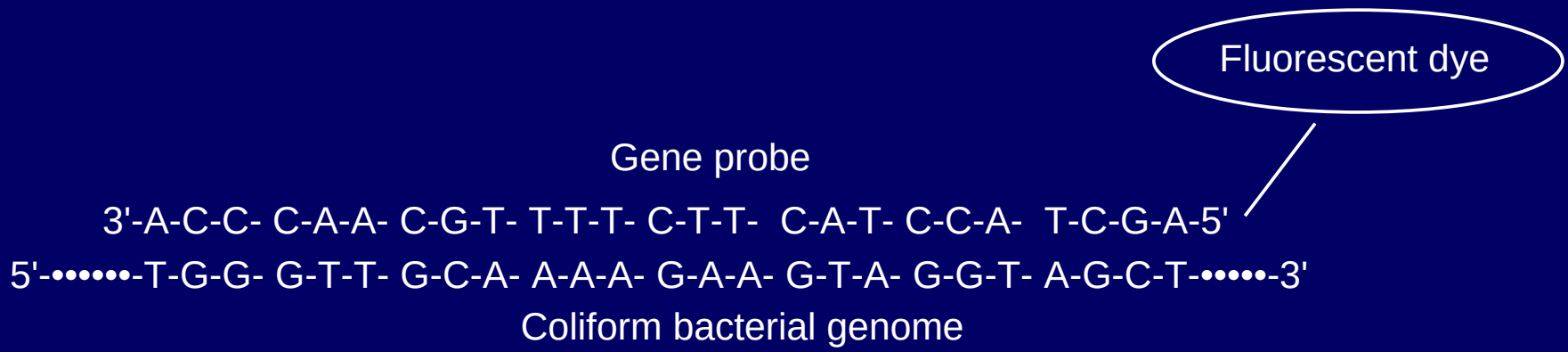
Name of WWTP	Process	Absorbance of WW solids (per cm)	Absorbance of bulk liquid medium (per cm)
Mt View Sanitary District, CA	TF w/ low loading	3,300	0.164 (69%)
Sacramento, CA	Pure O_2 AS	74,300	0.152 (70%)
Dublin, CA	Air AS	45,400	0.141 (72%)
San Jose, CA	Bio N	10,700	0.145 (72%)
Frankenmuth, MI	Bio N/Bio P	54,200	0.118 (76%)
City of Port Huron, MI	Chemical P	569,000	0.159 (69%)

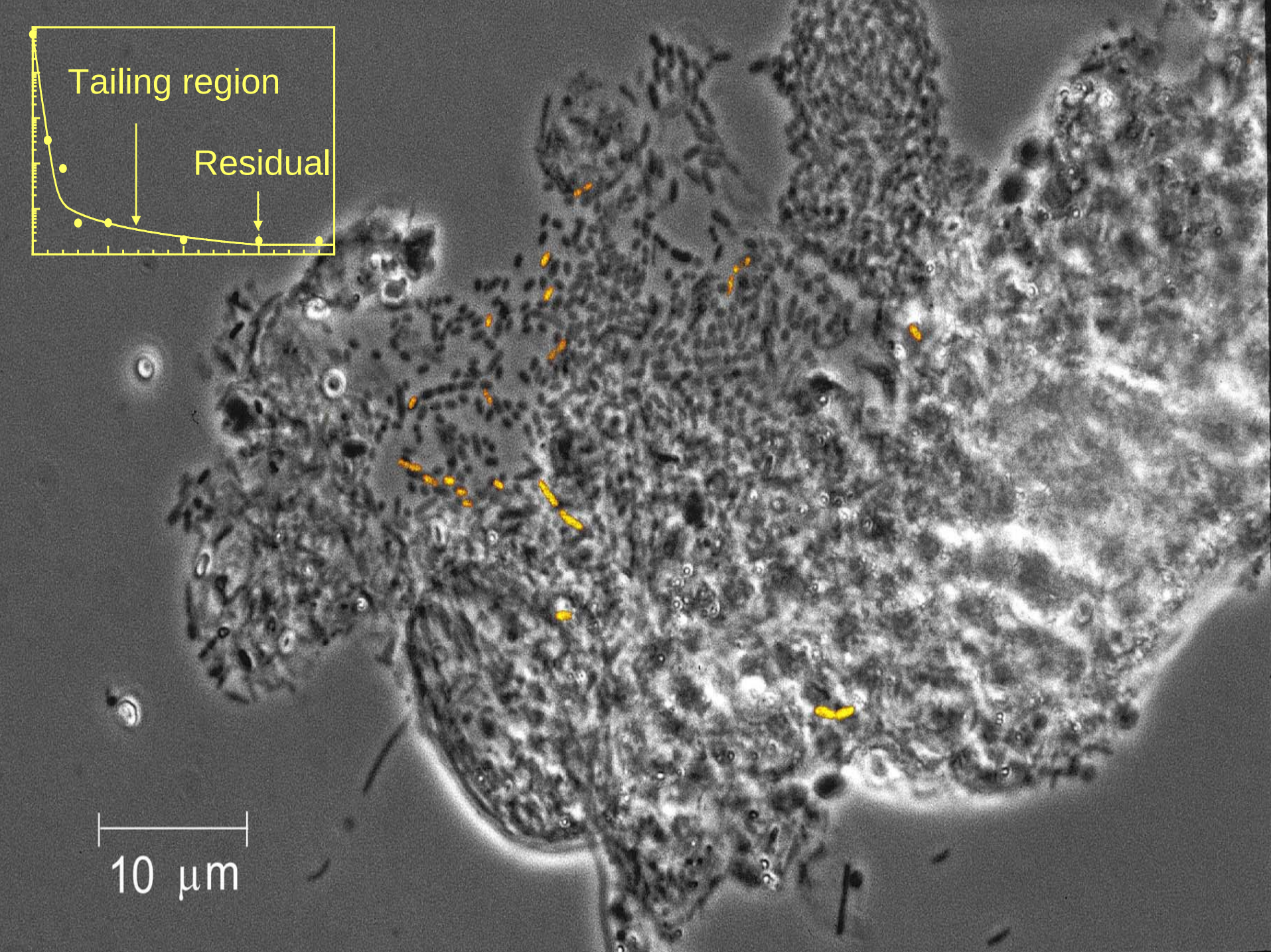
Principal Finding

- UV light does not penetrate wastewater solids.

