Calgon Carbon

Making Water and Air Safer and Cleaner

Advanced Oxidation for Taste & Odor in Drinking Water and Scale Up of UV AOP Reactors from Bench Tests using CFD Modeling

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Calgon Carbon Corporation

K-Water

November 28, 2011

Who Is Calgon Carbon Corporation?

- We solve customer purification and separation problems with a variety of technologies
- World's Largest Producer of Granular Activated Carbon. Carbon Technology is our core competency
- Diverse Product Portfolio
- 1000+ employees
- 240 Patents
- 10 sales offices – 6 countries
- 14 manufacturing facilities – 6 countries

- Revenues: > $500 M
- On New York Stock Exchange (CCC)
- 60 + Years of Experience in Drinking Water and Wastewater Treatment

Calgon Carbon UV History

- Started in Advanced Oxidation (MP + Hydrogen Peroxide) in 1985, acquired by CCC in 1996
- Progressed to Drinking Water 1997, CCC innovation for *Cryptosporidium*
- Entered Wastewater Market with in 2004
- Entered Ballast Water Market - Hyde Marine (UV and filtration) in 1995, acquired by CCC 2010

Why is Calgon Carbon UV Unique?

- Use advanced science and technology to develop products
- World Leader in Advanced Oxidation – 25 years experience and over 400 installations
- Validate all products – true sizing and performance verification, not just "manufacturer's claims"
- Have <u>never</u> had to 'upgrade' a system due to performance or design issues
- Highest powered lamps on the market for both DW and WW – basis for low Operating and Maintenance and smallest footprint
- Focus on real Cost of Ownership for lowest 20 year Net Present Value


Calgon Carbon
UV Technologies
BUILDING
2000

UV Manufacturing Facility

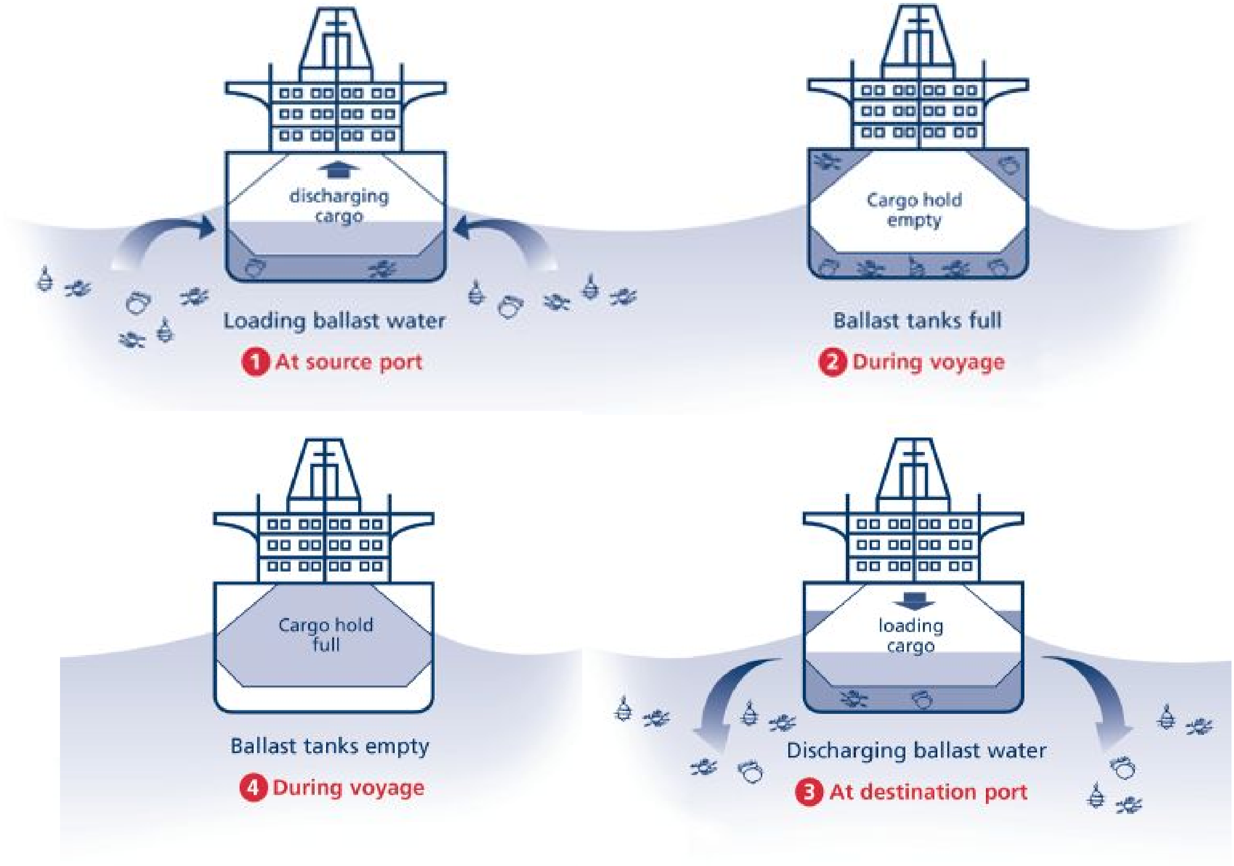
Rayox® UV-Oxidation Systems

Rayox®

Rayox® Tower at Gencorp Aerojet

Ballast Water Treatment

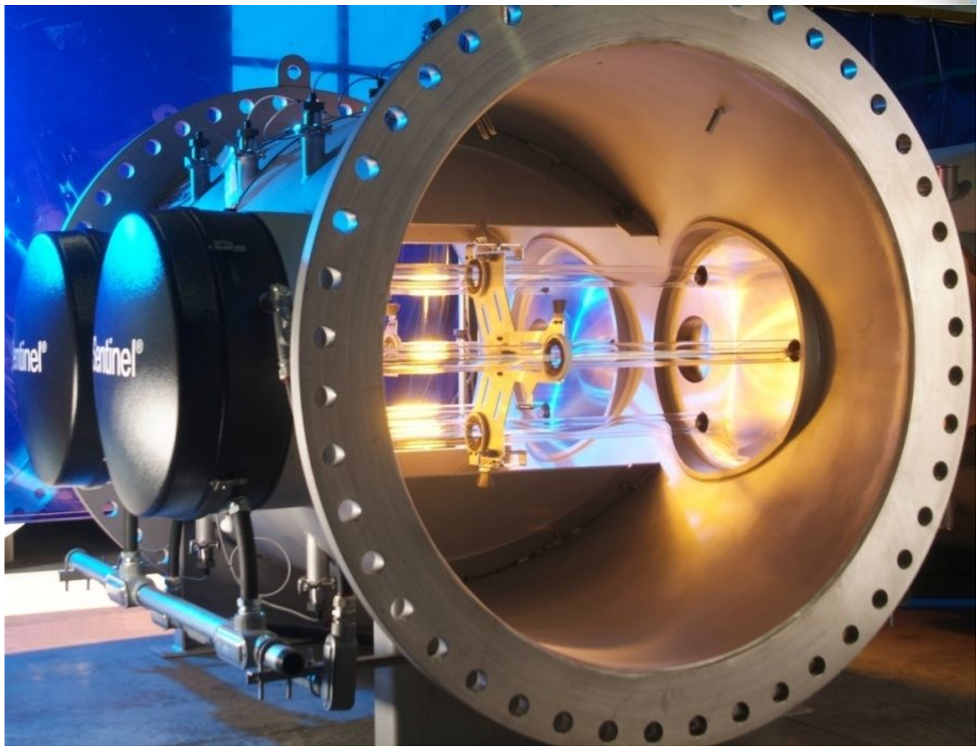
§The issue: Transfer of invasive species via ships' ballast water



UV Disinfection

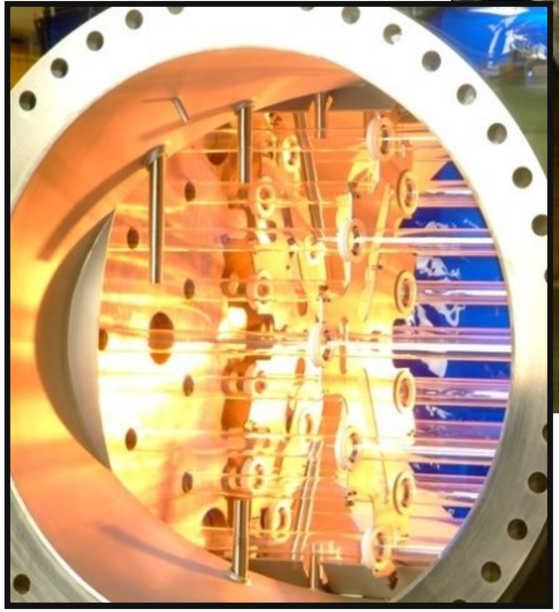
Wastewater – C3500

Drinking Water Sentinel



Sentinel® Chevron AOP

- Disinfection and Taste & Odor Destruction
- 2 - 18 lamp configuration
  San Francisco - 9 lamps
  Cincinnati - 5 lamps,
  Boston – 5 Lamps
  Scottsdale – 18 lamps
- Only 1.8m long with up to 360,000 watts!
- Also available in 600mm 9x10 kW version



White River – Indianapolis
(5) 1200mm 20 kW reactors 454 MLD

San Francisco, CA
(12) Chevron Reactors 1,211 MLD

Calgon Carbon

Sentinel® Drinking Water Installations

- Montreal Canada – 2,950 MLD
- Boston MA – 1703 MLD
- Washington DC – 1,135 MLD
- San Francisco CA –1,211 MLD
- Cincinnati OH – 870 MLD
- Winnipeg, MB – 780 MLD
- Johor Singapore – 454 MLD
- Indianapolis IN – 454 & 151 MLD
- E.L. Smith, AB – 360 MLD
- Stromlo, AU – 284 MLD
- Rossdale, AB – 185 MLD
- Kelowna, BC – 185 MLD
- West View, PA – 151 MLD
- Harnett County, NC – 136 MLD
- Pawtucket, RI – 119 MLD
- Burl Oak, ON – 121 MLD
- Mountain House, CA – 114 MLD

Calgon Carbon AOP Experience

Customer	City	State	Process	# & type of lamp
R F Weston - Groveland Wells	Groveland	MA	UV OX/GAC	4 x 30
Norair engineering - Greenwood	Greenwood	VA	UV OX/GAC	1 x 30
URS Radion	Haverton	PA	UV OX/GAC	3 x 30
International Technology Corp - Fort Ord	Fort Ord	CA	UV OX/GAC	12 x 30
Unifeld Engineering - transbas	Billings	MT	UV OX/GAC	2 x 30
Trans Mountain Pipe Line Co	Burnaby	BC	UV OX/GAC	3 x 30
O'Brien & Gere - Picillo Farms	Coventry	RI	UV OX/GAC	2 x 30
Raytheon	Waco	TX	UV OX/GAC	4 x 30
TRW - VSSI	Mesa	AZ	UV OX/GAC	3 x 30
Cameco Corporation	Blind River	ON	UV OX/GAC	9 x 30
Michigan Dept of Environ Quality - Rancor	Cadillac	MI	UV OX/GAC	4 x 30
Ransom Environmental	Wakefield	MA	UV OX/GAC	2 x 30
Parsons - Pharmacia & Upjohn	NorthHaven	CT	UV OX/GAC	2 - 4 x 30
Lowry Environmental	Aurora	CO	UV OX/GAC	1 x 30
ICI	Montreal	QC	UV OX	3 x 30
Environment Canada	Ottawa	ON	UV OX	3 x 10
Domtar	Trenton	ON	UV OX	1 x 6
U S Navy	Indian Head	MD	UV OX	4 x 30
T R Miller	Brewton	AL	UV OX	2 x 30
Nestle's Beverage	Freehold	NJ	UV OX	2 x 5
Atochem	France		UV OX	3 x 6
RMOW	Elmira	ON	UV OX	8 x 30
Uniroyal Chemical - Process Water	Elmira	ON	UV OX	9 x 30
Uniroyal Chemical - Ground Water	Elmira	ON	UV OX	9 x 30
T R Miller	Brewton	AL	UV OX	2 x 30
International Paper	Joplin	MO	UV OX	2 x 30
Mobil Oil	Albany	NY	UV OX	3 x 30
W R Grace	Woburn	MA	UV OX	2 x 5
Unocal	Fremont	CA	UV OX	1 x 30
Ambassador Laundry	Santa Barb:	CA	UV OX	2 x 5
Imperial Oil	Troy	ON	UV OX	1 x 30
Mobil Oil - South Salem	Hawthorne	NY	UV OX	1 x 5
Rohr Industries	Riverside	CA	UV OX	1 x 30
Superior Plating Inc	Minneapolis	MN	UV OX	1 x 5
Hydro Quebec	Gentilly	QC	UV OX	1 x 30
Trade Waste	Australia		UV OX	1 x 6
N C Rubber	Kitchener	ON	UV OX	1 x 10
B P Research	Cleveland	OH	UV OX	1 x 5
Martin Marietta - Furr	Charlotte	NC	UV OX	1 x 5
Martin Marietta	Denver	CO	UV OX	1 x 30
L'Air Liquid	France		UV OX	2 x 5
Uniroyal Chemical	Elmira	ON	UV OX	6 x 30
Artes Ingegneria Spa - Bono	Italy		UV OX	2 x 10
Hoechst Celanese - Needmore	Salisbury	NC	UV OX	6 x 30
E G & G Florida	KSC	FL	UV OX	3 x 30

Customer	City	State	Process	# & type of lamp
Roy F Weston - Pine Bluff	Pine Bluff	AR	UV OX	3 x 30
Solarchem	Markham	ON	UV OX	
Solarchem	Markham	ON	UV OX	3 x 30
Hoechst Celanese - Spartanburg (2)	Spartanburg	SC	UV OX	3 x 30
Whiting Turner - China lake	China Lake	CA	UV OX	2 x 30
EA Engineering - McClellan AFB	Sacramento	CA	UV OX	6 x 30
University of Waterloo	Waterloo	ON	UV OX	1 x 1
Masco Corporation	Troy	MI	UV OX	2 x 30
Shipley - Capaccio	Marlboro	MA	UV OX	2 x 30
Roy F Weston - Charles George Landfill	Tyngsboro	MA	UV OX	3 x 30
Laidlaw Waste Management	Adrian	MI	UV OX	1 x 30
Western Summit Constructors	Littleton	CO	UV OX	1 x 30
Secor - Beechcraft	Boulder	CO	UV OX	4 x 30
CPQ Resisa	Spain		UV OX	3 x 30
Phelps Dodge Magnet Wire Co	Fort Wayne	IN	UV OX	1 x 30
Harding Lawson - Sullivan's Ledge	New Bedford	MA	UV OX	4 x 30
Harris Contracting	Minneapolis	MN	UV OX	1 x 30
Mitsui Toatsu Plant Services Inc	Japan		UV OX	1 x 1
Halliburton NUS - Brooks AFB	San Antonio	TX	UV OX	1 x 30
Freer Mechanical - Lockheed	Fort Worth	TX	UV OX	6 x 30
Six Nations Housing	Ohsweken	ON	UV OX	3 x 30
Osram Sylvania	Hillsboro	NH	UV OX	1 x 30
Earth Burners - Dwyer Fire	Duluth	MN	UV OX	2 x 30
Montgomery Watson	Griffith	IN	UV OX	1 x 30
Eka Nobel	Marietta	GA	UV OX	3 x 30
Jacobs Engineering - Otis AFB	Cape Cod	MA	UV OX	3 - 2 x 30
U S Filter	Warrendale	PA	UV OX	3 x 1
Radian Corporation - Travis AFB	Fairfield	CA	UV OX	2 x 30
TransAmerica Life Assurance Co	Waterloo	ON	UV OX	1 x 10
GenCorp Aerojet	Sacramento	CA	UV OX	21 x 30
OHM - Maryland Wood	Trenton	MD	UV OX	2 x 30
OHM - Vance AFB	Enid	OK	UV OX	3 x 30
CH2M Hill - McClellan AFB	Sacramento	CA	UV OX	1 x 30
Geomatrix	Mountain View	CA	UV OX	2 x 30
Environment Canada	Ottawa	ON	UV OX	1 x 1
Daejo Biotech Corp	Korea		UV OX	1 x 1
Pacificorp	Salt Lake City	UT	UV OX	1 x 30
U S Filter	Puyallup	WA	UV OX	1 x 30
ChemWaste Management	Arlington	OR	UV OX	1 x 30
Alexander von Humboldt (Germany)	India		UV OX	1 x 1
Siemens Microelectronics	Scottsdale	AZ	UV OX	2 x 30
Akzo Nobel	Sweden		UV OX	1 x 1
Carlton University	Ottawa	ON	UV OX	1 x 1
Filtration Treatment	Pearl Harbour	HI	UV OX	1 x 30
Mitsui Toatsu Plant Services Inc	Japan		UV OX	1 x 10

Calgon Carbon AOP Experience (cont'd)

Customer	City	State	Process	# & type of lamp
Trade Waste	Australia		UV OX	2 x 30
United Technologies	East Hartfor	CT	UV OX	1 x 1
Imperial Oil - North Property	Toronto	ON	UV OX	1 x 10
Hercules Canada Inc	Burlington	ON	UV OX	1 x 10
Hoechst Celanese - Spartonburg (1)	Spartanburg	SC	UV OX	3 x 30
Six Nations Council	Ohsweken	ON	UV OX	1 x 30
Halliburton NUS - Kelly AFB	San Antonio	TX	UV OX	1 x 30
GREEFF Fabrics Inc	Santa Monic	CA	UV OX	1 x 30
Gelman Sciences Inc	Ann Arbor	MI	UV OX	3 x 30
Root Lowell Manufacturing	Lowell	MI	UV OX	2 x 30
Solarchem	Markham	ON	UV OX	1 x 1
Roy F Weston - Kelly AFB	San Antonio	TX	UV OX	9 x 30
Roy F Weston - Kelly AFB	San Antonio	TX	UV OX	3 x 30
Hoechst Celanese - Perimeter	Salisbury	NC	UV OX	9 x 30
Environment Canada	Ottawa	ON	UV OX	1 x 1
H E Sargent	Winthrop	ME	UV OX	2 x 30
Hercules Aerospace Co	Rocket Cent	WV	UV OX	2 x 30
Saco Defense	Saco	ME	UV OX	1 x 30
Texaco	Port Arthur	TX	UV OX	1 x 1
MacCemar	Belgium		UV OX	1 x 1
Purex Industries Inc	Millville	NJ	UV OX	6 x 30
Hargis & Associates	La Jolla	CA	UV OX	1 x 30
Westinghouse Hanford Co	Richland	WA	UV OX	1 x 10
Foley Company	Desoto	KA	UV OX	1 x 30
Collymore Associates - Servall Laundry	Bronx	NY	UV OX	3 x 30
BASF	Wyandotte	MI	UV OX	2 x 30
GenCorp Aerojet	Sacramento	CA	UV OX	3 x 30
Imperial Oil - South Property	Toronto	ON	UV OX	1 x 10
Davidson Instrument Panel	Farmington	NH	UV OX	1 x 30
U S Army - APG	APG	MD	UV OX	2 x 1 x 30
Fagan	Australia		UV OX	4 x 30
Fagan - NZFC	New Zealand		UV OX	4 x 30
Jalbert Associates	Norfolk	VA	UV OX	2 - 4 x 30
Ciba Geigy	Cambridge	ON	UV OX	1 x 30
THAN	Pleasant Hill	IA	UV OX	2 x 30
Dainippon Ink & Chemicals	Japan		UV OX	1 x 1
Malcolm Pirnie	Vineland	NJ	UV OX	1 x 1
Huls Canada	Toronto	ON	UV OX	1 x 30
Adtechs - Ontario Hydro	Bruce Penn	ON	UV OX	1 x 10
Foster Wheeler - Kelly AFB	San Antonio	TX	UV OX	6 x 30
Fagan	Australia		UV OX	1 x 1
University of Wester Ontario	London	ON	UV OX	1 x 1
Coding Products	Kalkaska	MI	UV OX	2 x 30
Argonne National Laboratory	Argonne	IL	UV OX	1 x 30
General Electric	Hudson Fall	NY	UV OX	2 x 30
Quanterra labs	Sacramento	CA	UV OX	pump

