UV Disinfection of Water and Wastewater

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UV Disinfection Workshop

UV Disinfection Basics

1. UV Basics
2. Applications of UV Disinfection
3. UV Reactor Design
4. Factors Affecting UV Disinfection
5. UV Reactor Validation Water and Wastewater

UV Disinfection of Wastewater

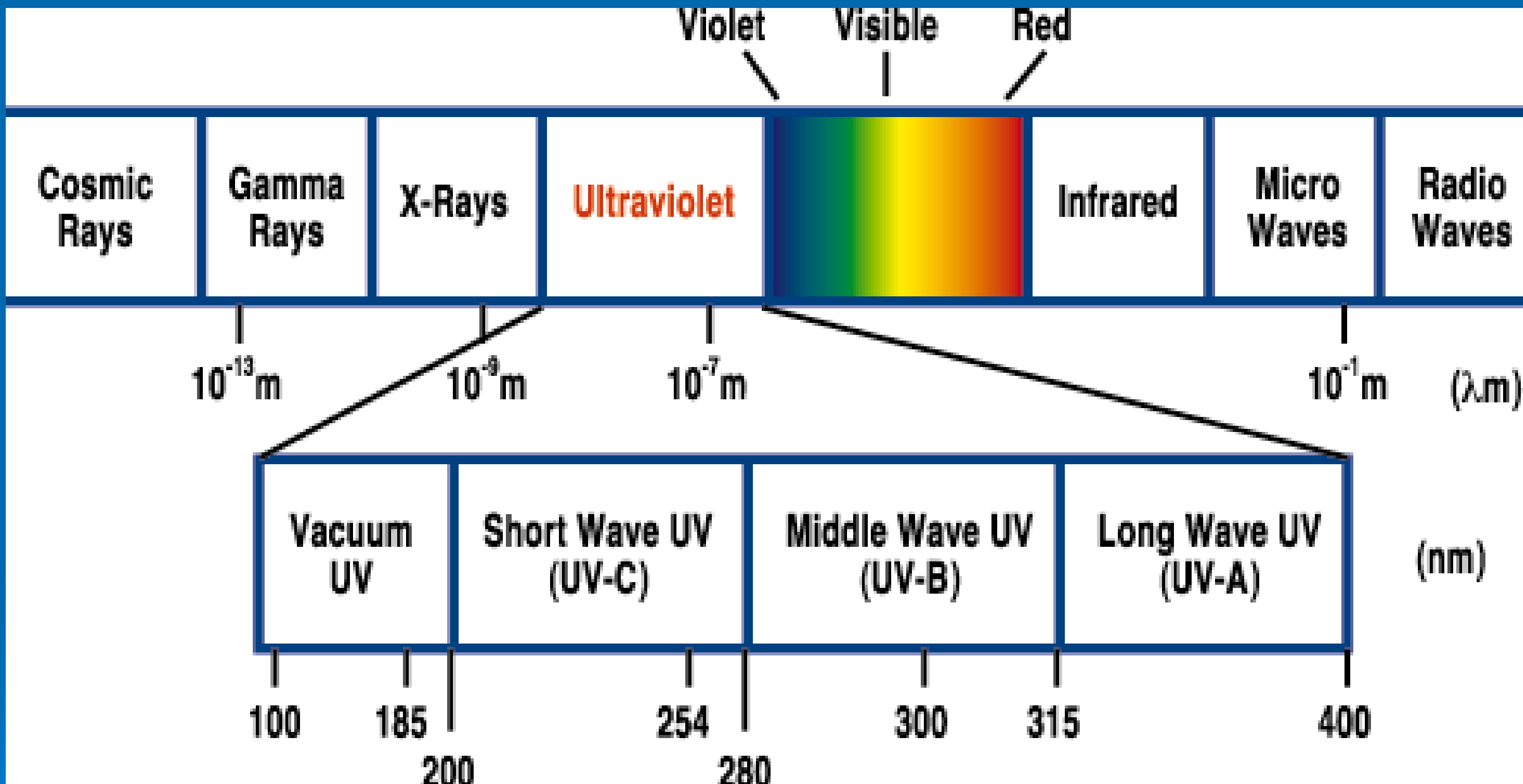
1. Sizing a UV System for a WWTP

UV Disinfection of Drinking Water

1. Why UV
2. Regulatory Status: Canada and United States
3. Ultraviolet Disinfection Guidance Manual USEPA
4. UV Installation Design
5. Case Studies
6. CFD

UV Water and Wastewater Training and Maintenance

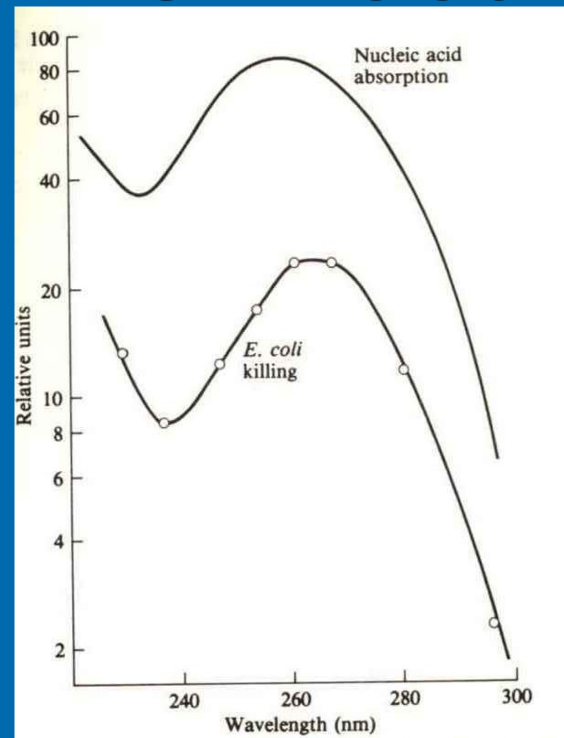
What is Ultraviolet Light?

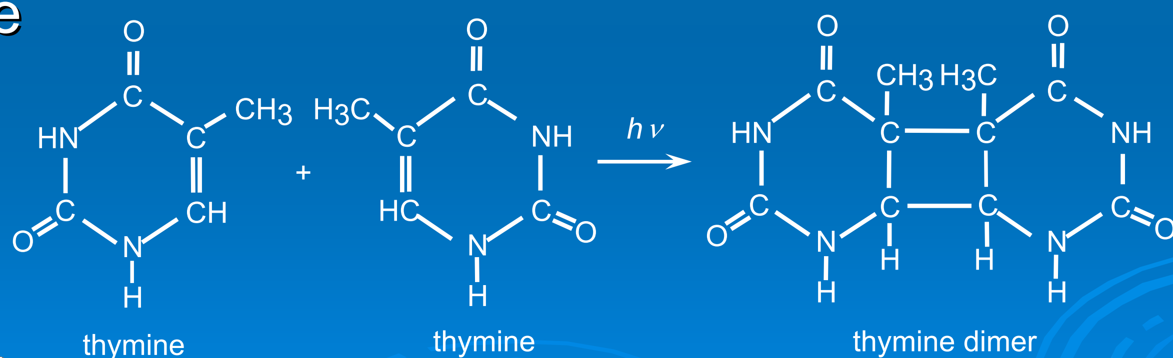


1 X 10^{-9} m = 1 nm (nanometre)

Mechanism of UV Disinfection

- UV Photons Absorbed by DNA in Pathogens, Prevent the Proper Replication of the Organism's Genetic Material
- Photochemistry Involves Dimerization of Two Thymines to Cause Inhibition of the Cell's Replication Mechanism
- An Organism that Cannot Replicate Properly Cannot Survive





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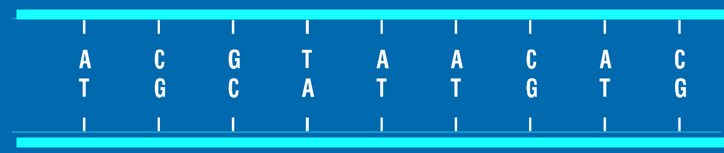
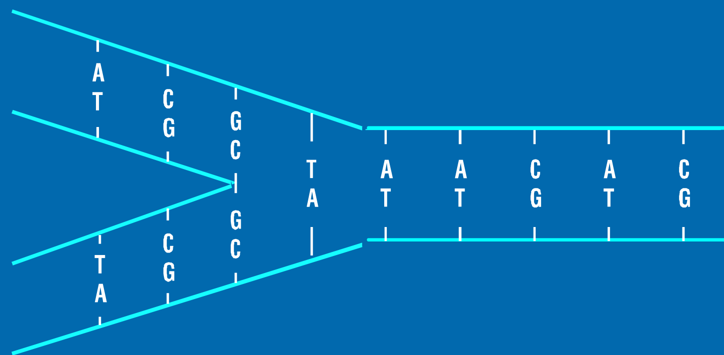
Disruption of the DNA by the Action of UV Light

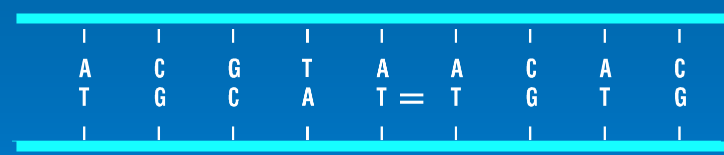
Hypothetical DNA Double Strand



Replicating DNA



Dimerization of Thymine Nucleotides



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Advantages of Ultraviolet Disinfection

- **Physical process not a chemical process**
- **Does not create toxic compounds which may affect the aquatic biota or a source of drinking water**
- **Inactivates viruses and vegetative and spore forming bacteria**
- **Inactivates *Cryptosporidium* and *Giardia***
- **Is cost competitive with chlorination, ozonation and chlorination/dechlorination**
- **Eliminates handling and storing of dangerous toxic chemicals**
- **Uniform Fire Code is not applicable (USA)**
- **Minimizes building requirements**
- **Very few moving parts**

UV Dose or Fluence

($mW \cdot sec/cm^2$ or mJ/cm^2)

Quantity of UV Light That Does the Work

Dose = I x T

I = Intensity (mW/cm^2)

T = Time (seconds)

1. As the flow rate increases, the number or output of the UV lamps must be increased proportionally to maintain the same disinfection requirements.
2. Therefore, the UV system must be designed for the maximum flow rate at the end of the lamp life.

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How Do We Measure What Dose It Takes To Inactivate a Microorganism

We Use a Collimated Beam Device

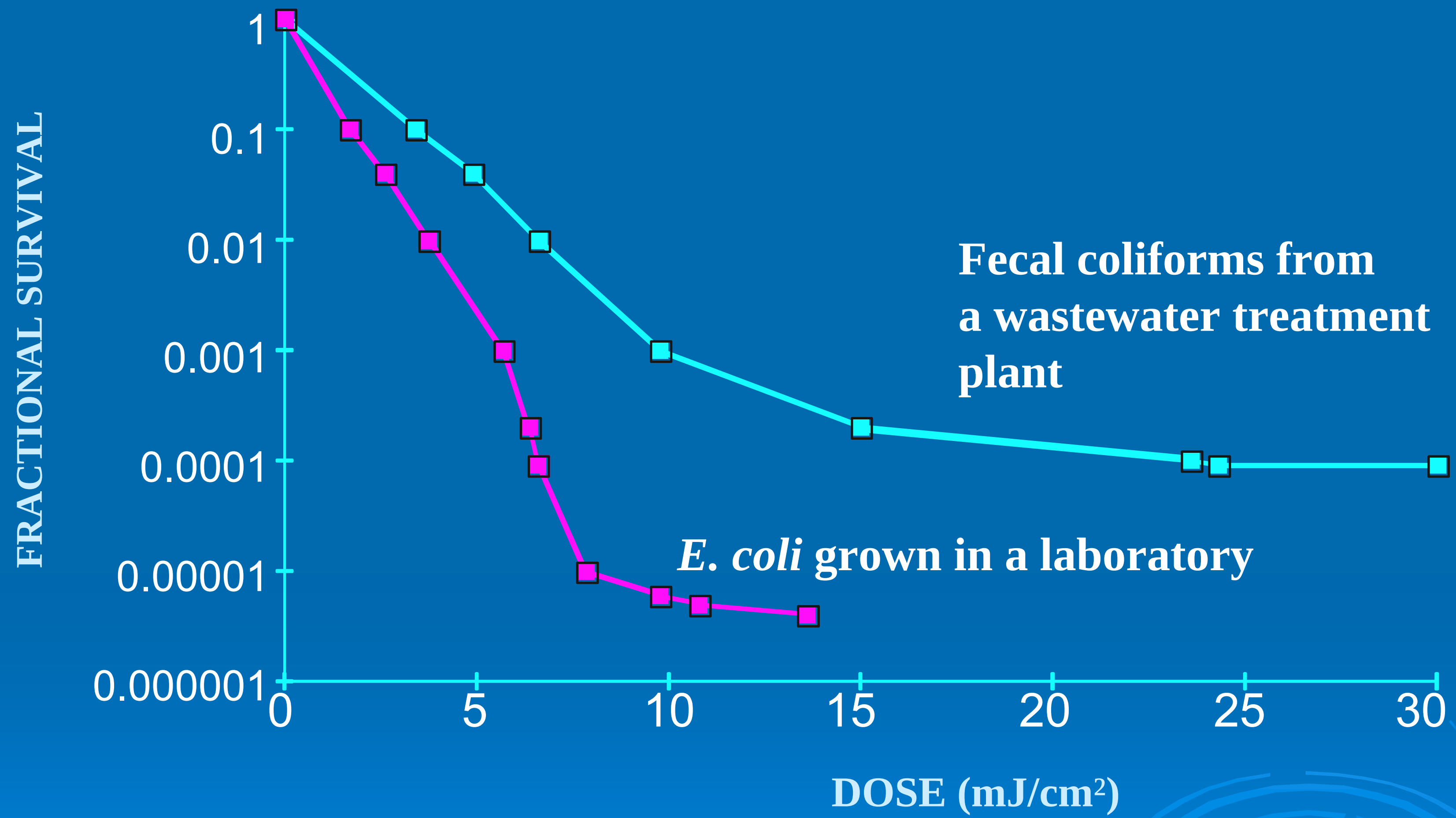
Collimated Beam Test

1. Mixed sample is exposed for fixed time (s)
2. Measure UV intensity with a radiometer
3. Calculate dose
4. Plot curve of log reduction vs dose

Collimator

Sample with Stir Bar

Dose Response Curve



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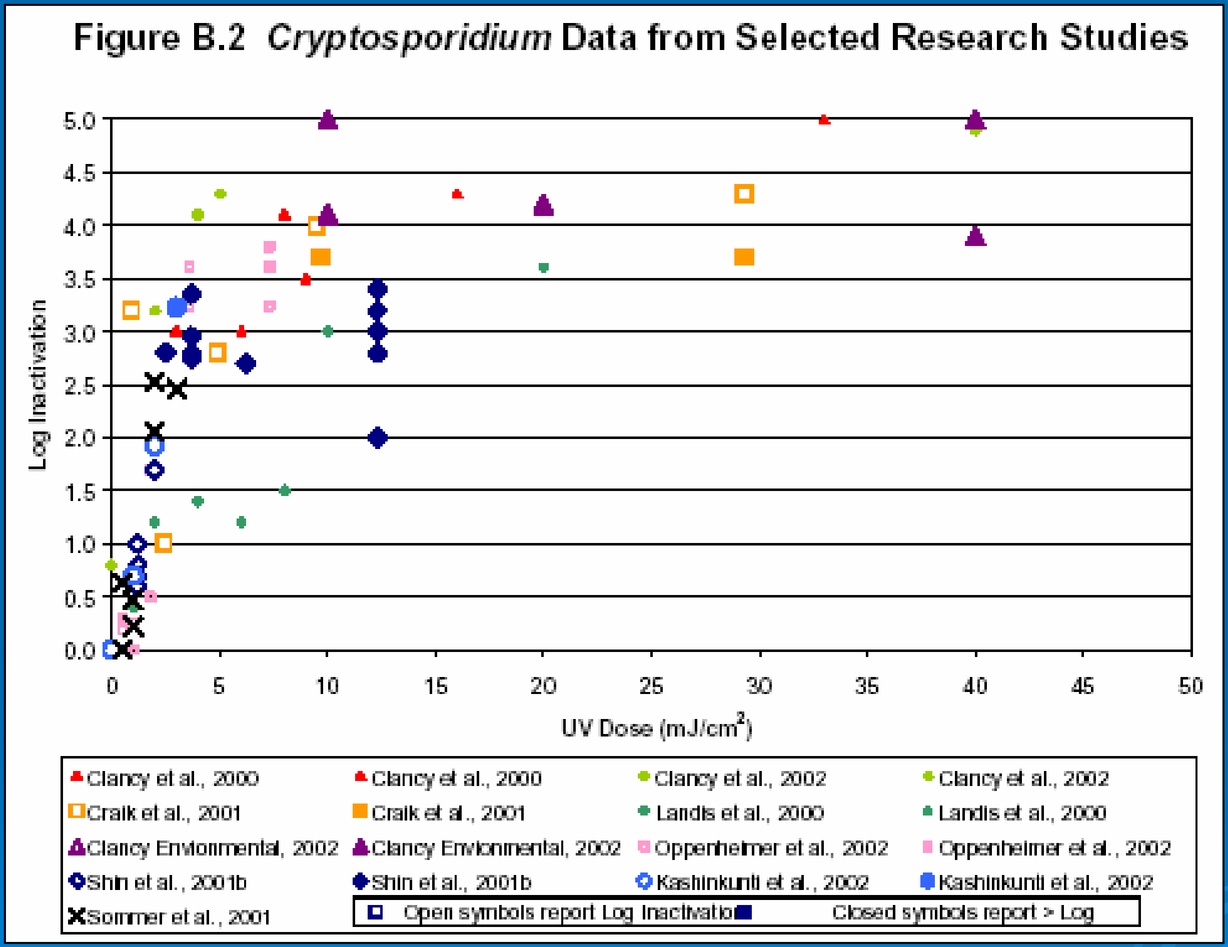
Pathogens' UV Sensitivity

Pathogen	Average UV Dose, mJ/cm^2 required for inactivation			
	1 log (90%)	2 log (99%)	3 log (99.9%)	4 log (99.99%)
Protozoa				
Cryptosporidium parvum oocysts	1.3	2.5	4.3	5.7
Giardia lamblia cysts	0.3	0.7	1.3	1.7
Bacteria				
Vibrio cholerae	0.8	1.4	2.2	2.9
Shigella dysenteriae	0.5	1.2	2	3
Escherichia coli 0 157:H7	1.5	2.8	4.1	5.6
Salmonella typhi	1.8	4.5	6	7.7
Shigella sonnei	3.2	4.9	6.5	8.2
Salmonella enteritidis	5	7	9	10
Virus				
Hepatitis A virus	5.5	11	17.2	23
Poliovirus Type 1	6	11.4	18.6	25.8
Coxsackie B5 virus	6.9	13.7	20.6	30
Rotavirus SA 11	8	16.9	24	36

Non-Pathogenic Organisms' UV Sensitivity

	Average UV Dose, mJ/cm^2 required for inactivation			
Pathogen	1 log (90%)	2 log (99%)	3 log (99.9%)	4 log (99.99%)
Bacteria				
Escherichia coli	3.5	4.8	6	7.2
Streptococcus faecalis	6.1	7.7	9	10
Bacillus subtilis spores	32.5	44.5	56	78
Enterococcus	8.3			
Fecal coliform	6.6			
Total coliform	6.7			
Clostridium perfringens	35.4			
Total heterotrophic bacteria	6.7			
Virus				
MS-2	19	40	61	
ΦX174	2.8	5.8	8.6	9.3
PRD-1	10	17	24	30
B-40	12	18	24	30

Summary of Available UV Inactivation Data for *Cryptosporidium*



US EPA UVDGM

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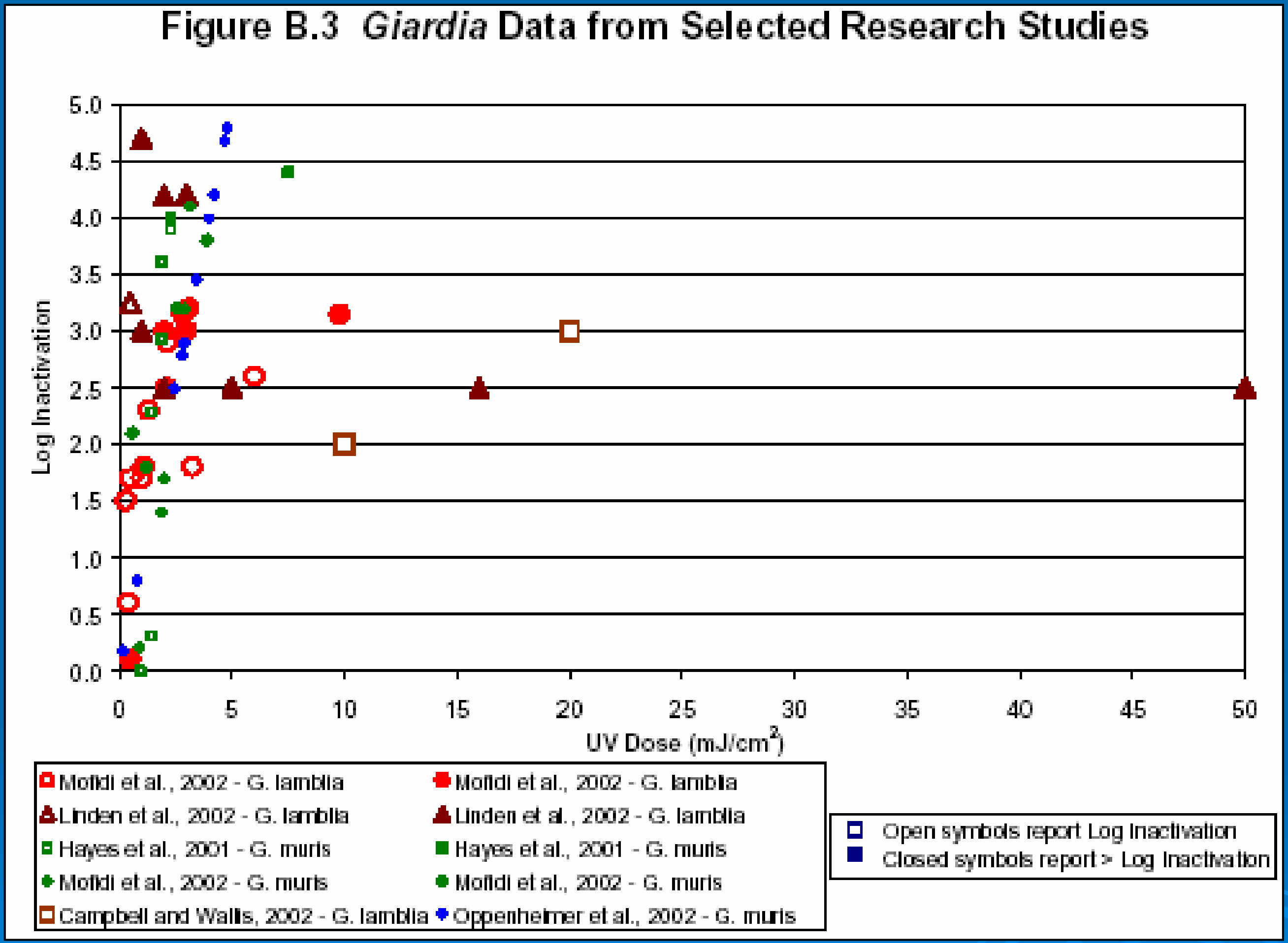
Summary of Available UV Inactivation Data for *Giardia*



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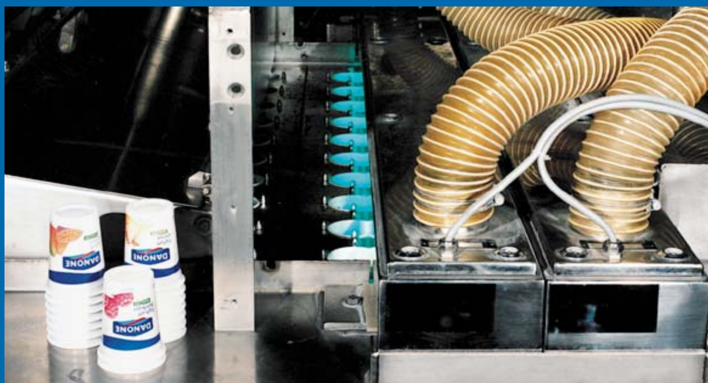
UV Markets/Applications

- Air Disinfection, Surface Disinfection, Food, UV Curing
- Groundwater Remediation/VOC Reduction (w/ Oxidation)
- Drinking Water Taste & Odor Elimination (w/ Oxidation)
- Wastewater Disinfection
  - Traditional
  - Recycle / Reuse
- Drinking Water Disinfection
  - Surface Water
  - Groundwater
  - ASR Wells

Food Applications

Disinfection of yogurt cups



Disinfection of cheese

Disinfection of buckets

Disinfection of transport boxes

Disinfection of conveyor belts

Disinfection of sealing foil

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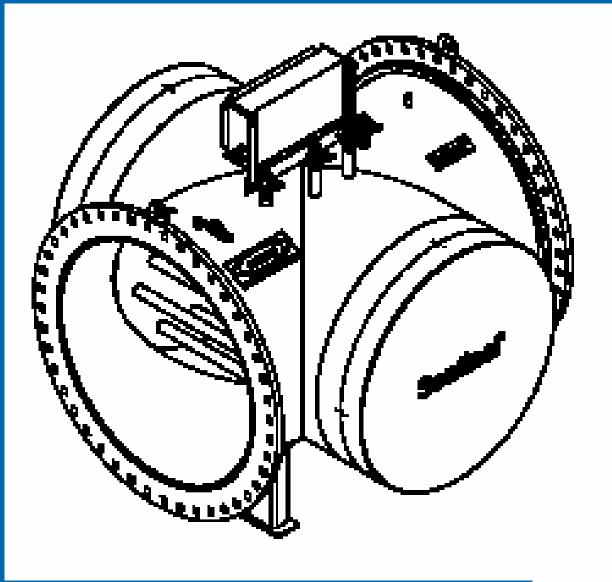
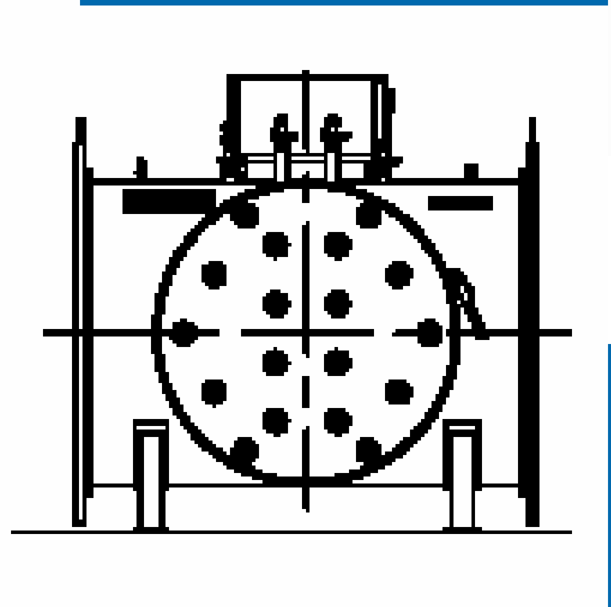
Groundwater Remediation Advanced Oxidation





