# USING UV DOSE RESPONSE FOR SCALE UP OF UV/AOP REACTORS

**Keith Bircher**

*Calgon Carbon Corporation, 7100 Woodbine Ave.*

*Markham, ON, L3R5J2, Canada*

## ABSTRACT

*A method for scale up of UV/AOP reactors that uses bench scale testing to determine the UV Dose required per log destruction ($D_L$) of a particular contaminant that can be used to define water quality. This can then be used in CFD Modeling to size a full-scale UV reactor and in performance testing. Results from full scale testing of this method are presented.*

***Keywords: Advanced Oxidation; AOP; Pilot Testing; Scale up; CFD; Geosmin; MIB; Ultraviolet; UV; Dose per Log; $D_L$***

## BACKGROUND

Traditional methods using Electrical Energy per Order ($E_{EO}$) (Bolton et al., 2001) to compare the performance of various full scale AOP technologies, while useful, are not effective in translating collimated beam or bench testing to full-scale. While most parameters that affect the $E_{EO}$ of a reactor (lamp output, lamp efficiency, path length) can be scaled up from laboratory scale to full-scale without much difficulty, Computational Fluid Dynamic modeling (CFD) is needed to predict the hydraulic or mixing efficiency of a flow-through UV reactor. This article describes a method that has been developed that uses bench-scale testing to determine the UV Dose required per log destruction of a particular contaminant ($D_L$).

UV Dose for Medium Pressure UV/$H_2O_2$ reactors is defined as the integral, by wavelength, of the fluence, weighted by the $H_2O_2$ absorption coefficient relative to its value at 254 nm ($H_2O_2$ weighted fluence). This is similar to UV dose in disinfection reactors, which is weighted by the germicidal (DNA) absorption spectrum (germicidal fluence) or by the action spectra of specific microbes. As in disinfection UV reactors, and unlike the $E_{EO}$, $D_L$ is independent of the lamp spectral output, the UV transmittance and the path length that UV traverses in a reactor. Unlike disinfection reactors, however, $D_L$ in AOP reactors is dependent on the $H_2O_2$ concentration and the scavenging potential of the water. Therefore tests must be performed on a representative sample of water at one or more $H_2O_2$ concentrations to determine the scavenging potential, or better still, if the contaminant(s) of concern are used in the bench testing, the $D_L$ of the contaminant. This can then be used in CFD modeling to determine the destruction of the contaminant at each point in the reactor, and hence the full-scale performance incorporating the hydraulic efficiency can be determined. This empirical method greatly simplifies the CFD modeling of an AOP reactor where otherwise the simultaneous chemical reactions would need to be modeled, and is also more reliable due to its empirical base.

## VALIDATION FACILITY AT *PORTLAND, OREGON*

This test facility is located at the Groundwater Pumping Station of the Columbia Southshore Wellfield in Portland, Oregon. The Columbia Wellfield is a 90 mgd supplemental drinking water supply owned and operated by the Portland Water Bureau. The well field can provide up to 50 mgd of groundwater to the test train with the following water quality:

- UVT: 96.8 – 98.6%
- TOC: 0 – 1.4 mg/L
- Hardness: 38 – 144 mg/L
- Alkalinity: 34 – 169 mg/L CaCO3
- pH: 5.8 – 8.8
- Temp: 11 – 18 °C
- Chlorine: none

### *Test train*

Water was introduced to the test train through two 24-inch lines that direct the water into the 30-inch diameter pipe. The influent flow was controlled by three valves (one on each of the 24-in inlet pipes and one on the outlet 30-in pipe), allowing flows up to 50 mgd to be provided to the test train, depending on the headloss through the reactor. The components upstream of the reactor included backflow prevention, a 30-inch diameter magnetic flow meter, and a 120-gpm injection loop into which the UV absorber, target contaminants, and hydrogen peroxide were added and premixed prior to injection into the main water stream using a multiport diffuser. The dosing rate of the target contaminants and hydrogen peroxide were monitored using rotameters. The UV absorber used was calcium lignosulfonate. The test train is shown in **Figure 1**.

***Continued on pg 14***

*Continued from pg 13*

The inlet sample port was located after the inlet static mixer approximately 1 ft upstream of the inlet 90° bend. The effluent sampling port was located approximately 15 ft downstream of the 30-inch effluent static mixer. Stab tubes are positioned to draw samples from a radial location approximately 8 inches inside the pipe.