Customer	City	State	Process	# & type of lamp
CCOT	Tucson	AZ	UV OX	1 x 1
Nan Ya Plastics (EBSL)	Taiwan		UV OX	4 x 30
CCC	Pittsburgh	PA	UV OX	2 - 1 x 1
Hewlett Packard	Puerto Rico		UV OX	2 x 30
Oriental Chemical Industries	Korea		UV OX	1 x 1
OHM ABL Corporation	Keyser	WV	UV OX	2 x 30
CCOT	Netherlands		UV OX	1 x 6
Becton Dickenson	East Rutherford	NJ	UV OX	1 x 30
GenCorp Aerojet	Sacramento	CA	UV OX	9 x 30
Young Chang - Samsung	Korea		UV OX	3 x 30
August Mack Environmental Inc	Wildwood	FL	UV OX	4 x 30
NangYan Tech University	Singapore		UV OX	1 x 1
Sabic	Saudi Arabia		UV OX	1 x 30
Chemviron	United Kingdom		UV OX	1 x 1
Mitsui Toatsu Plant Services	Japan		UV OX	1 x 30
Radian Intenational - Travis AFB	Fairfield	CA	UV OX	2 x 30
Brown & Williamson Tobacco Corp	Macon	GA	UV OX	1 x 1
T R Miller	Brewton	AL	UV OX	4 x 30
Sigma Environmental	Oak Creek	WI	UV OX	1 x 30
R F Weston - Kelly AFB Zone 4	San Antonio	TX	UV OX	3 x 30
Koester Environmental - Robins AFB	Warner Robins	GA	UV OX	6 x 30
Kimberly Clark	Owensboro	KY	UV OX	1 x 30
Allied Signal	Tooele	UT	UV OX	1 x 30
NASA	KSC	FL	UV OX	Special
Salcon Limuted	Singapore		UV OX	6 x 1
Honeywell	Tampa	FL	UV OX	1 x 30
Honeywell	Tampa	FL	UV OX	4 x 30
B-Project	Japan		UV OX	1 x 10
Kimberly Clark	Owensboro	KY	UV OX	2 x 30
CFE - MCEC	Japan		UV OX	1 x 30
National Institute of Health	Bethesda	MD	UV OX	1 x 30
Cornell	Ithaca	NY	UV OX	2 x 30
August Mack Environmental Inc	Wildwood	FL	UV OX	3 x 30
Mercury Aircraft	Hammondsport	NY	UV OX	1 x 30
Aberdeen / IT Group	Edgewood	MD	UV OX	3 x 30
Kelly Air Force Base	San Antonio	TX	UV OX	3 x 30
SAIC Kelly AFB	San Antonio	TX	UV OX	3 x 30
Eaton	Westminster	SC	UV OX	2 x 30
Eatontown	Eatontown	NJ	UV OX	3 x 30
Danville	Danville	PA	UV OX	1 x 30
Lockheed-Martin	Littleton	CO	UV OX	2 x 30
Honeywell (Besly Site)	Greenfield	MA	UV OX	4 x 30
Parsons Engineering (Honeywell)	Sarasota	FL	UV OX	2 x 30
Nucleoelectrica Argentina (NA SA)	Buenos Aires	Argentina	UV OX	1 x 30
Blind River Refinery (Cameco Corp.)	Blind River	ON	UV OX	3 x 30
Gulfstream WWTP	Savannah	GA	UV OX	1 x 30
O'Brien & Gere of N. A.(GE Hudson Falls)	Hudson Falls	NY	UV OX	3 x 30

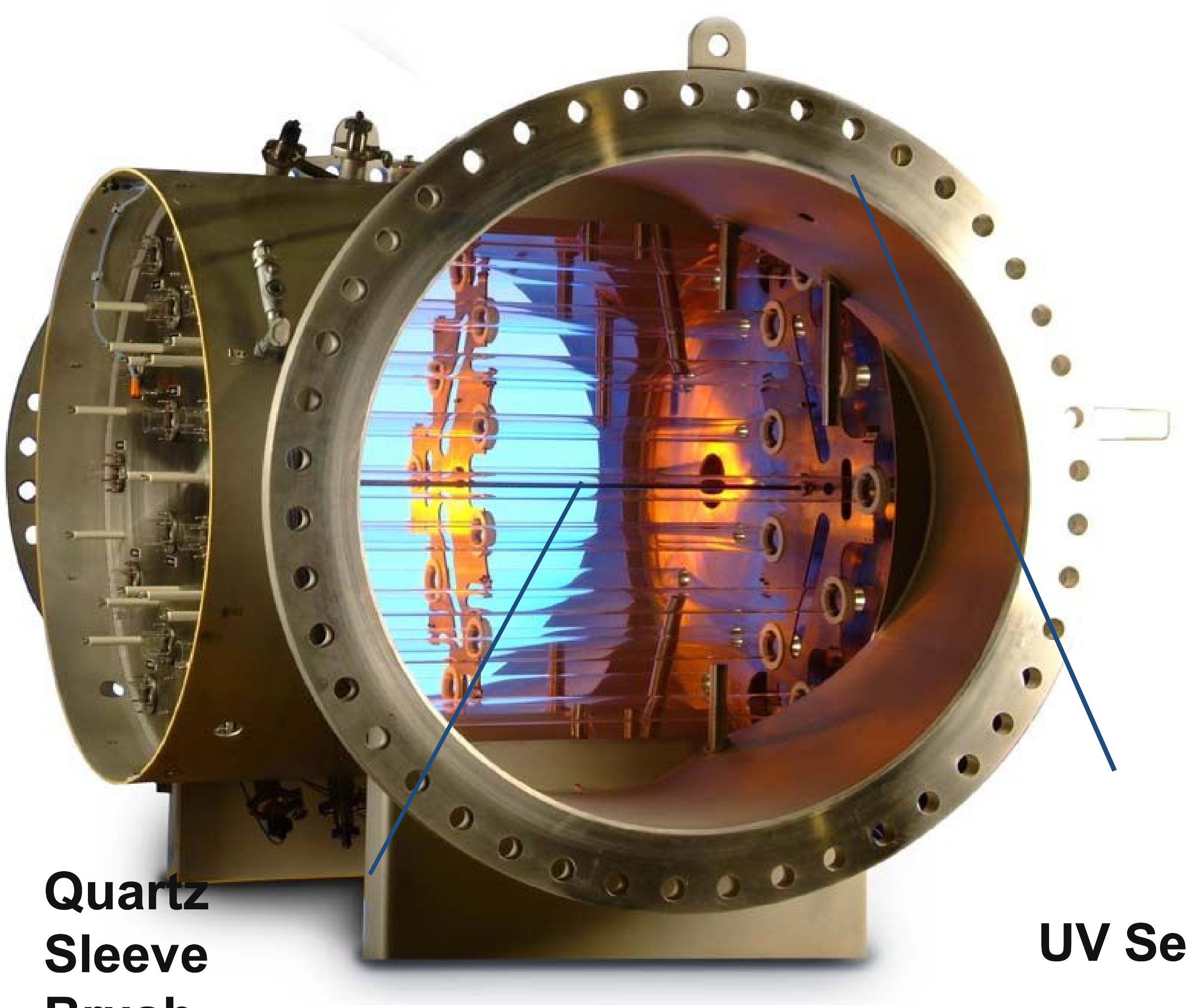
Drinking Water – AOP Conclusion

- Calgon Carbon UV has the longest history and experience in advanced oxidation over any other UV company (> 25 years)
- Calgon Carbon UV has installed the largest medium pressure drinking water disinfection systems in the world
- Calgon Carbon has more AOP installations (>350) than any other UV company
- Calgon Carbon UV has third-party tested its DW AOP reactors in Portland USA
- The combination of drinking water experience, expertise in AOP, and third party testing for T&O AOP is evidence that Calgon Carbon UV is the <u>most qualified</u> company for all Drinking Water AOP projects

Sentinel® Chevron 600mm
9 x 10 kW

- UV Intensity Sensors
  - One sensor per lamp
  - Mechanical cleaning
  - Reference sensors yearly calibration
- Instrumentation
  - Temperature alarm
  - Moisture alarm
  - Wiper system alarm
- Ballasts
  - Electromagnetic
  - One lamp per ballast

Sentinel Chevron 18 x 20 kW



- UV Intensity Sensors
  - Ø One sensor per lamp
  - Ø Mechanical cleaning
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- Instrumentation
  - Ø Temperature alarm
  - Ø Moisture alarm
  - Ø Wiper system alarm
- Ballasts
  - Ø Electromagnetic
  - Ø One lamp per ballast

Electromagnetic versus Electronic Ballast

ELECTROMAGNETIC

- More tolerant of line voltage variations (-40% - +10%)
- Control cabinet can be installed up to 152m from the reactor
- Attenuates voltage spikes 6000:1
- More reliable and robust than electronic ballasts – less affected by temperature
- Rapid lamp warm up and re-strike
  - As low as 1 min. to full power and 2.5 min. for hot re-strike)

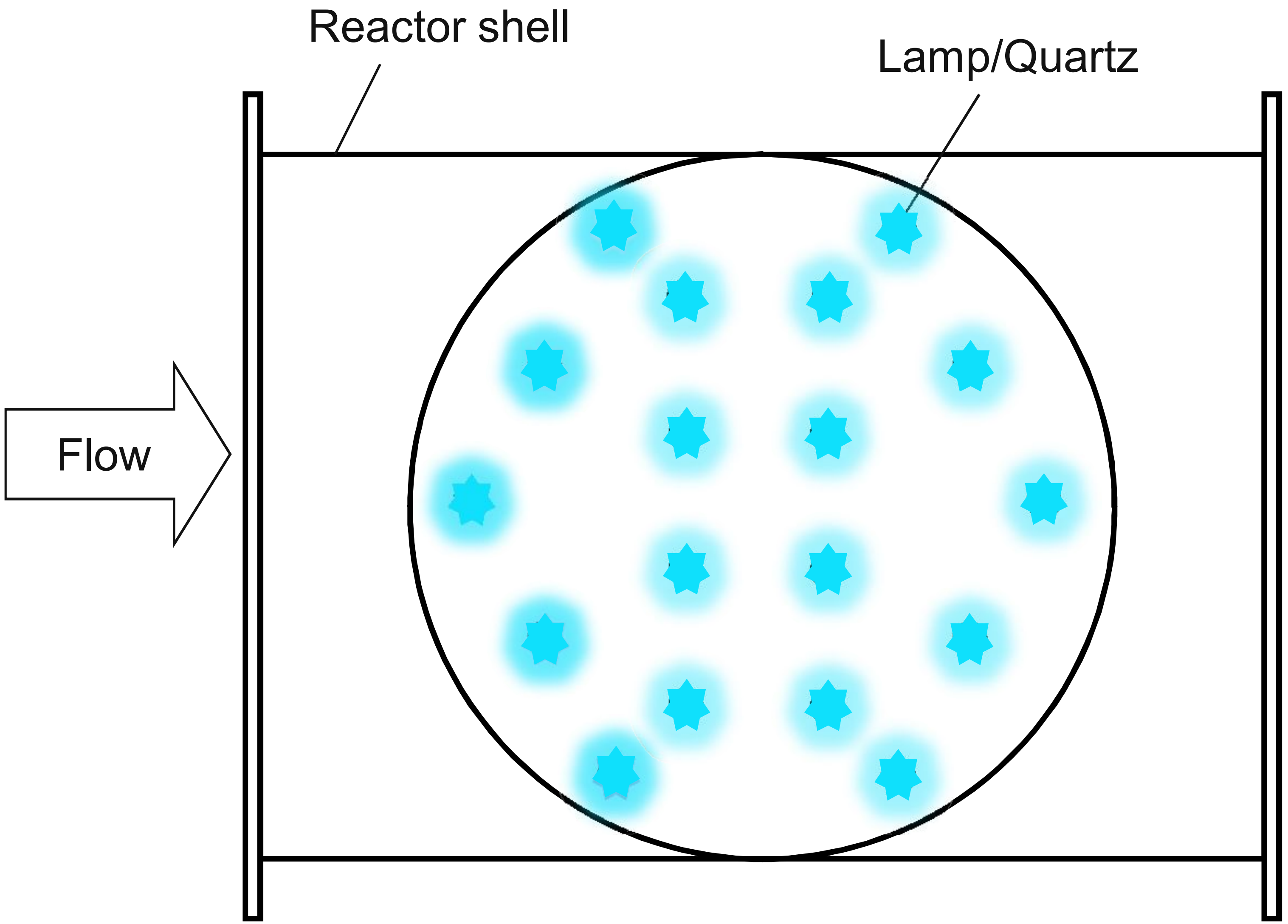
ELECTRONIC

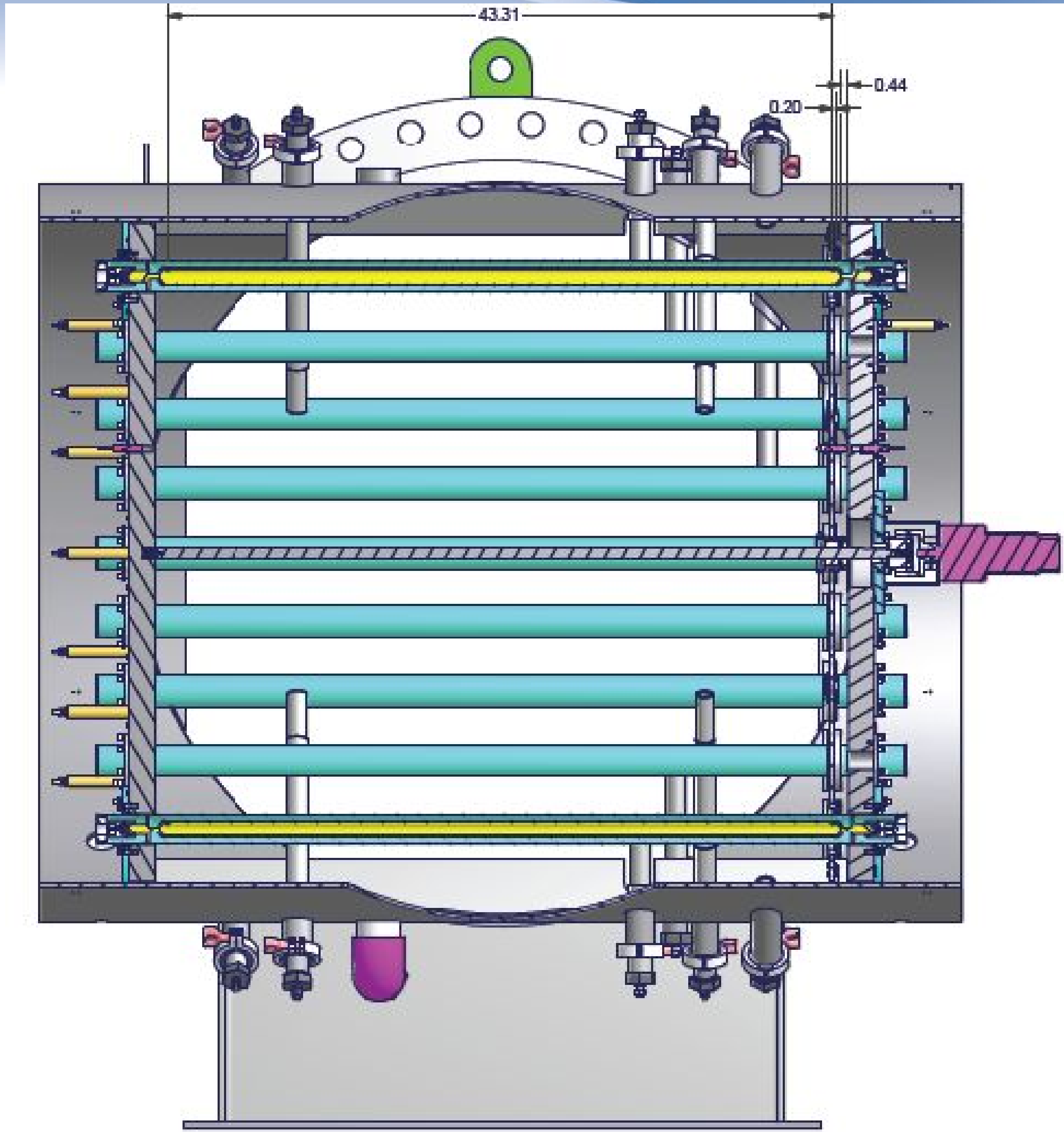
- Power surge or dips will extinguish lamps or destroy the ballast
- Cabinets must be installed within 20 meters of the respective reactor
- Spikes will shut off or damage the ballast card
- Must be in air conditioned room
- 10 minutes for lamps to come up to full power

Mechanical Quartz Cleaning

- Low maintenance**– replace brushes only every 5 years**
- **No chemical costs, hassles, waste, inventory, equipment, piping**
- **No elastomer seals that can burn with UV and leak**