Reactors used in groundwater remediation (VOC destruction)

UV Disinfection of Wastewater

C^{3}150

C^{3}500

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UV Disinfection of Drinking Water

UV Reactor Design

- Lamps
- Ballasts
- Reactor Configuration
- Sensors
- Cleaning System
- Alarms

Low and Medium Pressure Lamps

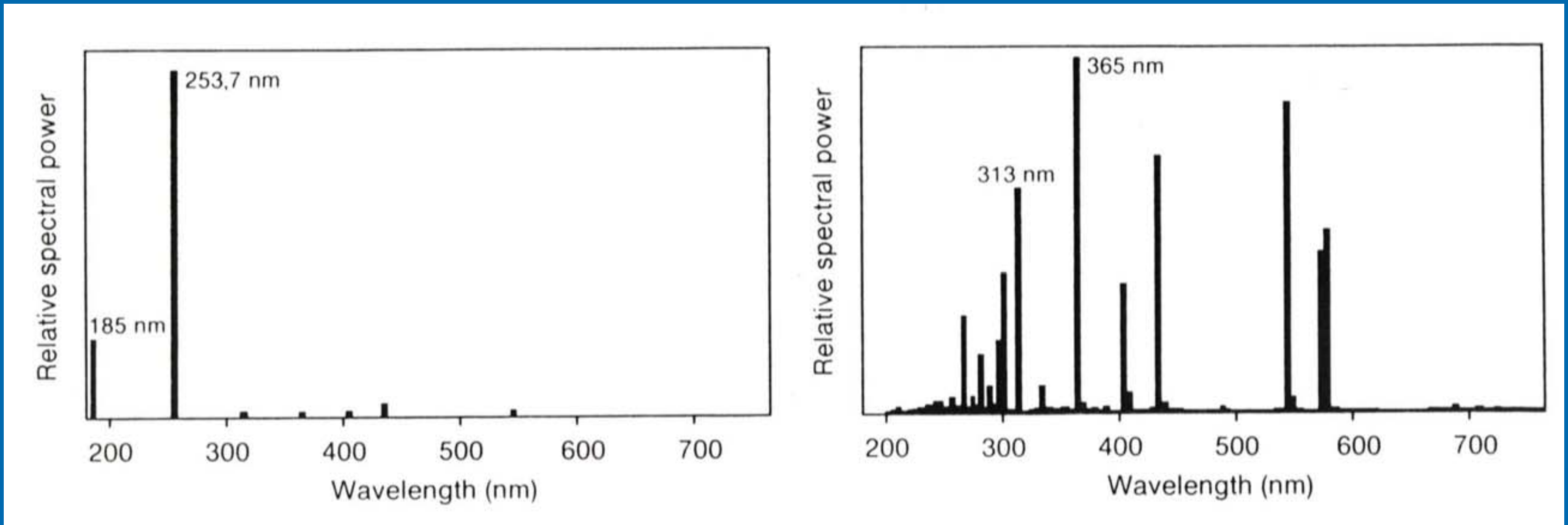
Low Pressure Mercury Lamp

- 25 to 40 percent conversion of power to germicidal UV light
- Operating temperature of 40 °C to 160 °C
- Minimum life of one year

Medium Pressure Mercury Lamp

- 10 to 15 percent conversion of power to germicidal UV light
- Operating temperature of 600 to 800 °C
- Maximum life of one year

Comparison of a Low and Medium Pressure Mercury Lamp Spectrum



Low Pressure

Medium Pressure

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Lamp Comparison

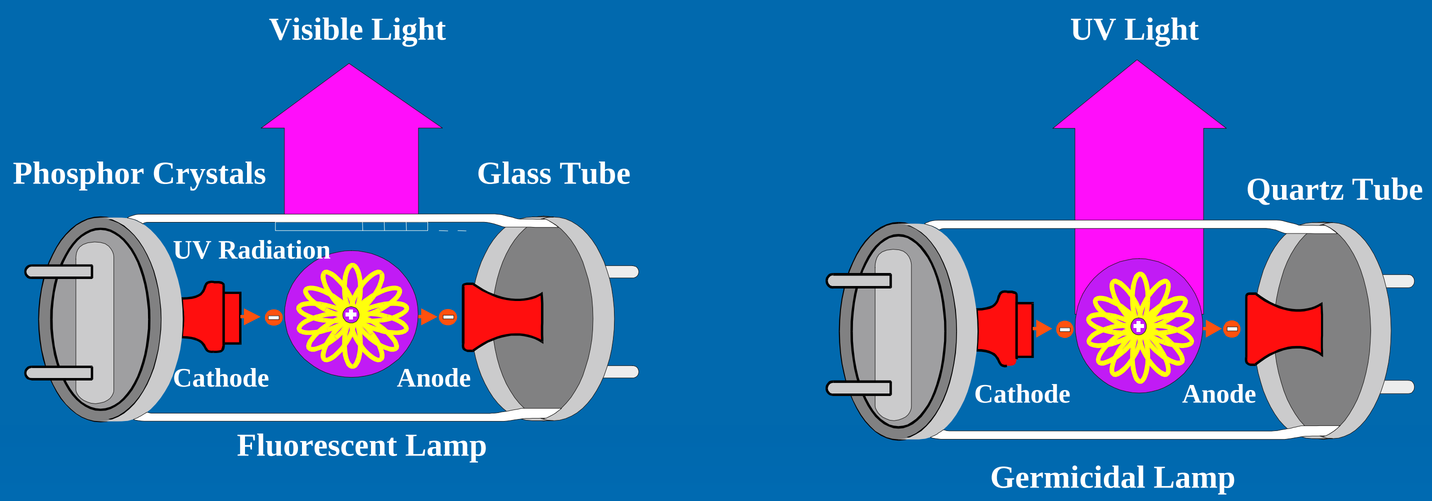
- **Medium Pressure Lamps**
  - **Primarily Drinking Water**
  - Fewer lamps
  - Less lamp related maintenance over the life of the system
  - Compact design - small foot print
    - Easily retrofitted into existing drinking water systems saving money in design and construction
- **Low Pressure Lamps**
  - **Primarily Wastewater**
  - Higher electrical efficiency – lower power consumption
  - Output can be effected by water temperature
  - Usually not economical to provide a UV Sensor for every lamp

Lamp Output

- Low Pressure Lamps
  - 65 W to 1200 W maximum
- Low Pressure Amalgam Lamps
  - Up to 600 W
- Medium Pressure Lamps
  - Up to 30,000 W maximum

Fluorescent Lamp and Germicidal Lamp

UV Energy Is Generated By A Germicidal Lamp

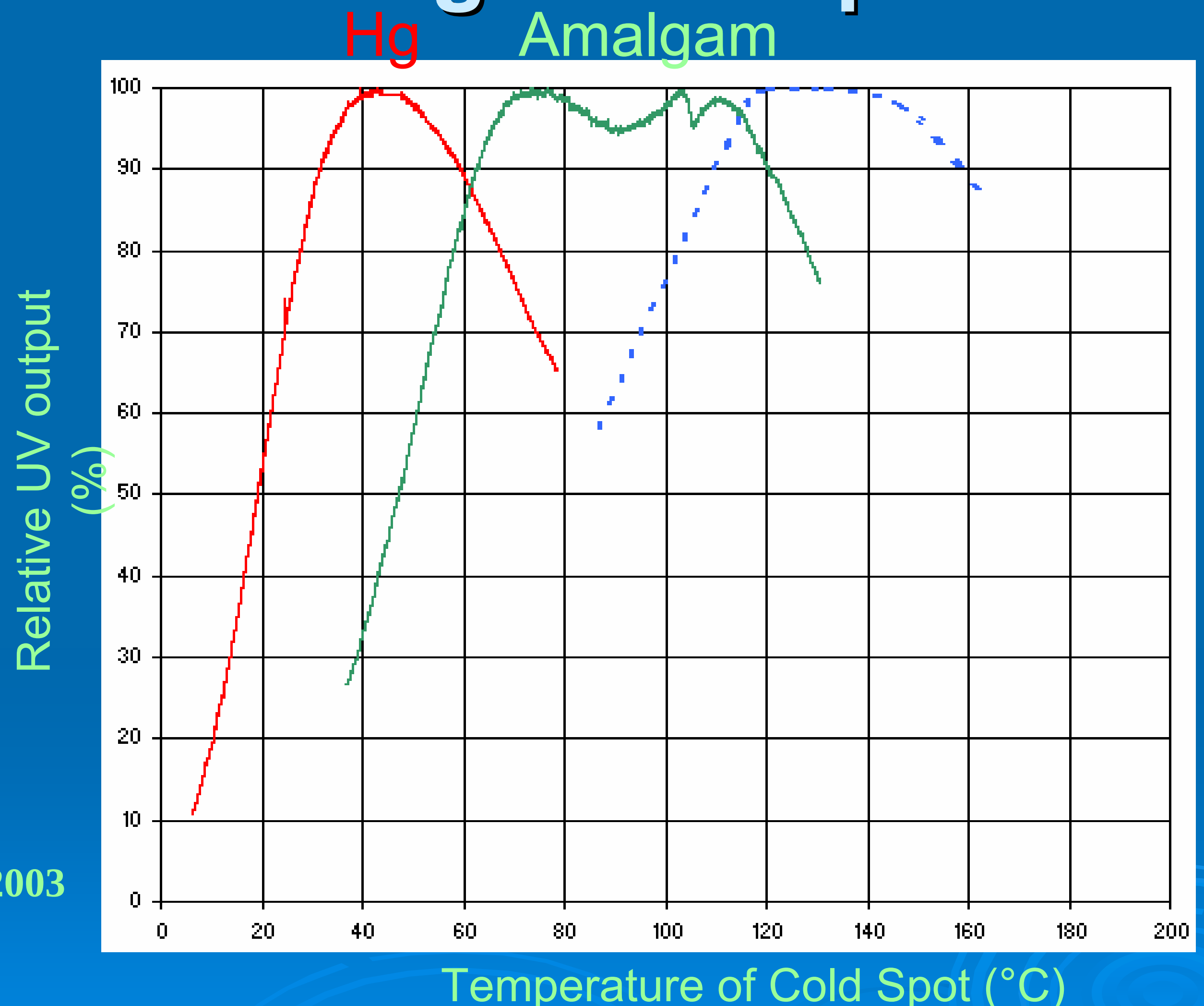


Germicidal lamps operate electrically on the same principle as fluorescent lamps.

Terminology
Low Pressure Mercury Lamps

- Regular UV Lamp (LOLO) e.g. G64T5L
- High Output Lamp (LPHO)
- Instant Start Lamp
- Rapid Start Lamp
- Continuous Heated Electrodes
- Amalgam Lamp
- Coated Lamp

Optimum UV Output of a Standard and Amalgam Lamp



Philips Lighting 2003

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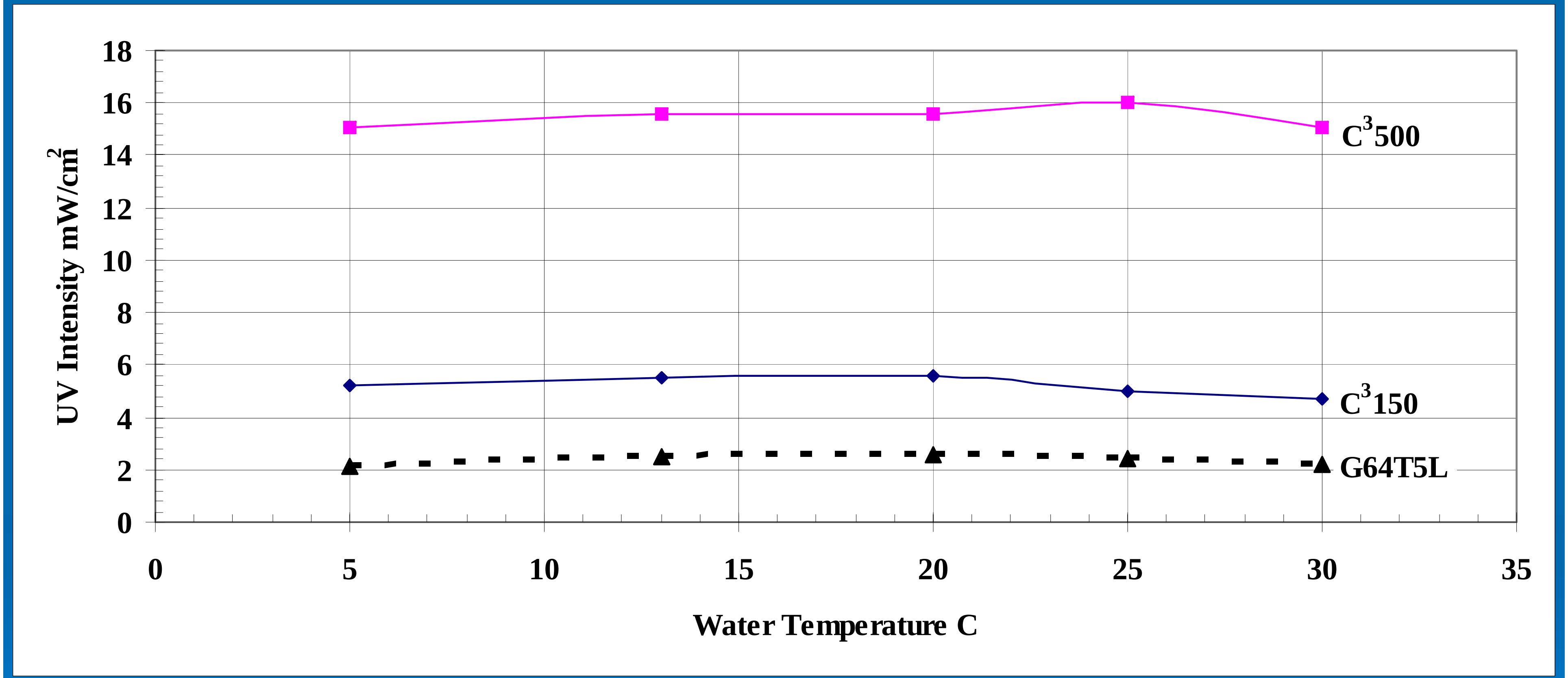
Effect of Temperature on Lamp Output



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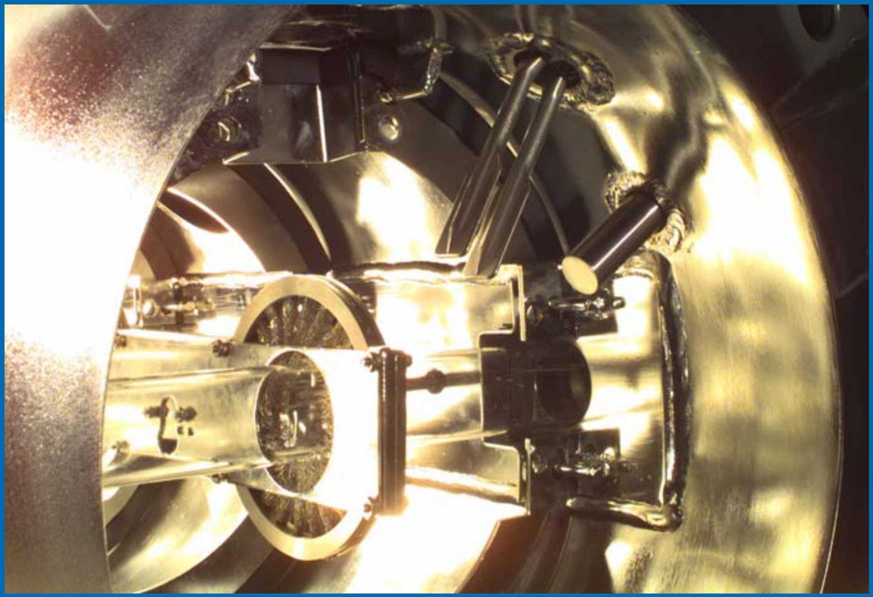
Construction of a Medium Pressure Mercury Lamp

Medium Pressure Lamp

High Intensity
Medium
Pressure Lamps



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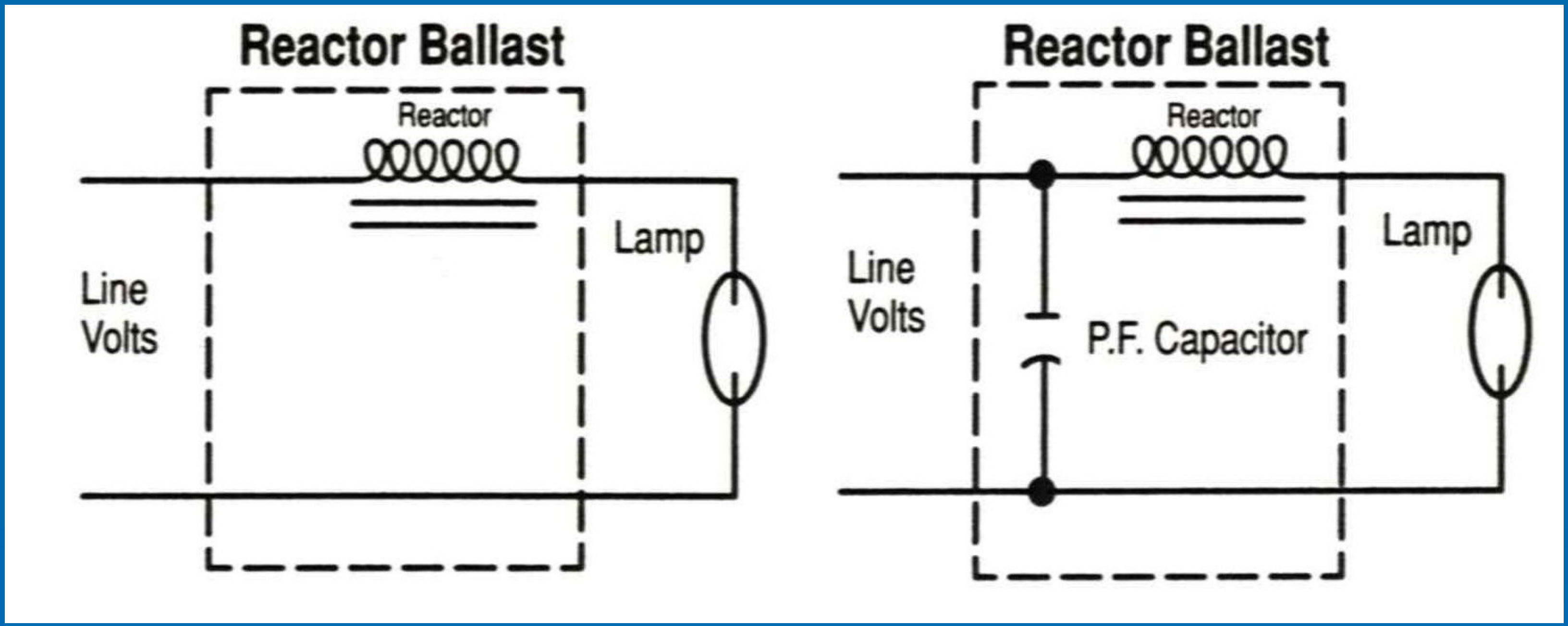
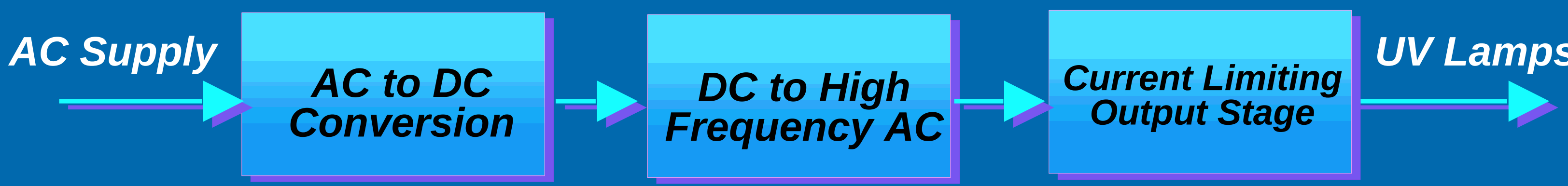
Core/Coil Ballast



How Do Electronic Ballasts Work?



ELECTRONIC BALLAST
(Functional Block Diagram)

Electronic Ballast

The electronic ballast has completely replaced the core-coil ballast for operating low-pressure mercury lamps. The advantages of the electronic ballast are:

- Size
- Weight
- Energy Saving
- Optimum Lamp Operation
- Power Conditioning

Electromagnetic Power Supply for Medium Pressure Lamps

- Electromagnetic power supply

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Electromagnetic Ballasts

- Fully variable
- More tolerant of line voltage variations (-30% - +10%)
- More reliable and robust
- Used in medium pressure UV systems

Low Pressure Mercury Lamp Electronic Power Supply

C^3150

C^3500

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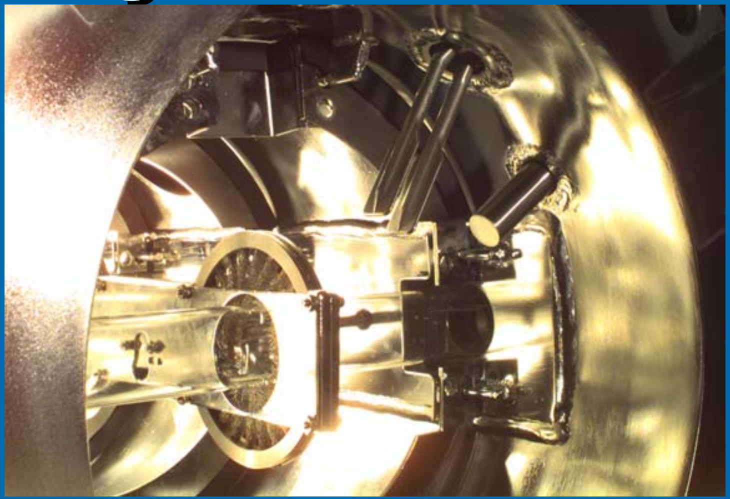
Wiper Systems



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UV Sensors

- Ensures adequate dose is being applied
- Continuous on-line monitoring of UV intensity
- Mounted in dry-well configuration
  - No system down time for sensor recalibration and replacement
- One sensor per lamp for medium pressure lamp systems, one per bank for low pressure/amalgam
- Must respond only to light in the germicidal range
- Sensors must be traceable to international standard (NIST or DIM/DVGW)
  - Linearity ≤ 1%
  - Temperature Drift ≤ 2.5%
  - Long term Stability ≤ 1% per 1,000 hours

UV Intensity Sensors

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UVT Monitors

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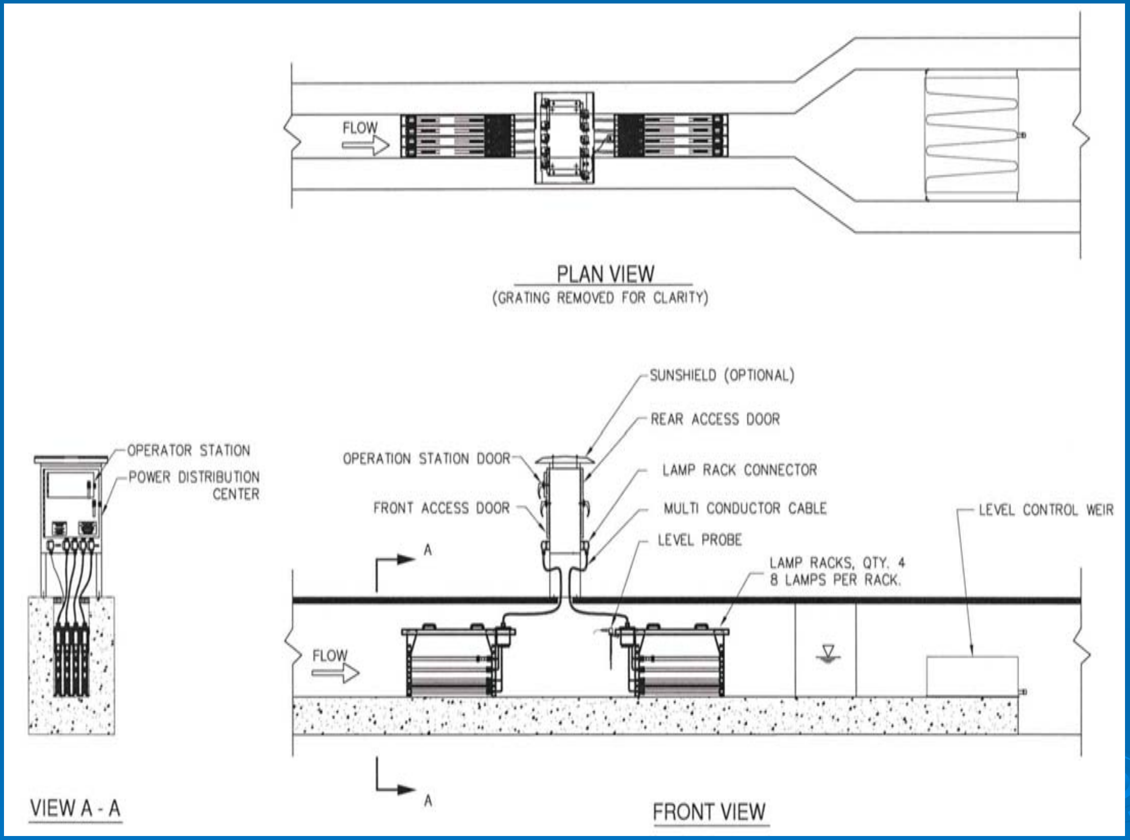
Temperature and Level Sensors



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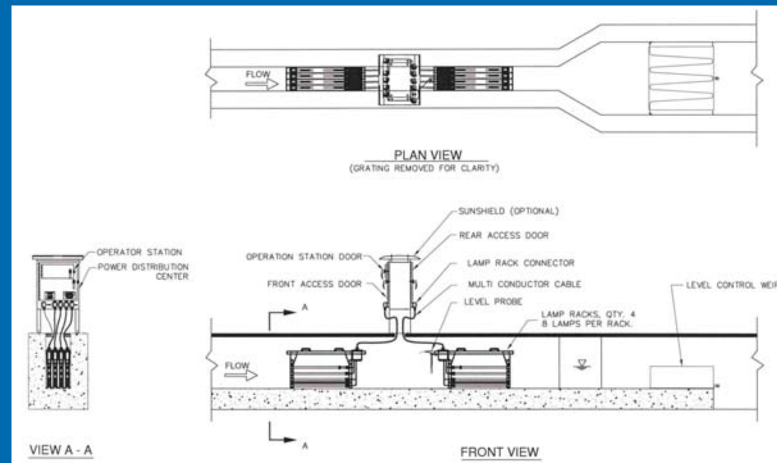
Chambers or Open Channel



Typical UV Disinfection Reactor for Drinking Water

- Materials of Construction
  - High quality 316L Stainless Steel Vessel
  - Viton seals in high temperature and UV exposure locations
  - EPDM seals for durability and longer life
- Flexible Lamp Configuration
  - Configuration can be selected to accommodate %T and pressure drop requirements

Monitoring and Alarms

- Continuous Monitoring
  - Probes calibrated monthly
  - Transmittance/Turbidity verified weekly if using continuous recording device
- Disinfection System Monitoring
- Alarms
  - High Priority
  - Low Priority