Development of a 16S rRNA probe

- Determine a sequence unique to coliform
- Synthesize a complementary sequence
- Attach a fluorescent dye to unique sequence
- Add oligonucleotide probe to wastewater
- View sample under a fluorescent microscope

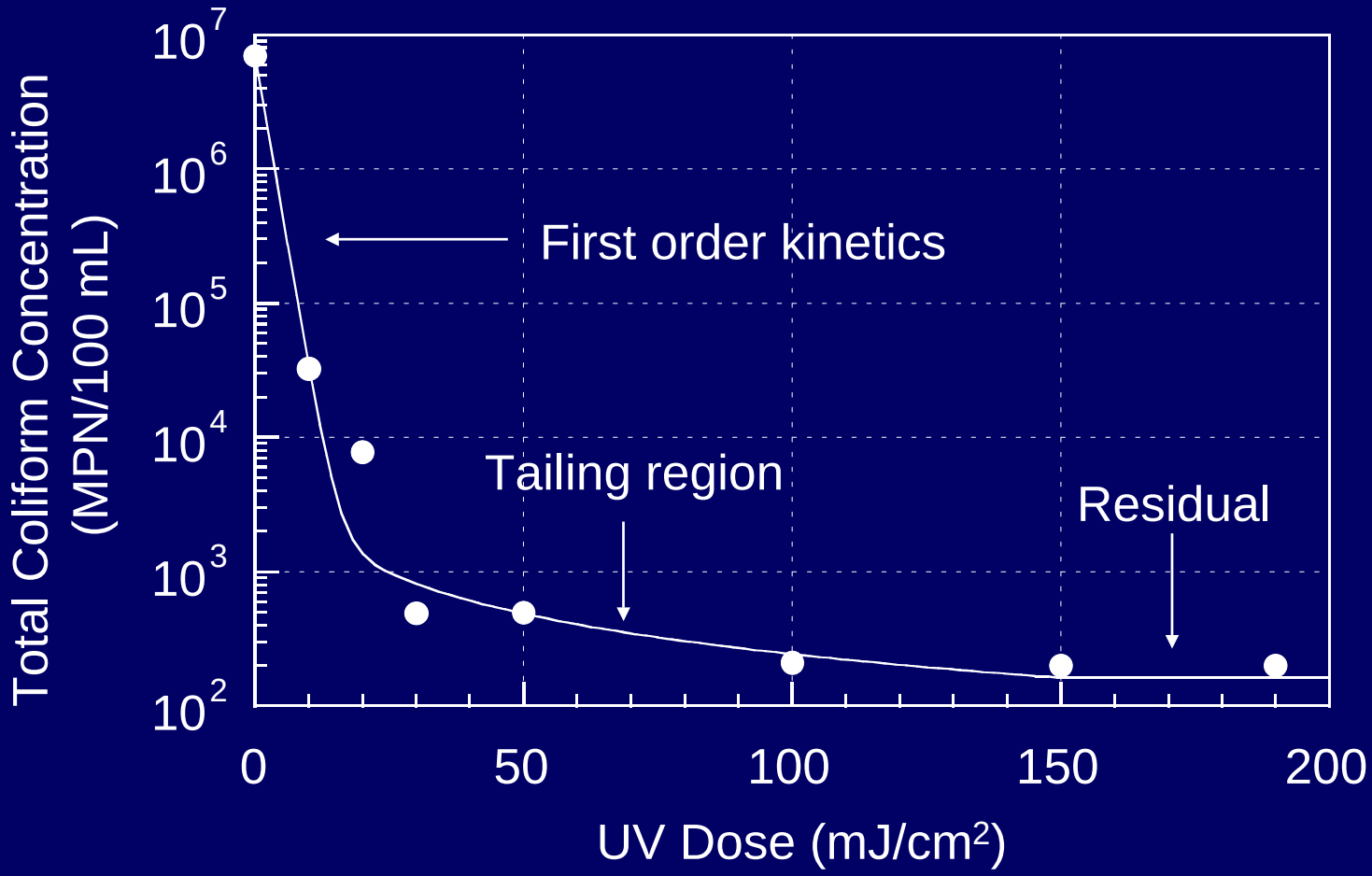



Tailing region
Residual
10 μm

Principal Findings

- All particles do not contain coliform bacteria
- Light penetrates wastewater particles through pathways arising from porous structure
- Coliform bacteria are not necessarily located in the most shielded regions within a wastewater particle

Typical Log-Survival/UV Dose Curve



Modeling the Inactivation of Coliform Bacteria

$$N(d) = N_D(d) + N_P(d)$$

- N(d) = total measured number of surviving total coliform bacteria after applied UV dose “d”
- N_D(d) = total measured number of surviving dispersed coliform bacteria after applied UV dose “d”
- N_P(d) = total measured number of surviving particle associated coliform bacteria after applied UV dose “d”

Modeling the Inactivation of Disperse Coliform Bacteria

$$N_D(t) = N_D(0)e^{-k_{in}It}$$

- $N_D(t)$ = total number of surviving disperse coliform bacteria at time t
- $N_D(0)$ = total number of disperse coliform bacteria prior to the application of UV light
- k_{in} = coliform bacteria inactivation rate coefficient
- I = average intensity applied to the bulk liquid medium
- t = exposure time