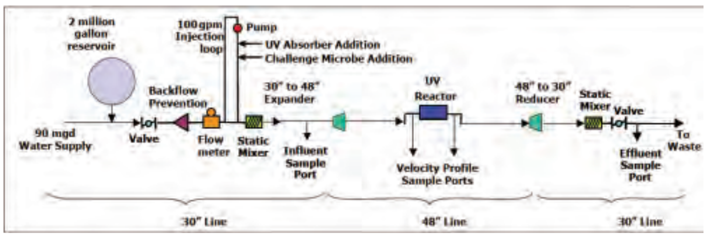



**Figure 1:** *Test Train at the Portland, Oregon Validation Facility. Hydrogen Peroxide and MIB/geosmin are added in place of the Challenge microbe and the effluent valve is now downstream of the Effluent Sample Port*

### *Reactor influent/effluent piping*

Figure 2 shows the piping arrangement used for the 48" Sentinel AOP validation testing.

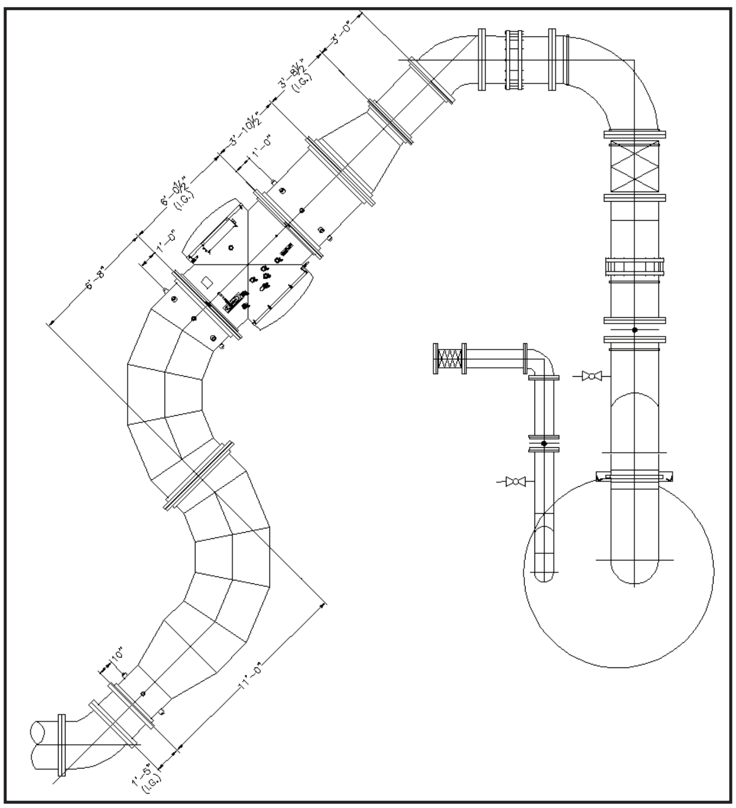


**Figure 2.** *Reactor Specific Piping. Plan View*

## PARALLEL BATCH TESTING

Parallel bench tests were performed to determine:

- The rate of target destruction or Dose per log defined above, and
- The scavenging potential of background water constituents

Tests can be performed using LP (monochromatic) or MP lamps and can be run under different conditions. The test reactor can be a mixed batch reactor, e.g. 30L batches in a 36 cm diameter reactor, or Collimated Beam with a Petri dish. Either the contaminants of concern or a surrogate can be used with a known •OH rate constant.

In this case parallel testing was performed using a pilot batch unit located at the site. The pilot unit consisted of a 40 Liter cylindrical stainless steel reactor equipped with a 1 kW MP lamp with a similar spectral UV output to the 20 kW lamps used in the full-scale system. The 1 kW lamp was mounted vertically in the reactor and separated from the water by a quartz sleeve. A mixer in the reactor ensured complete mixing of the sample during the tests. The pilot unit had a steel shutter which, when closed, served to block the UV light from entering into the sample water.

During each test, 30 L of the water from the influent to the full-scale UV Reactor was added to the pilot unit. In this manner, the bench tests were conducted on the exact same water and peroxide concentration as the full-scale tests. The UV lamp was then ignited with the shutter closed and the mixer started. The lamp was first allowed to warm up, and the UV shutter was then opened and the test started. The shutter was closed and samples taken at periodic intervals corresponding to increasing UV doses. A stopwatch was used to obtain the cumulative exposure time. Bench-scale sampling was performed at zero UV exposure and 3 increasing UV doses.