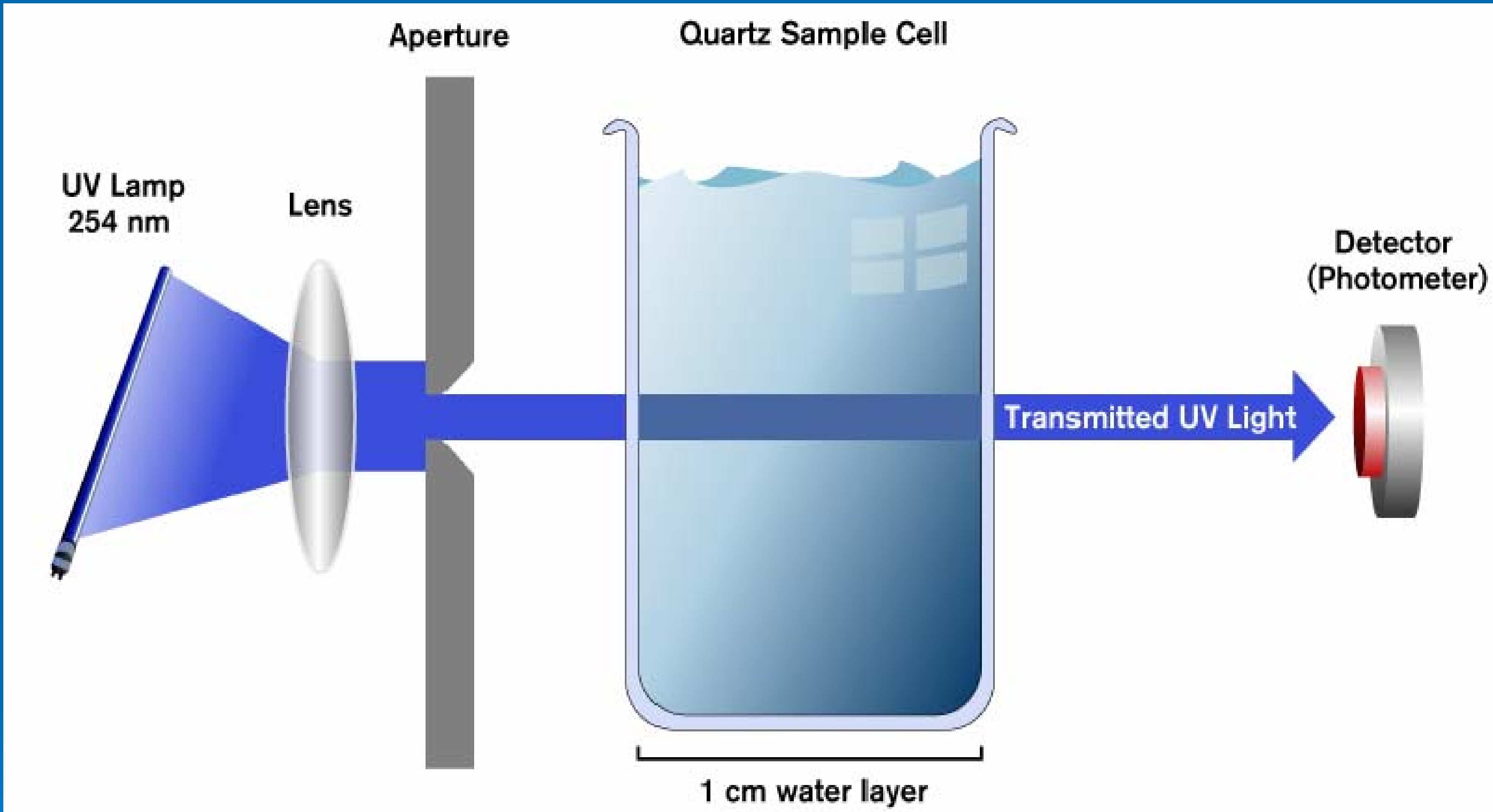
Types of Alarms

- High/Low Flow
- High/Low Intensity
- High Pressure
- High Temperature
- Moisture Alarm
- Lamp Failures Single and an a Joining
- Ballast Failures
- Power Failure
- PLC Failure

Factors Affecting UV Disinfection

- UV Transmission (Minimum) Examples
- Turbidity, Total Suspended Solids (Maximum) Examples
- Alkalinity (Cleaning System)
- Hardness (Cleaning System)
- Dissolved Ions (Cleaning System) Example: Iron
- Flow Rate (Maximum, Average, and Minimum)
- Permit Limit (Number of Lamps) Examples
- Temperature (Wastewater and Air) Examples
- Redundancy
- Space
- Power Consumption (Type of Lamp)
- Equipment Design Factors Examples

UV Transmittance



Typical UV Transmittances

Water	UVT_{254}, percent
Filtered potable	85 - 99
Raw potable	20 - 99
Filtered secondary effluent	65 - 80
Secondary effluent	40 - 75
Primary effluent	5 - 35
Raw wastewater	5 - 10

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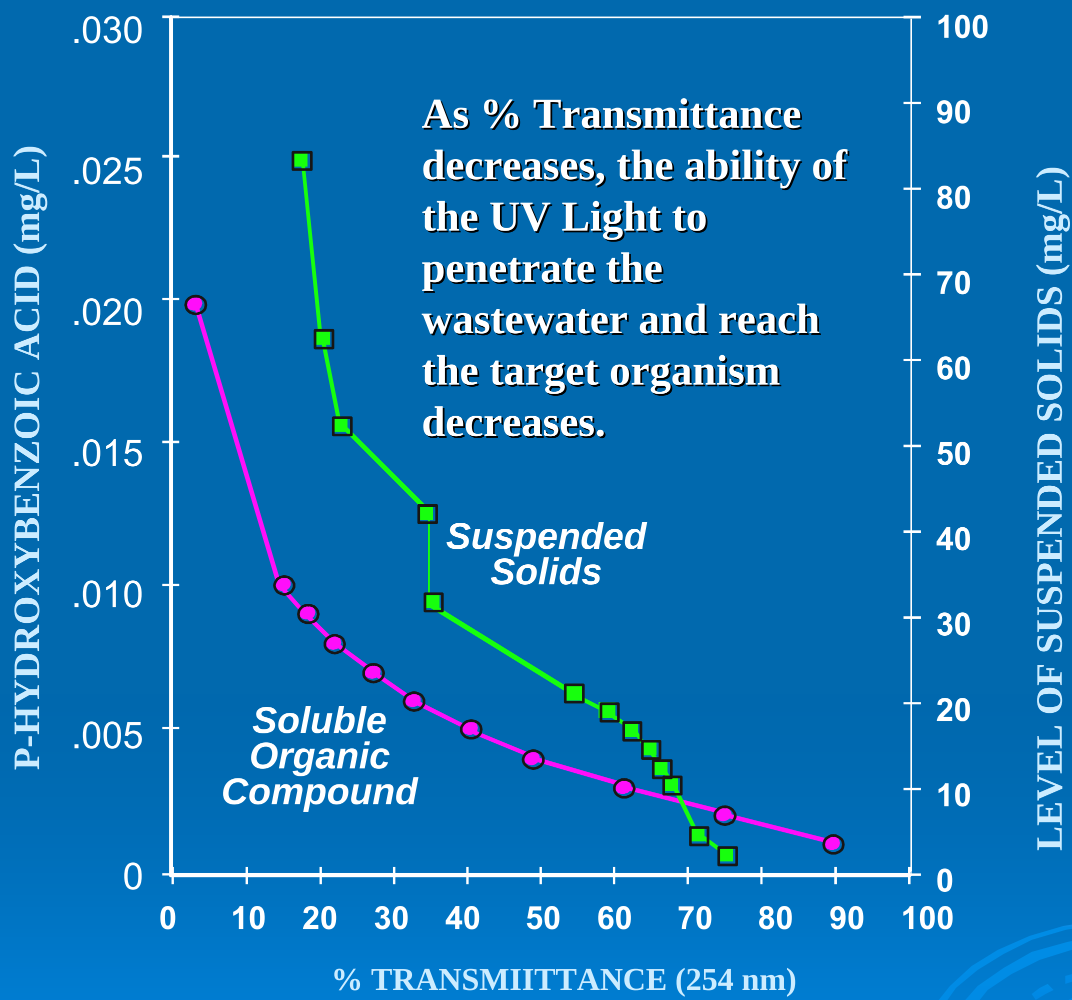
Effect of Organic Compounds or TSS on UV Transmittance



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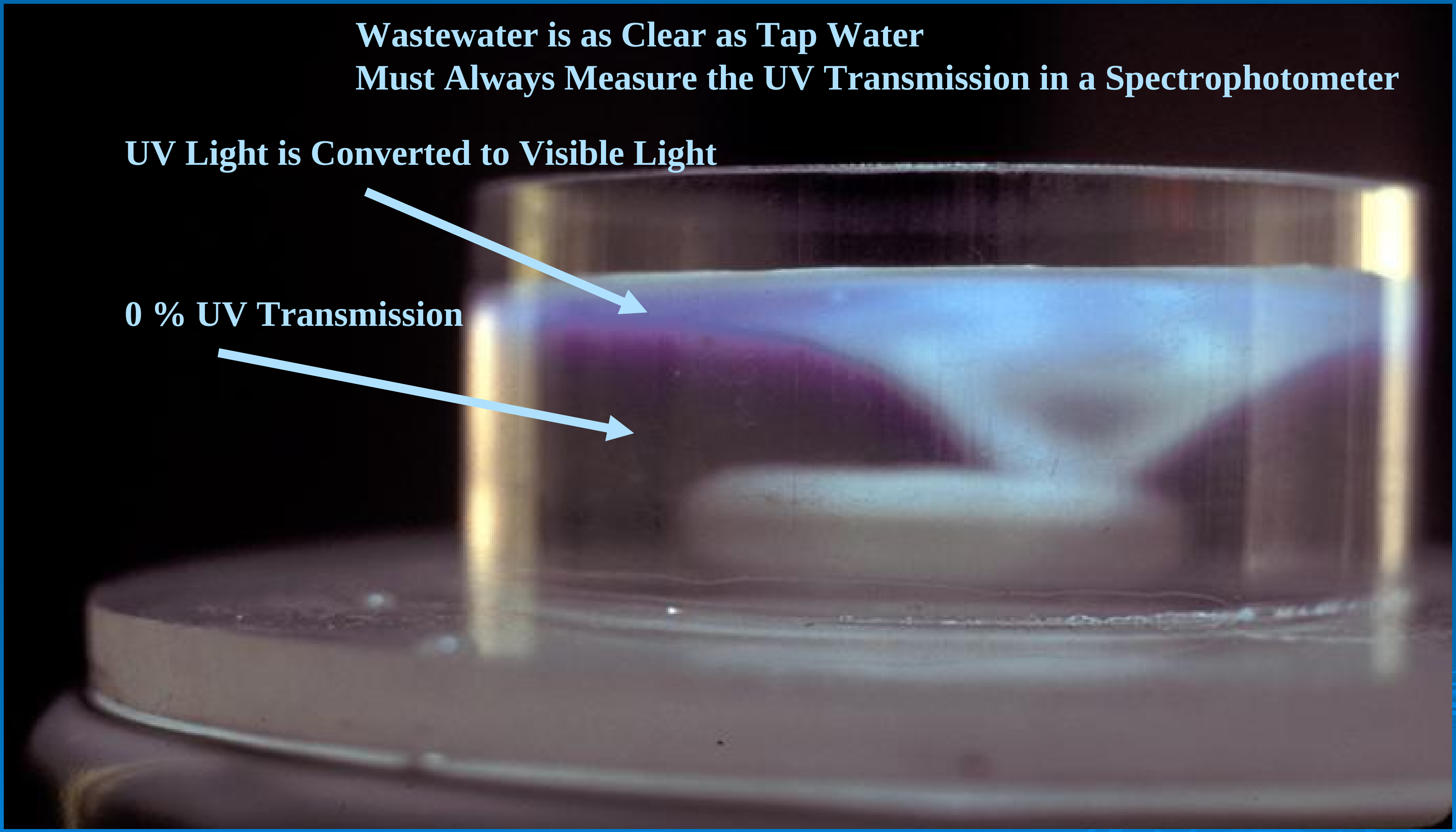
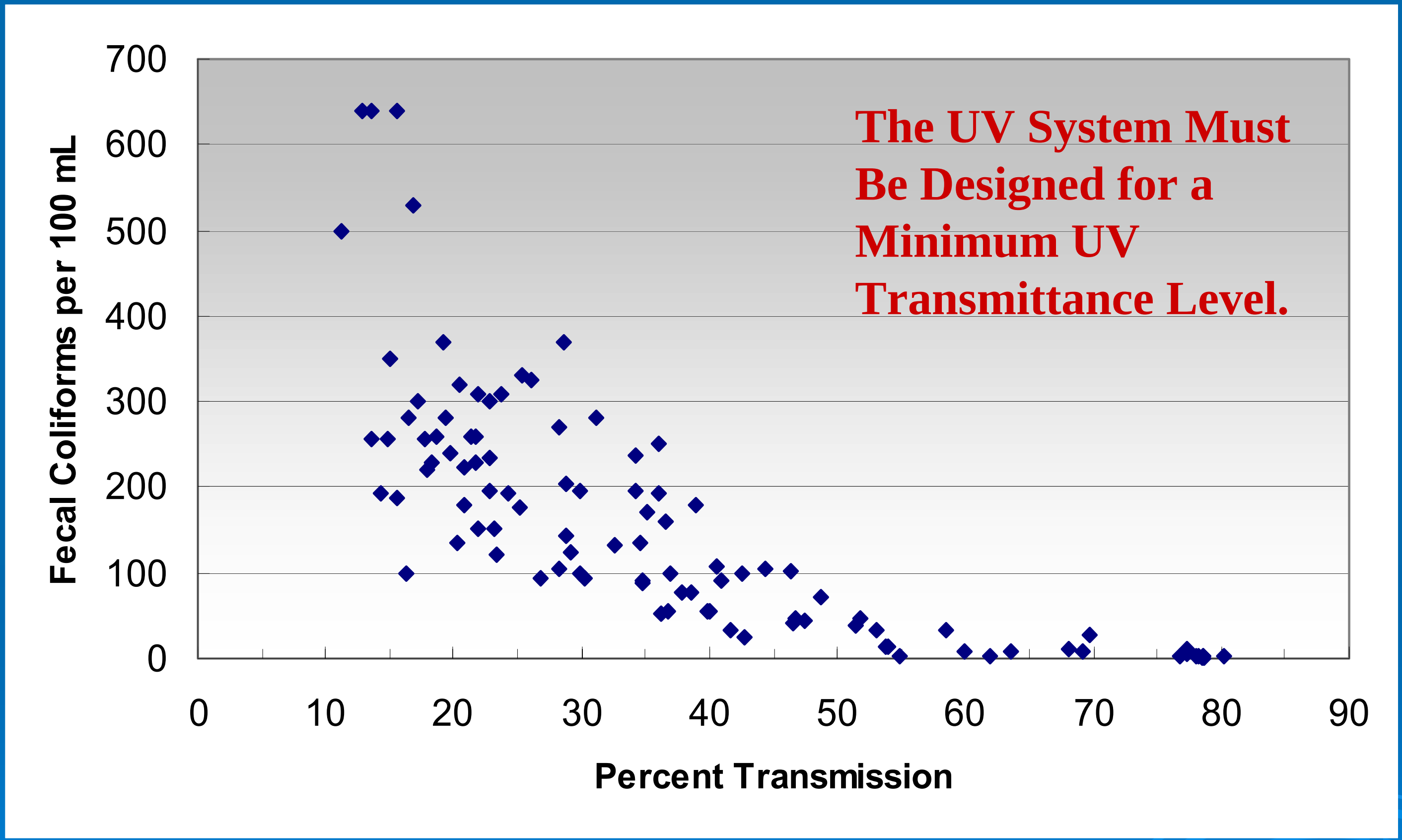
The UV Light is Being Converted to Visible Light by an Unknown Organic Compound



Effect Of Varying % Transmittance On Disinfection



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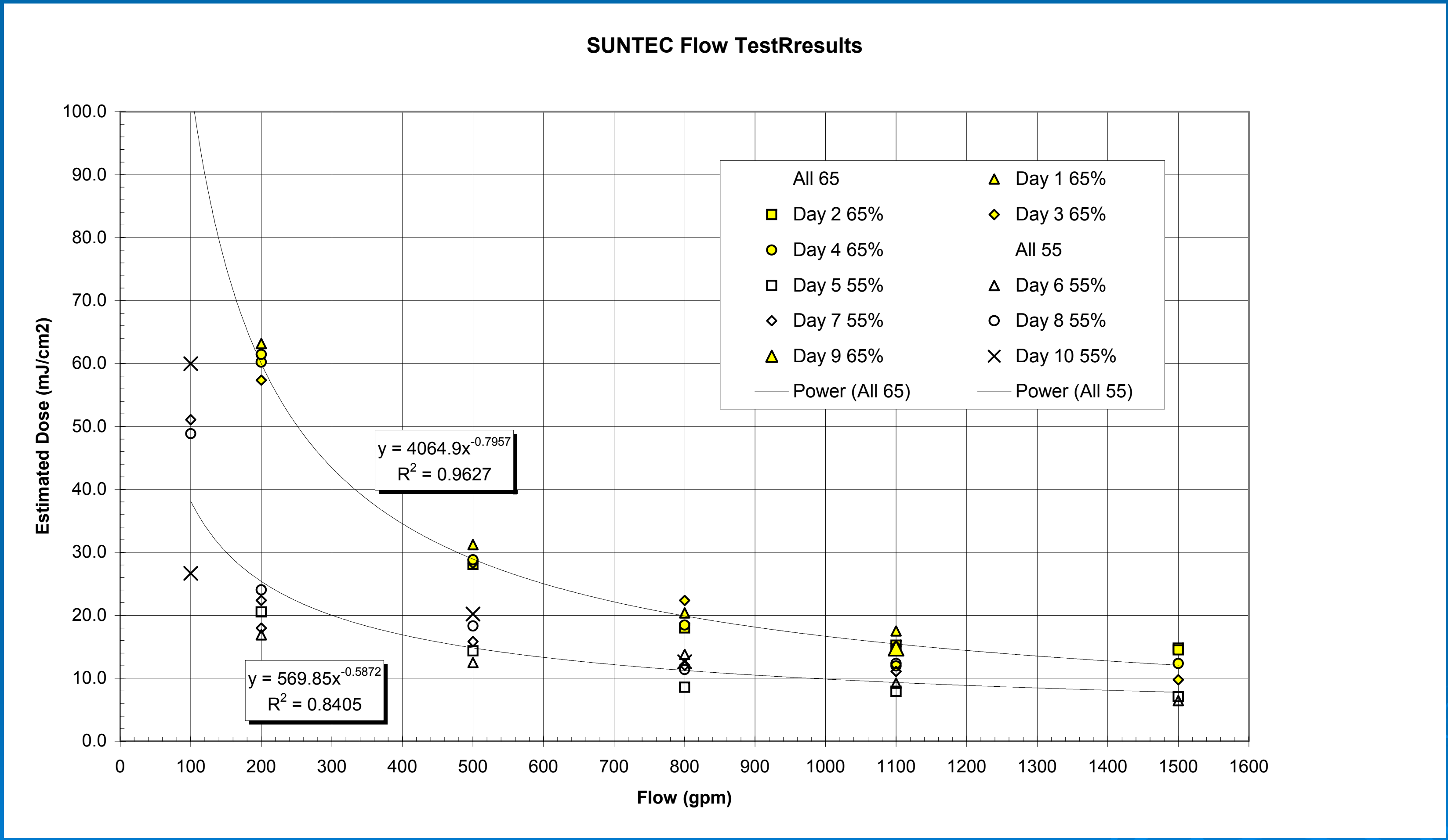
Effect of UV Transmission on UV Dose



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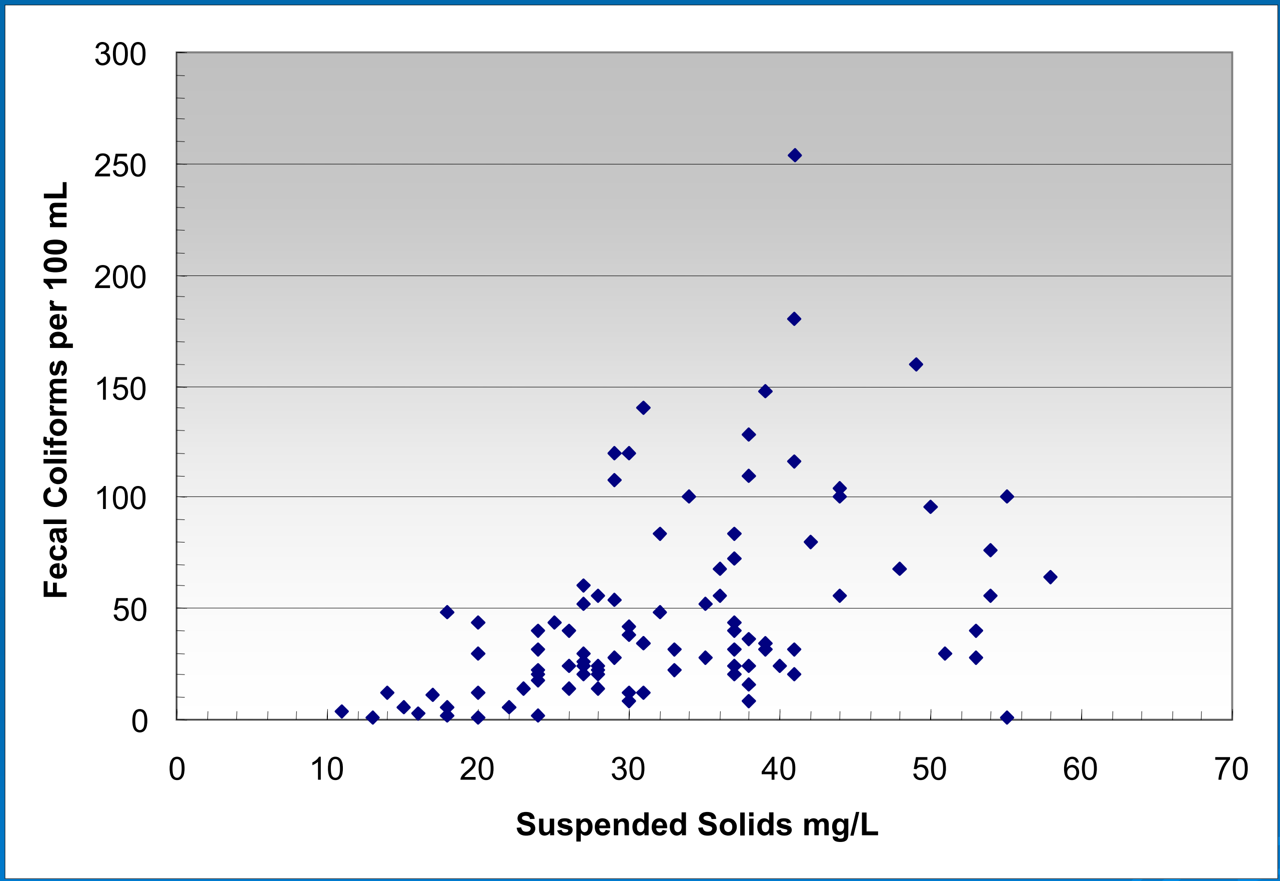
Effect Of Suspended Solids On Disinfection



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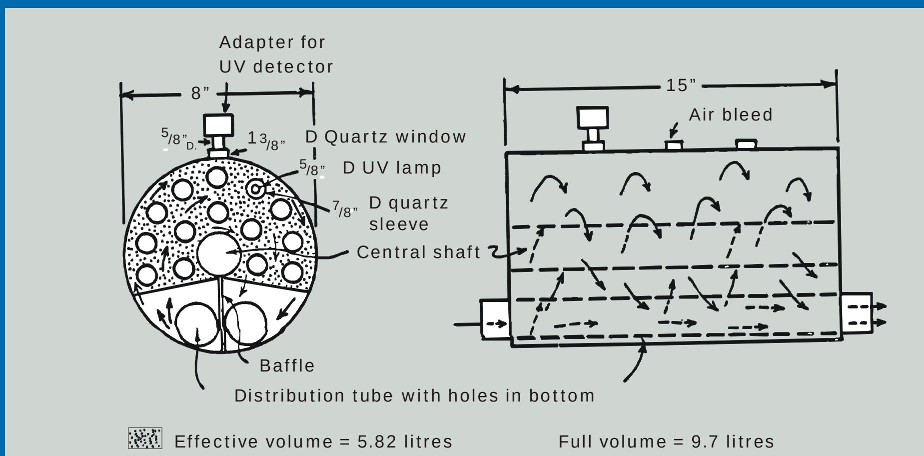
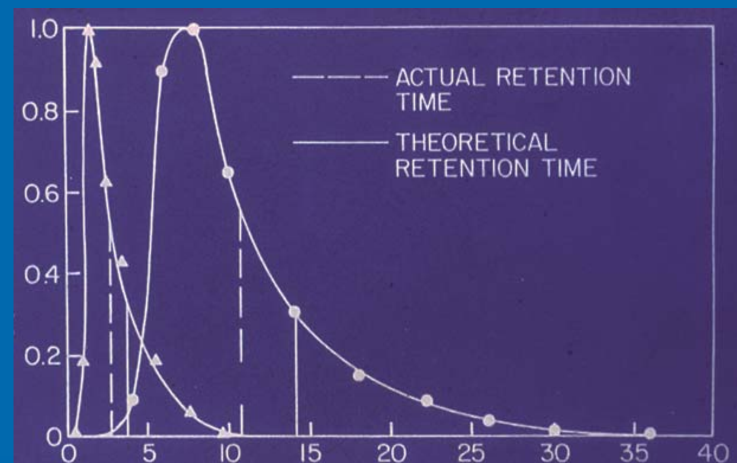
UV System Hydraulics
Poor Hydraulics