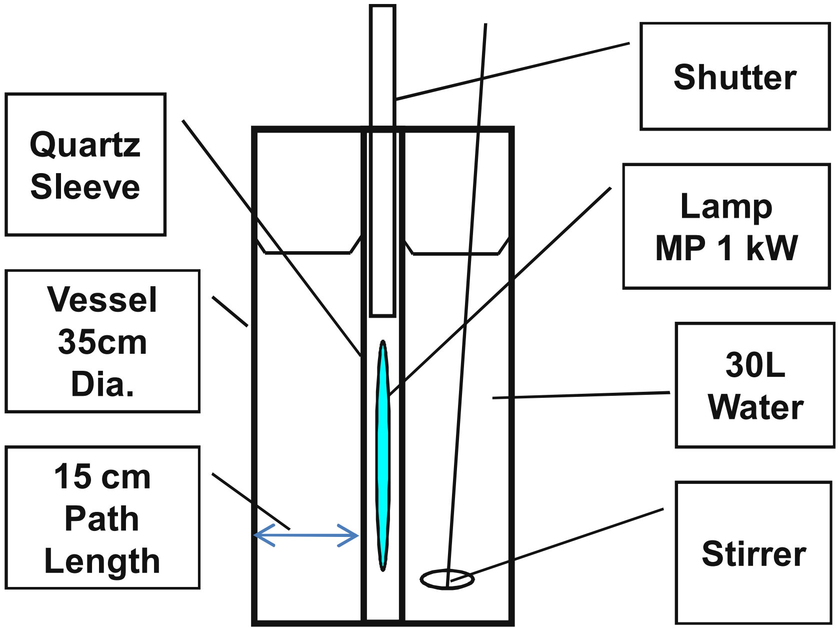
Reactor details and design




43.31
0.44
0.20

K Water Siheung Design Test

- Used Batch Reactor
  - 30 L water for the test
  - More accurate than collimated beam
- Used 1 kW Medium Pressure Lamp
  - Same spectral Output as Full Scale Reactors
  - Reduces scale up errors for MP lamp spectral output
- Used 14 cm Path Length
  - More accurate scale-up than Collimated Beam
- Multiple exposures on same water
  - Reduces dosing and sample errors



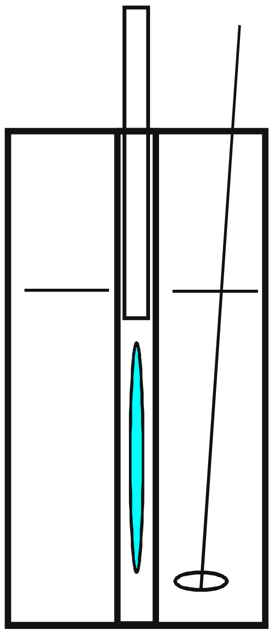
Analysis of the Siheung Water

Analysis Parameter	Units	Result
TSS (Total Suspended Solids)	ppm	<2
TDS (Total Dissolved Solids)	ppm	120
Conductivity	uS/cm	176.6
pH	No Units	6.84
COD (Chemical Oxygen Demand)	ppm	4
TOC (Total Organic Carbon)	ppm	1.13
Iron (Fe Total)	ppm	<0.04
Mg (Magnesium Hardness)	ppm (as CaCO3)	22.5
Ca (Calcium Hardness)	ppm (as CaCO3)	58.8
Hardness (Total)	ppm (as CaCO3)	81.3
Alkalinity (Methyl)	ppm (as CaCO3)	55
Common Anions (IC)		
Fluoride (F-)	ppm	<0.1
Chloride (Cl-)	ppm	10.6
Bromide (Br-)	ppm	<0.2
Nitrate (NO3-)	ppm	10.7
Phosphate (PO4-)	ppm	<0.5
Sulfate (SO4-)	ppm	13.1

UV Transmittance of the Siheung Water

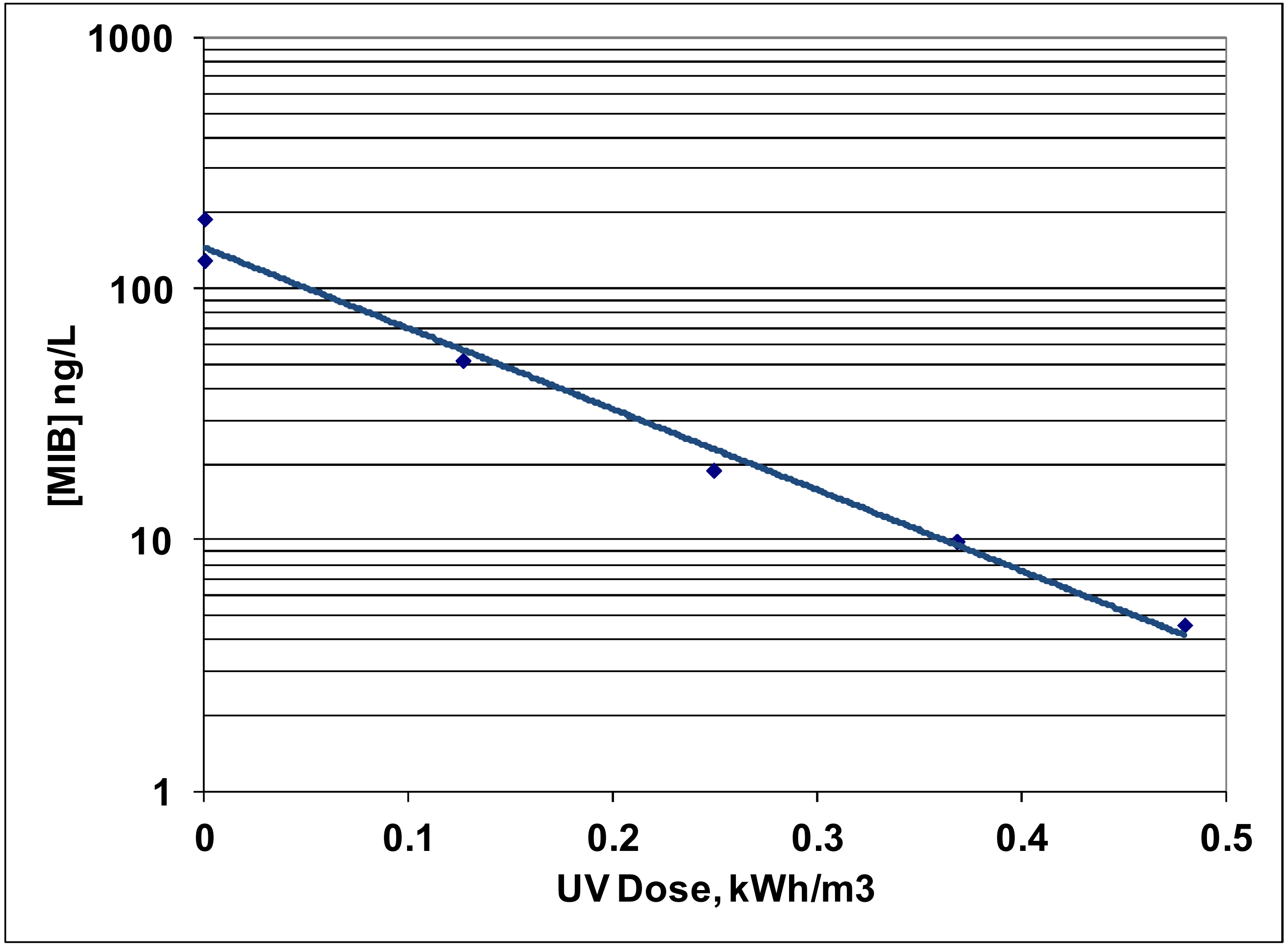
Wavelength	Received water Abs.	Received water %T
200	1.607	2.5
210	1.321	4.8
220	0.656	22.1
230	0.154	70.1
240	0.033	92.7
250	0.016	96.4
254	**0.015**	**96.6**
260	0.012	97.3
270	0.01	97.7
280	0.009	97.9
290	0.008	98.2
300	0.007	98.4

Design Test Results



Sample ID	UV Dose (kWh/m^3)	pH	H2O2 (ppm)	MIB (ppt)
1-0	0.00	6.79	9.7	190
1-1	0.13	6.77	9.5	52
1-2	0.25	6.78	9.4	19
1-3	0.37	6.82	9.1	9.9
1-4	0.48	6.82	8.9	4.6

Design Test Results, 9.7 ppm H_2O_2

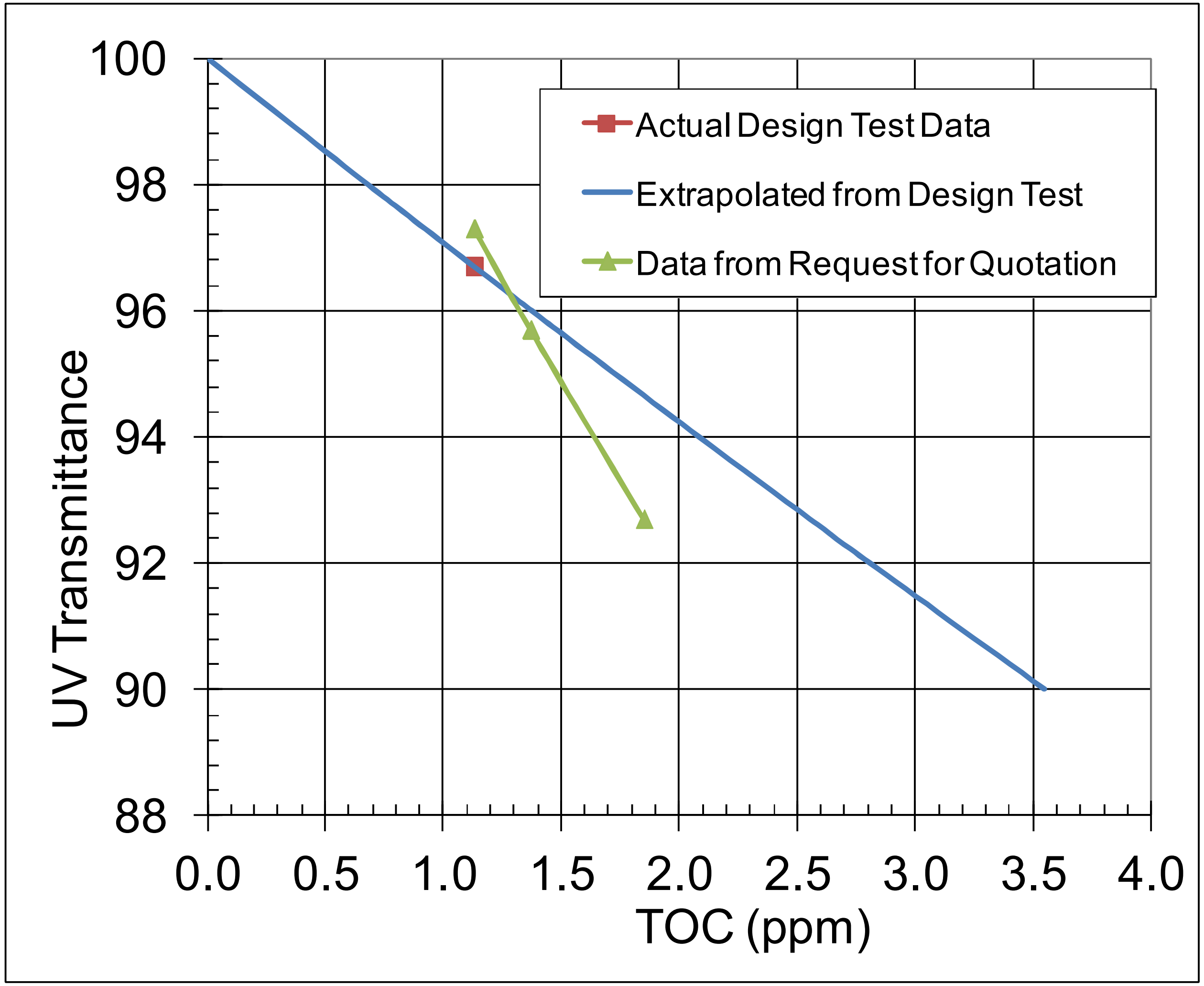


Scale-up:
Slope (EE/O) from graph is adjusted for:

- UV Transmittance
  - from 96 to 92.7%T design – reduces slope
- TOC
  - higher TOC - reduces slope
- Peroxide Concentration
  - Higher peroxide - increases slope
- Path Length
  - Longer path length to absorb UV in full-scale reactor make better use of UV – increases slope

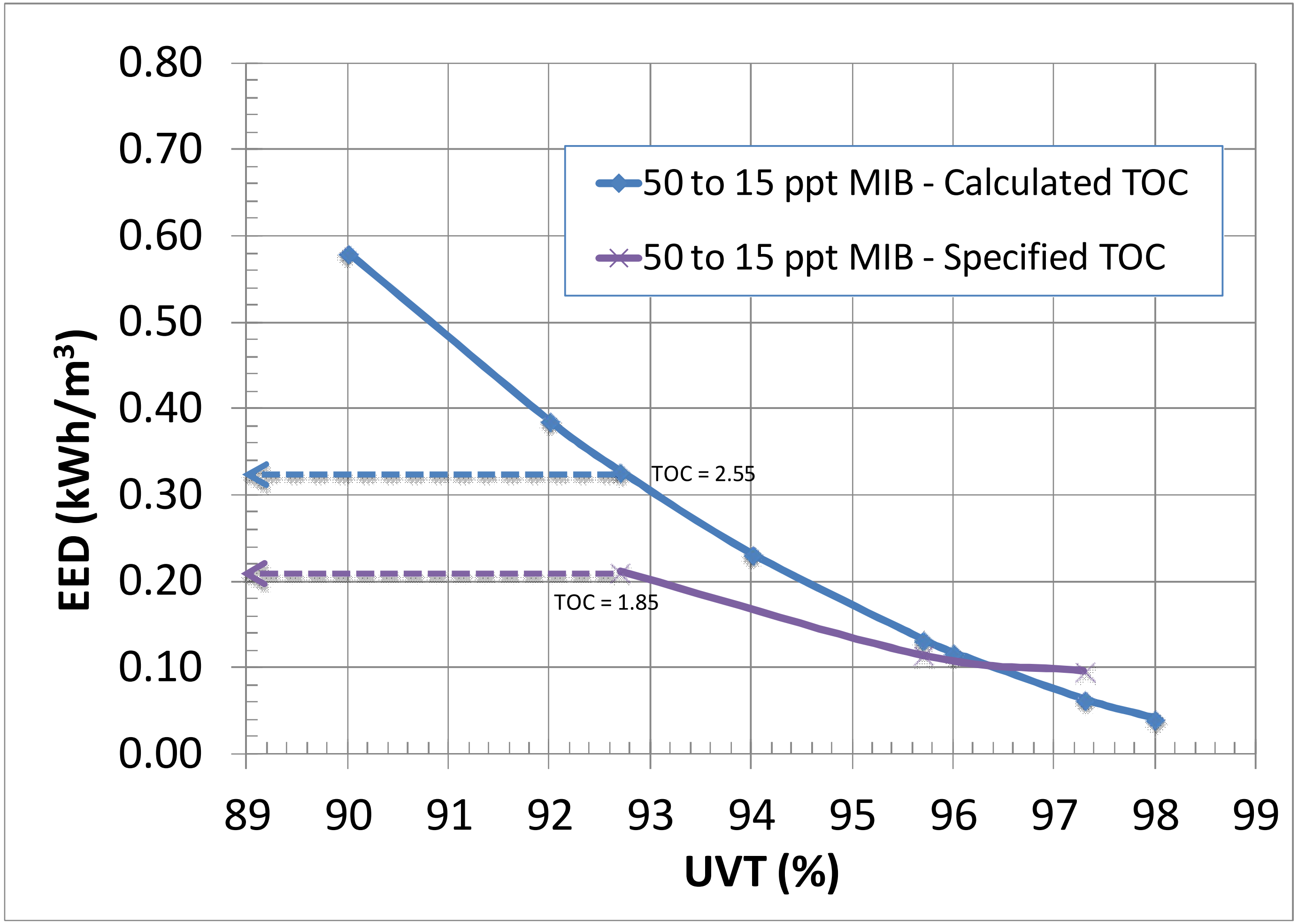
All this can be done with CFD or using a spreadsheet

UV Transmittance vs TOC



- At these high UVT values UVT is proportional to TOC
- Extrapolation should pass through 100%T
- Request for Quotation values do not follow this rule
- Therefore at design UVT of 92.7% TOC of 1.85 is too low
- Results in system that is too small

EED required vs. UVT for different TOC curves (10ppm H_2O_2)

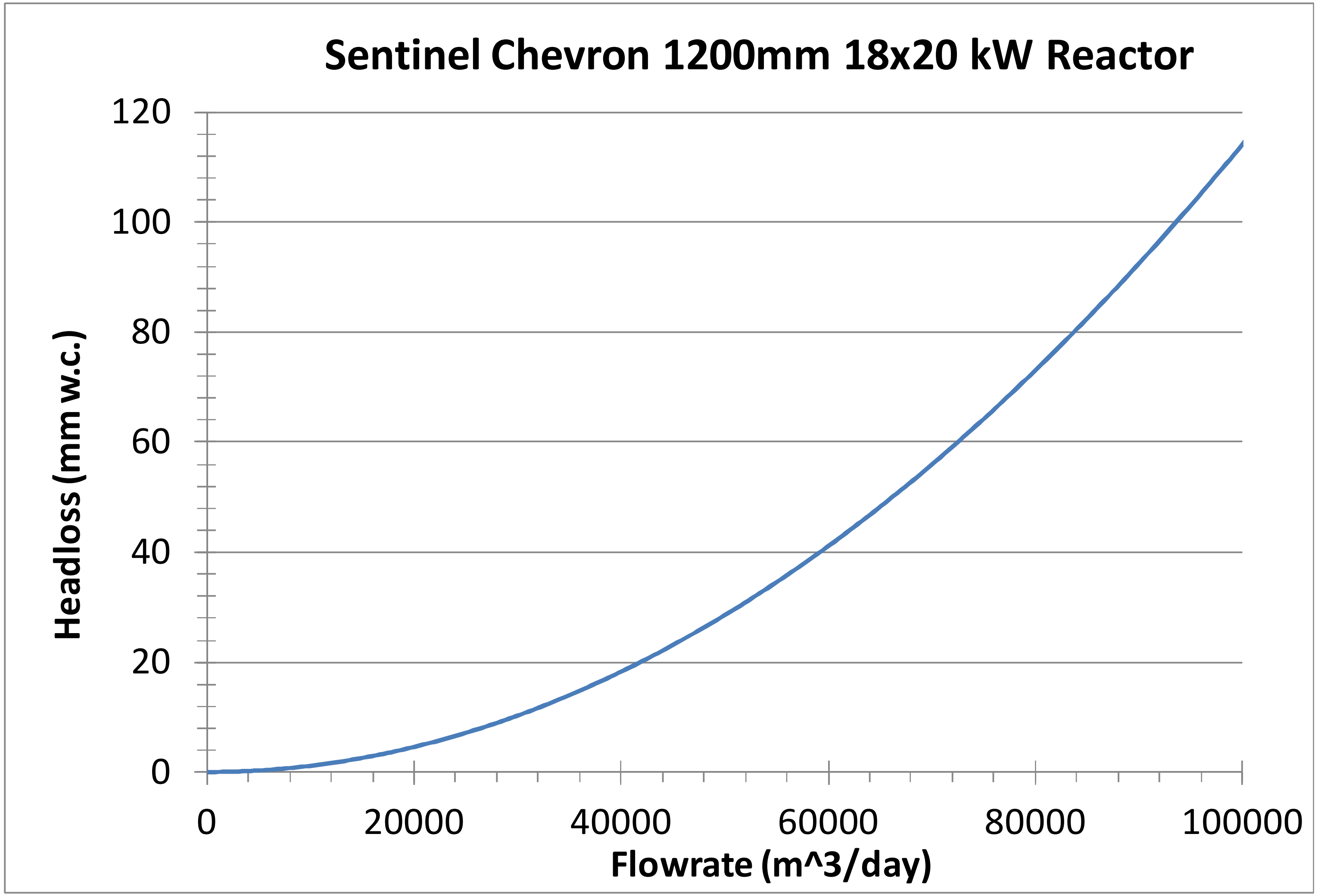


- Different design TOC values result in different EED values
- System would require 50% higher dose if TOC projected from design test is used