Modeling the Inactivation of Particle Associated Coliform Bacteria

- Assumptions
  - enumeration of coliform bacteria with the multiple tube fermentation technique results in the most shielded coliform bacterium (critical coliform bacterium) in each particle dictating inactivation performance of the entire particle, regardless of the actual number of coliform bacteria associated with each particle

Modeling the Inactivation of Particle Associated Coliform Bacteria

- Assumptions, continued
  - once the critical particle diameter is exceeded, the probability of inactivating the critical coliform bacterium in each affected particle is independent of the size of the particle containing coliform bacteria

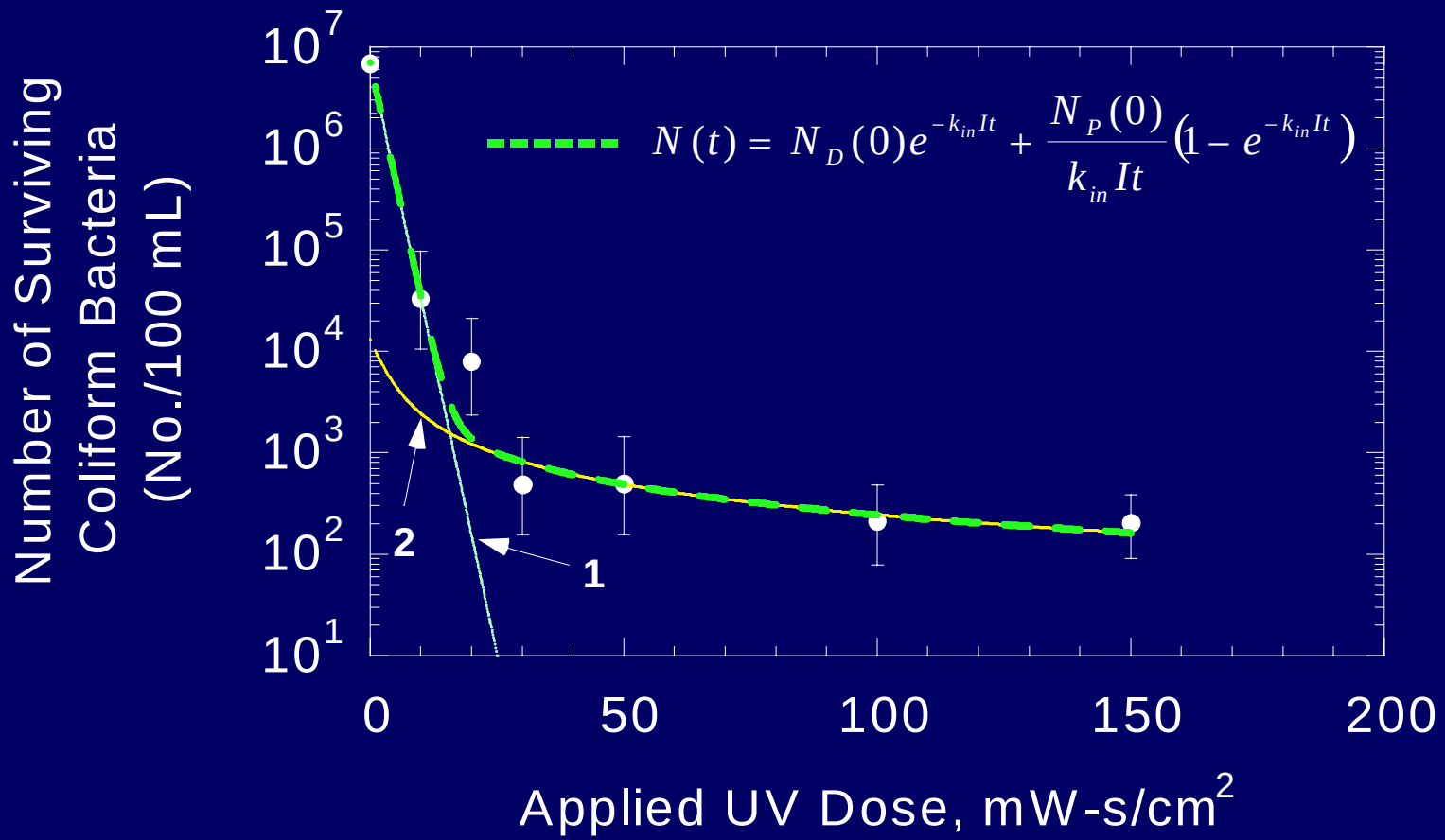
Modeling the Inactivation of Particle Associated Coliform Bacteria

- Assumptions, continued
  - the fraction of average intensity applied to the population of critical coliform bacteria is uniformly distributed between 0 (no applied intensity) and 1 (equal to the average intensity in the bulk liquid medium)