Unit #1

Unit #1 Hydraulics

Johnson and Qualls, 1981

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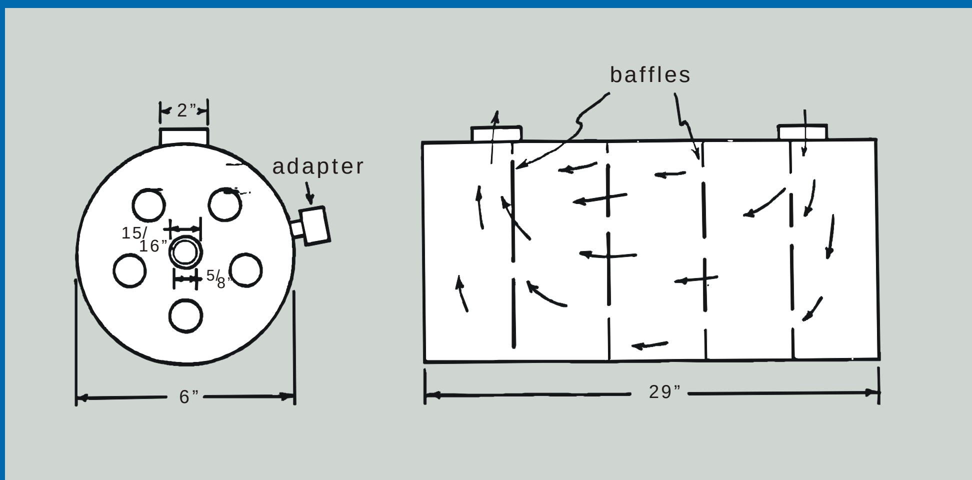
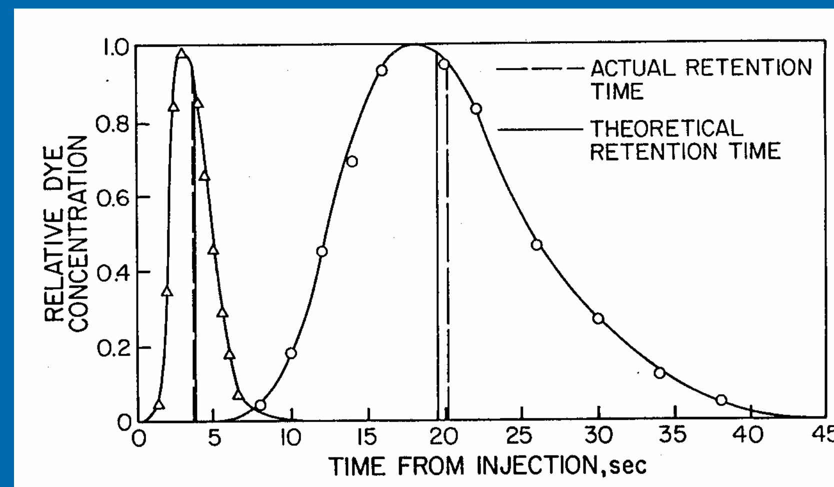
UV System Hydraulics
Good Hydraulics





Johnson and Qualls, 1981

Unit #2

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Comparison of Units #1 and #2 with a Bioassay using *E. coli*

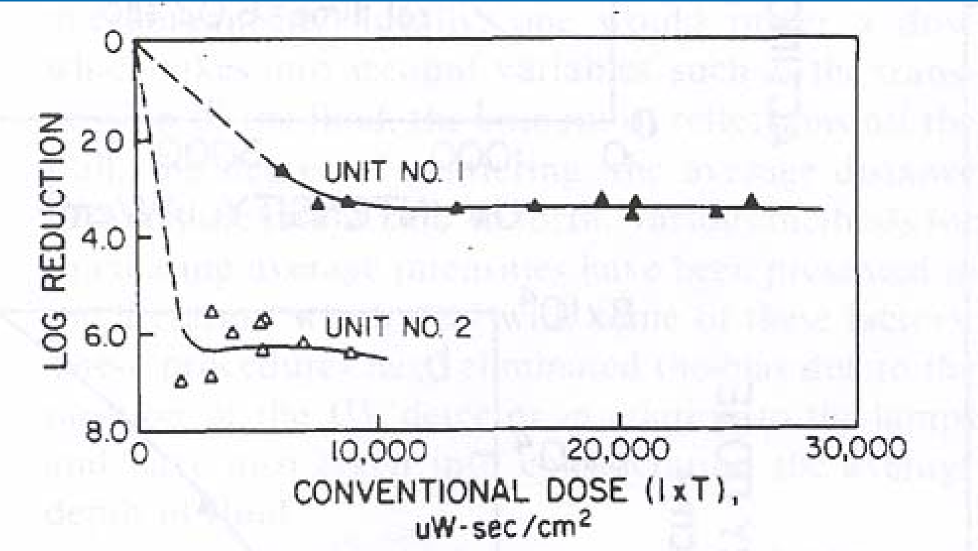

Figure 5. Log reductions of E. Coli vs. conventional dose

Johnson and Qualls, 1981

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UV System No Cleaning

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Manual Cleaning

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Automatic Cleaning

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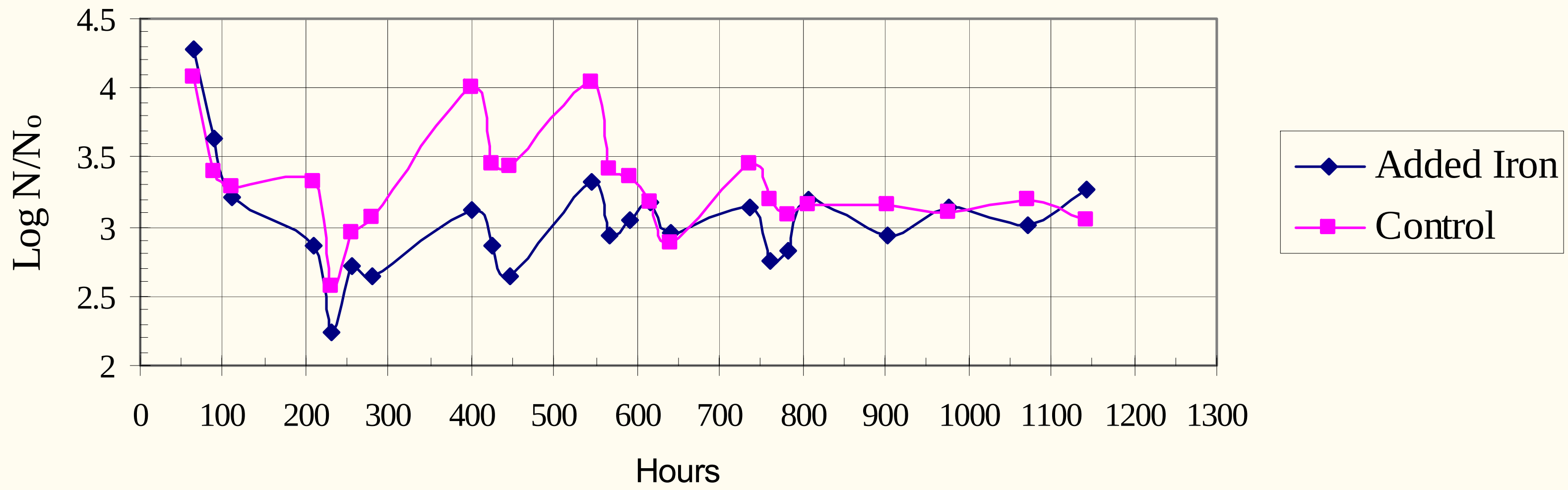
Effect of the Automatic Cleaning System

Figure 5: Log of N/N_o of the fecal coliforms after the UV units with and without added iron.



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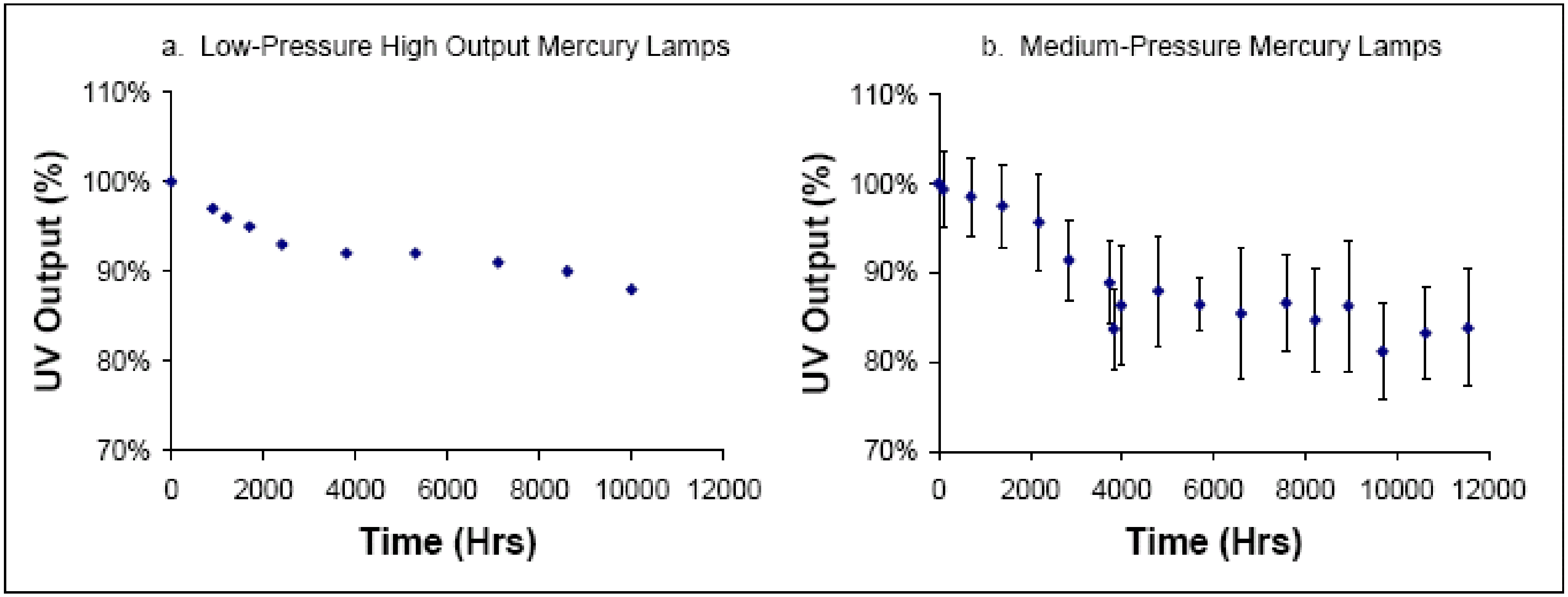
Water and Wastewater Source

1. What is the minimum UV transmission
2. Are there industrial inputs
3. Filtration
4. What is the coagulant

Disinfection Requirement

- Drinking water
- Wastewater discharge to a river, lake etc.
- Water reuse

Low and Medium Pressure Lamp Life



Source: (a) Adapted from WEDECO, (b) adapted from Linden et al. (2004)

US EPA UVDGM

Bioassay for a UV System for Wastewater

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What is a Bioassay?

- It is a microbiological method of determining the delivery of UV light by a UV system under specific conditions of the UV unit and the water.

Why Perform a Bioassay

- With the introduction of electronic ballasts and proprietary lamps all the UV systems are different.
- Allows the comparison of low and medium pressure UV lamps
- A standardized bioassay allows the direct comparison of different UV systems and this allows the consultant to tell each manufacturer how many lamps they must use to deliver a specific UV fluence (Dose)
- Under the proper conditions a bioassay insures that the UV fluence or UV dose claimed by the manufacturer is actually delivered by the UV equipment.
- A bioassay confirms the UV output of the UV lamps under actual operating conditions as versus measurements in air.
- A bioassay eliminates any disagreements that may take place over how to calculate the UV fluence (Dose) within a reactor.

Factors Measured by a Bioassay

- UV Transmission
- Hydraulics (Retention Time, Turbulence)
- Wastewater Source
- Disinfection Requirement (UV Fluence or Dose)
- Lamp Output (New, End of Life, % Germicidal Light)

How is a Bioassay Performed?

- Basic Steps in a Bioassay

1 Select a microorganism that is UV resistant, not pathogenic and easy to grow or is already present in the effluent

2 Irradiate the microorganisms with exact UV fluences (intensities) to create a calibration curve of UV fluence or dose versus log inactivation

3 Set-up a UV system to simulate worst case conditions of the lamps and water

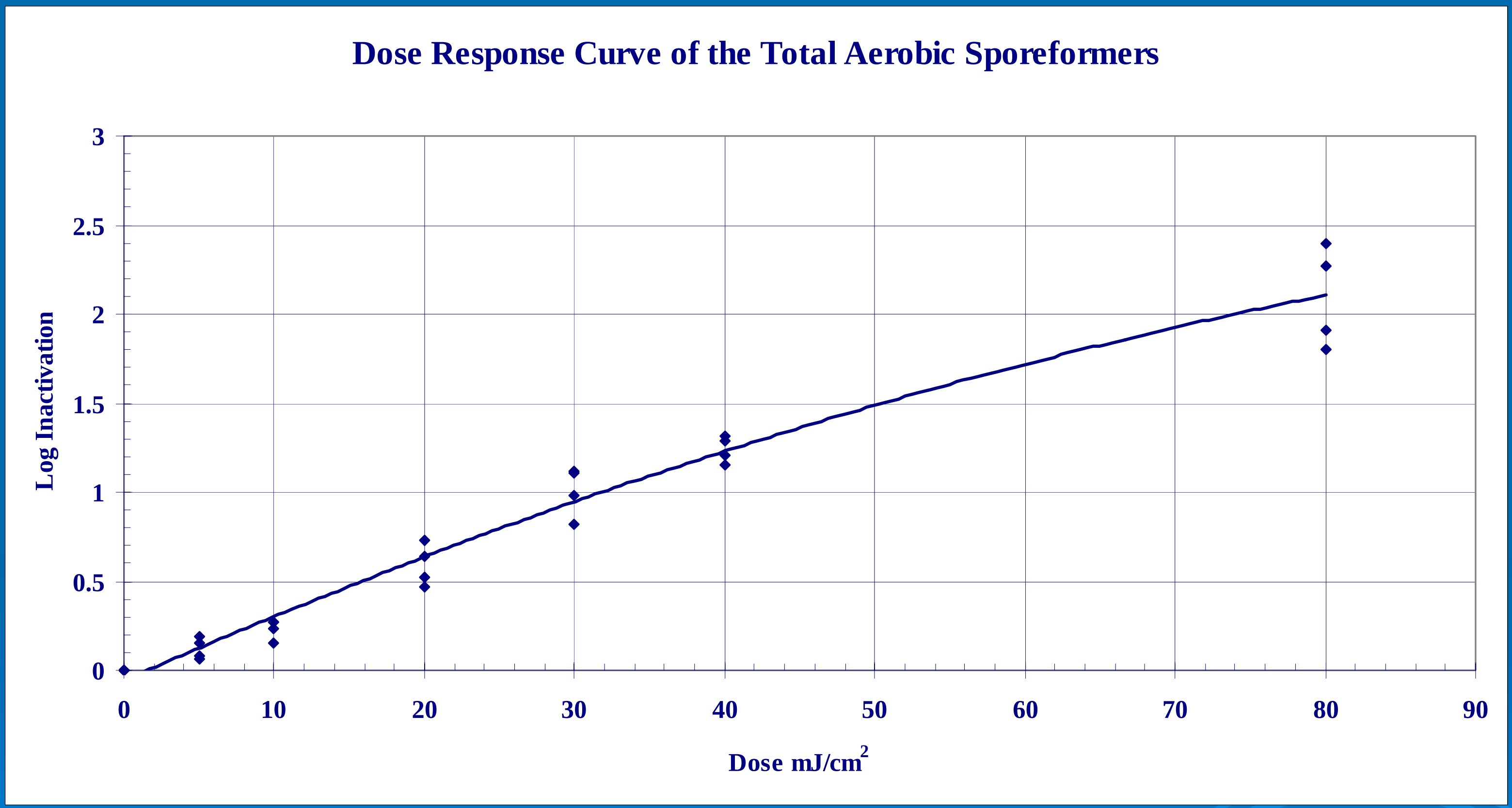
4 Put the calibrated microorganisms through the UV unit at different flow rates and measure the numbers in the influent and effluent to get the log inactivation

5 Using the calibration curve create a curve of flow per lamp versus UV fluence or dose

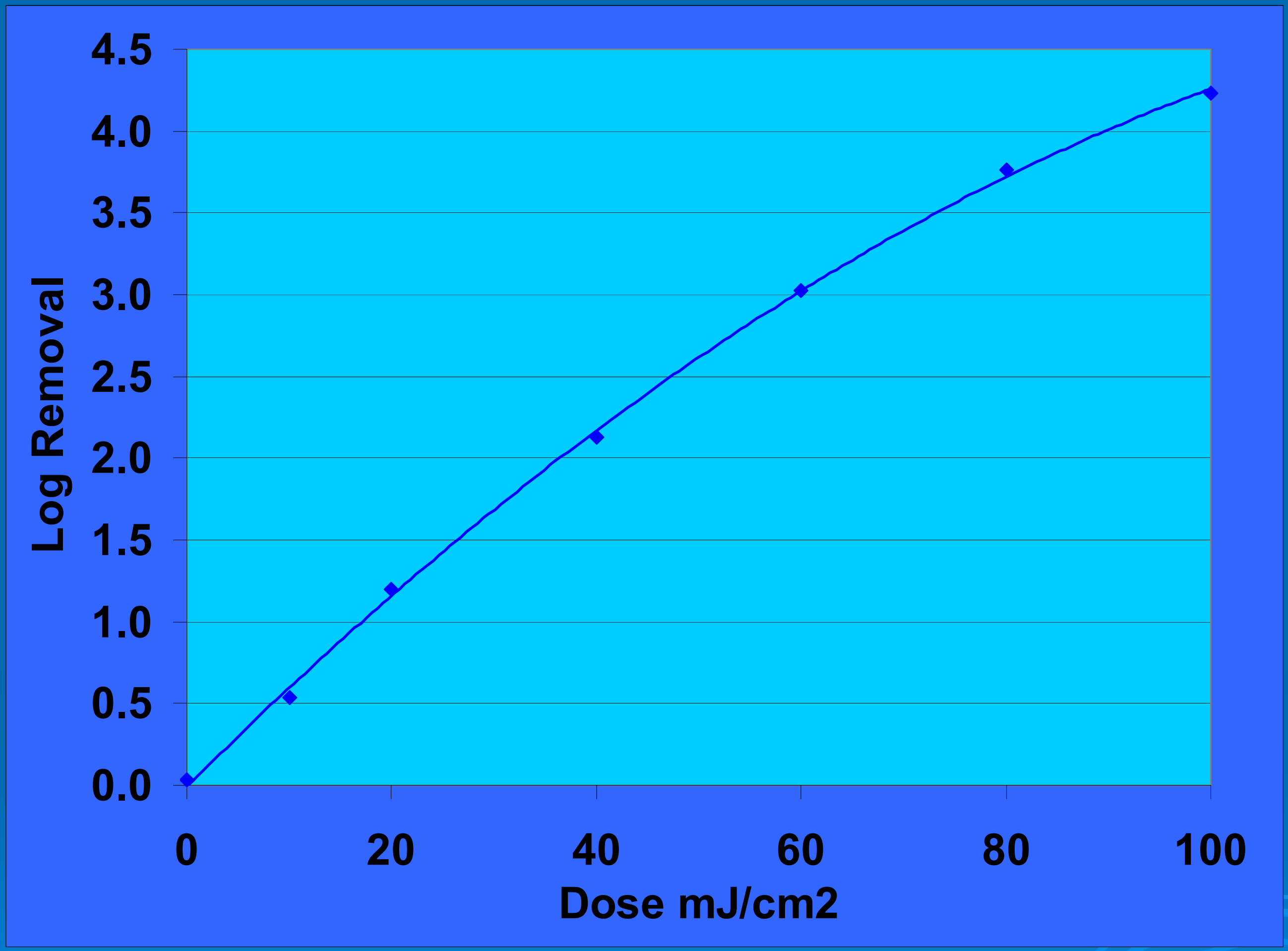
6 Create a report describing the exact test conditions

Pilot or Bioassay UV System

Calibration Curve a UV Resistant Microorganism from a Wastewater Treatment Plant



Calibration Curve of MS2 Coliphage used for UV System Bioassays



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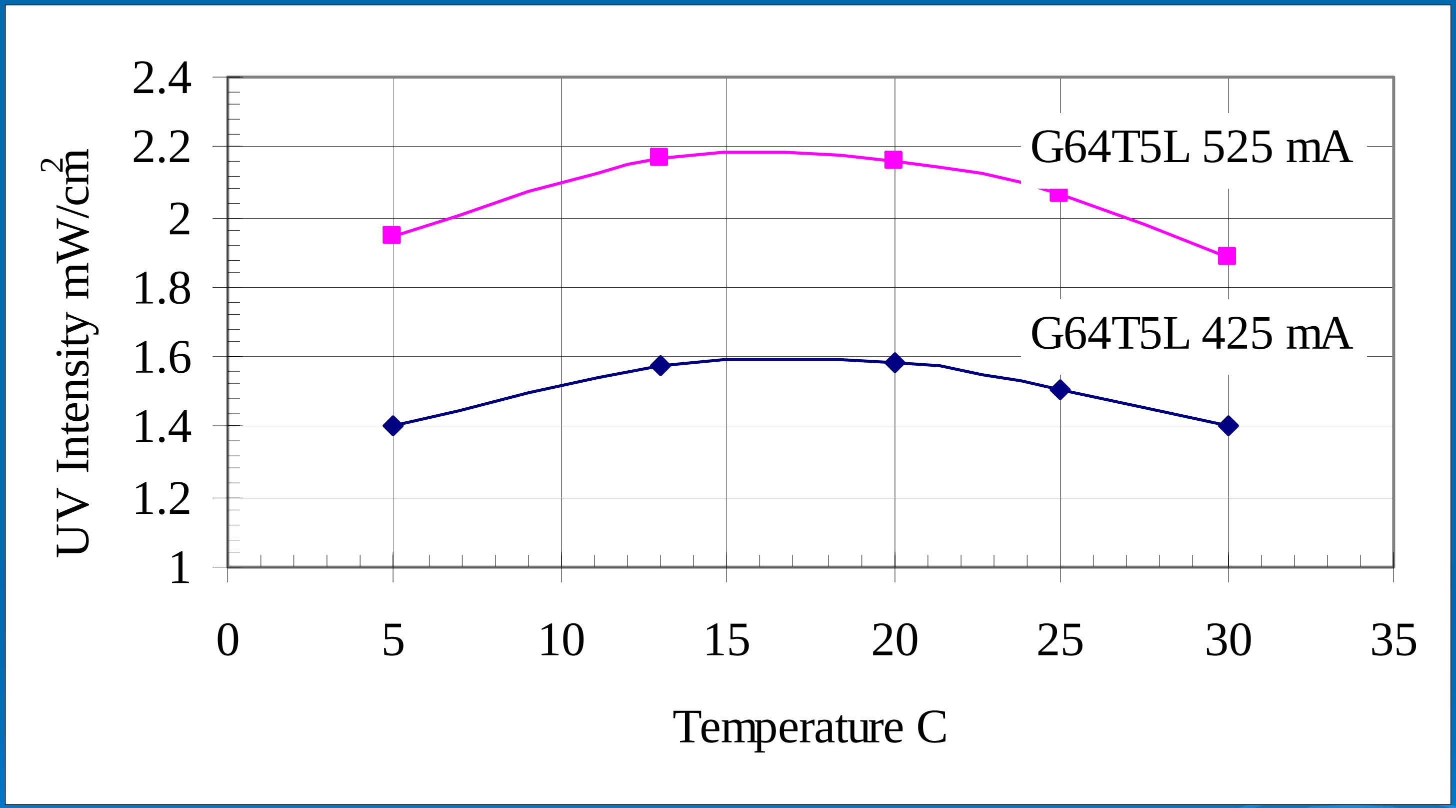
Effect of Lamp Current on UV Output



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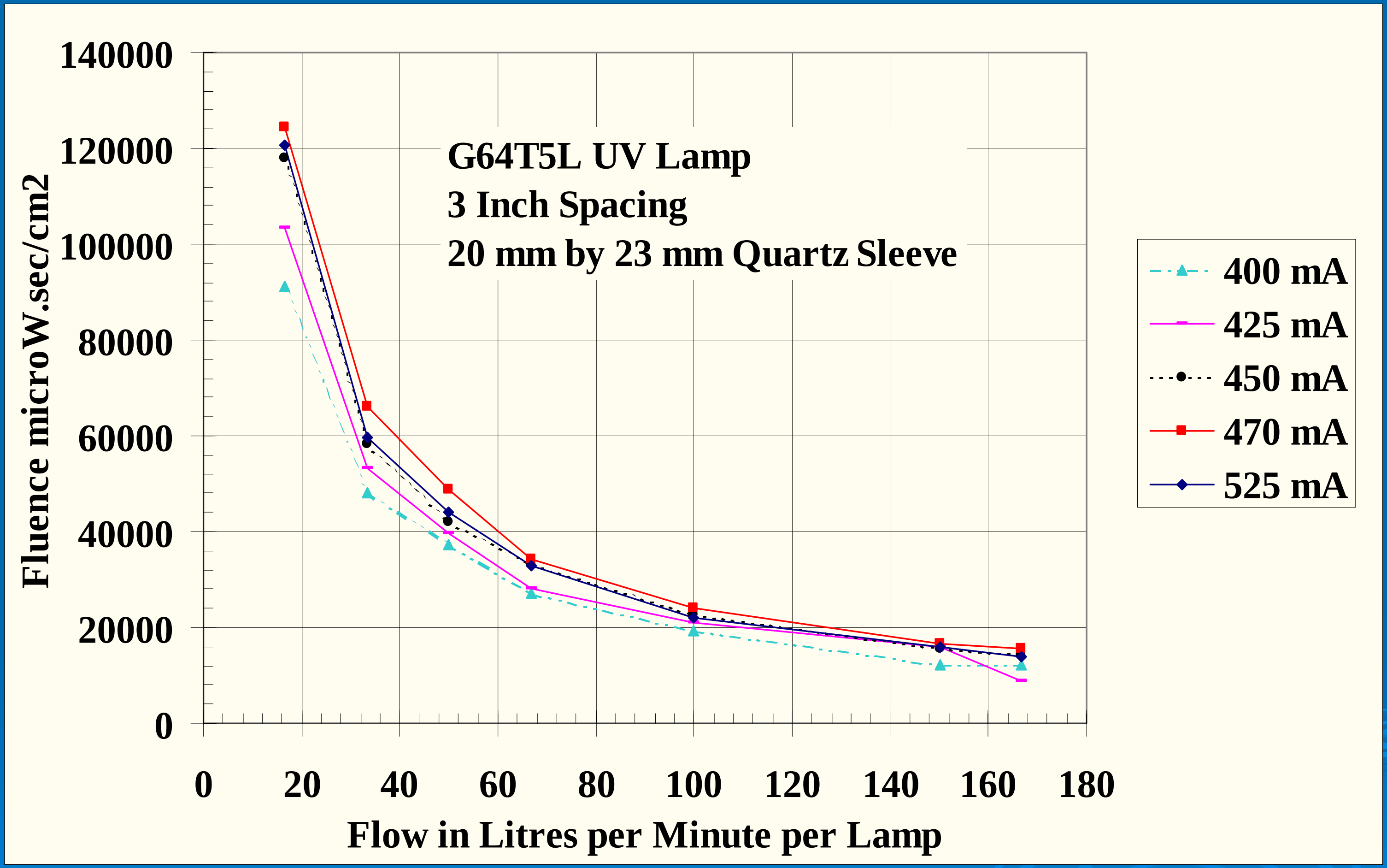
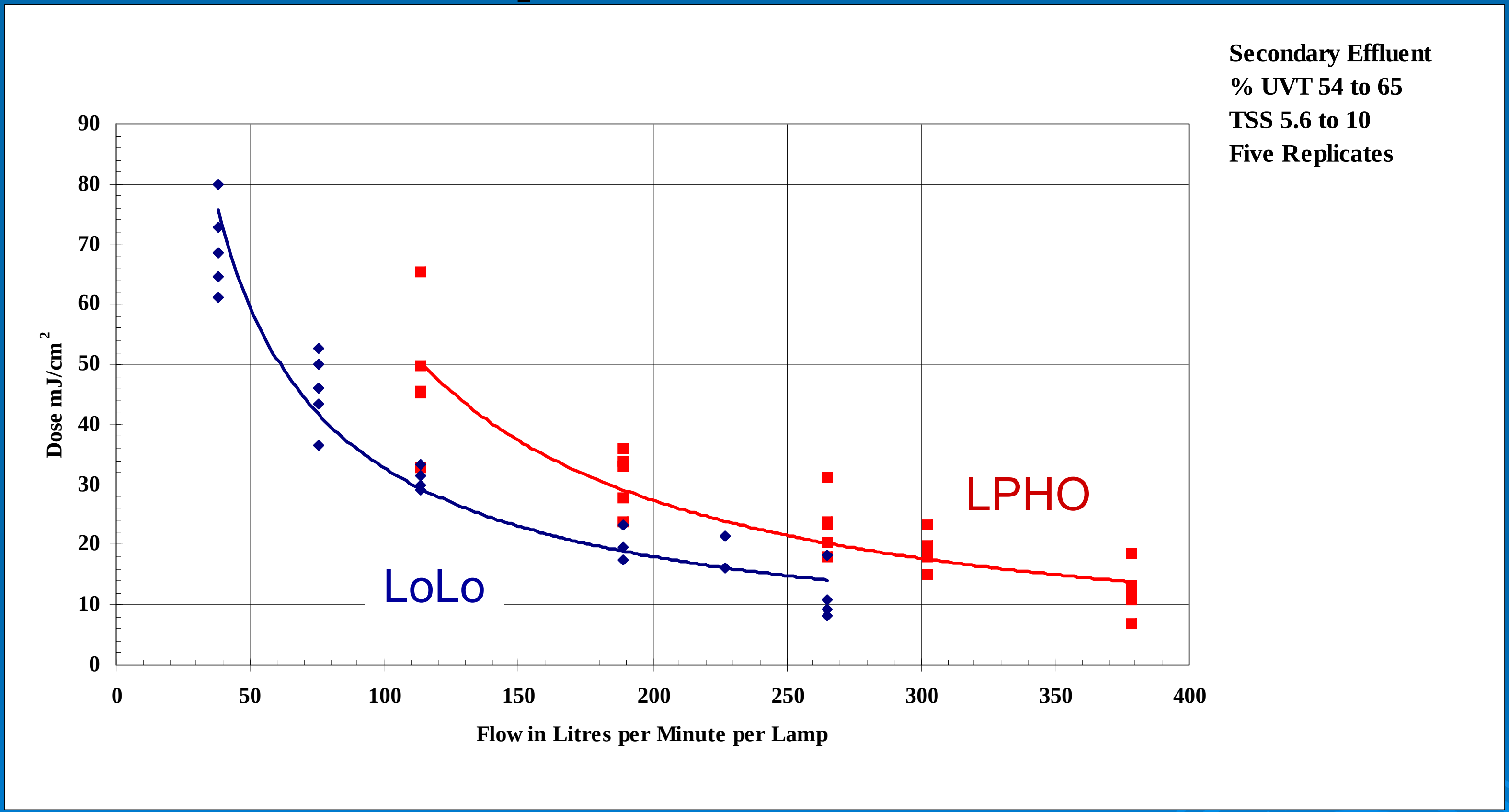
Effect of Lamp Output on UV Fluence or Dose