Design Options

- Assume Specified TOC at 92.7%T of 1.85 ppm
  - EED = 0.21
- Requires 4 reactors each with 18 x 20 kW lamps
  - **Equivalent to 8 reactors each with 16 x 12 kW lamps for 760 mm system**
- To save space can arrange as 2 trains each with 2 reactors
- Overall pressure drop less than 4 trains with 760mm pipe diameter

Pressure drop of Sentinel 18 x 20 kW Reactor



Pressure drop – 2, 3 and 4 trains

	Sentinel 1200 mm Reactor	Sentinel 1200 mm Reactor	Sentinel 1200 mm Reactor	16 Lamp 760mm Reactor
Trains	2	3	4	4
Pipe Diameter mm	1200	1200	1200	760
Length of pipe m	5	5	5	5
Total Flow, m3/d	129,000	129,000	129,000	129,000
Flow/Train, m3/d	64,500	43,000	32,250	32,250
Reactors per train	2	1.5	1	2
Flow m3/s	0.747	0.498	0.373	0.373
Pipe velocity m/s	0.66	0.44	0.33	0.82
Velocity Head Pipe, mm	22	10	6	34
Entrance/Exit Loss, mm	26	11	6	39
Valves, mm wc	13	6	3	20
Friction, mm	0.8	0.4	0.2	2.6
Reactors, mm	82	31	13	151
Total Pressure Drop, mm wc	122	49	23	213

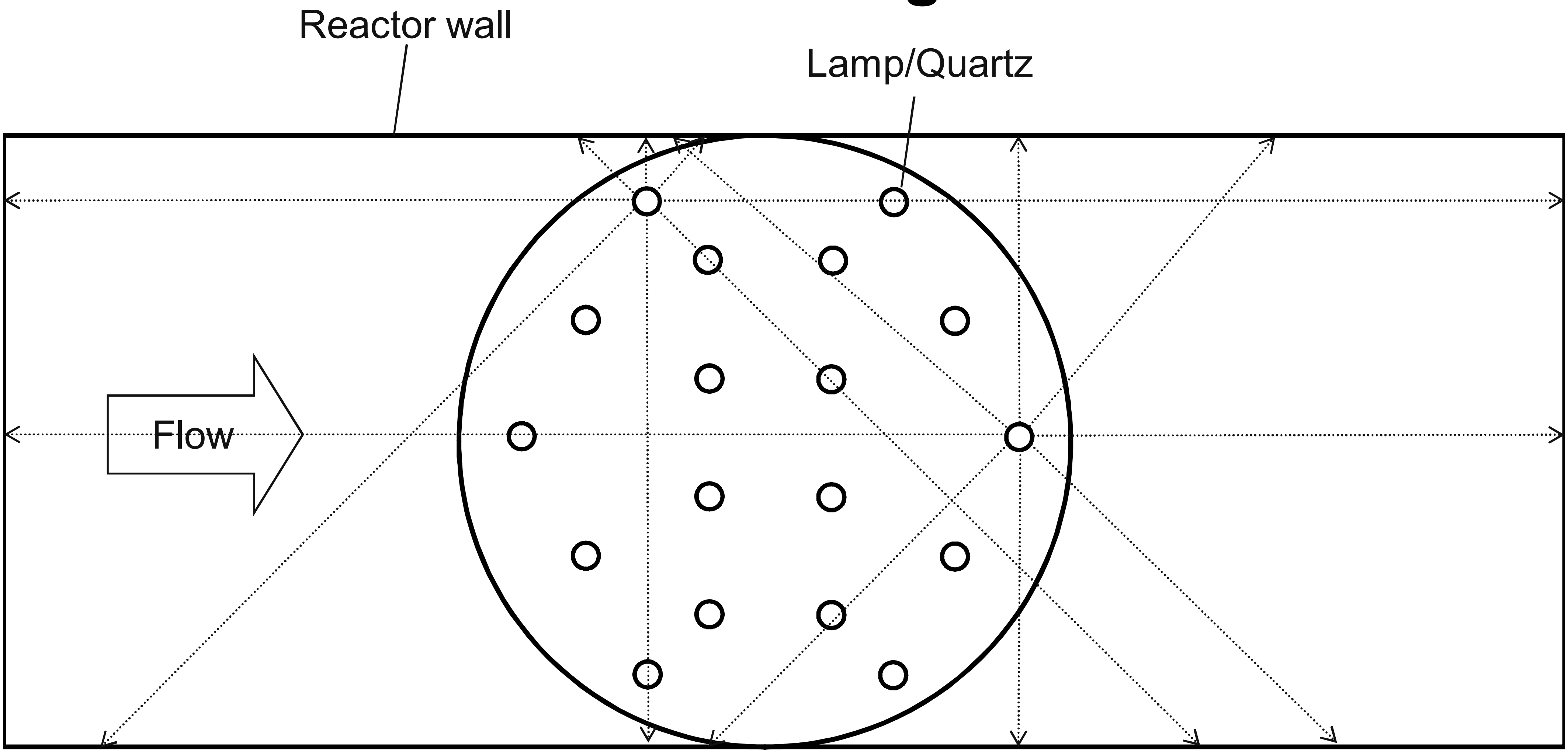
Life Cycle Cost

- Operating # of Lamps and Power should be based on average operating UVT, not design UVT
  - If not could result in selection of the more expensive system that does not turndown as effectively
- Must include Ballast cost - should use number of ballasts installed, not ballasts operating
  - Ballast life guarantee not based on operating hours
- Must include Quartz Sleeve and Wiper Costs
- IF ALL OF THESE ITEMS ARE NOT INCLUDED, THE TRUE COST OF OWNERSHIP IS NOT BEING REPRESENTED FAIRLY AND UV SYSTEM COMPARISONS ARE INACCURATE!

Critical design factors

- **Primary Design Factors**
- **Design flowrate**: Determines the number of lamps, sizing, power consumption
- **Target contaminants**: Rate of reaction with •OH radicals and/or direct photolysis affects sizing
- **Influent and effluent concentrations**: High log-reduction goals require more lamps, bigger footprint
- **UV Transmittance**: Low background UVT ☐ less direct and indirect photolysis, so more UV and/or peroxide are required
- **Secondary Design Factors:**
- **COD**: Consumes •OH radicals
- **Alkalinity/pH**: Determine the relative quantities of carbonate and bicarbonate in the water, both of which consume •OH radicals
- **Iron**: Affects the UV transmittance of the water, increases fouling potential.
- **Nitrate**: Absorbs UV below 250 nm that would otherwise photolyze H_2O_2

Variable Reactor Path Length



Presented at IUVA Conferences:
Paris (May, 2011) and Toronto, September, 2011

SCALE UP OF UV AOP REACTORS FROM BENCH TESTS USING CFD MODELING

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Markham, Ontario, Canada

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Boise, Idaho, USA

Background on Scale up
Electrical Energy per Order (EEO)

- EEO is used to compare the performance of various full scale AOP technologies
- most parameters that affect EEO (lamp output, lamp efficiency, path length) can be scaled up from laboratory to full-scale without much difficulty
- EEO cannot be used to predict the hydraulic or mixing efficiency of a flow through reactor

Dose per log inactivation

- A new metric is proposed that uses bench scale testing to determine the UV Dose required per log destruction of a particular contaminant (D_L)
- However dose is not measured in Electrical Energy but in peroxide weighted fluence in the same way as dose is calculated in a disinfection reactor (weighted germicidally)
- D_L can be used in Computational Fluid Dynamic modeling (CFD) to predict the hydraulic or mixing efficiency of a flow through reactor

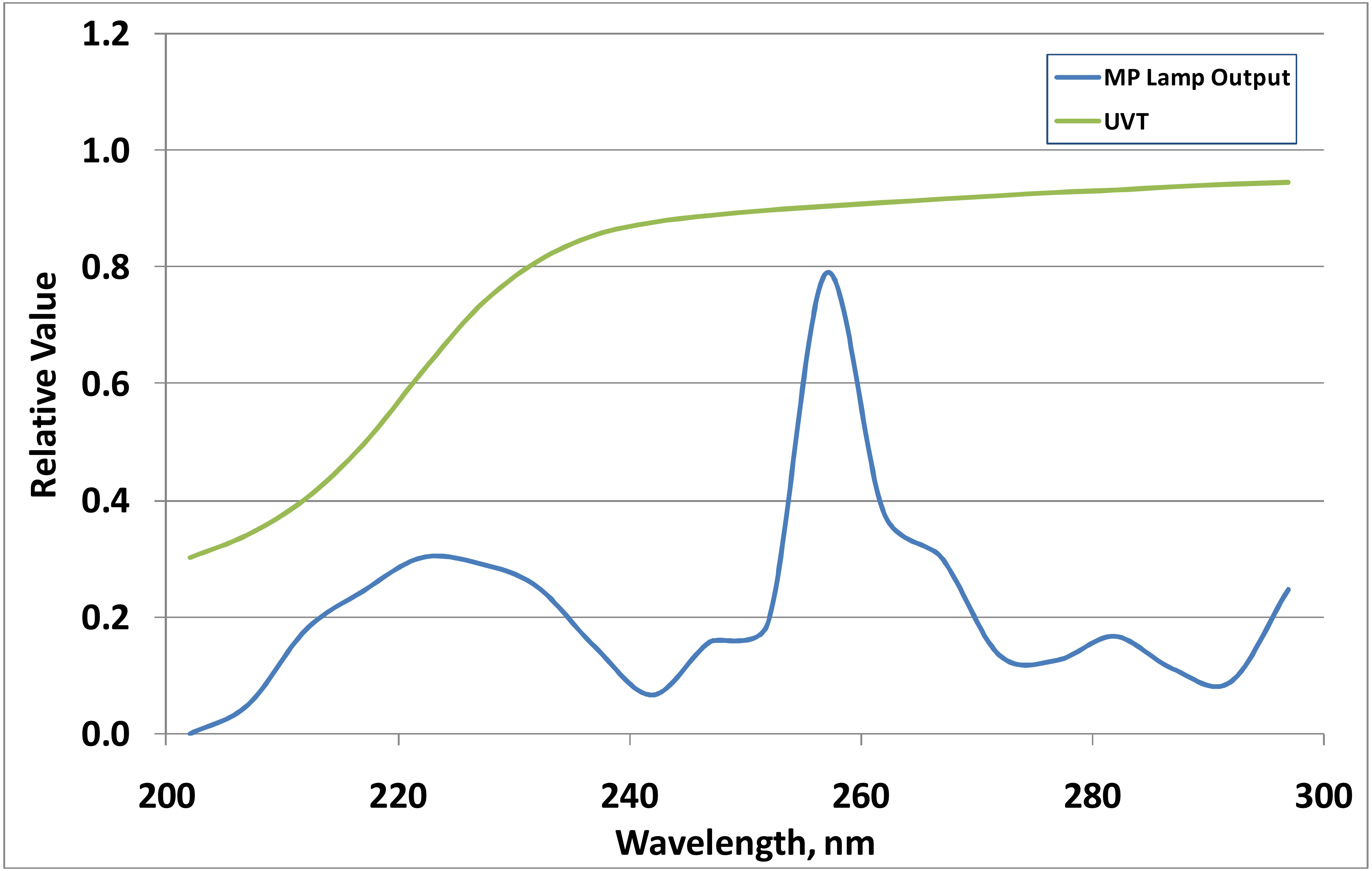
Dose per log (D_L)

- As in disinfection reactors, and unlike the EEO, D_L is **independent** of:
  - Lamp type (MP or LP), lamp efficiency or spectral output
  - UV transmittance
  - path length that UV traverses in a reactor
- Unlike disinfection reactors, however, D_L in AOP reactors is **dependent** on
  - peroxide concentration
  - scavenging potential of the water
- It is therefore a water dependent, but reactor independent parameter that can be used to specify the characteristic of the water

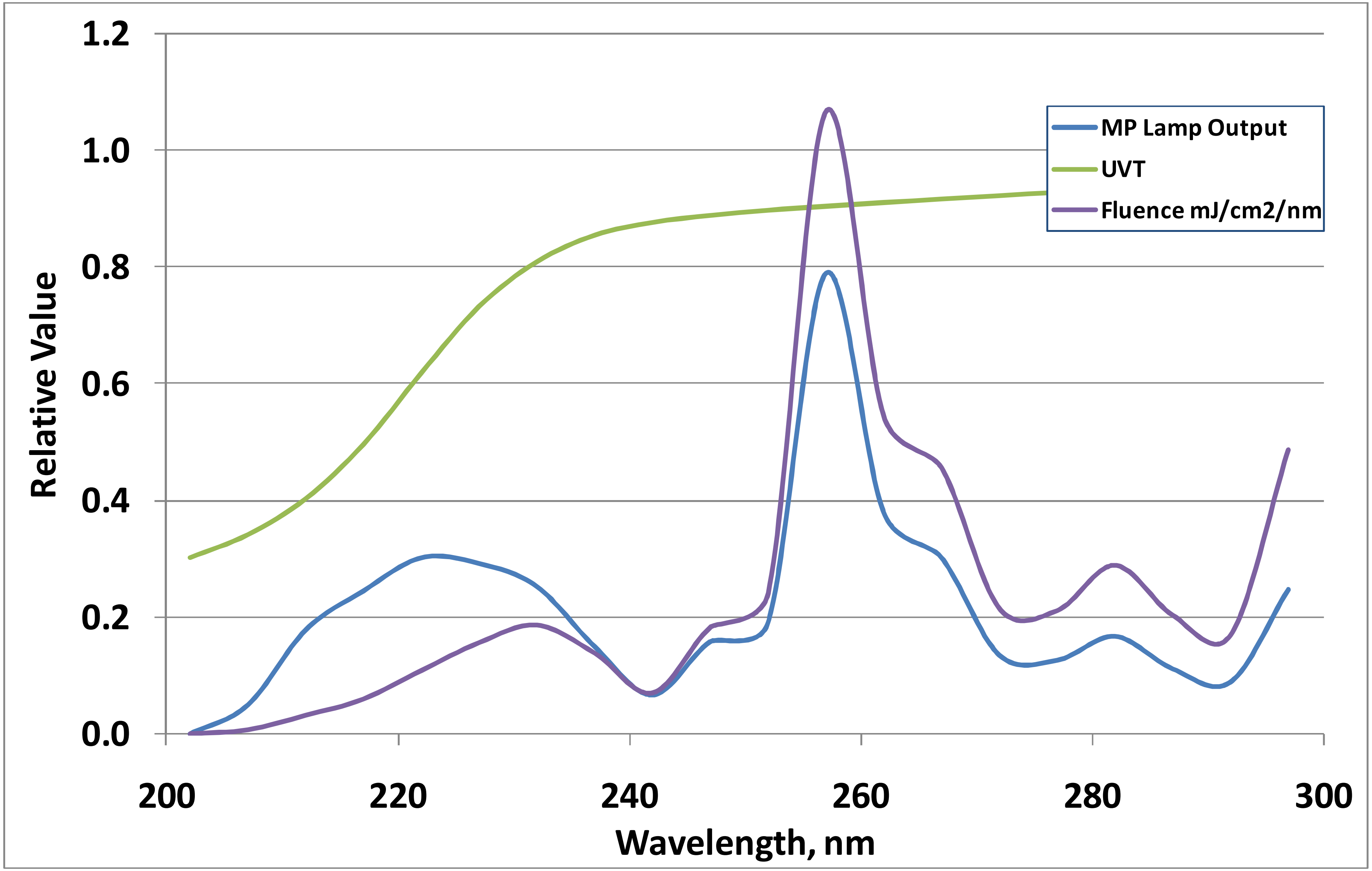
Spectral Effects

- MP Lamps emit UV in a broad band between 200 and 300 nm (where peroxide absorbs)
- Therefore full background spectral absorbance of water must be included when using MP lamps