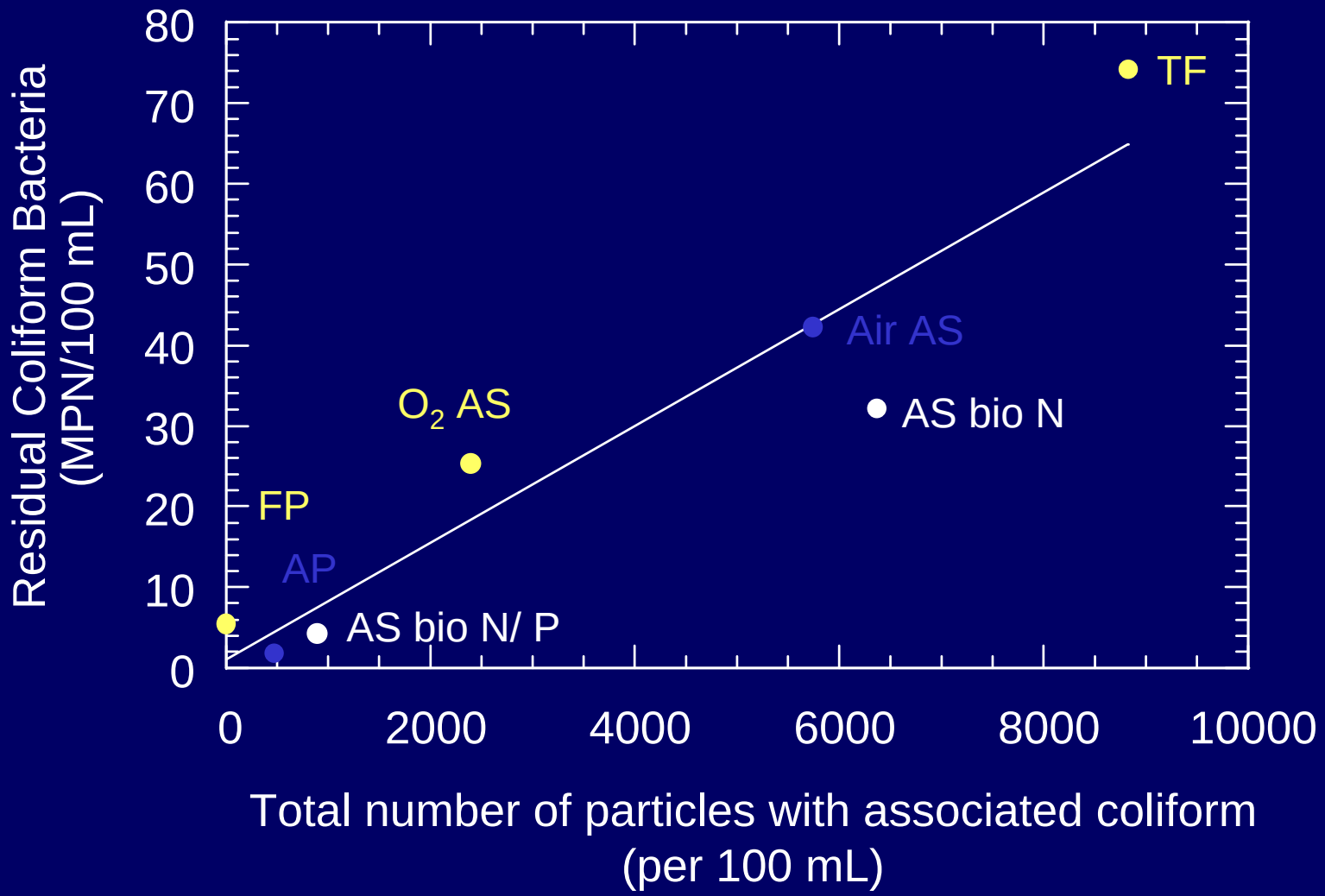
Modeling the Inactivation of Particle Associated Coliform Bacteria