Dose of the LPHO and G64T5L UV Systems Using Total Aerobic Sporeformers



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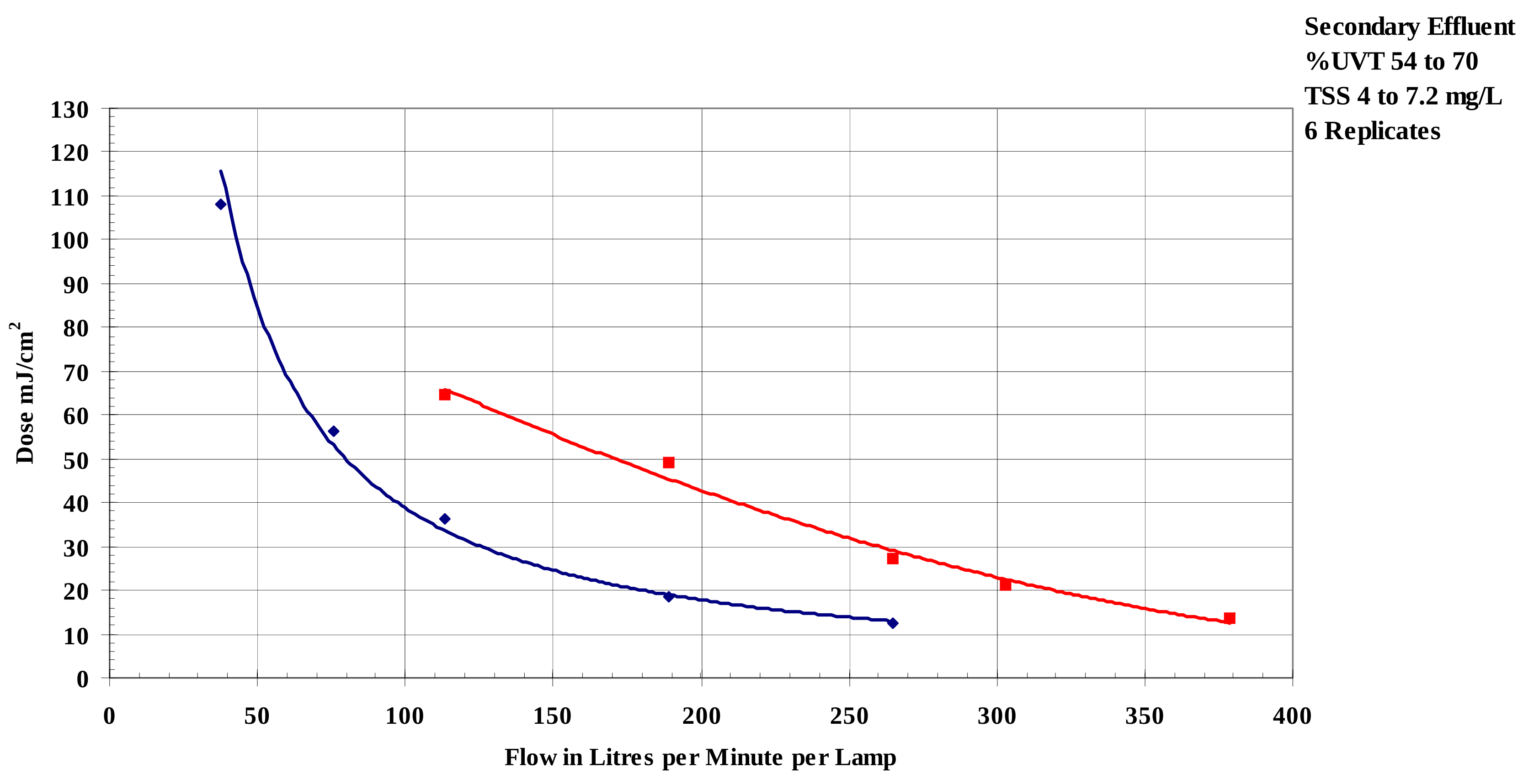
Dose of the LPHO and G64T5L UV Systems Using Fecal Coliforms



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Standard Test Protocols

- NWRI/AWWARF UV Guidelines
  - Drinking Water
  - Water Reuse
- ETV/EPA/NSF Program
  - Stormwater
  - Secondary Effluent
  - Water Reuse
- German DVGW W294
- Austrian ONORM 5873-1
- US EPA UVDGM

Validation of UV Reactors for Drinking Water

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What is Validation

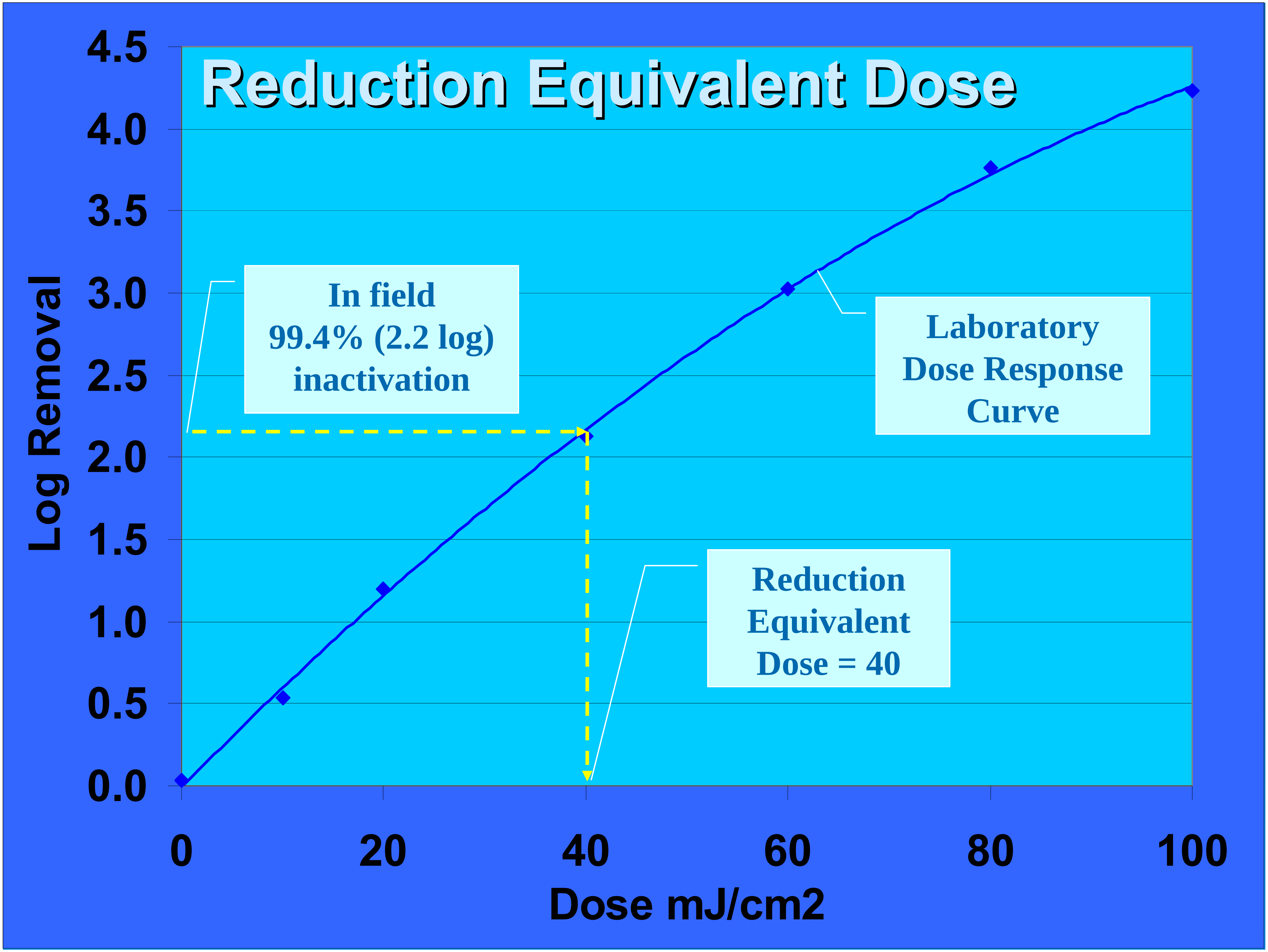
- Reactors are tested at a 3rd party validation facility or on-site
- Test is performed using surrogate micro-organism under design and operating conditions
- Report is issued that certifies reactor performance

What is a Surrogate Organism

- Micro-organism that can be cultured in large quantities in the laboratory
  - Must be easy and reliable to analyze
  - Preferably benign to humans
  - Has UV dose response similar to target organism (*Cryptosporidium*, *Adenovirus*)
- *Bacillus subtilus* (spores) and *MS2 phage* (virus that grows on bacteria) commonly used

Bioassay Test Method

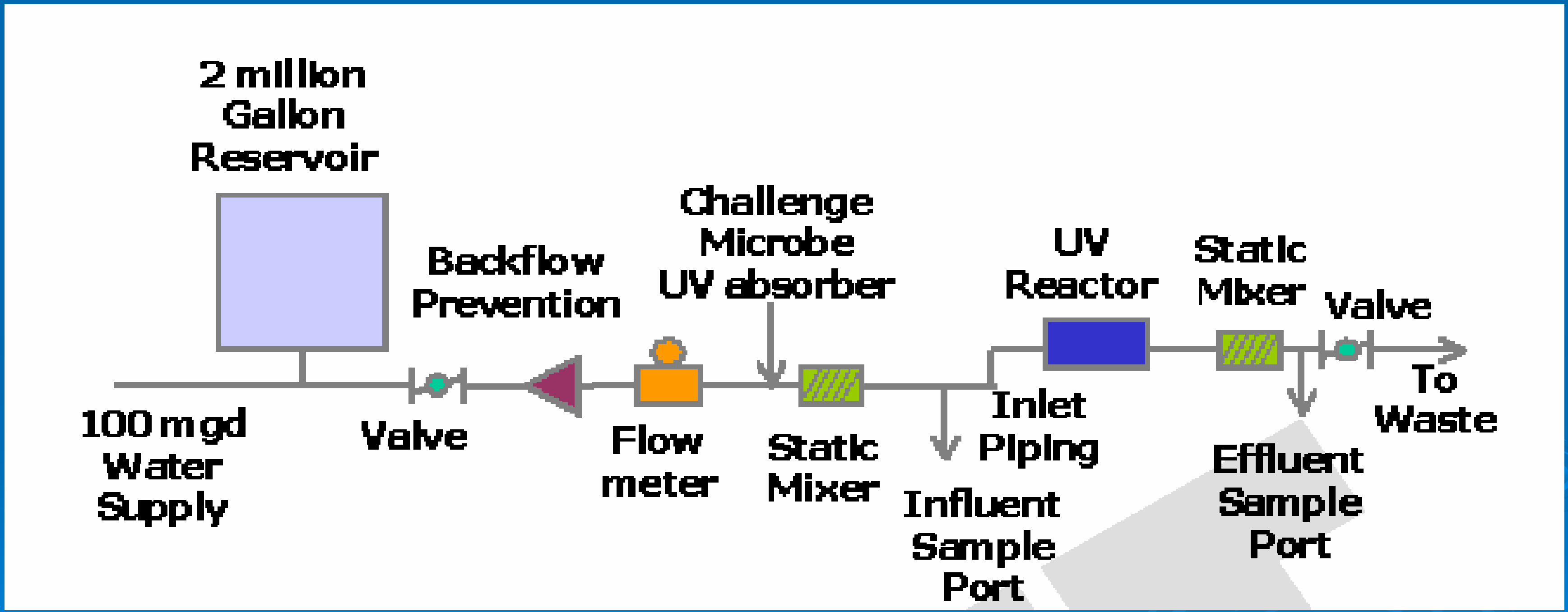
- %Transmittance adjusted with "colouring" agent.
  - Lignin Sulfonate or Humic Acid used
- Surrogate micro-organism metered into water before UV reactor at concentrations of 10^3 to 10^6 organisms/mL.
- Samples taken before and after reactor.
- Dose calculated from reduction achieved


Reduction Equivalent Dose
In field 99.4% (2.2 log) inactivation
Laboratory Dose Response Curve
Reduction Equivalent Dose = 40
Log Removal
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
Dose mJ/cm2


Portland
UV Disinfection
Validation Facility
PORTLAND
WATER WORKS
UV System
Validation Team
carollo
engineers
CEC
Clancy Environmental Consultants, Inc.
UV System
Manufacturers
CALGON
CALGON CARBON CORPORATION
WEDECO
Ultraviolet Technologies

Validation Facility, Portland, OR

- Ground Water
  - >96% UVT
  - Capacity to deliver > 40 MGD
  - No chlorine



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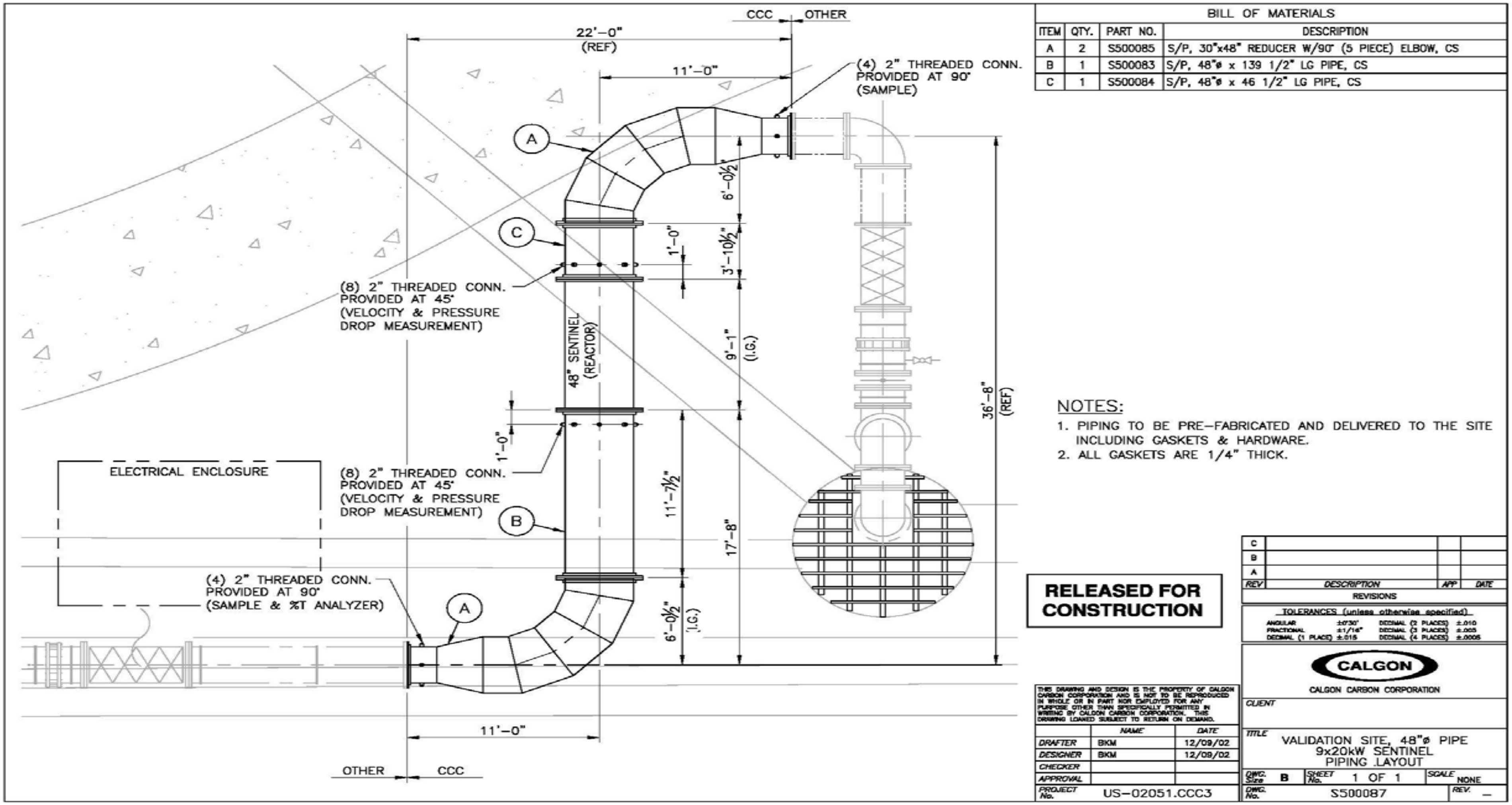
Validation Layout



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Sentinel Validation

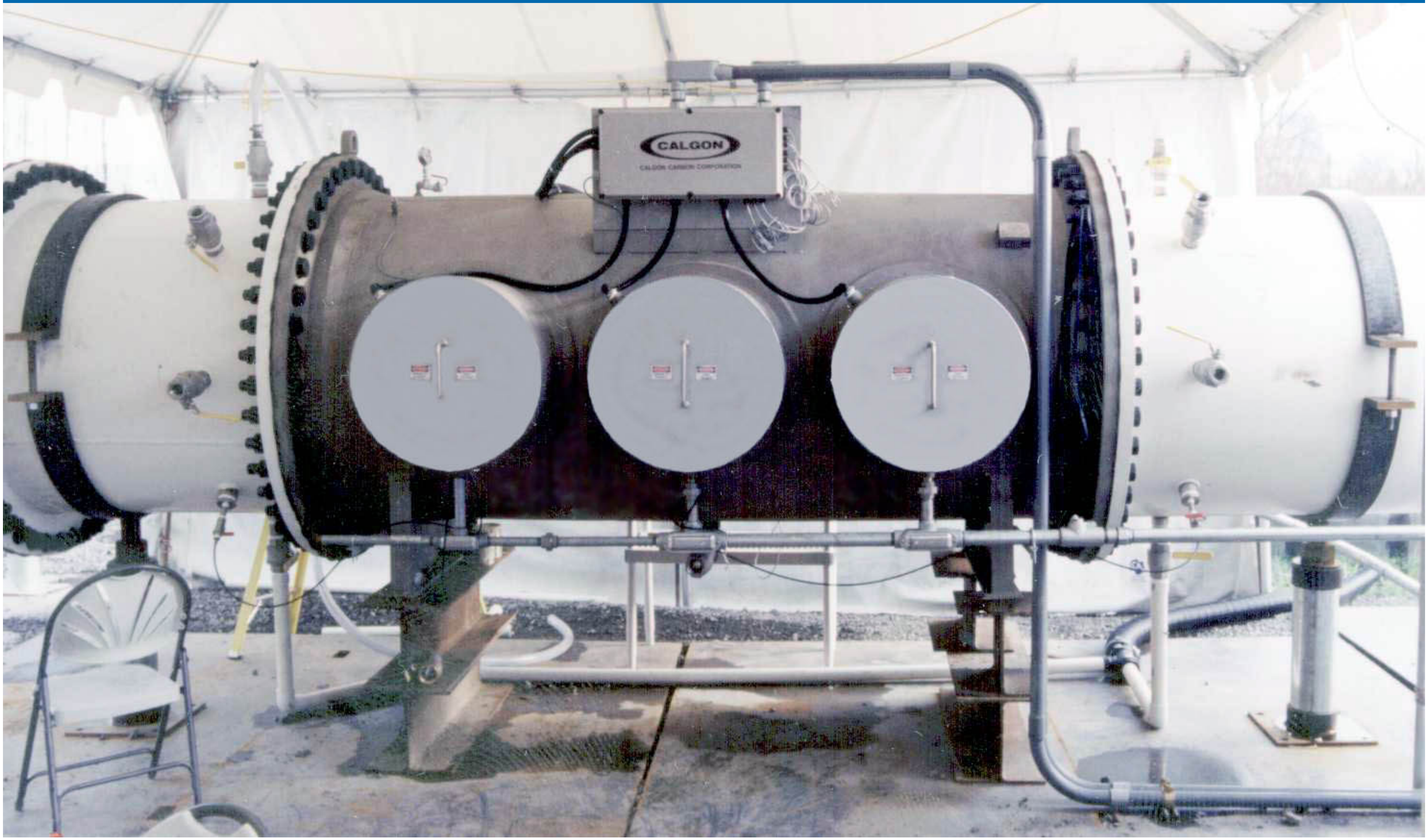
18 inch reactor undergoing testing

Control Cabinets

Inlet piping showing mixers, magnetic flow
meter,
MS2 and LS injection, 90 degree bend