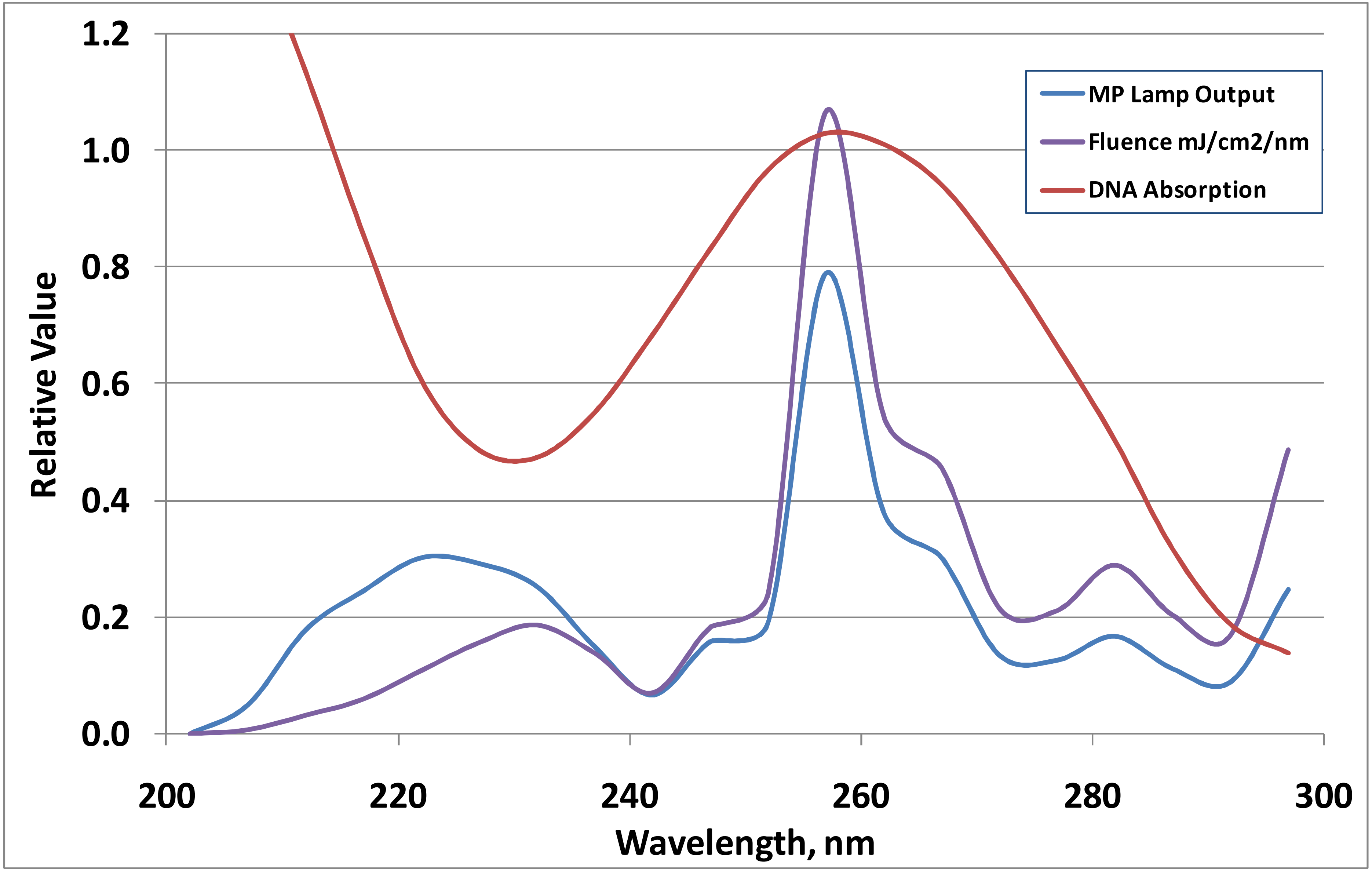
Lamp Output and UV Transmittance



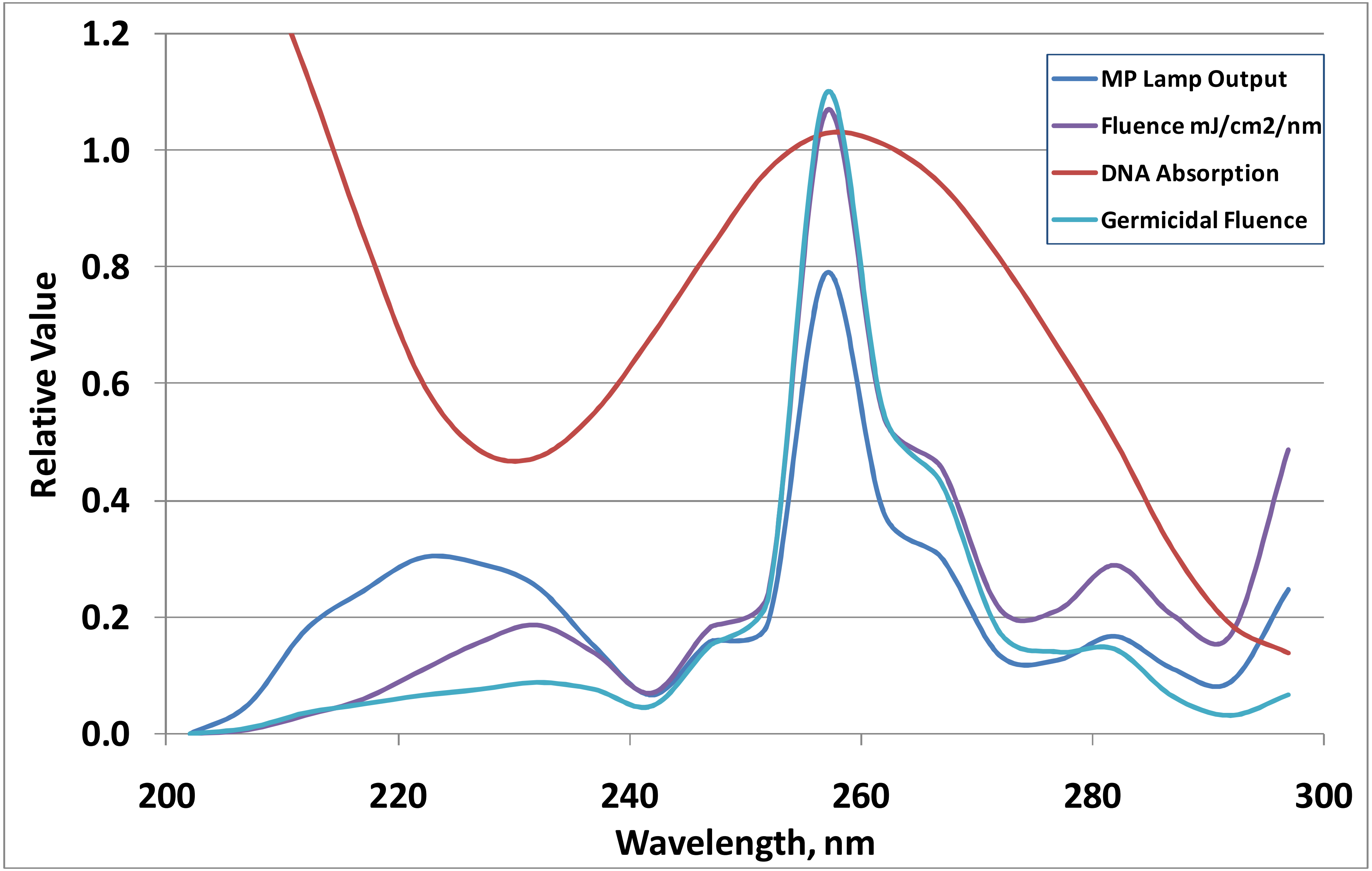
UV Fluence (Dose)



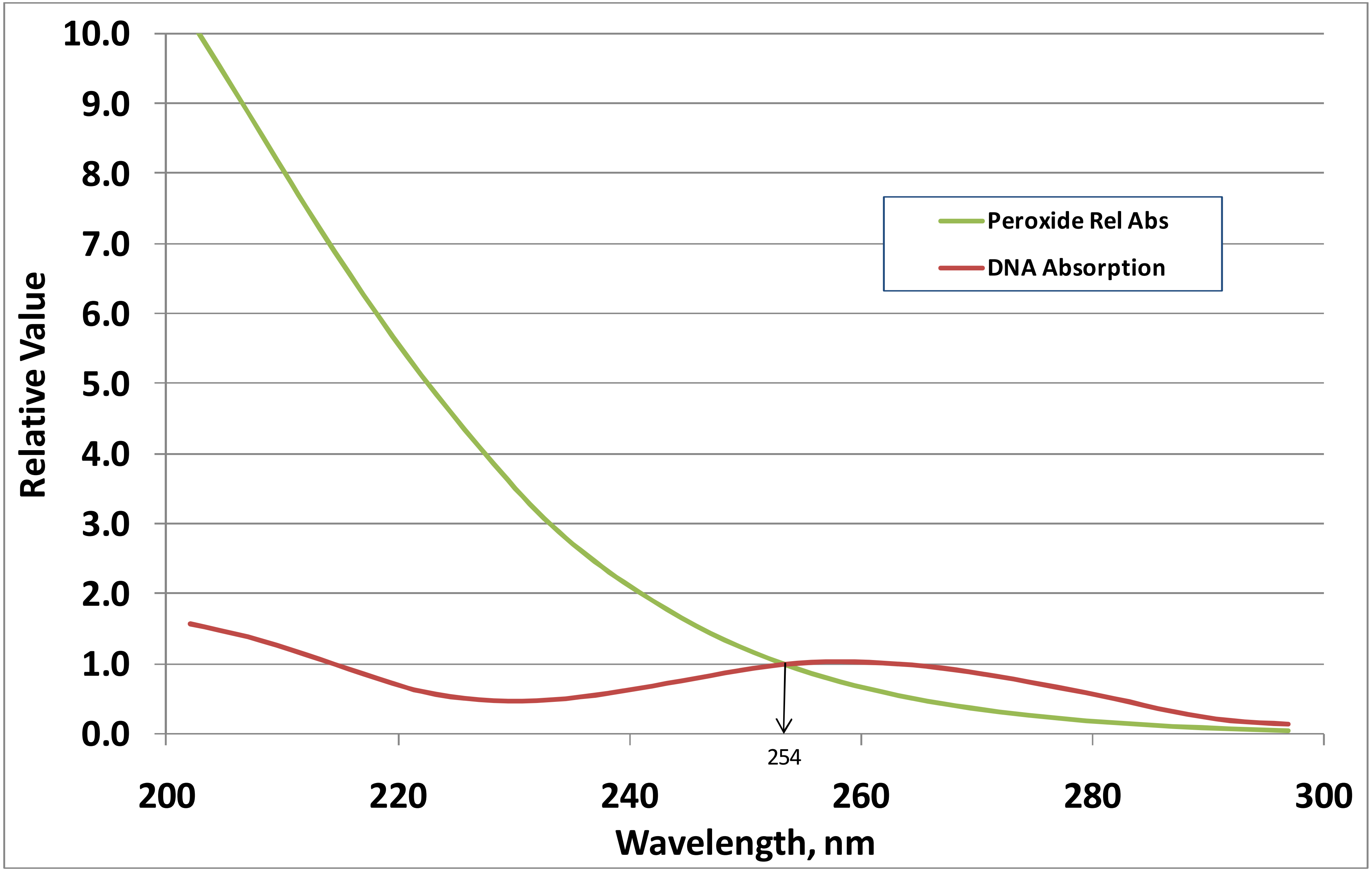
Germicidal Action Spectra



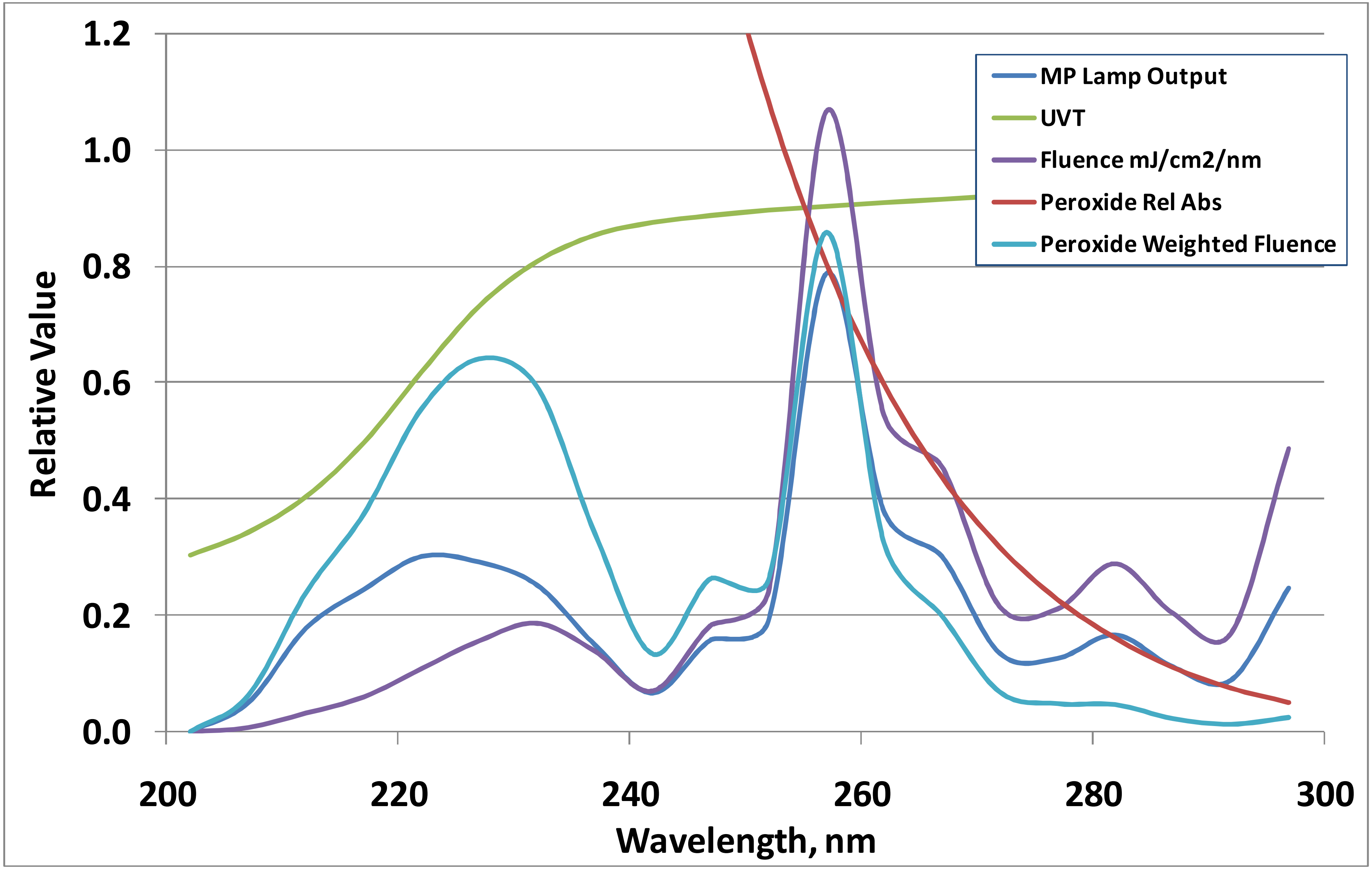
Germicidal Dose (Fluence)

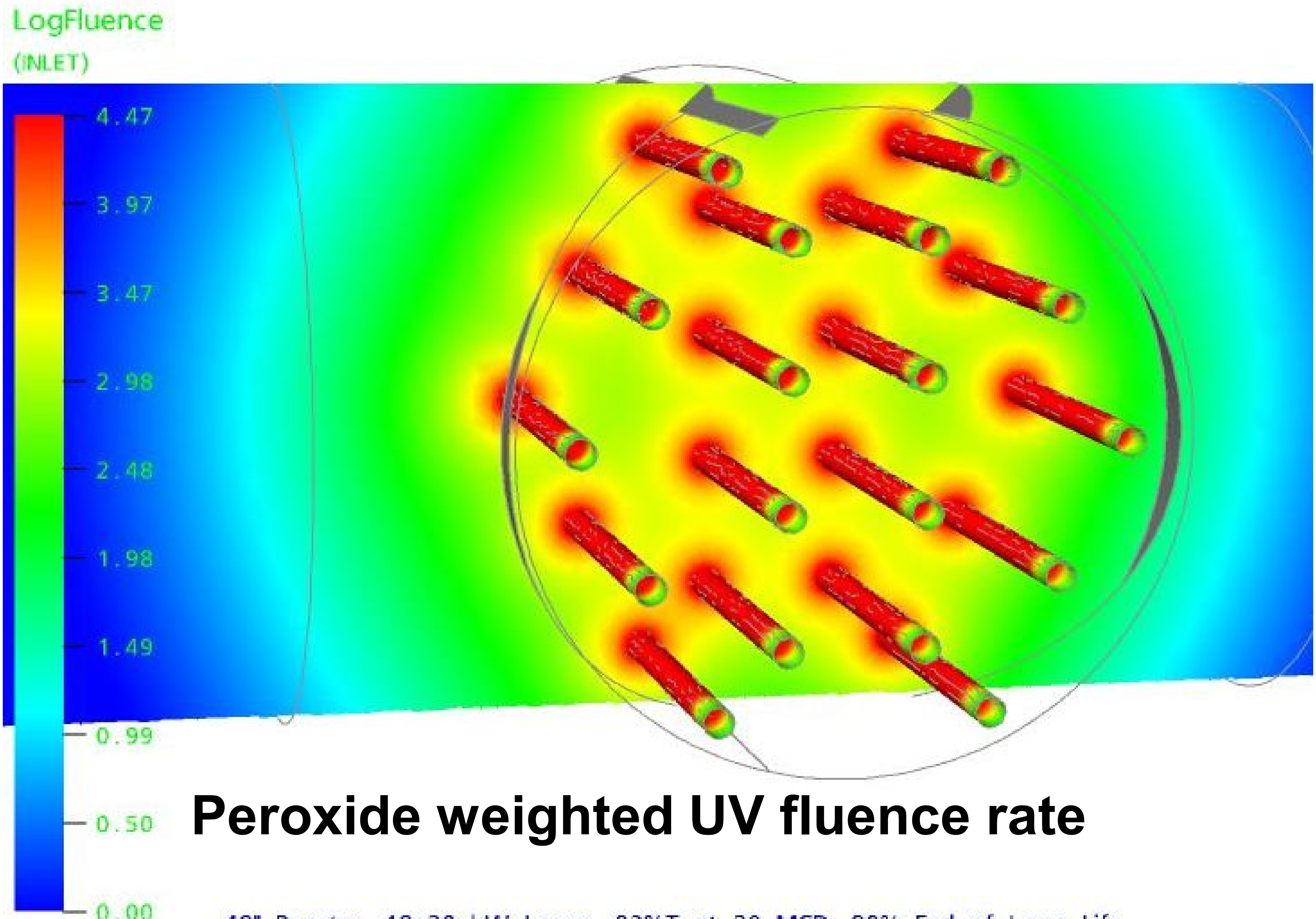


Peroxide Relative Absorbance



Peroxide Weighted Dose (Fluence)