$$N_P(t) = \frac{N_P(0)}{k_{in} I t}\left(1 - e^{-k_{in} I t}\right)$$

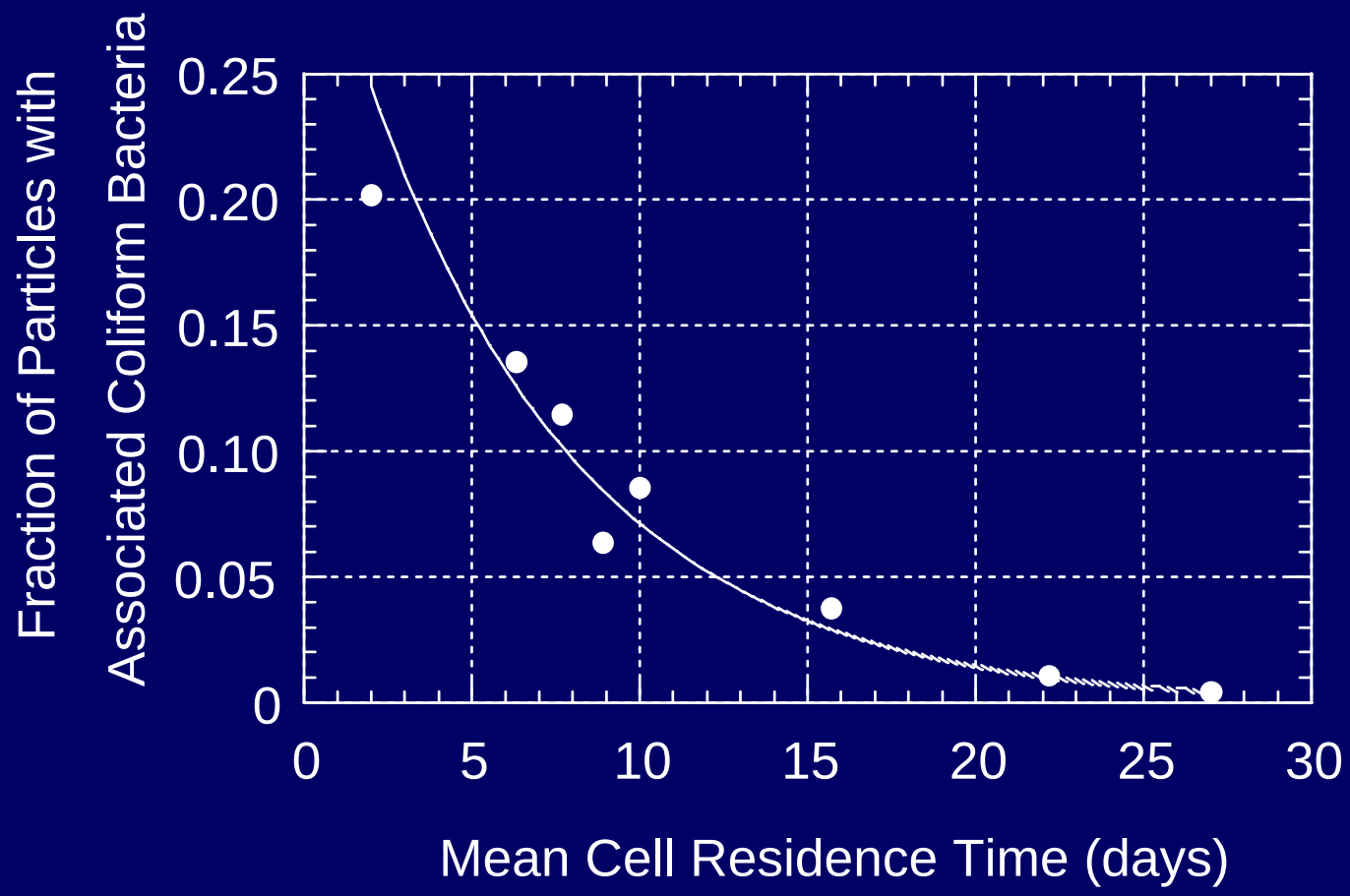
Fit of Model to Experimental Data



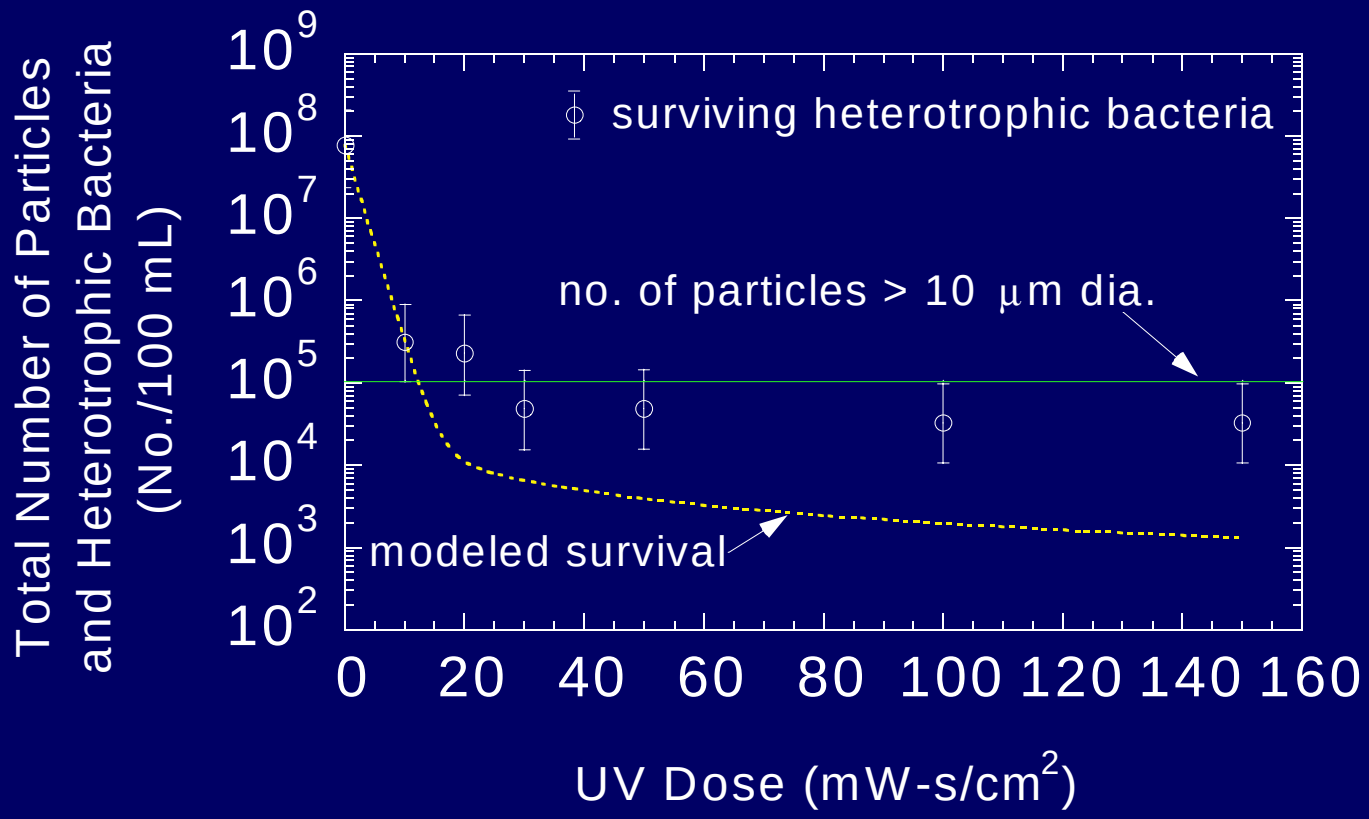
Impact of Treatment Process Type on PAC Formation



Impact of MCRT on PAC Formation



Applicability of Model to Other Particle Associated Organisms



Issues to Consider During Design

Regulatory Issues

- Coliform Bacteria Are Only Indicator Organisms
  - Virus
  - Protozoa
  - Pathogenic Bacteria
- Discharge Permit Limitations
  - Production of equivalent “Title 22” for unrestricted reuse
  - Disinfection byproducts
- Antidegradation

Design Issues

- Appropriate Application to Specific Effluent Quality
- Hydraulic Conditions
  - Diurnal low flow at start-up
  - Peak flow at design capacity
  - Maintenance of rarely used equipment
  - Risk of lamp breakage
- Filter Impacts
  - Pulses
  - Backwash
  - Filter to waste

Design Issues

- UV Guidelines dictate transmittance forming the basis of design.
  - 55% for granular medium filtration
  - 65% for microfiltration
  - 80% for reverse osmosis
- One year of transmittance monitoring can be used to increase design transmittance.
- A change from 55% to 65% decreases size of UV facility by approximately 33 percent.