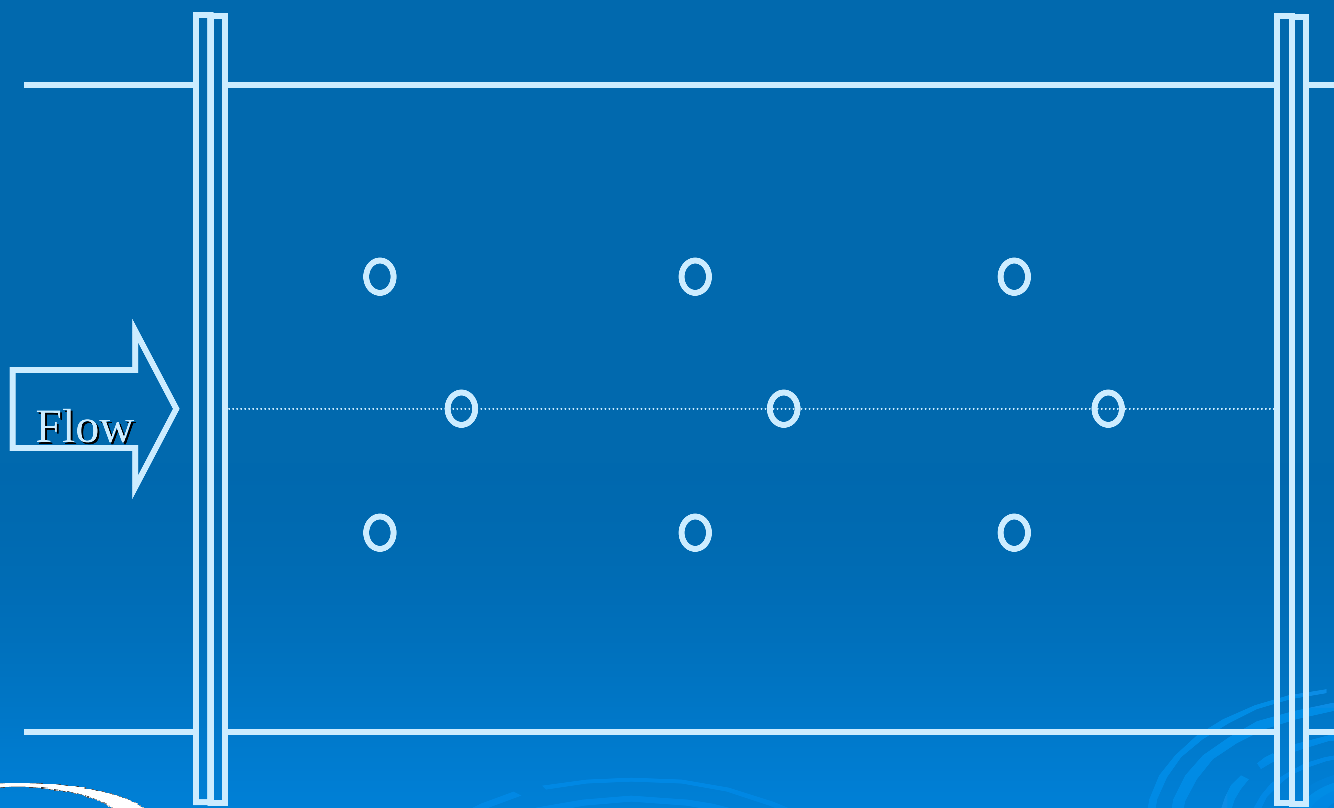
Outlet piping with discharge

Validation Reactor, Portland

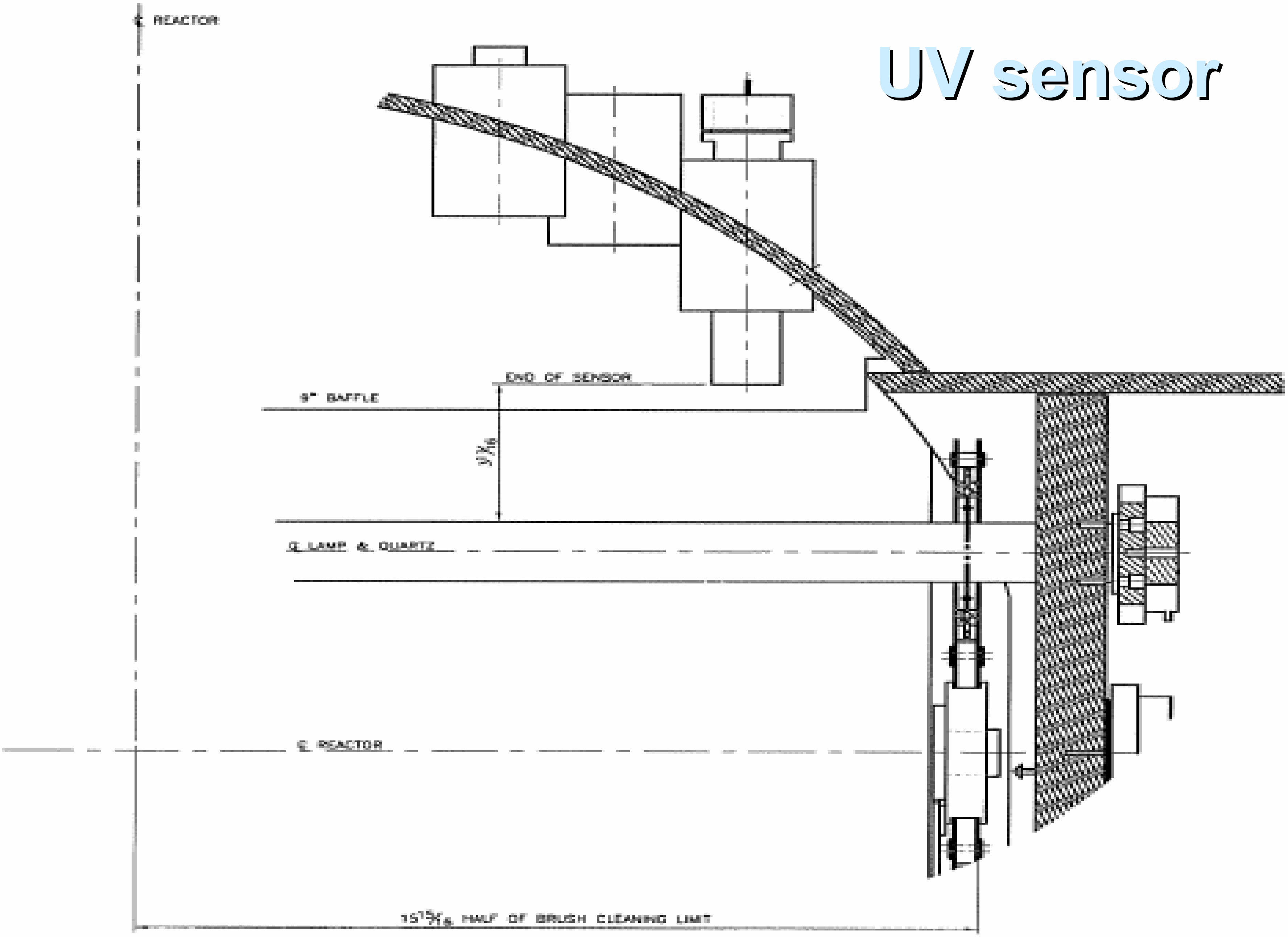


Modular Design

- 3 Banks, 3 Lamps/Bank

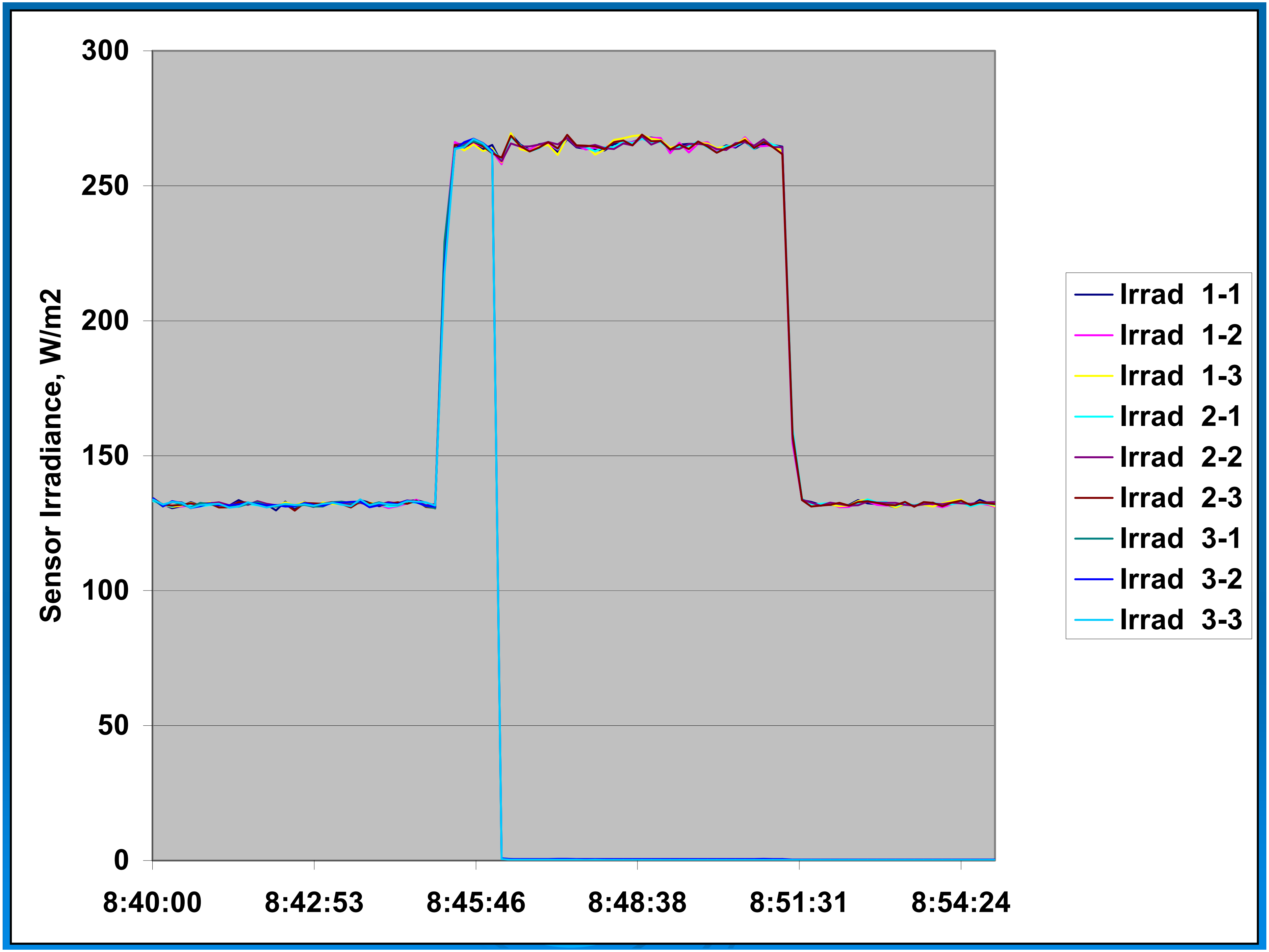


UV sensor

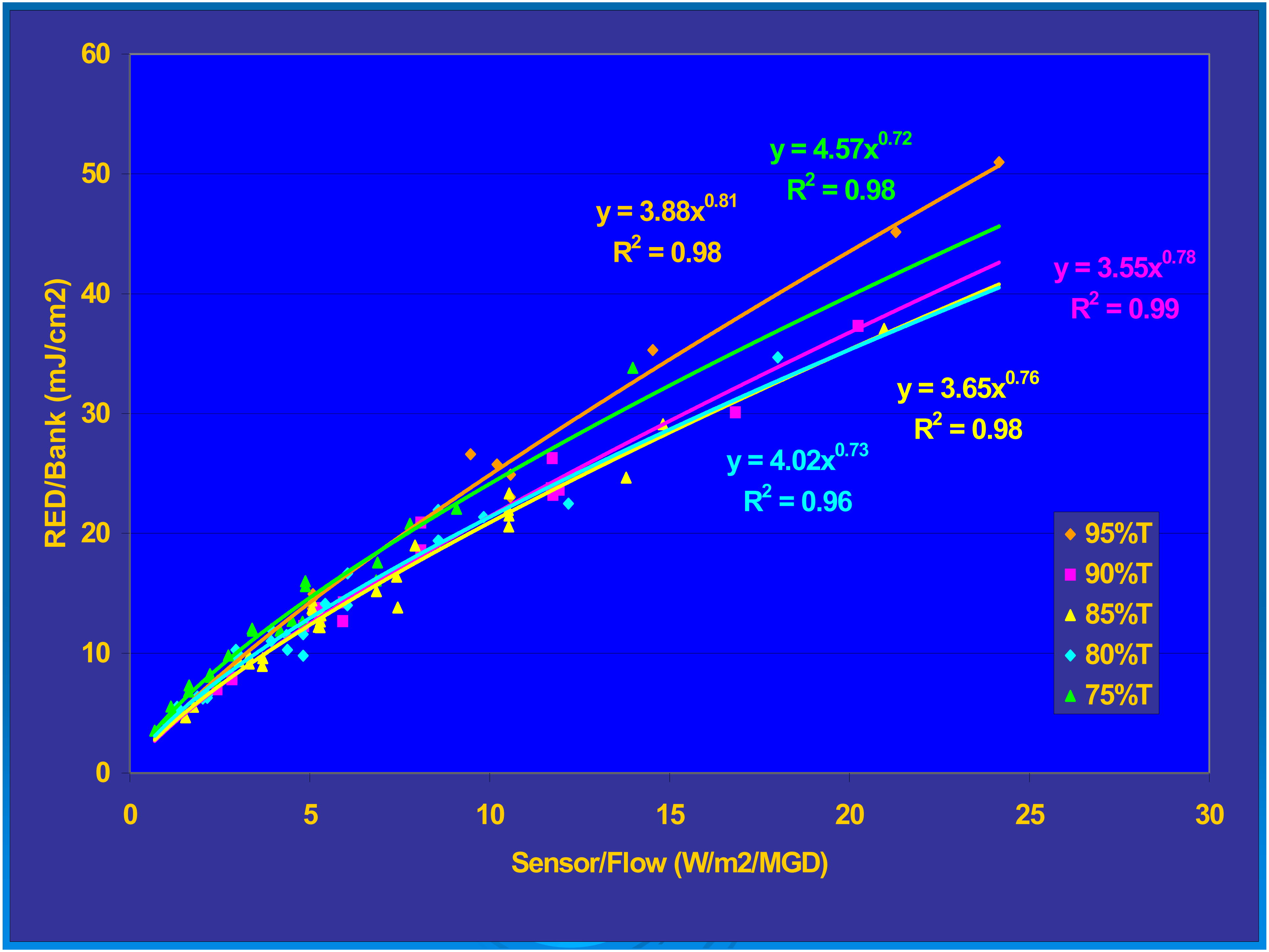


DETAIL B

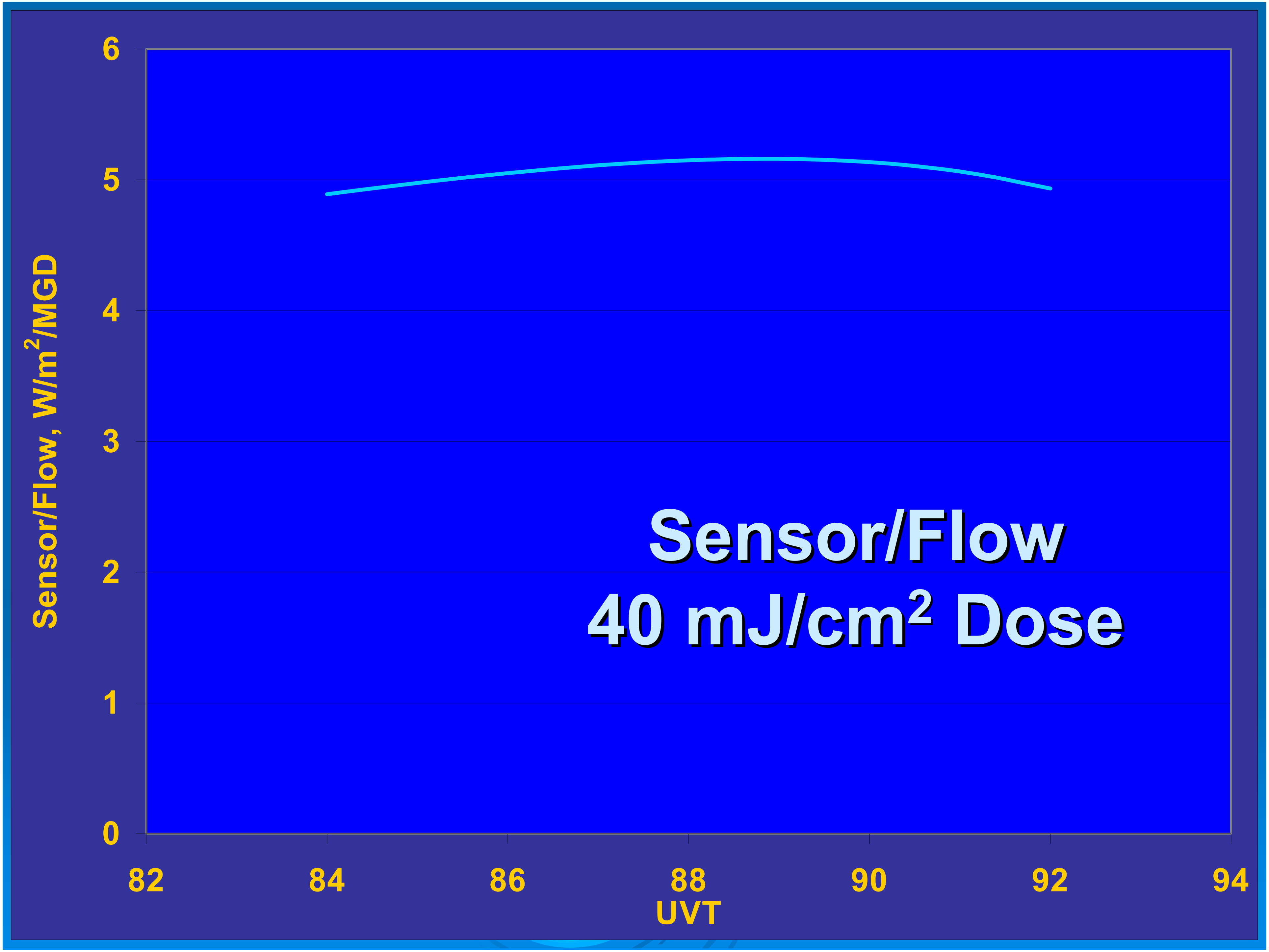
Day	New Test ID	Banks	No of Lamps	Flow mgd	%T	Lamp output %	Sensor W/m2	Est RED
5	73	1,2	6	20	95	35%	145	37
5	72	1,2	6	20	95	65%	269	58
5	81	1,2	6	20	90	35%	90	25
5	80	1,2	6	20	90	65%	166	41
5	78	1,2	6	20	90	100%	256	55
6	89	1,2	6	20	85	35%	55	16
6	88	1,2	6	20	85	65%	103	27
6	87	1,2	6	20	85	100%	159	38
6	95	1,2	6	20	80	45%	44	13
6	95	1,2	6	20	80	70%	69	20
6	94	1,2	6	20	80	100%	98	26
6	98	1,2	6	20	75	65%	40	13
6	97	1,2	6	20	75	100%	61	19
4	41	1,2	6	10	95	35%	145	61
1	1	1,2	6	10	90	35%	90	43
4	45	1,2	6	10	90	56%	143	60
5	54	1,2	6	10	85	40%	63	32
1	2	1,2	6	10	85	65%	103	46
5	52	1,2	6	10	85	95%	151	60
5	66	1,2	6	10	80	35%	34	20
1	4	1,2	6	10	80	65%	64	32
1	3	1,2	6	10	80	100%	98	45
5	70	1,2	6	10	75	35%	21	14
5	70	1,2	6	10	75	65%	40	24
1	5	1,2	6	10	75	100%	61	33
4	22	1,2	6	5	85	35%	55	48
4	27	1,2	6	5	80	35%	34	34
4	26	1,2	6	5	80	70%	69	57
4	39	1,2	6	5	75	35%	21	25
4	36	1,2	6	5	75	65%	40	40
4	35	1,2	6	5	75	100%	61	55
3	9	1,2	6	2.5	80	35%	34	57
3	14	1,2	6	2.5	75	35%	21	43
3	13	1,2	6	2.5	75	55%	33	59



Sensor Irradiance, W/m2
300
250
200
150
100
50
0
8:40:00
8:42:53
8:45:46
8:48:38
8:51:31
8:54:24
Irrad 1-1
Irrad 1-2
Irrad 1-3
Irrad 2-1
Irrad 2-2
Irrad 2-3
Irrad 3-1
Irrad 3-2
Irrad 3-3



60
50
40
30
20
10
0
RED/Bank (mJ/cm2)
0
5
10
15
20
25
30
Sensor/Flow (W/m2/MGD)
$y = 4.57x^{0.72}$
$R^2 = 0.98$
$y = 3.88x^{0.81}$
$R^2 = 0.98$
$y = 3.55x^{0.78}$
$R^2 = 0.99$
$y = 3.65x^{0.76}$
$R^2 = 0.98$
$y = 4.02x^{0.73}$
$R^2 = 0.96$
95%T
90%T
85%T
80%T
75%T



Sensor/Flow
40 mJ/cm² Dose
Sensor/Flow, W/m²/MGD
UVT
0
1
2
3
4
5
6
82
84
86
88
90
92
94

UV Sensor Position

- The UV sensor is positioned such that the sensor reading is proportional to dose
  For example:
  - 80%T, 100% Lamp output gives a sensor reading of 95 W/m^2 and a dose of 40 mJ/cm^2
  - 85%T, 70% Lamp output gives a sensor reading of 95 W/m^2 and a dose of 40 mJ/cm^2
  - 90%T, 53% lamp output also gives a sensor reading of 95 W/m^2 and a dose of 40 mJ/cm^2

Dose Pacing Control

- Validation provides equations for Dose vs UV Sensor/Flow
  - The equation is good for the normal operating range of plant UV Transmittance. For operation out of this range or over a very wide range of UVT the equations can be adjusted based on the measured UVT
- From this the UV Sensor Set-Point is automatically calculated by the system PLC based on the operating flow
- The Lamp Power is automatically adjusted to get this Sensor Set-Point value at each lamp regardless of the water %T
- Lamp Banks are turned on and off automatically as required

Sizing a UV System for Wastewater

Always Remember Worst Case Conditions

Design Conditions WWTP UV System

Design Parameters	Value
Peak Flow (ML/D)	87
Average Flow (ML/D)	43.5
Influent Fecal Coliforms	200,000
Effluent Fecal Coliforms	200
Target UV Dose	40 mJ/cm^2
UV Transmittance	65 %
TSS	30 mg/L

Sizing a UV System

- UVDIS
- Pilot Testing
- Lamp and Quartz Sleeve Testing
- Experience

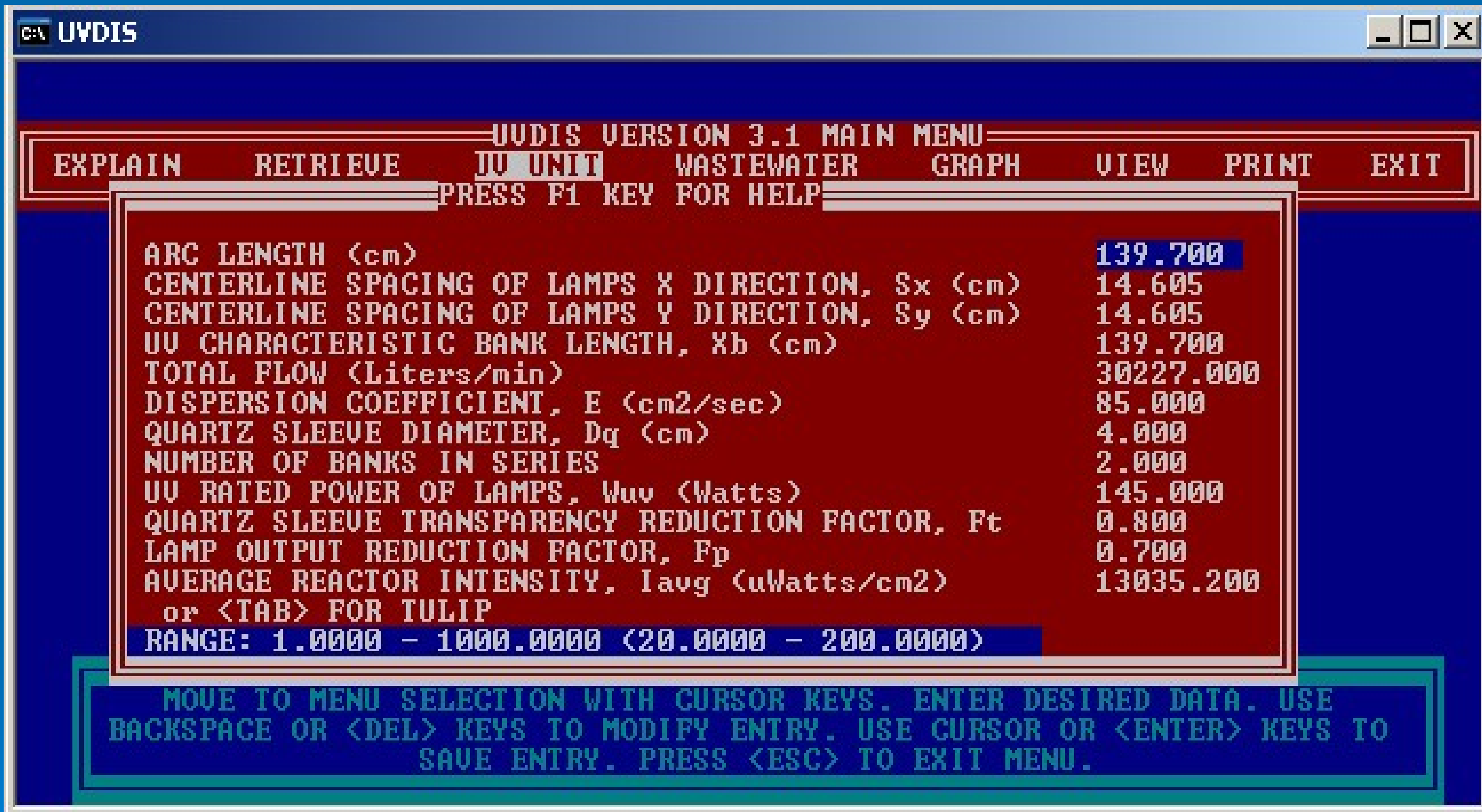
UVDIS

Developed by HydroQual Inc. for the U.S. EPA

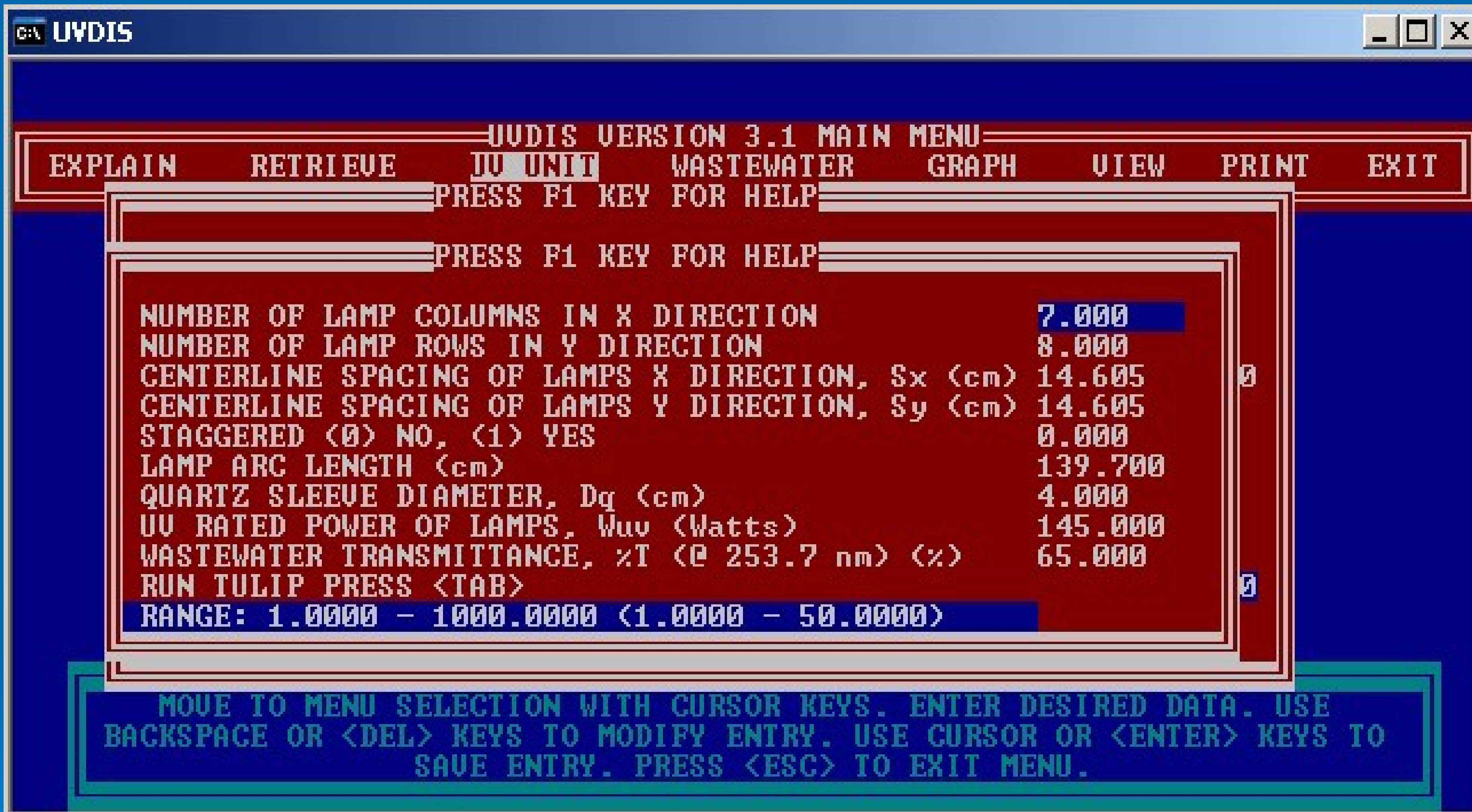
Four Sections:

1. Tulip: Determines the average intensity with the lamp array
2. UV Unit: Describes all the characteristics of the UV system and the number of banks in series
3. Wastewater and disinfection limit
4. Output