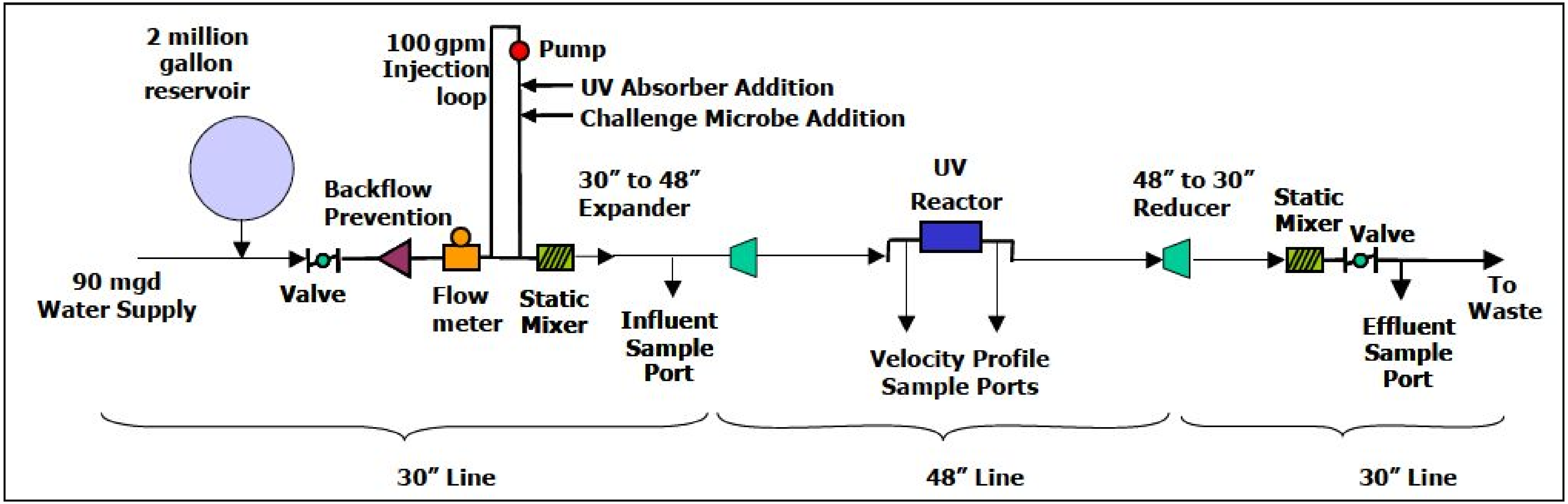




Peroxide weighted UV fluence rate

48" Reactor, 18x20 kW Lamps, 92%T at 30 MGD, 80% End of Lamp Life

Full Scale and Bench Testing at Portland UV Validation Site



Portland UV Validation Site

UVT	96.8 – 98.6	%
TOC	0 – 1.4	mg/L
Hardness	38 – 144	mg/L
Alkalinity	34 – 169	mg/L
pH	5.8 – 8.8	
Temp	11 – 18	°C
Chlorine	0	mg/L

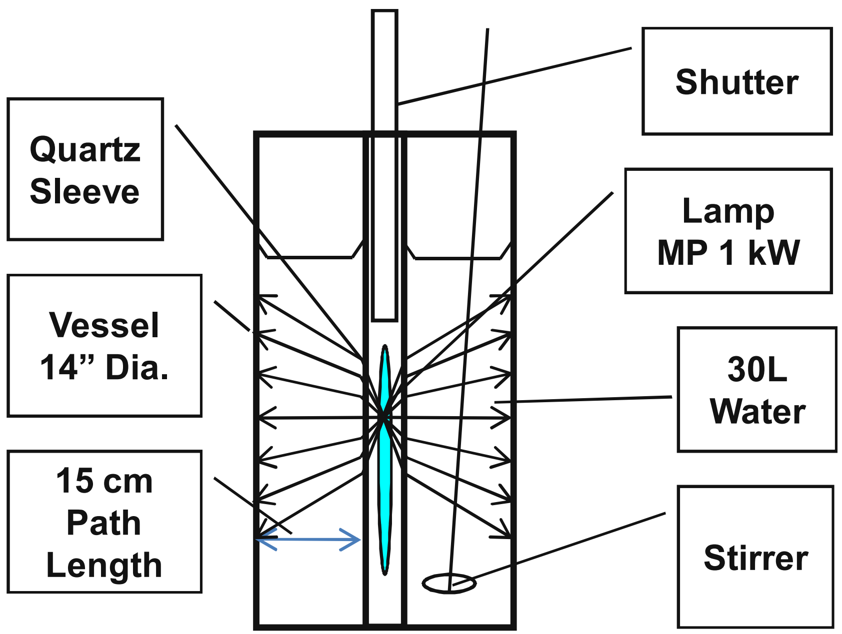
- High quality groundwater feed
- Outfall to Columbia Slough
- Can accommodate UV absorbers (LSA, Superhume), seeded microbes (MS2, T1, T7), and chemical additions (MIB, geosmin)

Portland UV Validation facility

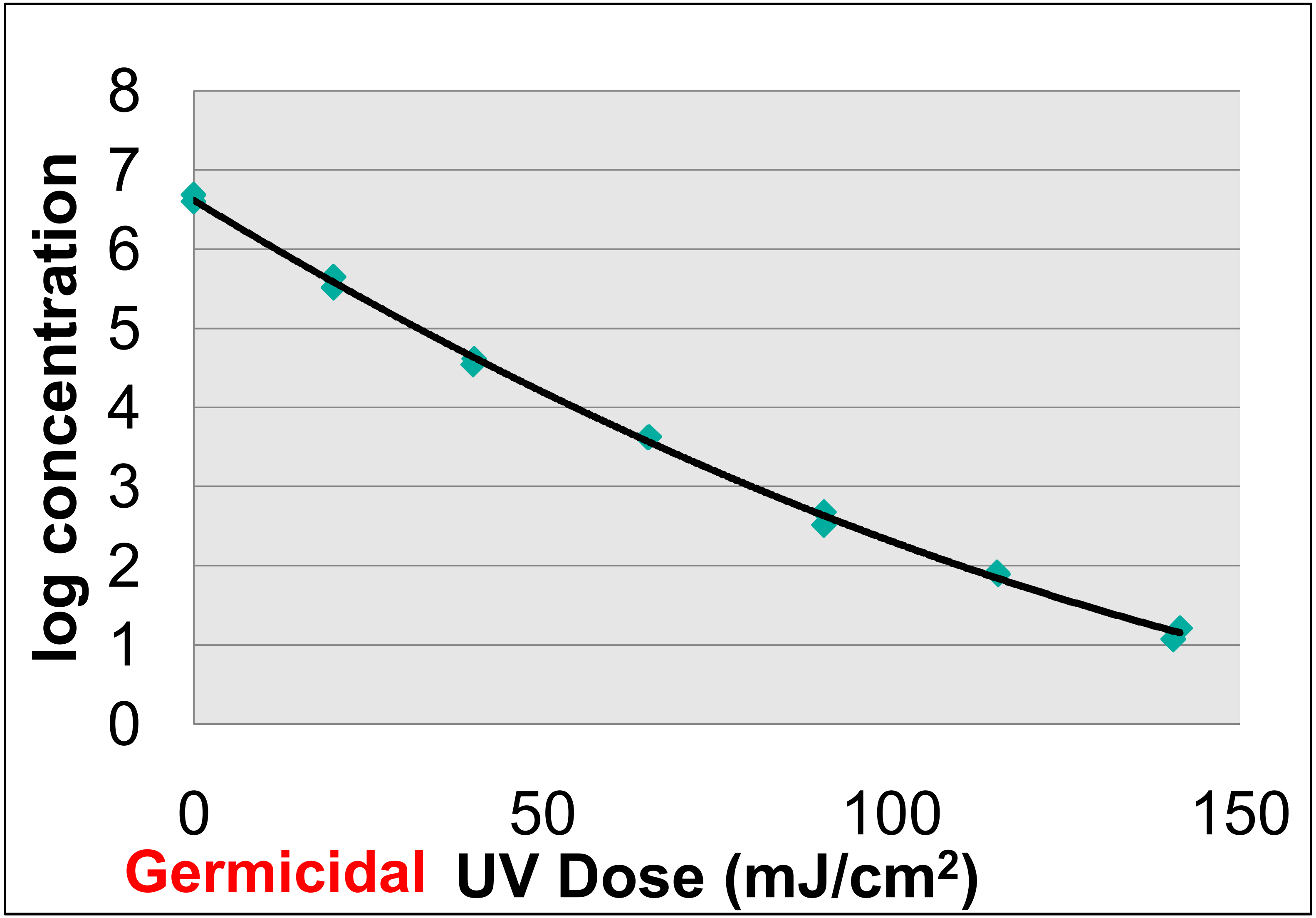
Annular Batch Test Reactor

Measurement of D_L

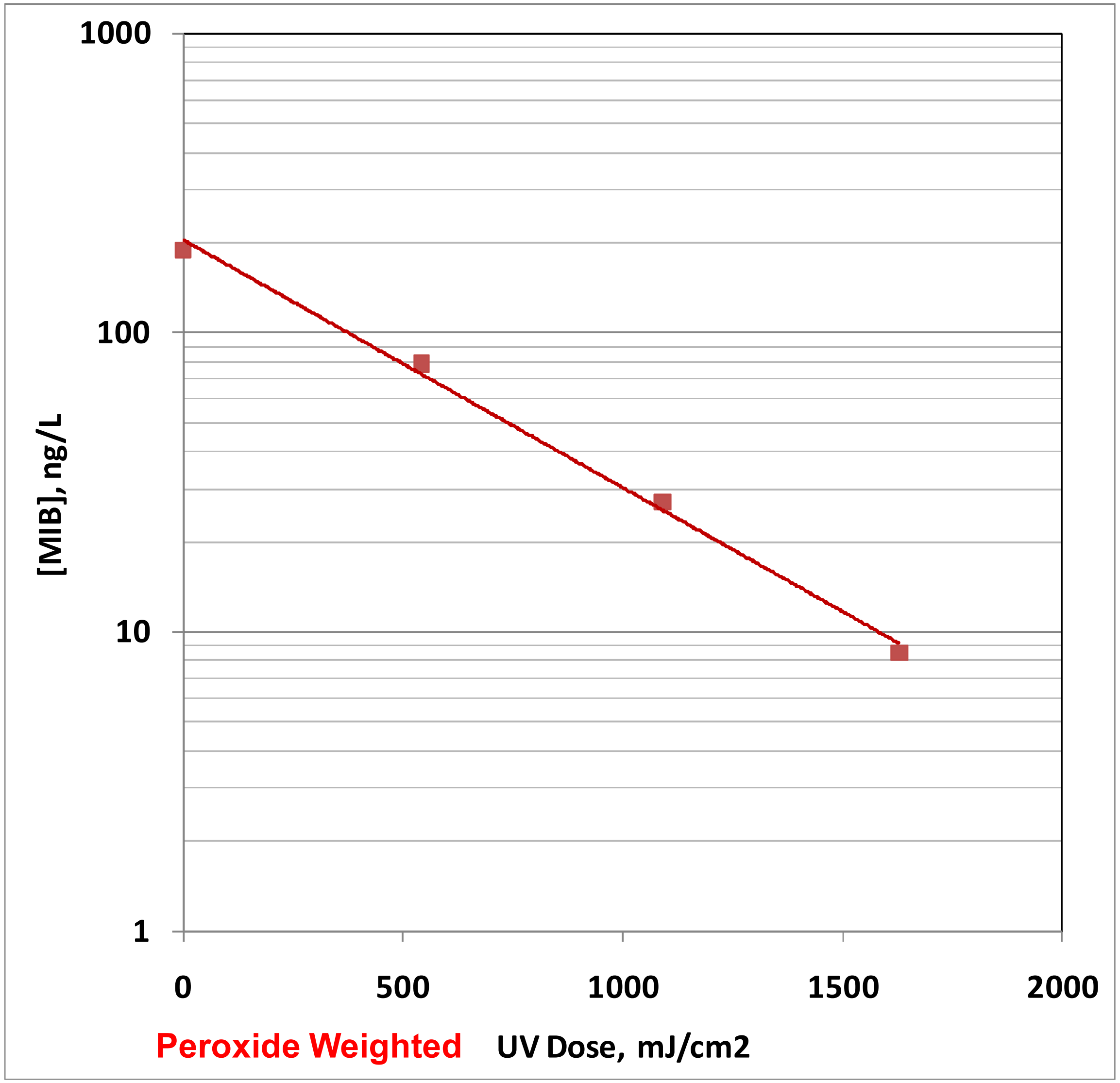
- Batch Reactor
  - 30 L mixed reactor
  - More accurate than collimated beam
- 1 kW Medium Pressure Lamp
  - Same spectral Output as Full Scale Reactors
  - Reduces scale up errors for MP lamp spectral output
- 14 cm Path Length
  - More accurate scale-up than Collimated Beam



Bioassay Dose-Response (MS2)

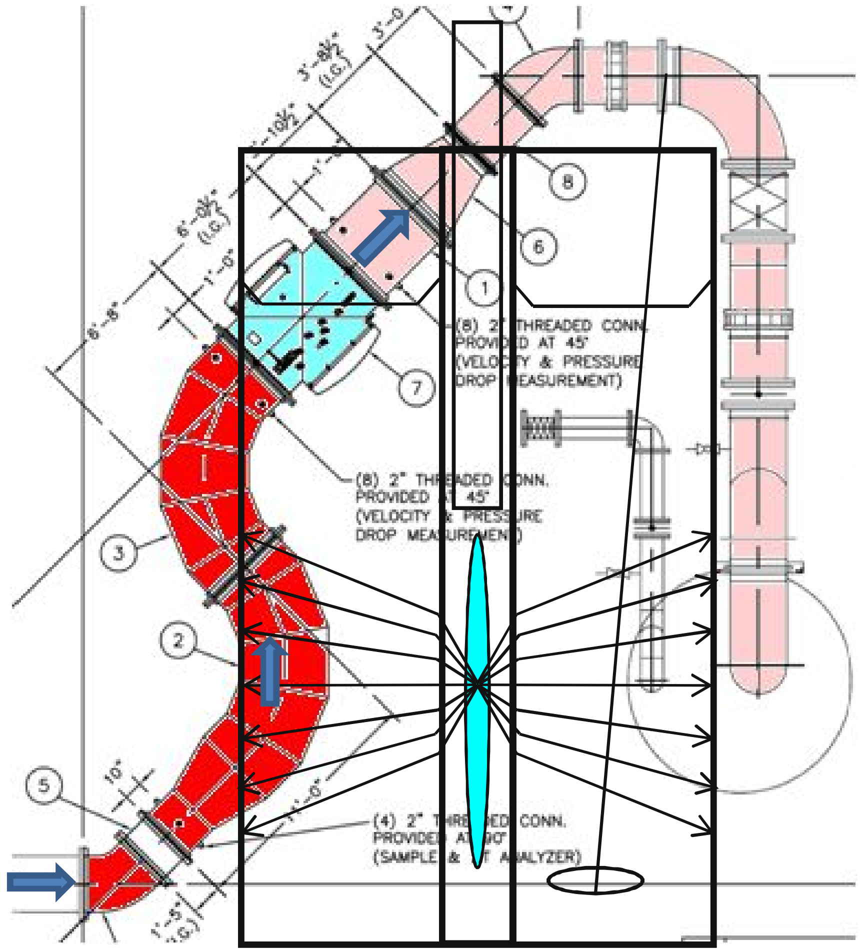


Taste and Odor (MIB) Dose Response



Use of bench results and CFD to predict full-scale AOP

- Adjust UVT, add H_2O_2, MIB and Geosmin, upstream of full-scale reactor
- Draw off influent water to fill batch reactor. Take influent and effluent samples
- Timed exposure within batch reactor produces **peroxide-weighted** dose-response curves for target compounds
- Dose-response results and CFD are combined to predict full scale performance and compare with measured results