Design Curve Development

Need for Bioassay Validation

- Complex reactor hydraulics
- Several different lamp manufacturers
  - different emission spectra
  - wavelength intensity variations
  - germicidal impact a function of wavelength
- Equivalent basis for comparison
- Ensure adequate dose delivery

Required Tests

- Determination of the dose-response relationship for MS2 bacteriophage in a collimated beam test apparatus.
- Measurement of MS2 bacteriophage inactivation through the pilot scale UV disinfection equipment.

Critical Requirements

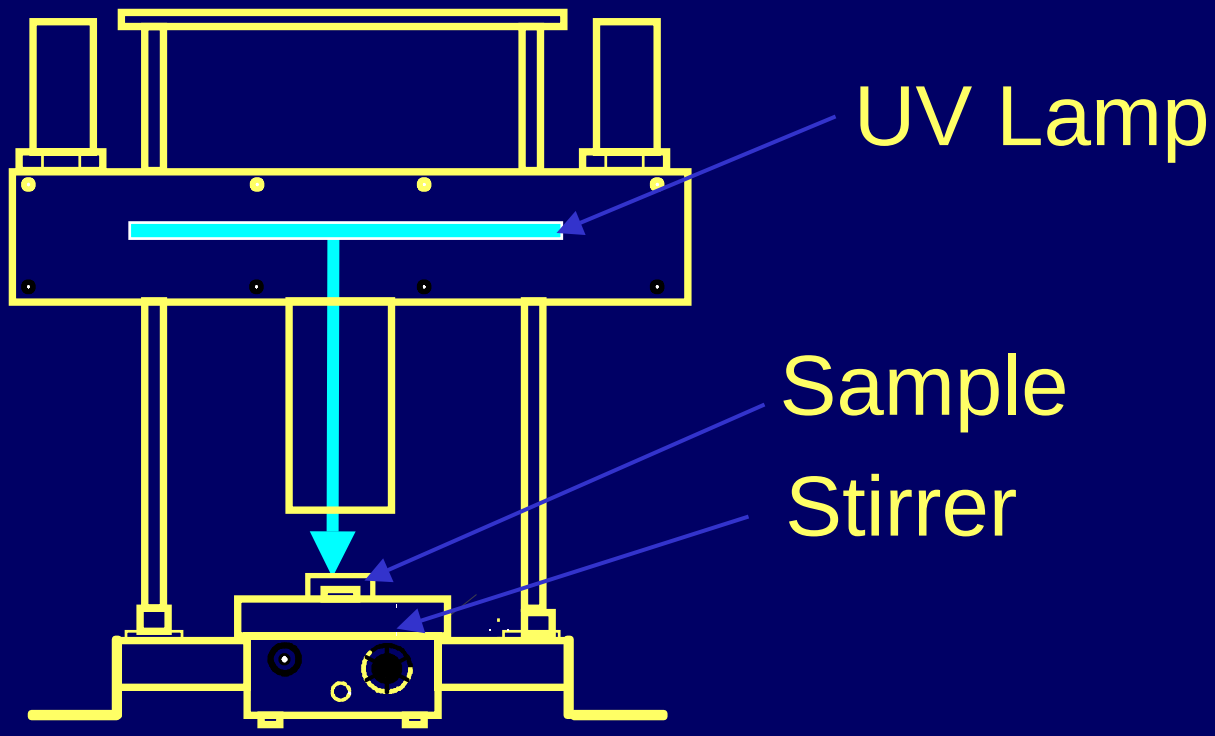
- Seeded disperse phage
- Depth of flow over the uppermost lamps not to exceed one-half of the lamp spacing (open channel/parallel flow systems)
- Similar to full-scale facility
  - energy usage
  - lamp spacing
  - lamp type
  - cleaning system

Critical Requirements (continued)

- Redundant bank in place (when applicable)
- Range of hydraulic loading rates per lamp to be utilized in full-scale facilities
- Range of ballast outputs to be utilized in full-scale facilities
- Applicable wastewater transmittance range

UV Disinfection Pilot Facility

Collimated Beam Apparatus



Pilot Test Conditions

Pilot Flow (L/min)	Hydraulic Loading Rate (L/min-lamp)	Virus Titer Concentration (PFU/mL)	Virus Injection Flow Rate (L/min)	Resulting Virus Concentration (phage/mL)
25	6.25(a)	$1x10^9$	0.25	$1x10^7$
50	12.50	$1x10^9$	0.5	$1x10^7$
100	25.00	$1x10^9$	1.0	$1x10^7$
225	56.25	$1x10^9$	2.25	$1x10^7$
330	82.50	$1x10^9$	3.33	$1x10^7$

(a) Based on four-lamp pilot system

Pilot Test Data

Flow Rate (L/min)	Inlet Concentration (phage/mL)	Log_{10} Inlet Concentration [Log_{10}(inlet)]	Outlet Concentration (phage/mL)	Log_{10} Outlet Concentration [Log_{10}(outlet)]
100	1.07×10^7	7.03	3.47×10^3	3.54
	7.76×10^7	6.89	3.55×10^3	3.55
	6.46×10^6	6.81	7.41×10^3	3.87

Average Log_{10}(inlet) = 6.91

Inlet standard deviation = 0.11

$n_1 = 3$

Average Log_{10}(outlet) = 3.65

Outlet standard deviation = 0.19

$n_2 = 3$

Statistical Analysis

Lower 75% Confidence $= \left(\bar{y}_1 - \bar{y}_2\right) - t_{0.125}\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$

$\bar{y}_1$ = avg. inlet conc.