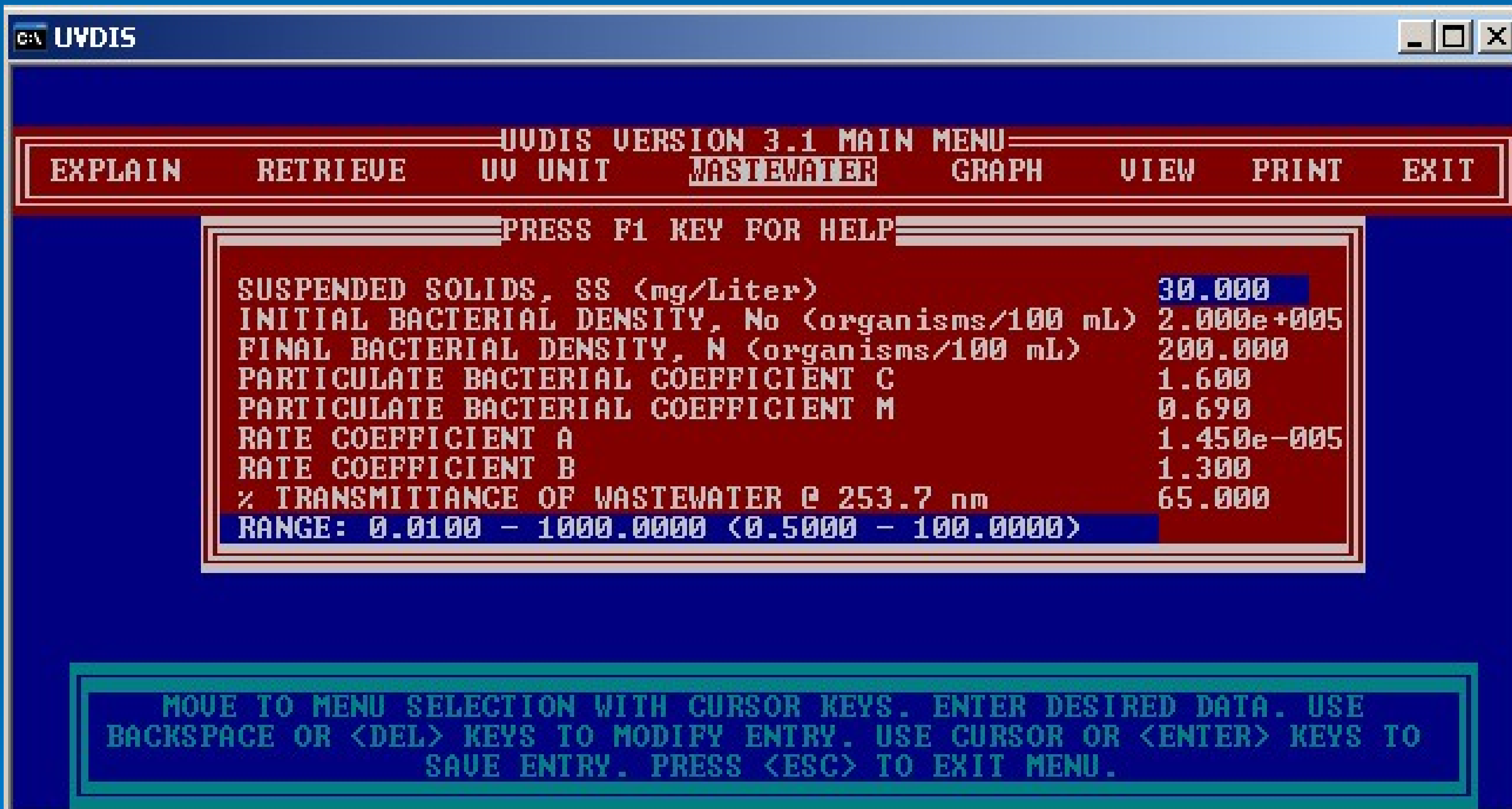
UVDIS: UV Unit for WWTP



UVDIS: Average Intensity within a Bank



UVDIS: Wastewater Characteristics



UVDIS: UV System Output

Q [LPM]	30227.00
TSS [mg/L]	30.00
%T @ 253.7 nm	65.00
I_{adg} [uW/cm2]	7299.71
F_p*F_t	0.56
K	1.53
E [cm2/sec]	85.00
N_o {per 100 mL]	200,000
N {per 100 mL]	200
Log N/N_o	-3.00
Log N'/N_o	-3.04
Q/W_n {LPM/Wn]	2.45
W_n [watts @ 253.7 nm]	12361.2
Number of Lamps	85
Number of Banks	2

Pilot Testing

Test the UV system under actual operating conditions to get information on the inactivation of fecal coliforms, total coliforms, *E. coli*, Enterococci, and total aerobic sporeformers

This is used to confirm the results of UVDIS

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WWTP UV System Configuration

Configuration	Sizing Based on Specifications	Sizing Based on UVDIS
Number of Channels	2	2
Banks per Channel	2	2
Racks per Bank	7	6
Lamp per Rack	8	7
Total Racks	28	24
Lamp per Bank	56	42
Lamps per Channel	112	84
Total Number of Lamps	224	168
Calculated Dose	45 mJ/cm^2	34 mJ/cm^2

UV Disinfection of Drinking Water

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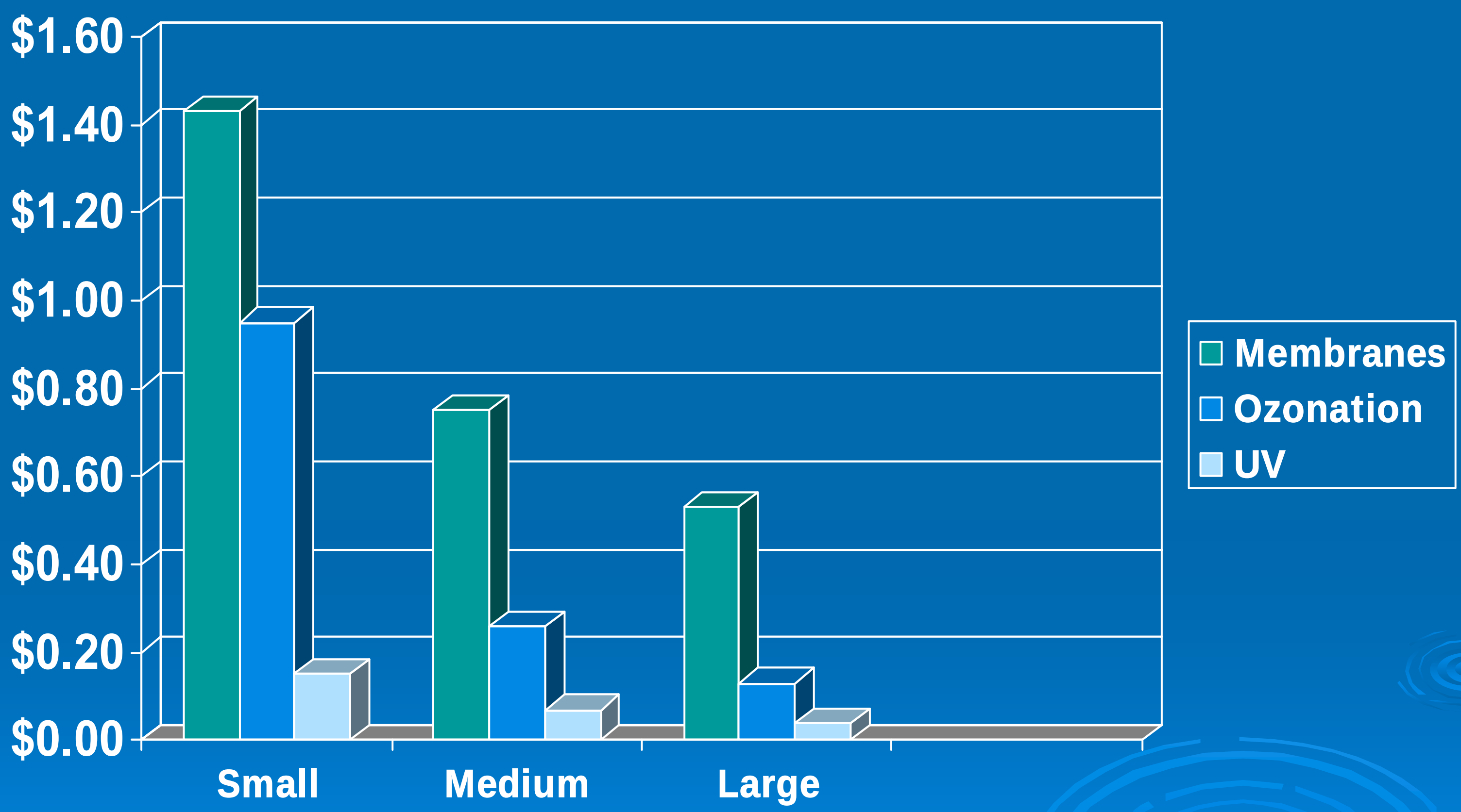
UV Disinfection of Drinking Water Prior to 1998

- Used in homes, cottages, point of use and point of entry, and Europe
- Prior to 1998, it was believed that high UV doses were necessary to inactivate *Cryptosporidium* and *Giardia*
- Calgon Carbon showed that only low doses of UV were necessary to inactivate *Cryptosporidium* and therefore prevent infection
- Due to this research and the need to reduce disinfection by-products, UV is now considered the leading disinfection technology for *Cryptosporidium* and *Giardia*

Why UV?

- Lowest cost treatment compared to ozone and membranes (Capital and Operating)



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Advantages of UV Disinfection

- Fast kinetics - reaction time in seconds
- No harmful by-products are produced
- No hazards associated with chemicals, such as handling, disposal, over or under feeding
- Water chemistry and constituents, such as pH, taste, odour, colour etc. are unchanged
- Environmentally responsible and increasingly embraced technology

Disadvantages of UV Disinfection

- No residual disinfection in distribution system
- Not good for primary disinfection where suspended solids are present
- Usually used as additional barrier in conjunction with chlorine/filtration

US Regulations

- 2005 Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR)
  - Additional inactivation requirement for *Cryptosporidium*
  - UV sanctioned as a treatment technology – EPA UV Disinfection Guidance Manual

LT2ESWTR

- Became law in December 2005
- 2 year sampling period for *Cryptosporidium*
- Rule requires *Cryptosporidium* treatment for large plants (>787 m^3/h) if detected in source water
  - UV, Ozone or Membranes
- Estimated that 30 – 70% of plants will need to install treatment

EPA UV Disinfection Guidance Manual

- Final Document November 2006
- Provides recommendations on validation testing
- Sets out dose requirements for disinfection credits
  - *Cryptosporidium*, *Giardia* and Viruses
- Applies safety factors in accordance with the precision of the testing

Dose Requirements for *Cryptosporidium* and *Giardia*

- Looked at all research results
- Determined dose statistically with 80% confidence interval

Collimated Beam Apparatus

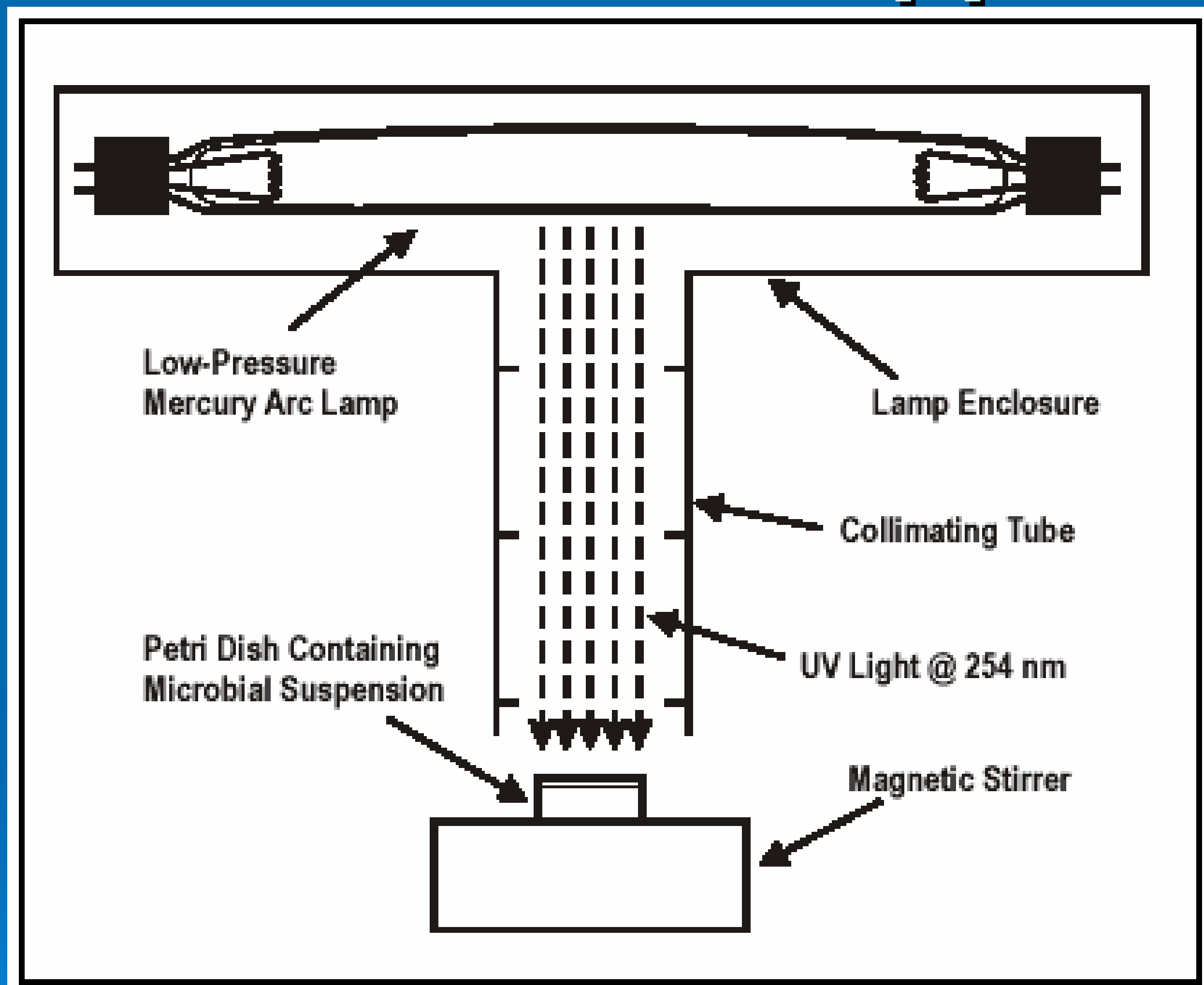


Figure B.2 *Cryptosporidium* Data from Selected Research Studies

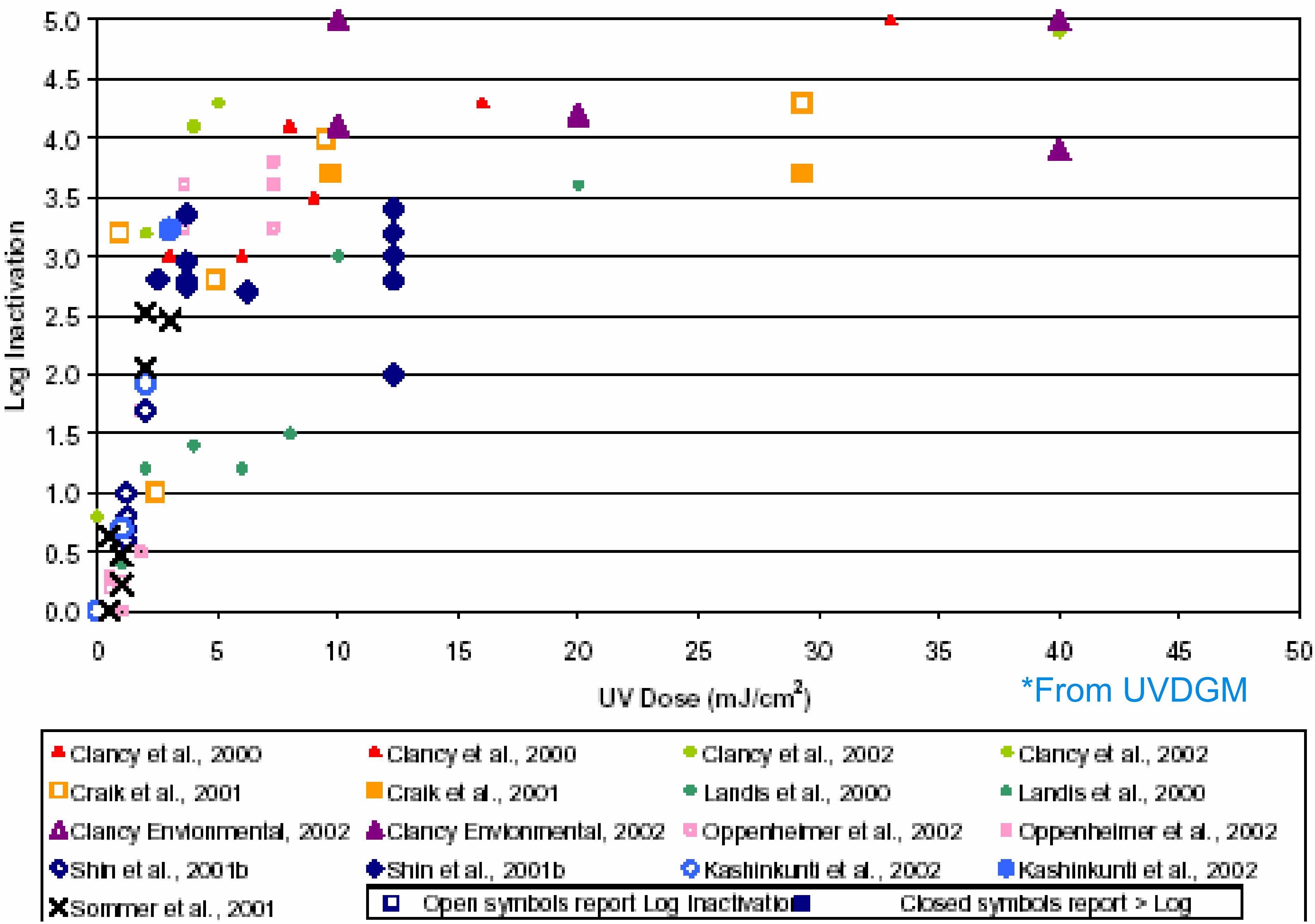
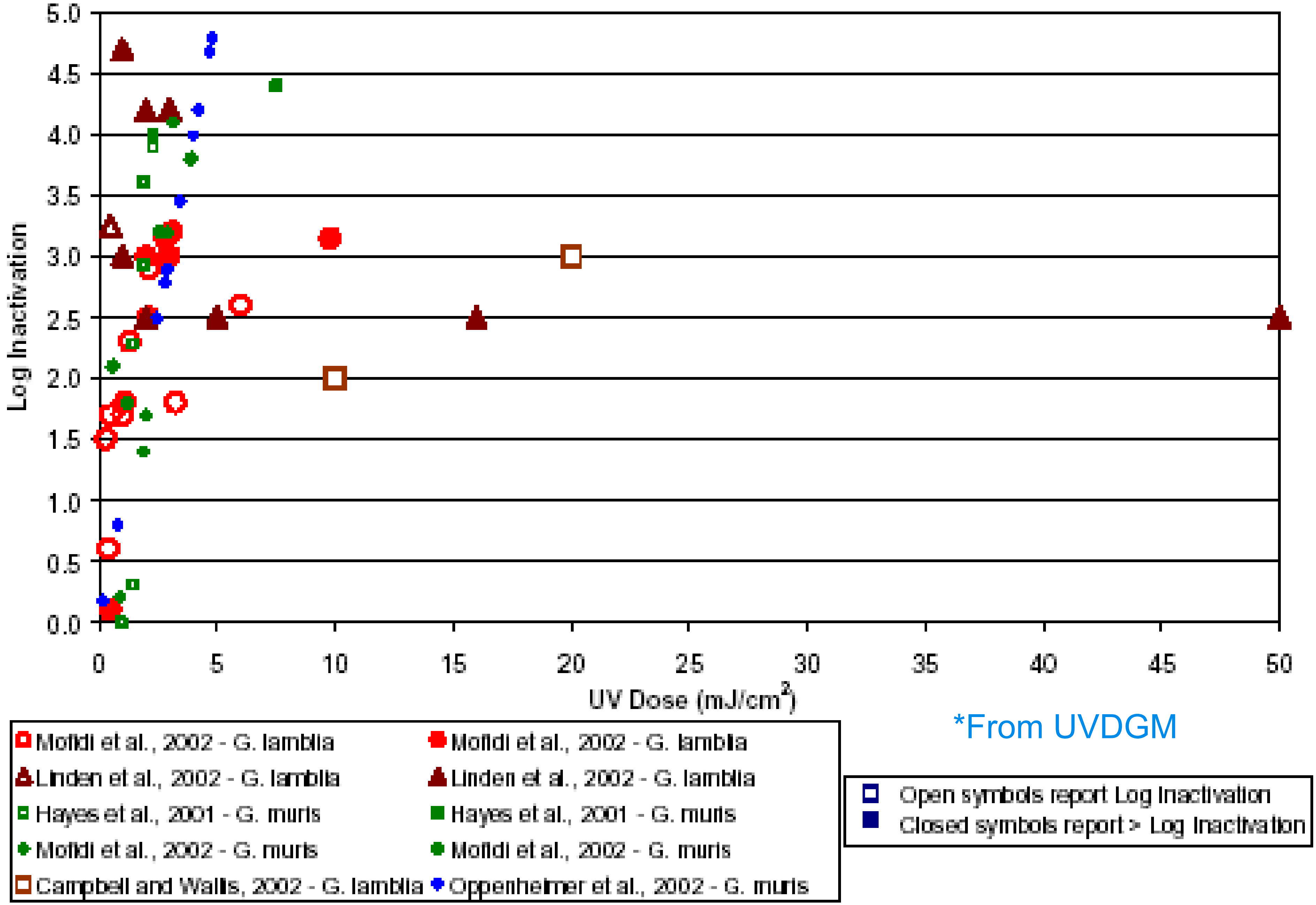


Figure B.3 *Giardia* Data from Selected Research Studies



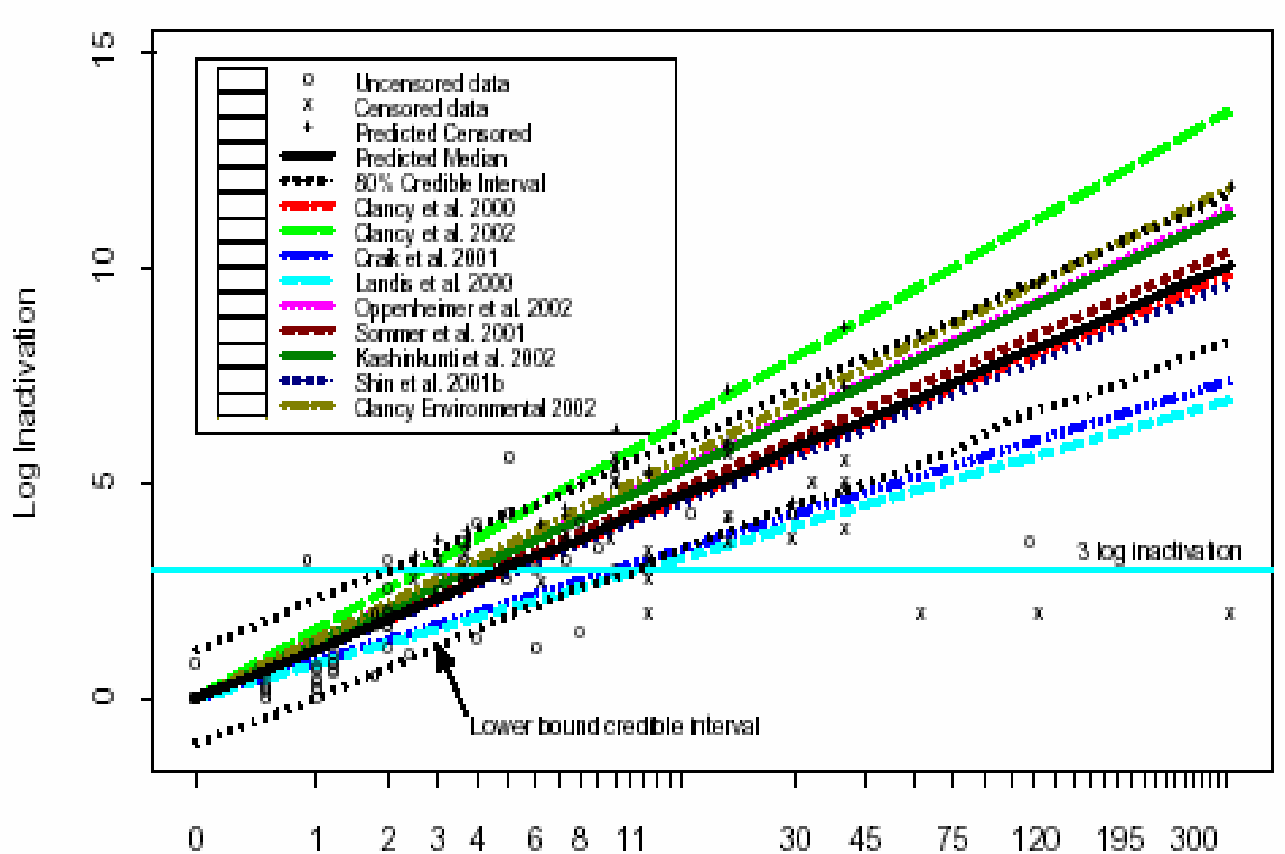
*From UVDGM

Statistical Analysis of Results

- Different Studies
  - Require special statistics
- Meta-analysis with Bayesian parameter estimation techniques
  - Summarizes and integrates multiple research studies as either totally related or totally unrelated or exchangeable but not identical or completely unrelated
- Regression coefficients for each study were estimated using the same calculations and allowed to differ between studies

Confidence Intervals for Cryptosporidium

Figure B.4 *Cryptosporidium* Modeled Data and Predictive Credible Intervals



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UVDGM Dose Tables

Table 1.4. UV Dose Requirements[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	-	-
Giardia	1.5	2.1	3.0	5.2	7.7	11	-	-
Virus	39	58	79	100	121	143	163	186

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

*US EPA UVDGM

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The Validated Dose

To account for the uncertainty associated with UV reactor validation, divide RED_{calc} by the VF to determine the validated dose (D_{Val}), the target dose used in operation to ensure compliance:

1. If a UV intensity setpoint or UV Intensity-UVT Setpoint Approach is used:

$$D_{Val} = \frac{RED_{setpoint}}{VF} \qquad \text{Equation A.18}$$

VF = Validation Factor

$$RED_{calc} = 10^{a} \times UVA^{b} \times (S/S_o)^{c} \times (1/Q)^{d} \times B^{e} \qquad \text{Equation A.7}$$

Or in linear form:

$$\log(RED_{calc}) = a + b \times \log(UVA) + c \times \log(S/S_o) + d \times \log(1/Q) + e \times B \qquad \text{Equation A.8}$$

where:

RED_{calc}	=	RED calculated by the UV dose monitoring equation
A_{254}	=	UV absorbance at 254 nm
S	=	Measured UV sensor value
S_o	=	UV sensor value at nominal (maximum) lamp power for a new lamp in a new, unfouled sleeve being monitored by a calibrated UV sensor through a new, unfouled sensor port window measured at the same UVT value as for S
Q	=	Flow rate
B	=	Number of operating banks of lamps within the UV reactor
a, b, c, d, e	=	Model coefficients obtained by fitting the equation to the data