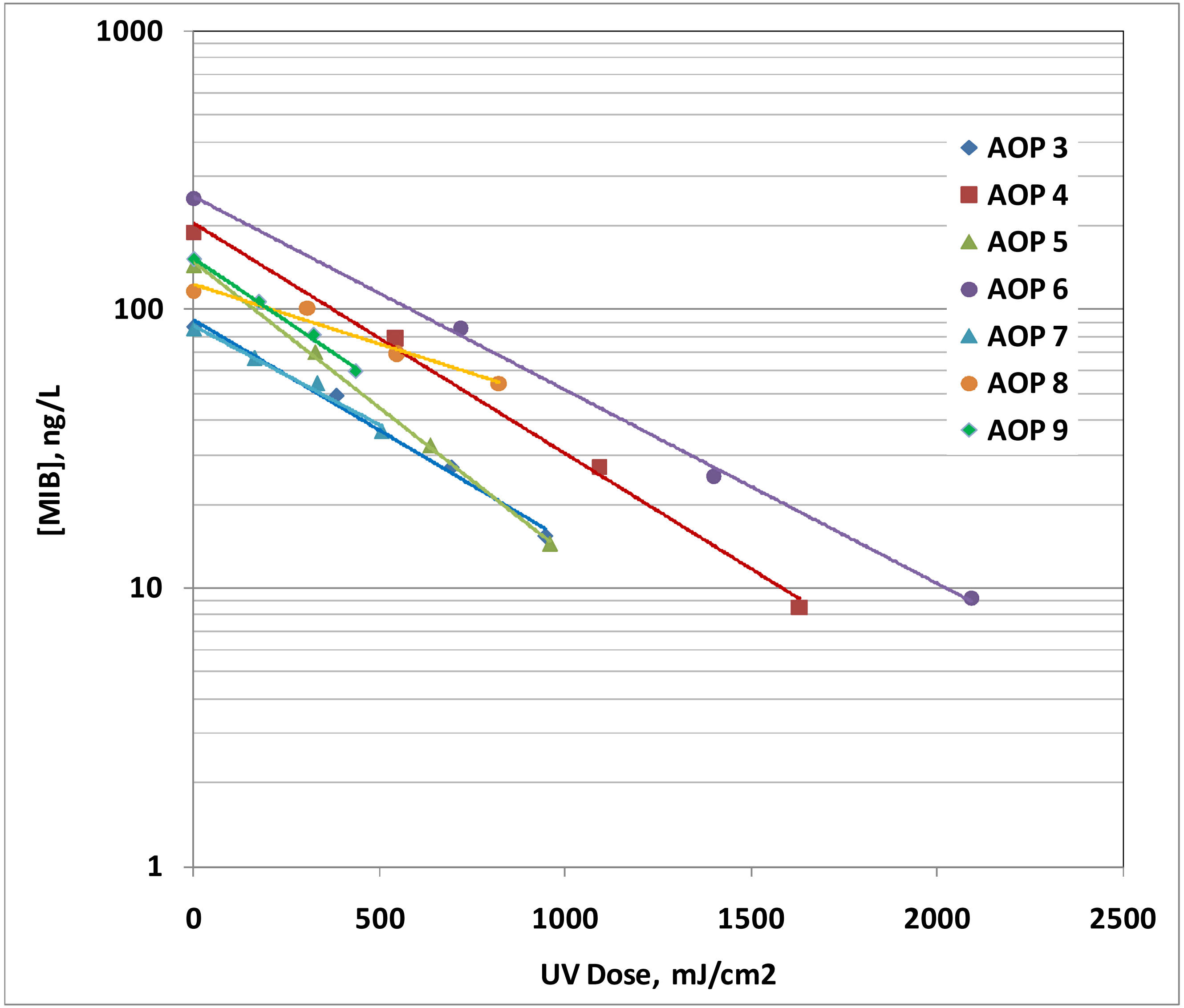


Test Plan and Scale-Up Methodology

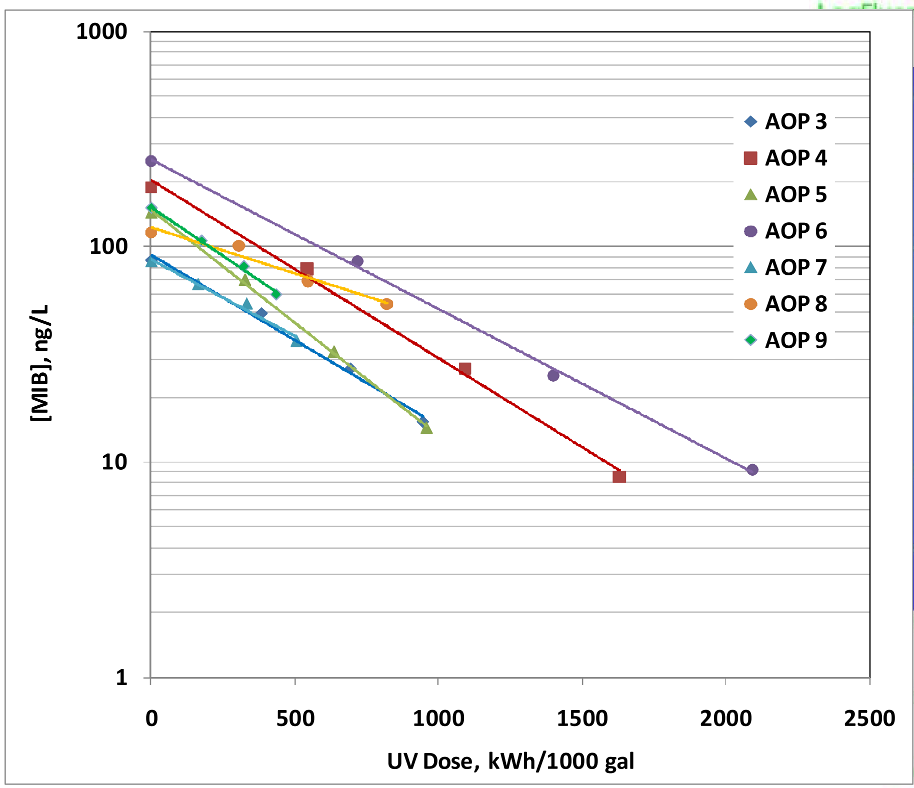
Test ID	AOP3	AOP4	AOP5	AOP6	AOP7	AOP8	AOP9
UV Transmittance (%)	94.9	95.4	89.6	95.4	90.6	90.1	84.6
H_2O_2 Concentration (mg/L)	4.53	4.22	9.35	4.56	9.82	4.02	15.22

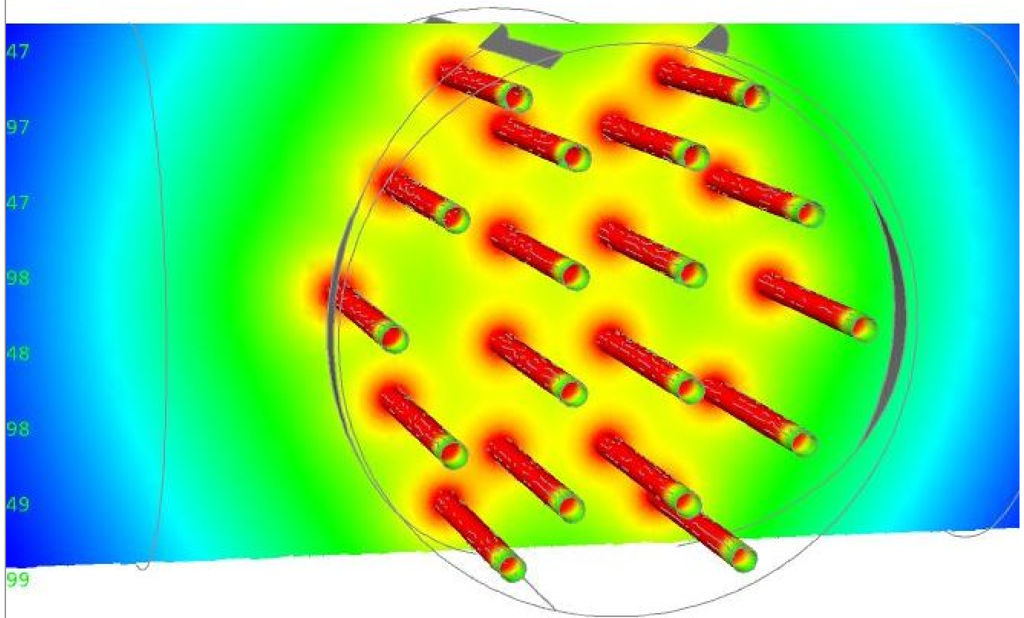
- Seven test conditions, varying UVT, [H_2O_2], number of lamps (9 lamps @ AOP6)
- Unlike bioassay testing, a dose per log destruction (D_L) must be determined for each test condition via bench-scale dose-response curves

Batch Test Results



CFD Modeling cont….



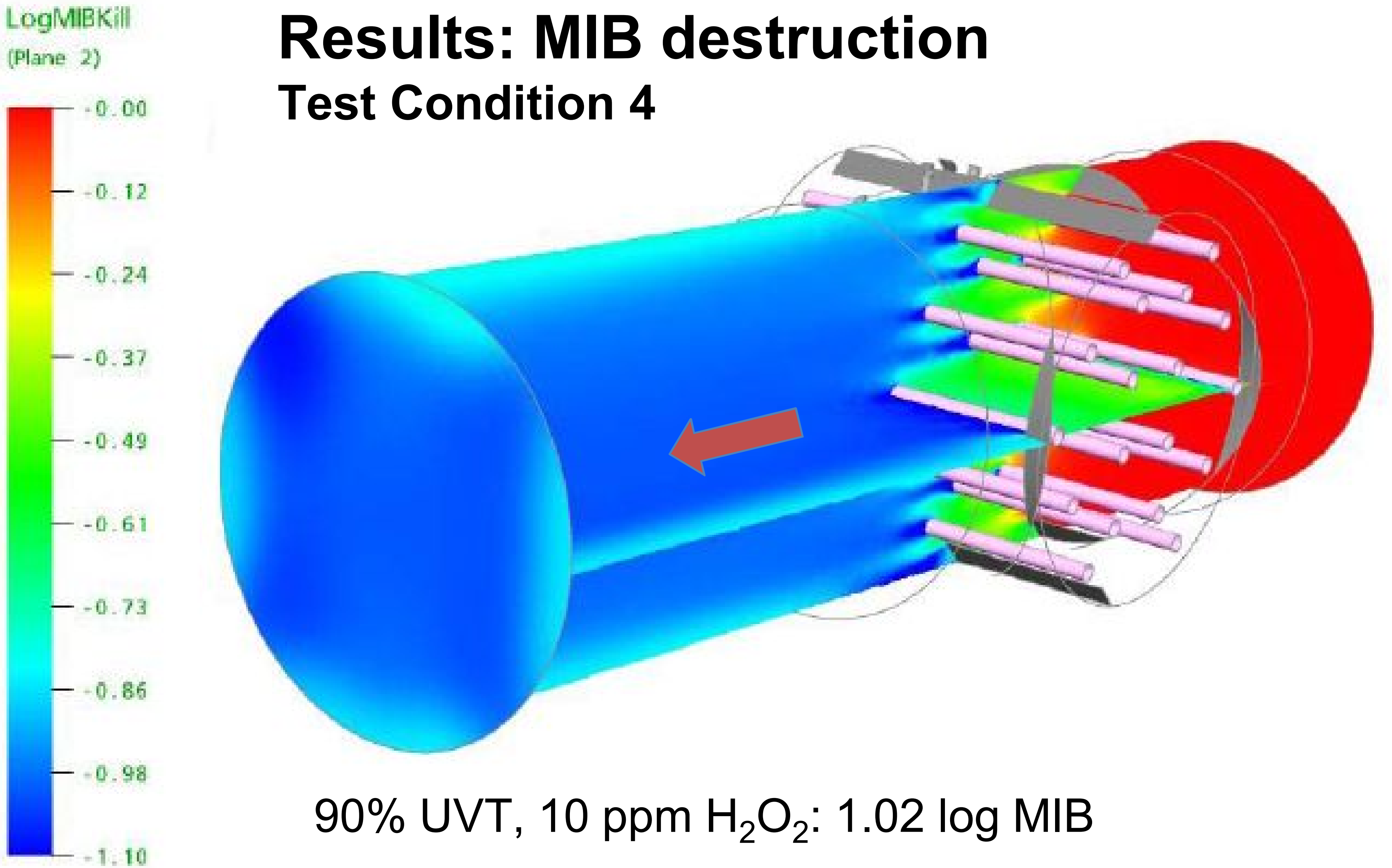


48" Reactor, 18x20 kW Lamps, 92%T at 30 MGD, 80% End of Lamp Life

- Intensity modeling → **peroxide-weighted** Fluence in each of the meshed CFD cells
- Combine with D_L → MIB/Geosmin destruction in each CFD cell
- Then with Fluid Dynamics to get the entire reactor performance

Results: MIB destruction

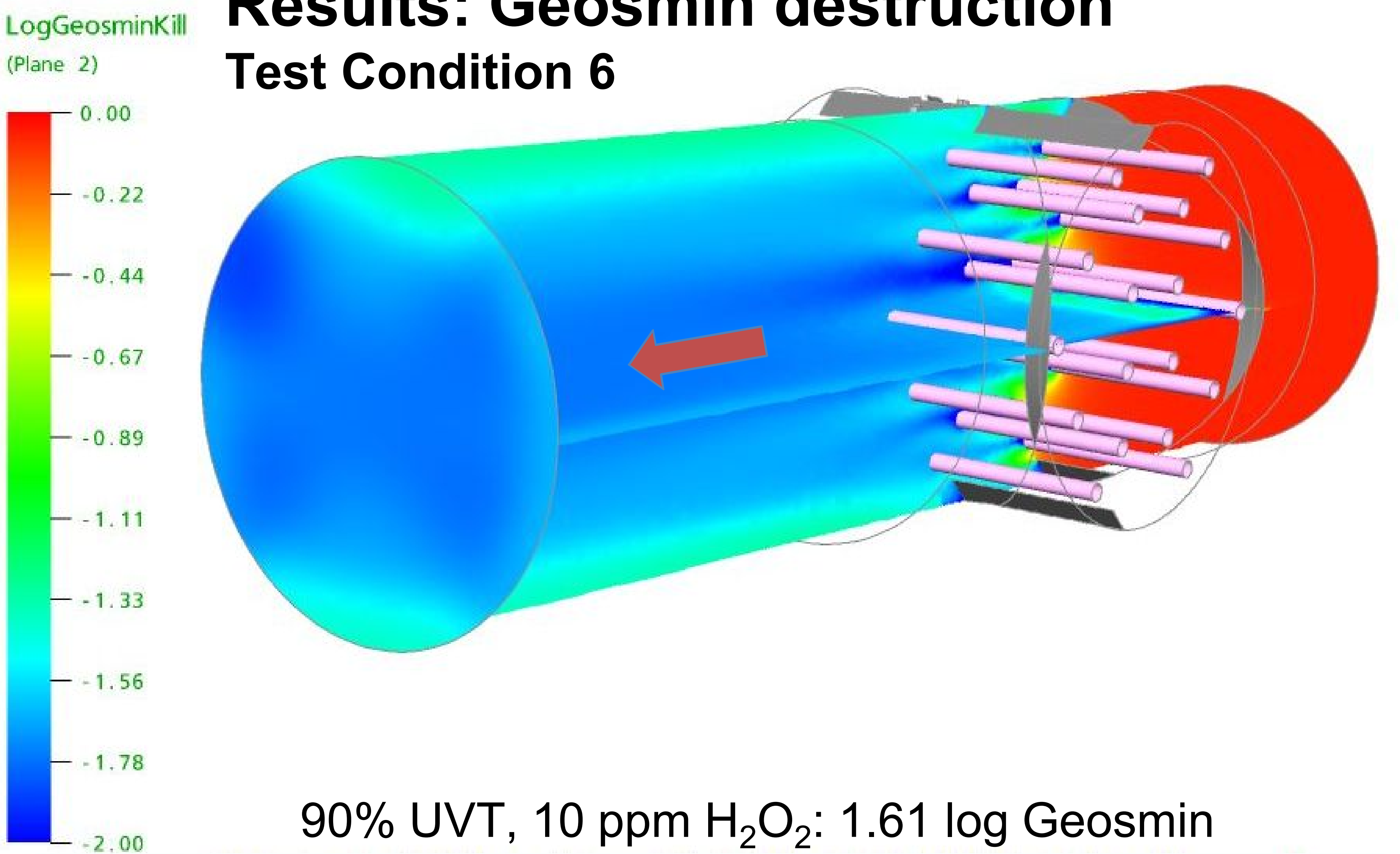
Test Condition 4



90% UVT, 10 ppm H_2O_2: 1.02 log MIB

Results: Geosmin destruction

Test Condition 6



90% UVT, 10 ppm H_2O_2: 1.61 log Geosmin

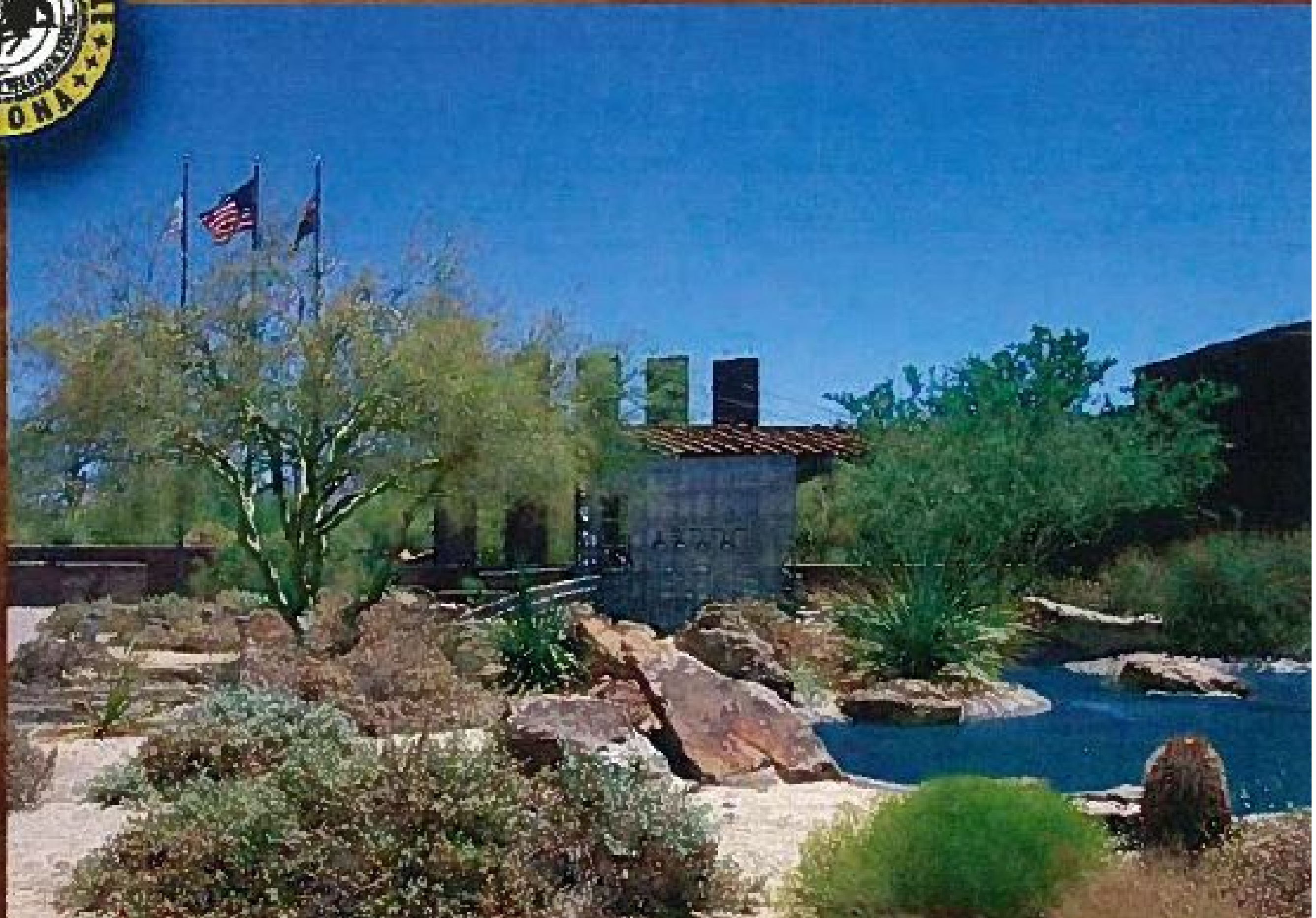
Predicted vs. Measured MIB and Geosmin Destruction

Test ID	3	4	5	6	7	8	9
MIB Predicted Log i	0.47	1.02	0.52	1.27	0.27	0.29	0.3
MIB Measured Log i	0.48	1.04	0.55	1.25	0.35	0.22	0.31
Deviation, log i	0.01	0.02	0.03	-0.02	0.08	-0.07	0.01
Geosmin Predicted Log i				1.61	0.33	0.37	0.31
Geosmin Measured Log i				1.67	0.44	0.37	0.36
Deviation, log i				0.06	0.11	0.00	0.05

- The performance of a full-scale UV/H_2O_2 AOP system can be reliably predicted from bench scale testing of a representative sample of water and a surrogate test compund (e.g. MIB, geosmin) and CFD
- D_L inversely proportional to k_{OH}
- Other compounds with varying treatability with UV/H_2O_2 (e.g. varying k_{OH}) can be accurately modeled using this approach