## PARALLEL BATCH TESTING

### *Water quality measurements*

Water quality measurements conducted on-site included the transmittance at 254 nm and 1 cm path length, spectral absorbance scans from 200 to 400 nm, total chlorine and $H_2O_2$ concentration.

### *Transmittance at 254 nm and spectral absorbance*

The 1-cm path length transmittance of the test water at 254 nm and the spectral UV absorbance were measured from 200 to 400 nm in one nm increments using a DR4000U spectrophotometer (HACH, Loveland, CO) with the results shown in **Table 1**.

### *Water characterization*

The $H_2O_2$ in samples from each test were quenched with Catalase and sent to Calgon Carbon's Analytical laboratory for characterization shown in **Table 2**.

### *Analysis of hydrogen peroxide*

Hydrogen peroxide was analyzed on-site using Horseradish Peroxidase to catalyze the reaction between o-dianisidine and hydrogen peroxide. Sulfuric acid was added to stabilize the product, producing a pinkish color with a maximum absorbance at 528 nm. A UV/Vis spectrophotometer was

**Table 1.** *Spectral absorbance (averaged over 5 nm bands) for seven different samples*

| | Run Number | | | | | | |
|---|---|---|---|---|---|---|---|
| **wavelength** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| **202** | 0.1853 | 0.1566 | 0.3130 | 0.1285 | 0.2579 | 0.2847 | 0.4238 |
| **207** | 0.1285 | 0.1157 | 0.2757 | 0.0971 | 0.1919 | 0.2251 | 0.3900 |
| **212** | 0.1009 | 0.0935 | 0.2299 | 0.0795 | 0.1531 | 0.1817 | 0.3284 |
| **217** | 0.0787 | 0.0733 | 0.1767 | 0.0633 | 0.1204 | 0.1409 | 0.2514 |
| **222** | 0.0599 | 0.0556 | 0.1349 | 0.0497 | 0.0970 | 0.1118 | 0.1952 |
| **227** | 0.0464 | 0.0431 | 0.1098 | 0.0406 | 0.0835 | 0.0953 | 0.1651 |
| **232** | 0.0384 | 0.0356 | 0.0952 | 0.0351 | 0.0752 | 0.0849 | 0.1478 |
| **237** | 0.0325 | 0.0300 | 0.0824 | 0.0305 | 0.0669 | 0.0750 | 0.1303 |
| **242** | 0.0286 | 0.0264 | 0.0715 | 0.0270 | 0.0596 | 0.0660 | 0.1136 |
| **247** | 0.0255 | 0.0233 | 0.0601 | 0.0238 | 0.0517 | 0.0563 | 0.0943 |
| **252** | 0.0232 | 0.0209 | 0.0503 | 0.0213 | 0.0448 | 0.0476 | 0.0767 |
| **257** | 0.0215 | 0.0193 | 0.0441 | 0.0196 | 0.0402 | 0.0422 | 0.0660 |
| **262** | 0.0202 | 0.0181 | 0.0412 | 0.0186 | 0.0377 | 0.0396 | 0.0612 |
| **267** | 0.0192 | 0.0173 | 0.0399 | 0.0179 | 0.0363 | 0.0385 | 0.0598 |
| **272** | 0.0183 | 0.0168 | 0.0393 | 0.0175 | 0.0352 | 0.0376 | 0.0595 |
| **277** | 0.0172 | 0.0162 | 0.0387 | 0.0170 | 0.0340 | 0.0366 | 0.0587 |
| **282** | 0.0160 | 0.0153 | 0.0373 | 0.0162 | 0.0323 | 0.0349 | 0.0565 |
| **287** | 0.0149 | 0.0145 | 0.0348 | 0.0153 | 0.0299 | 0.0324 | 0.0523 |
| **292** | 0.0136 | 0.0134 | 0.0311 | 0.0140 | 0.0269 | 0.0290 | 0.0461 |
| **297** | 0.0124 | 0.0123 | 0.0276 | 0.0129 | 0.0242 | 0.0260 | 0.0407 |
| **%T (254)** | 94.9 | 95.4 | 89.6 | 95.4 | 90.6 | 90.1 | 84.6 |