*UVDGM

The Validated Dose

The VF accounts for the random uncertainties and biases associated with validation testing. It is defined according to Equation A.13:

$$VF = B_{RED} \times (1 + U_{Val} / 100) \qquad \text{Equation A.13}$$

where:

B_{RED} = RED Bias
U_{Val} = Uncertainty of validation expressed as a percentage

$$U_{Val} = U_{IN} \qquad \text{Equation A.14}$$

where:

U_{IN} = Percent uncertainty of the interpolation equation used to predict RED

$$U_{IN} = \frac{t \times SD}{RED_{calc}} \times 100\% \qquad \text{Equation A.16}$$

where:

SD = Standard deviation of the differences between the measured and calculated RED values for each replicate ($RED_{mea} - RED_{calc}$)
t = t-statistic at a 95 percent confidence level for a sample size equal to the number of test conditions used to define the interpolation:

*UVDGM

$$D_{Val} \geq D_{Req}$$

RED Bias

Table G.3. RED Bias Values for 3.0-log *Cryptosporidium* Inactivation Credit as a Function of UVT and UV Challenge Microorganism Sensitivity

Cryptosporidium log inactivation credit		3.0						
Required UV dose (mJ/cm^2)		12						
Cryptosporidium UV sensitivity (mJ/cm^2/log I)		4.0						
UVT (%)		≥ 98	≥ 95	≥ 90	≥ 85	≥ 80	≥ 75	≥ 65
Challenge UV sensitivity (mJ/cm^2/log I)		RED Bias						
Lower	Upper							
0	≤2	1.00	1.00	1.00	1.00	1.00	1.00	1.00
>2	≤4	1.00	1.00	1.00	1.00	1.00	1.00	1.00
>4	≤6	1.05	1.10	1.15	1.17	1.19	1.21	1.23
>6	≤8	1.09	1.18	1.27	1.32	1.36	1.40	1.45
>8	≤10	1.12	1.23	1.38	1.47	1.52	1.58	1.66
>10	≤12	1.14	1.27	1.47	1.59	1.68	1.75	1.86
>12	≤14	1.16	1.31	1.55	1.71	1.82	1.92	2.06
>14	≤16	1.17	1.33	1.62	1.82	1.96	2.08	2.26
>16	≤18	1.18	1.36	1.68	1.92	2.09	2.24	2.45
>18	≤20	1.19	1.38	1.73	2.01	2.22	2.39	2.65
>20	≤22	1.20	1.39	1.78	2.10	2.34	2.54	2.84
>22	≤24	1.21	1.41	1.82	2.18	2.45	2.69	3.03
>24	≤26	1.22	1.42	1.85	2.25	2.56	2.83	3.21
>26	≤28	1.22	1.43	1.89	2.32	2.66	2.96	3.40
>28	≤30	1.23	1.44	1.92	2.38	2.76	3.10	3.58
>30	≤32	1.23	1.45	1.95	2.44	2.86	3.23	3.76
>32	≤34	1.24	1.46	1.97	2.50	2.95	3.35	3.94

*UVDGM

An Example of a Validated Dose for the Sentinel

$$D_{Val} = \frac{RED_{setpoint}}{VF}$$

D_{req} = Three Log *Cryptosporidium* Inactivation = 12 mJ/cm^2

$$D_{Val} \geq D_{Req}$$

RED_{bias} = 1.92 at 85 % UVT

U_{val} = 20 %

$$VF = B_{RED} \times (1 + U_{Val}/100)$$

VF = 1.92 X (1 + 20/100) = 2.3

$RED_{setpoint}$ = (12)*(2.3) = 27.6 mJ/cm^2

*UVDGM

UV System Design Parameters

- %T of Water
- Flow Rate
- Desired UV Dose
- Maximum Allowable Pressure Drop

Typical UV Systems for Drinking Water

Calgon Carbon Sentinel Series

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Installation Options

- Post Filter
  - One per filter
  - In combined flow
- Post Clearwell
  - Before pumps
  - After pumps

Some Installations

Plant name	*Location*	*Date of Installation*	*Pipe Size*	*Lamp Size kW*	*Peak Flow MGD*
West View	Pennsylvania	March ‘01	48”	20	40
E.L. Smith	Edmonton	March ’02	48”	20	95.1
Winnipeg	Manitoba	September ’04	48”	20	174
Loudoun County	Virginia	May ’05	36”	10	12
Rossdale	Edmonton	May ’04	36”	10	79.3
Cal Water – Bear Gulch	California	Late ‘05	18”	4	5
Lac La Biche	Alberta	January ’04	18”	4	4.4
Potomac	Washington DC	Late ’06/07	48”	20	300

Sentinel Installation
EL Smith WTP, Edmonton

Deacon Booster Pumping Station
Winnipeg, Manitoba
48 inch Reactors

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Lac LaBiche UV Installation

Lac LaBiche Sentinel UV Unit

Influence of Feed Water Quality on UV Performance

Parameter	Influence/effect	Limits
UV Transmittance	Could lead to the absorption of UV light	> 75 %T **@ 254nm**
Turbidity	Could lead to absorption of UV light/shielding of micro-organisms	< 5 NTU
Hardness	Could cause scaling on quartz sleeves resulting in poor UV transmission.	< 200 mg/L $CaCO_3$
pH	Can affect solubility of metals and leaching of metal particles from contact surfaces resulting in UV absorption	6.0 - 9.0
Suspended Solids	Absorption of UV light and shielding of bacteria	< 10 ppm

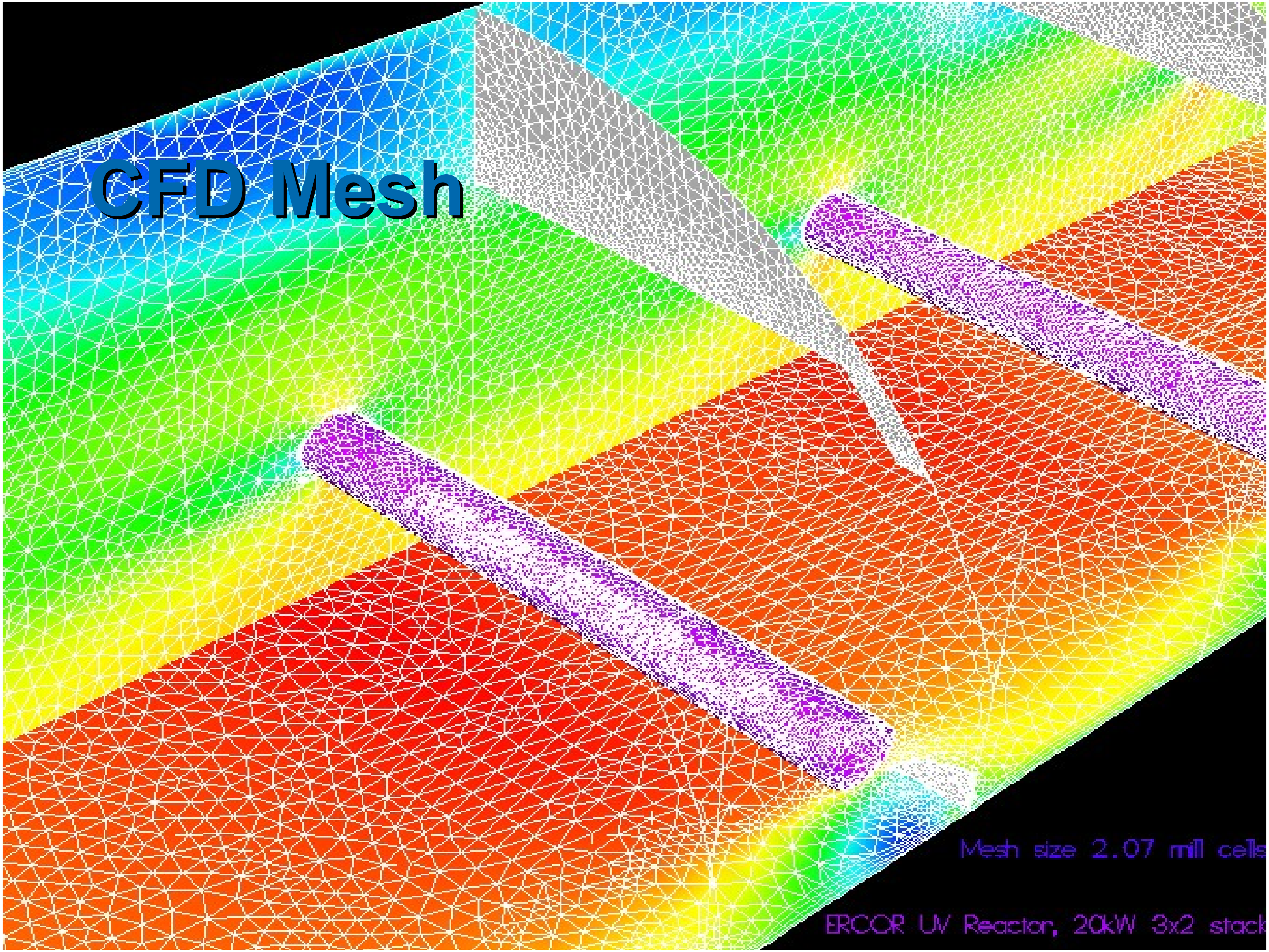
Computational Fluid Dynamics

- A mathematical model that can be used to simulate a bioassay to determine the RED
- Lowers the cost of equipment design
- Equipment can be tested to determine whether it will work when the hydraulics have not been tested by a bioassay

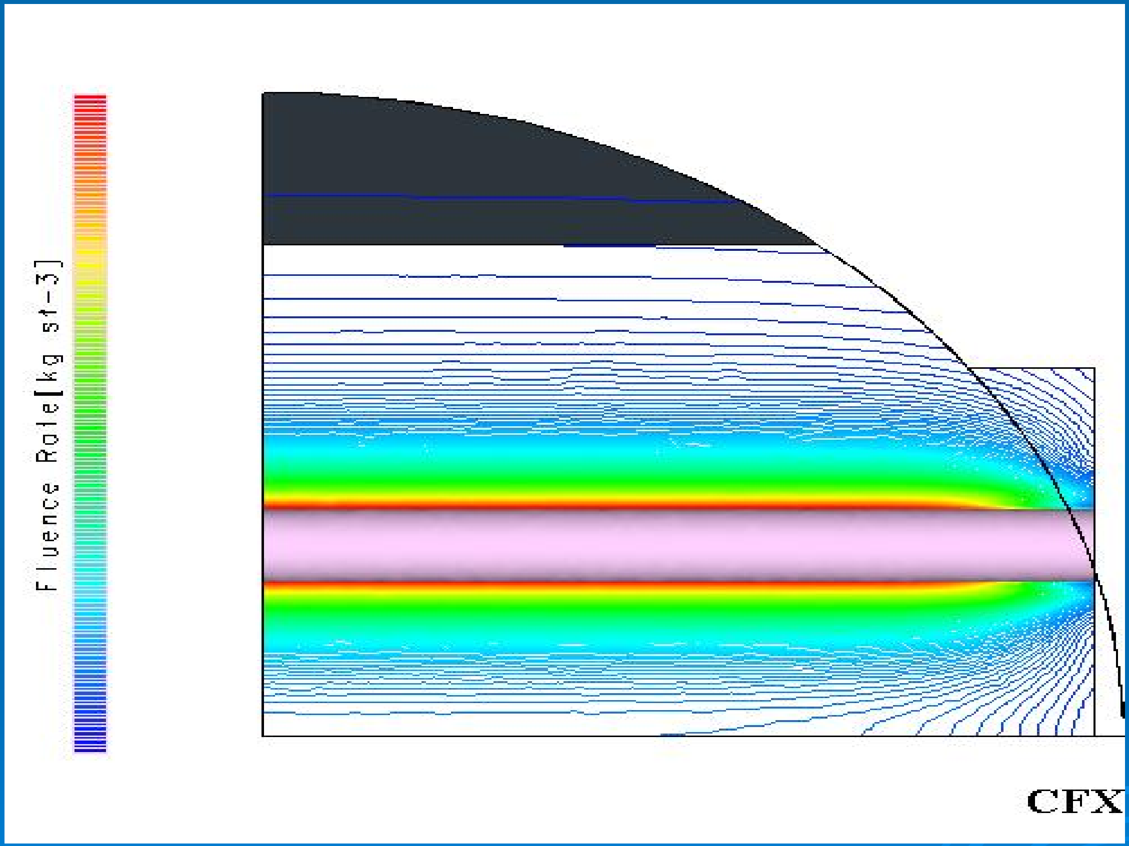
Computational Fluid Dynamics

- Mathematical model of the flow characteristics through the reactor
- Reactor broken down into ~2 million cells
- UV Fluence calculated for each cell
- Using AEA/CFX Software

CFD Mesh



Fluence Field within the UV Reactor



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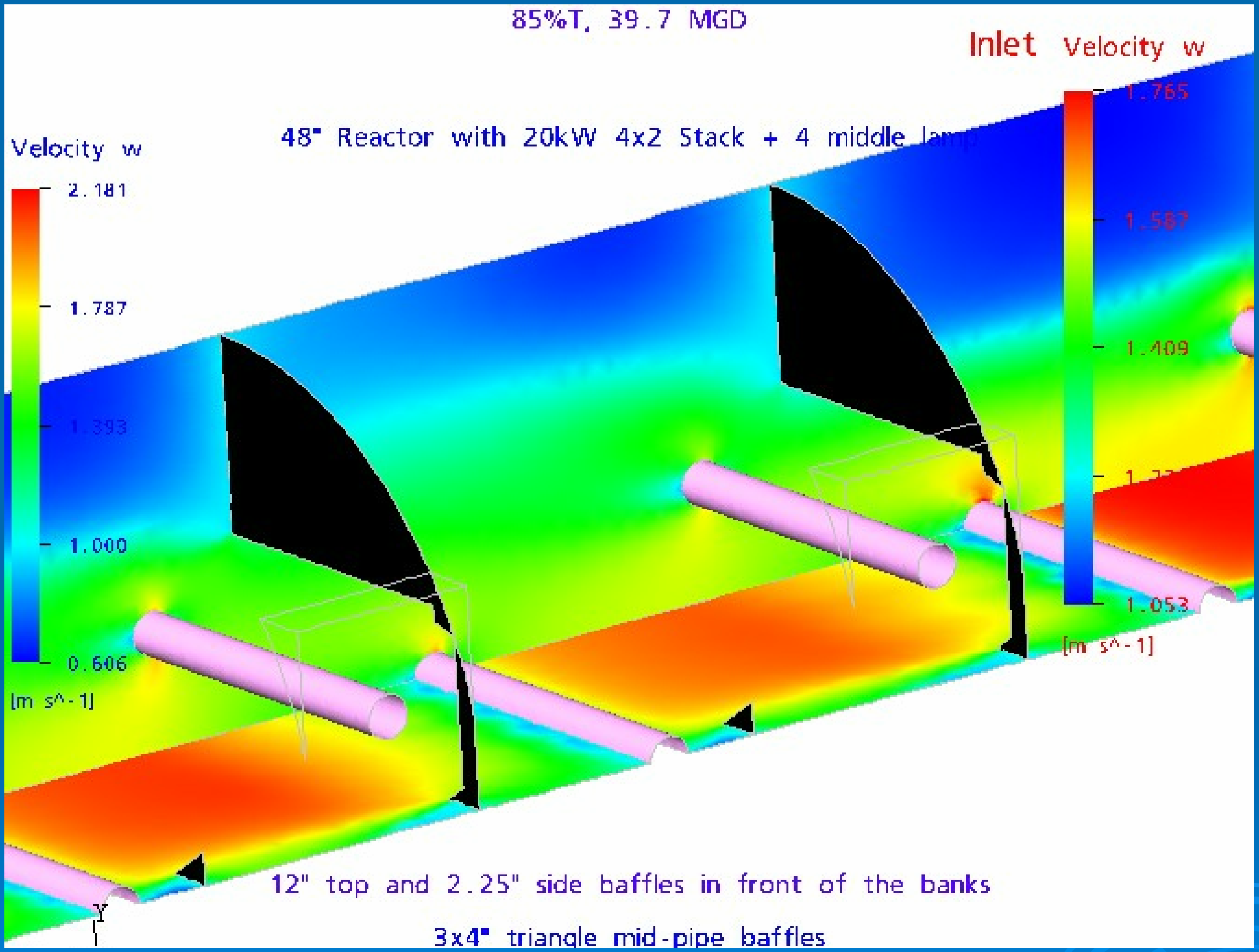
Velocity Profile in the UV Reactor



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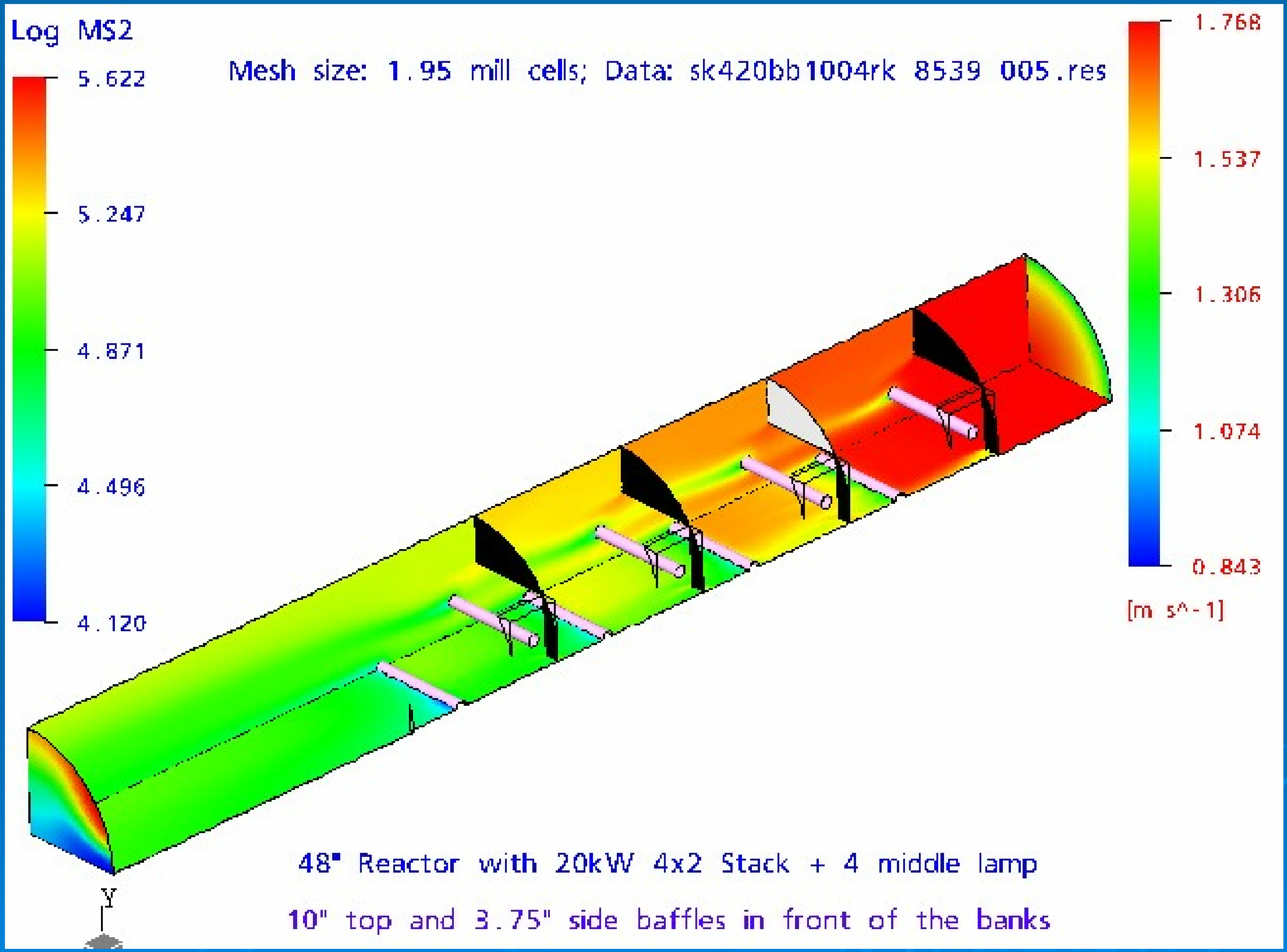
MS2 Profile in the UV Reactor



CFD vs Bioassay

- Results have shown that CFD can simulate a bioassay and different hydraulic conditions
- This saves time and money compared to doing on-site bioassays

UV Water and Wastewater Training and Maintenance

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UV Water and Wastewater Training and Maintenance

- Good operation of treatment process
- Proper operation of filtration process
- UV Operation
  - Starts with Training
  - Focus on Equipment Elements

Training Elements

- Design Flows and Characteristics
- Alarm Systems
- Mechanical Checks
- Control Logic for PLC
- Replacement of Basic Components
- **S**tandard **O**perational **P**ractice (SOP) for Operation and Maintenance

Maintenance Requirements

- Daily Transmittance/TSS/Turbidity measurements…Trend analysis
- Bacterial Measurements
- Weekly Module Examination
- Lamp Replacement
- Ballast Replacement
- Quartz Sleeve Replacement
- Sensor Calibration/Replacement
- Yearly Reactor Cleaning (Minimum)

When The Lights (Disinfection System) go out What is the Issue?????

- Mechanical
- Electrical
- Process

UV Issues - Mechanical

- Cleaning Systems
  - Chemical
  - Frequency
- On-line Monitoring/Sensors
- Hydraulic and Process Control Systems

Monitoring and Alarm

- Continuous Monitoring
  - Probes calibrated monthly
  - Transmittance/Turbidity verified weekly if using continuous recording device
- Disinfection System Monitoring
- Alarms
  - High Priority
  - Low Priority

Types of Alarms

- High/Low Flow
- High/Low Intensity
- High Pressure
- High Temperature
- Moisture Alarm
- Lamp Failures Single and an a Joining Lamp
- Ballast Failures
- Power Failure
- PLC Failure

Mechanical Check Summary

- Cleaning system to ensure acceptable performance
- Proper delivery of cleaning chemicals
- On-line transmittance measurements
- On-line intensity measurements
- Ballast closed loop-cooling system
- Flow meter calibration/headloss
- Level control operating and clean

Electrical Checks

- Lamps
  - Is there water inside the quartz sleeve?
  - Condensation?
- Ballast Output
  - Has the ballast shorted out?
- Wiring

Electrical Checks

- Lamps are energized?
- Lamps are connected?
- Useful lamp Life
  - 12,000 to 15,000 hours for LP
  - 5,000 – 8,000 hours for MP
- Ballast Output

Electrical Check Summary

- Power to UV system (everything connected)
- Power harmonics?
- Lamps on?
- Ballast on?
- Sensors functional and calibrated
- PLC operational and recording information

Process Checks

- Effluent Transmittance
- Effluent Total Suspended Solids
- UV Spectra
- Effluent Colour
- Industrial Dischargers
- Iron/Manganese/Hardness
- Microbial Testing Procedures

Reactor Maintenance

- Reactor walls shall be consistent with the manufacturer's recommendations
- Isolate each reactor for maintenance
- Concrete channels shall be coated to prevent organism growth in crevices
- All exposed materials shall be UV resistant
- Upstream, between, and downstream portions must be water and light tight and must prevent external materials from entering

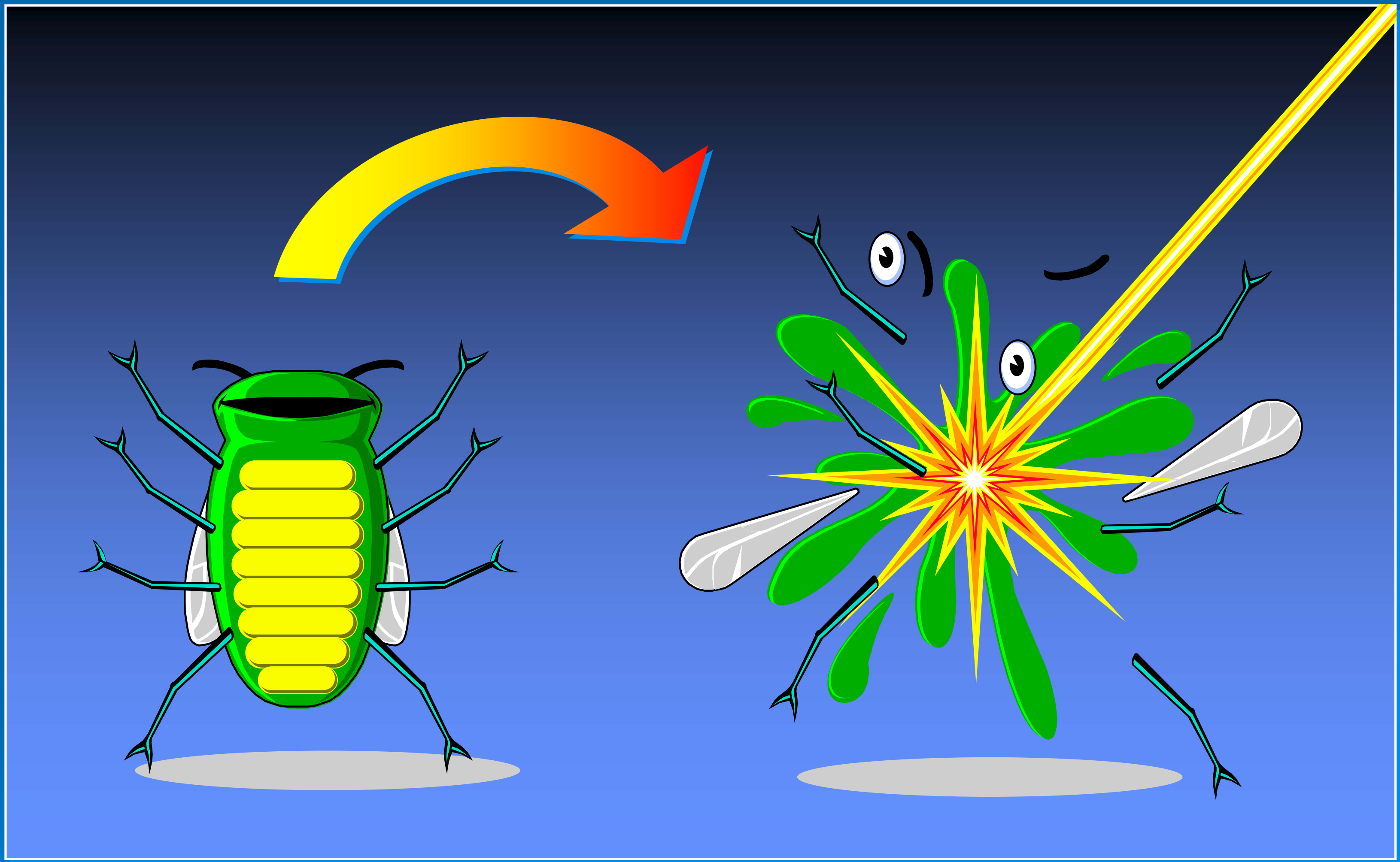
Process Check Summary

- Has a water quality change occurred?
  - Transmittance
  - Solids
  - Particle Size
- New industrial user
- Impact from algae
- Are sampling SOP's being followed
- Change in laboratory staff

Summary

- Trouble shooting can be challenging
- Key is identifying issues of the sub-system so that you can return to compliance

Thank you



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