$\bar{y}_2$ = avg. outlet conc.

$t_{0.125}$ = 75% confidence t - dist. statistic

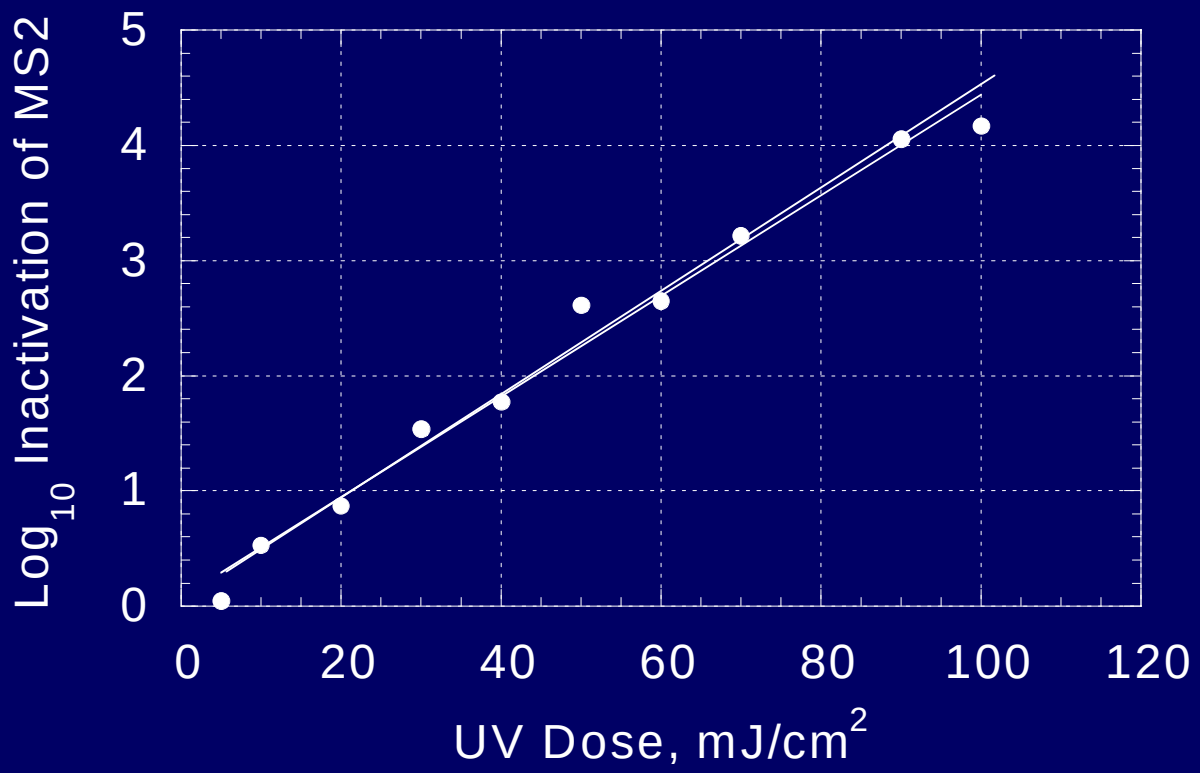
s_1^2 = inlet conc. variance

n_1 = no. of inlet replicates

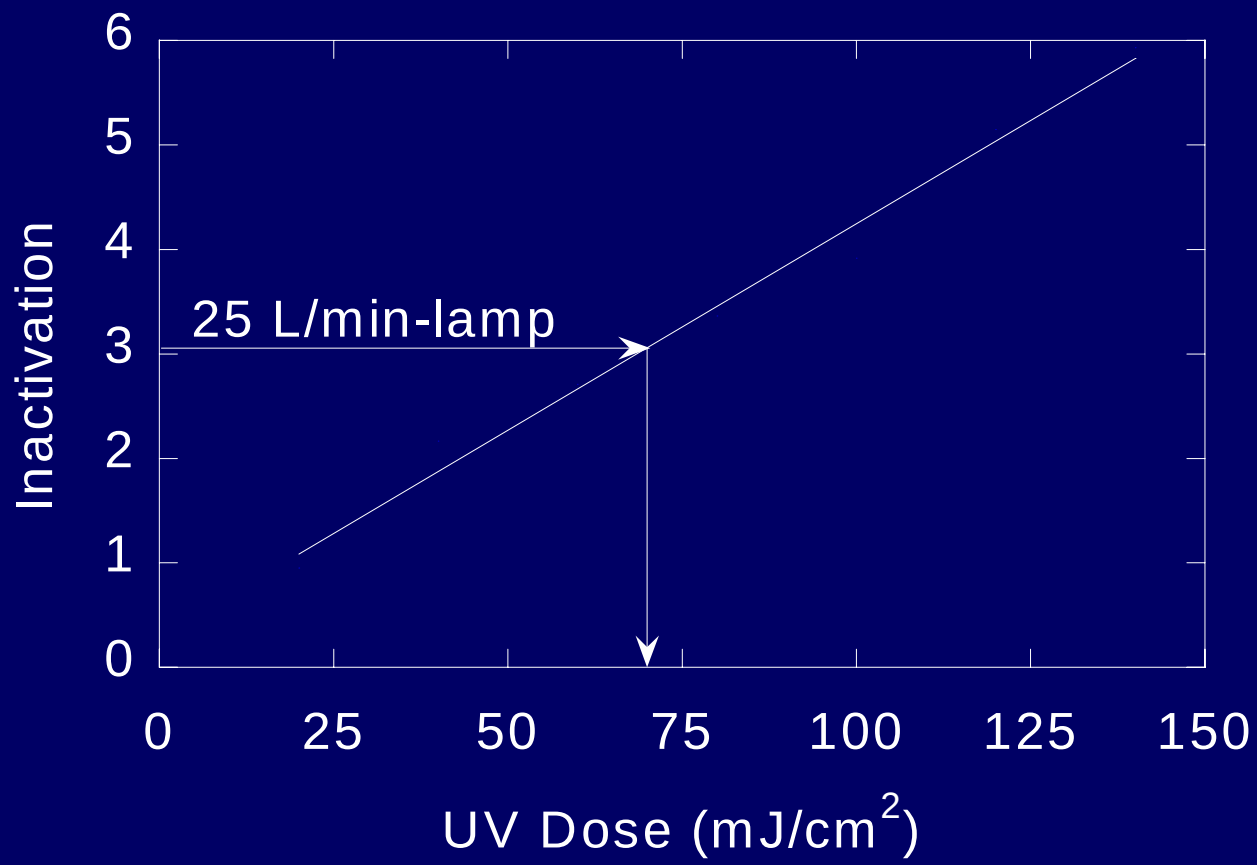
Inactivation Performance

Pilot Flow (L/min)	Hydraulic Loading Rate (L/min-lamp)	Average Log_{10} Inactivation	Lower 75% Log_{10} Inactivation
25	6.25	4.32	4.03
50	12.50	3.62	3.57
100	25.00	3.26	3.08
225	56.25	2.62	2.51
330	82.50	1.34	1.11

MS2 Dose-Response Relationship
(as measured using a collimated beam)



Dose Assignment



Design Curve

Hydraulic Loading Rate (L/min-lamp)	Bioassay Dose (mJ/cm^2)	Aged and Fouled Dose (mJ/cm^2)
6.25	94.9	38.0 (a) (b) (c)
12.50	83.1	33.2
25.00	70.5	28.2
56.25	55.9	22.4
82.50	46.0	18.4

(a) 0.5 lamp aging safety factor

(b) 0.8 lamp fouling safety factor

(c) Example Calculation: $(94.9\ mJ/cm^2)(0.8)(0.5) = 38.0\ mJ/cm^2$

Design Example

Design Conditions

- Diurnal low flow at startup = 4,153 L/min (1.58 mgd)
- Maximum peak hour design flow = 14,590 L/min (5.55 mgd)
- Minimum design dose = 100 mJ/cm^2
- Wastewater transmittance = 55 percent
- Maximum number of lamps per bank = 40 (validation limitation)

Facility Design

Hydraulic Loading Rate (L/min-lamp)	Aged and Fouled Dose (mJ/cm^2)
6.25	38.0
12.50	33.2
25.00	28.2
56.25	22.4
82.50	18.4

- 2 bank system = 50 mJ/cm^2 per bank
- 3 bank system = 33.3 mJ/cm^2 per bank
- 4 bank system = 25 mJ/cm^2 per bank
- 5 bank system = 20 mJ/cm^2 per bank

3-Bank Design: Channels

- Validated from 6.25 to 12.5 L/min

$$\text{Peak Channel Capacity} = \frac{12.5\ L/\text{min}}{\text{lamp}}\left(40\ \text{lamps}/\text{bank}\right) = 500\ \frac{\text{L}/\text{min}}{\text{channel}}$$

$$\text{Total Channels Required} = \frac{\text{Peak System Flow}}{\text{Peak Channel Capacity}} = \frac{14{,}590\ L/\text{min}}{500\ L/\text{min}-\textit{channel}} = 29.2\ \text{channels}$$