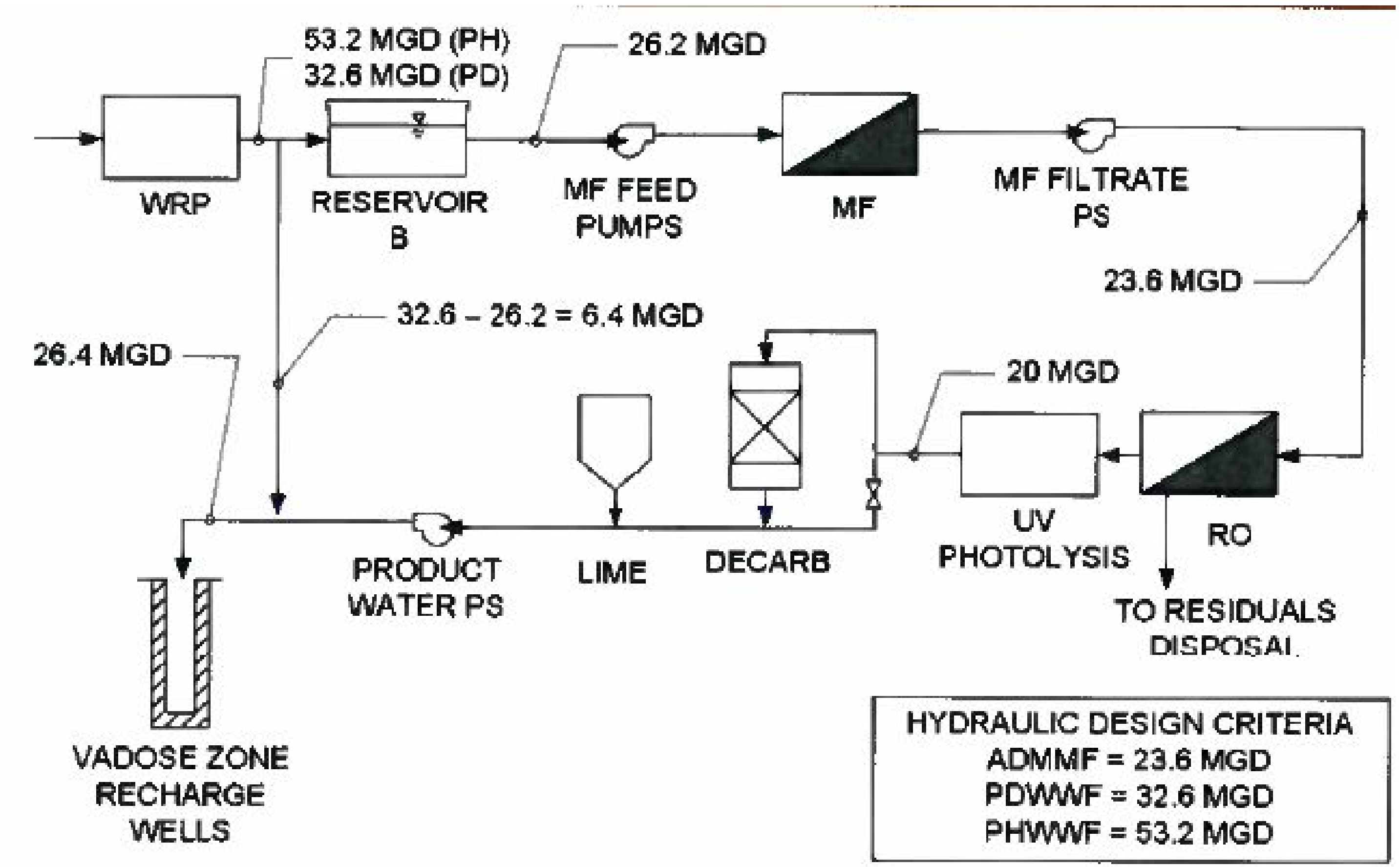
City of Scottsdale Advanced Water Treatment Facility Expansion

UV Coordination Meeting: Calgon



May 14, 2009

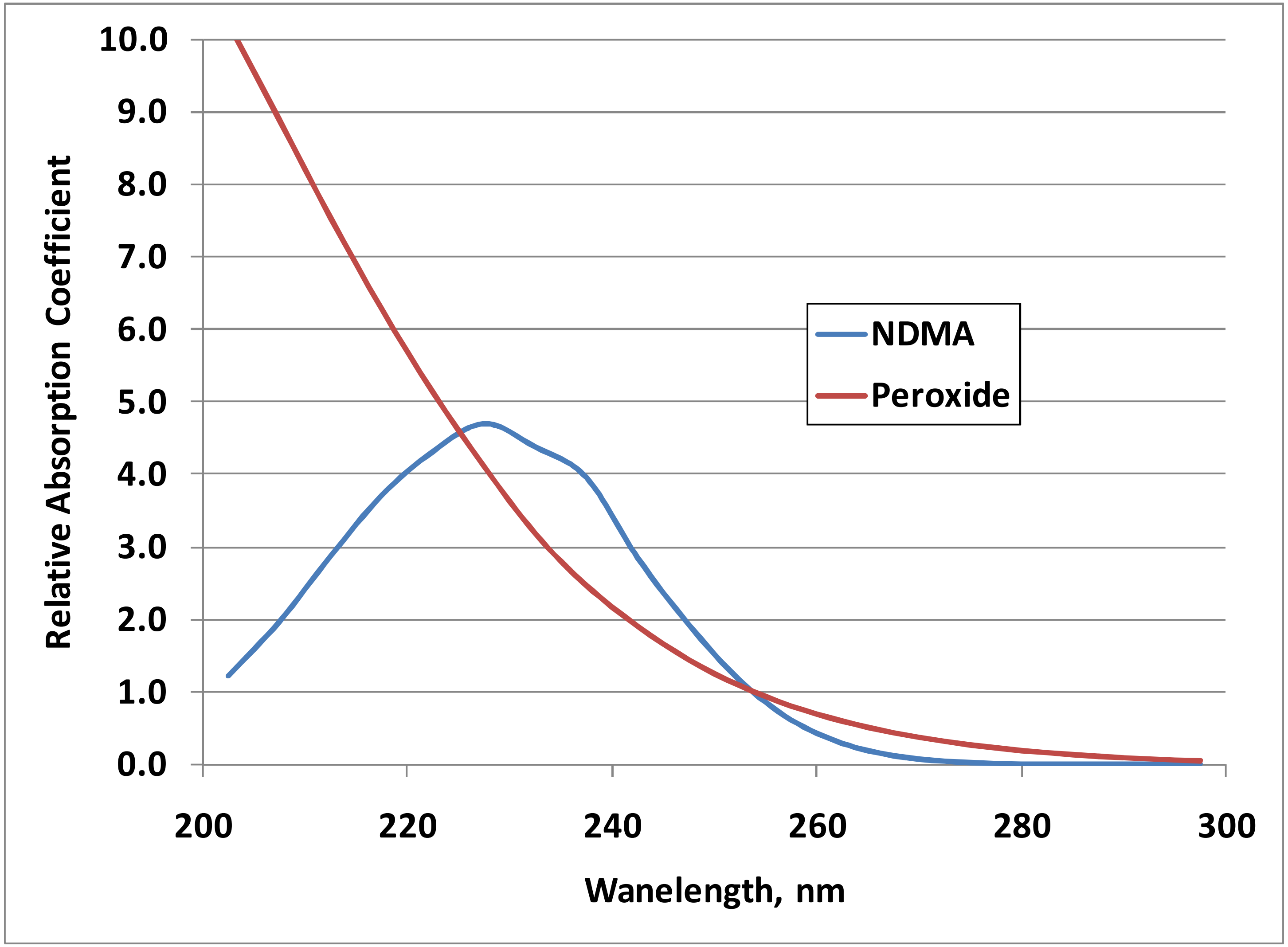
Indirect Potable Reuse Scottsdale Arizona



Application of Technique to NDMA - Scottsdale

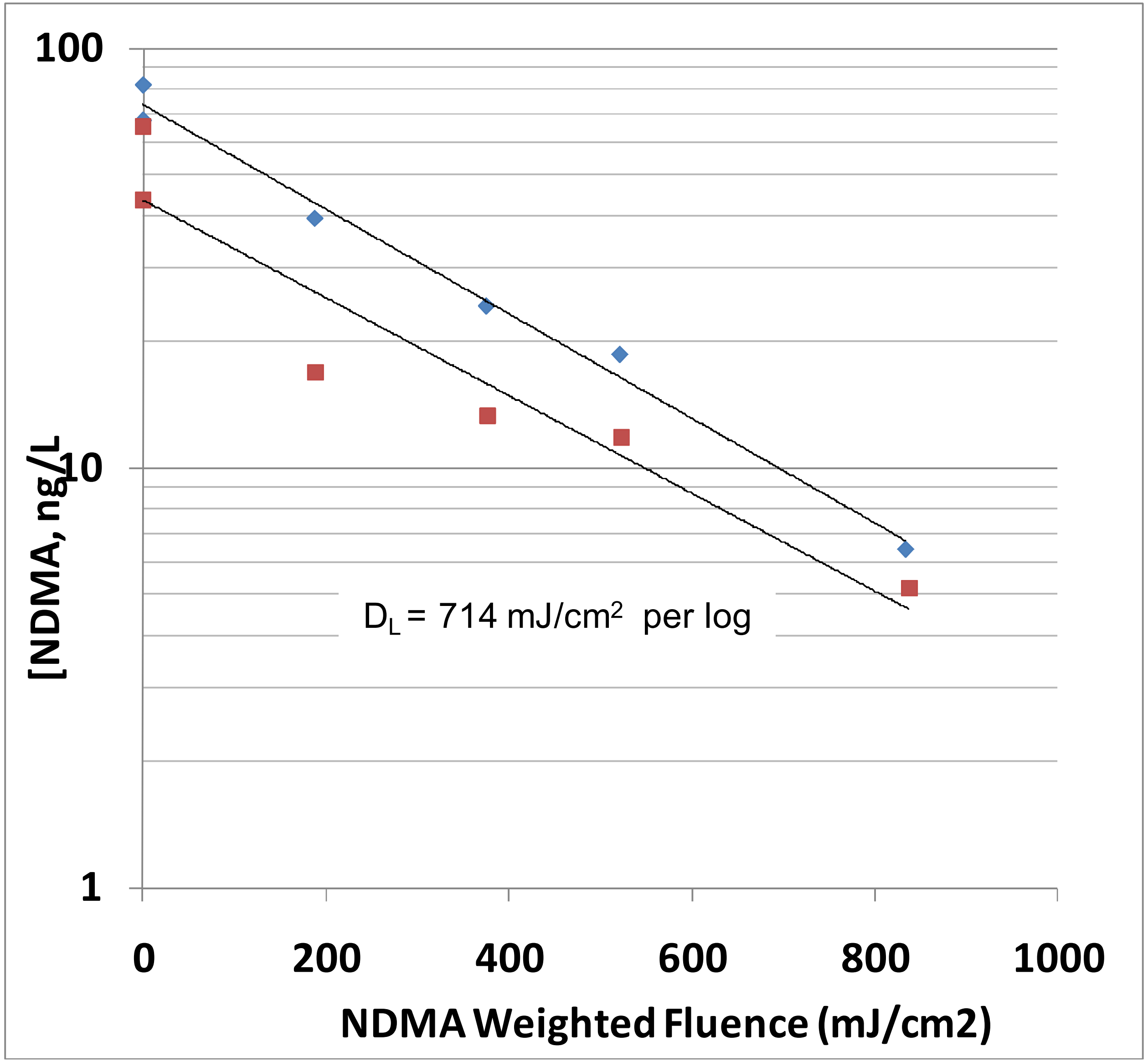
- NDMA is of particular interest to water reuse applications
- present after the final MF/RO treatment of sewage plant effluent for Indirect Potable Reuse (IPR).
- NDMA is unique in AOP treatment as its destruction by UV AOP is predominantly by direct photolysis and not via the hydroxyl radical.

Relative Absorption Coefficient



Dose per Log (D_L) of 714 mJ/cm^2/log

- typical for NDMA

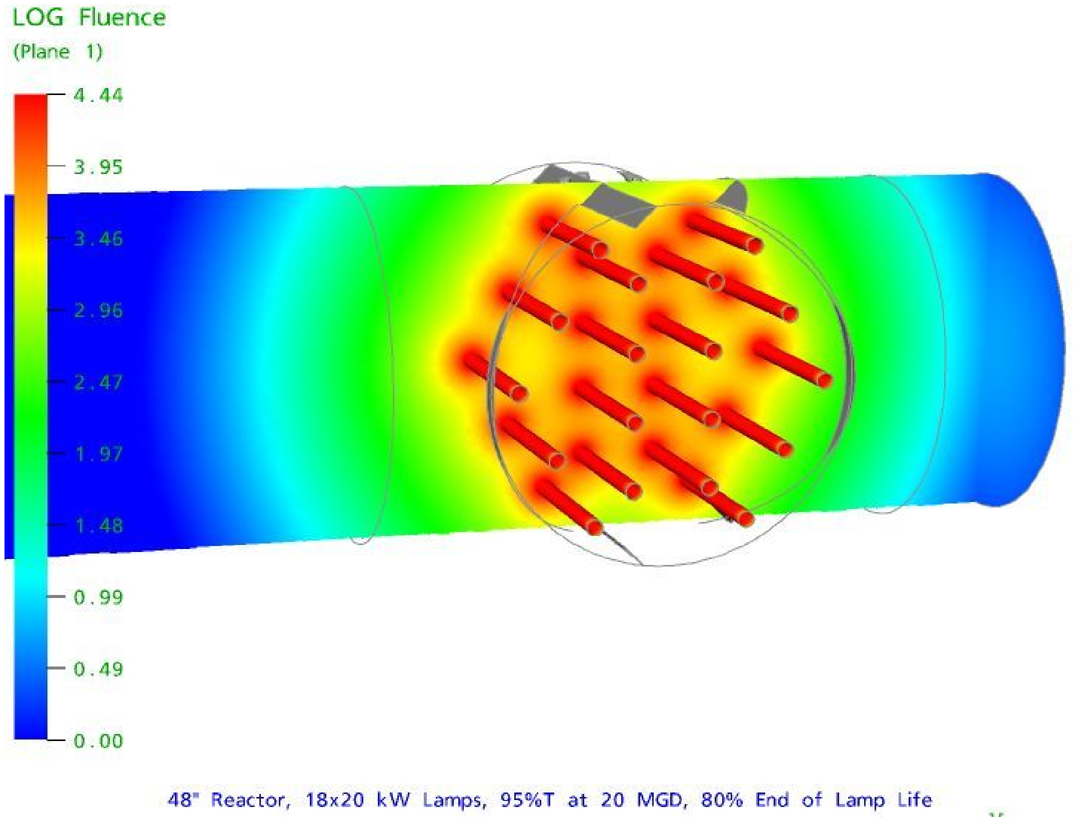


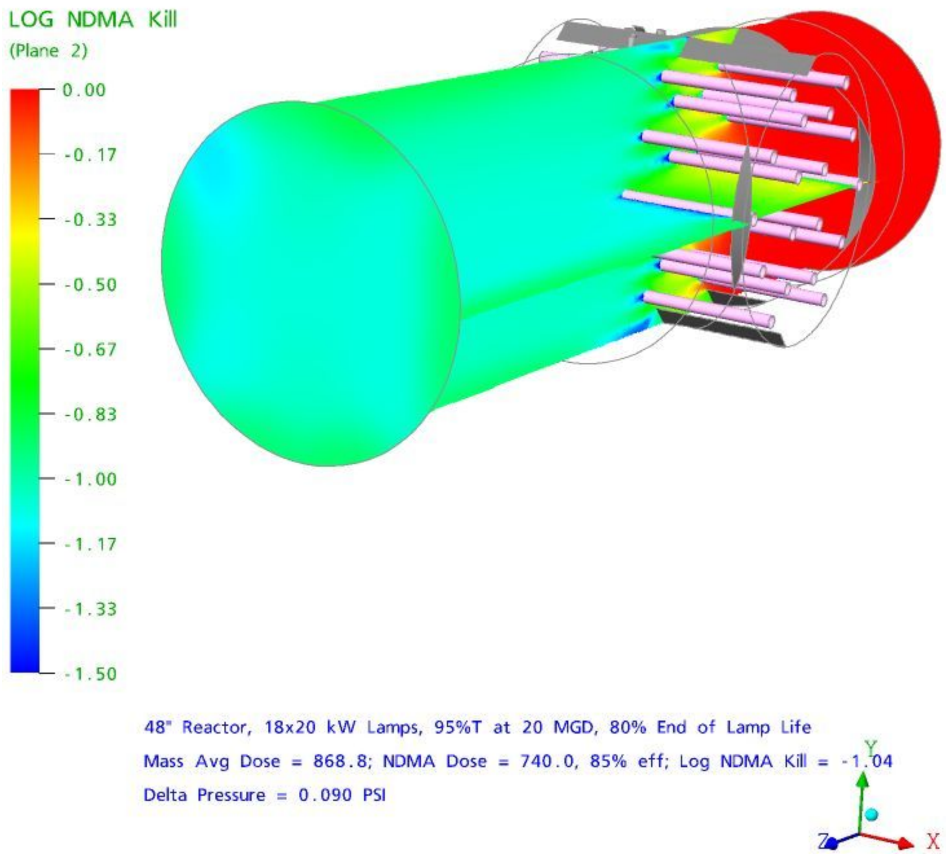
CFD for Scottsdale NDMA Destruction

Scottsdale WTP, AZ

Scottsdale WTP, AZ

NDMA Weighted Fluence >> NDMA Log Destruction





NDMA D_L

- Unlike peroxide the D_L for NDMA is independent of both the peroxide concentration and the water UVT.
  - the destruction is by direct photolysis and therefore the value of 714 mJ/cm^2/log obtained is typical of NDMA in any water
- This is the same as in disinfection reactors where the dose response and therefore D_L of an organism is independent of the water quality or UV absorbance.
- Therefore modeling NDMA in UV/AOP reactors is much more akin to disinfection reactors except that the action (absorption) spectrum is at lower wavelengths.

Conclusions

- Peroxide weighted Dose per log (D_L) can be used in CFD modeling to accurately predict the performance of the full scale UV AOP system from empirical performance data generated from bench scale testing.
- This empirical method greatly simplifies the CFD modeling of an AOP reactor where otherwise the simultaneous chemical reactions would need to be modeled. It is also more reliable due to its empirical base.
- DL is independent of equipment type but dependent on water quality and so could be used to specify the performance requirements of UV AOP systems and then checked in performance testing of the installed system

Advantages of specifying UV reactors using D_L

- Reduces risk for Consultant
  - Can independently measure and specify
  - Not dependent one vendor testing water
- Reduces risk to Purchaser/Owner
  - Can be measured in a performance trial
  - Not going to get some fly-by-night vendor hiding behind nefarious water quality parameters
- Reduces the risk for the Vendor
  - No surprises in unknown $OH^{\cdot}$ scavengers showing up in the water

Questions?