- Use 30 channels
- Reject: Too many channels

4-Bank Design: Channels

- Validated from 12.5 to 42.2 L/min

$$\text{Peak Channel Capacity} = \frac{42.2\ L/\text{min}}{\text{lamp}}\left(40\ \text{lamps}/\text{bank}\right) = 1689\ \frac{\text{L}/\text{min}}{\text{channel}}$$

$$\text{Total Channels Required} = \frac{\text{Peak System Flow}}{\text{Peak Channel Capacity}} = \frac{14{,}590\ L/\text{min}}{1689\ L/\text{min}-\textit{channel}} = 8.6\ \text{channels}$$

- Use 9 channels

4-Bank Design: Lamps

- At peak flow conditions:

$$\text{Flow per Channel} = \frac{14590\ L/\text{min}}{9\ \text{channels}} = 1622\ \frac{L/\text{min}}{\text{channel}}$$

$$\text{Lamps per Bank} = \frac{1621\ L/\text{min}}{42.2\ \frac{L/\text{min}}{\text{lamp}}} = 38.4\ \frac{\text{lamps}}{\text{bank}}$$

- Assuming use of an 8-lamp module:

$$\text{Number of Modules} = \frac{38.4\ \text{lamps}/\text{bank}}{8\ \text{lamps}/\text{module}} = 4.8\ \text{modules}/\text{bank}$$

- Use five modules (8 vertical x 5 horizontal)

4-Bank Design: Minimum Flow

- Validated from 12.5 to 42.2 L/min

$$\text{Peak Channel Capacity} = \frac{42.2\ L/\text{min}}{\text{lamp}}\left(40\ \text{lamps}/\text{bank}\right) = 1689\ \frac{\text{L}/\text{min}}{\text{channel}}$$

$$\text{Number of Operating Channels} = \frac{4153\ \frac{L}{\text{min}}}{1689\ \frac{\text{L}/\text{min}}{\text{channel}}} = 2.5\ \text{channels}$$

- Use 3 channels

4-Bank Design: Minimum Flow

- Validated from 12.5 to 42.2 L/min

$$\text{Flow per Channel} = \frac{4153\ L/\text{min}}{3\ \text{channels}} = 1384\ L/\text{min}$$

$$\text{Approach Hydraulic Loading Rate} = \frac{1384\ \frac{L}{\text{min}}}{40\ \text{lamps}} = 34.6\ \frac{L/\text{min}}{\text{lamp}}$$

- Minimum flow is acceptable.

Questions