**Table 2.** *Results of Preliminary Analysis of the Water*

| | Units | Run-3 | Run-4 | Run-5 | Run-6 | Run-7 | Run-8 | Run-9 |
|---|---|---|---|---|---|---|---|---|
| **TSS** | mg/L | <2 | <2 | <2 | <2 | <2 | <2 | <2 |
| **TDS** | mg/L | 220 | 160 | 160 | 130 | 260 | 240 | 230 |
| **Conductivity** | μS/cm | 345 | 254 | 249 | 200 | 412 | 377 | 358 |
| **TOC** | mg/L | 1.19 | 1.03 | 2.18 | 1.15 | 2.00 | 2.09 | 3.28 |
| **Alkalinity** | mg/L | 190 | 135 | 130 | 105 | 230 | 215 | 200 |
| **Common Anions** | | | | | | | | |
| **Fluoride ($F^-$)** | mg/L | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| **Chloride ($Cl^-$)** | mg/L | 5.3 | 4.2 | 4.0 | 2.7 | 5.7 | 5.4 | 5.0 |
| **Bromide ($Br^-$)** | mg/L | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| **Nitrate ($NO_3^-$)** | mg/L | 0.23 | 0.22 | 0.23 | 0.08 | <0.1 | <0.1 | <0.1 |
| **Phosphate ($PO_4^-$)** | mg/L | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| **Sulfate ($SO_4^-$)** | mg/L | 5.8 | 5.8 | 5.9 | 3.9 | 1.5 | 1.8 | 2.3 |

*Continued on pg 16*

*Continued from pg 15*

used to measure the absorbance at 528 nm to obtain the $H_2O_2$ concentration.

All influent, effluent, and batch reactor samples were analyzed for hydrogen peroxide immediately after each test.

### *Analysis of MIB and Geosmin*

All samples were quenched with Catalase to destroy any residual peroxide prior to shipping to the University of Toronto's Civil Engineering Department for analysis using GCMS.

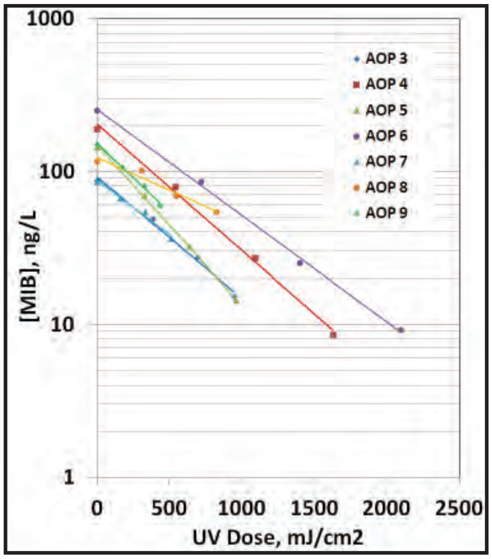
# BENCH REACTOR TEST RESULTS

A total of three runs were completed with MIB only, and four runs with MIB and Geosmin. The peroxide weighted fluence (dose) can be calculated in the batch reactor in a similar way that germicidal weighted fluence is calculated in collimated beam testing.

The bench test results are shown in **Table 3** below:

The MIB and Geosmin concentrations vs. the $H_2O_2$ weighted fluence from the Batch Testing is shown graphically in **Figures 3 and 4**. From this the Dose per log ($D_L$), which is characteristic of the water UVT and $H_2O_2$ concentration, for each of the tests was determined.

**Figure 3**. *MIB Concentration vs. UV Dose in Bench Tests*




# CFD MODELING TO PREDICT FULL-SCALE PERFORMANCE

For full scale CFD modeling, UV Intensity modeling (UVI) is used to calculate the peroxide weighted fluence in each of the meshed CFD cells (the UV reactor is divided into approximately 3 million cells). The $D_L$ above (from the batch testing) is used in the CFD model to compute the destruction

**Table 3.** *Bench Test Results*

| Test ID | AOP3 | AOP4 | AOP5 | AOP6 | AOP7 | AOP8 | AOP9 |
|---|---|---|---|---|---|---|---|
| UVT, % | 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 |
| **Sample ID** | **UV doses applied, mJ/cm$^2$** | | | | | | |
| Batch - 0 | 384 | 542 | 327 | 719 | 164 | 306 | 175 |
| Batch - 1 | 694 | 1091 | 637 | 1398 | 334 | 546 | 323 |
| Batch - 2 | 947 | 1630 | 959 | 2093 | 508 | 821 | 435 |
| Batch - 3 | 384 | 542 | 327 | 719 | 164 | 306 | 175 |
| | **MIB concentration ng/L** | | | | | | |
| Batch - 0 | 87 | 189 | 144 | 250 | 85 | 116 | 151 |
| Batch - 1 | 49 | 79 | 70 | 86 | 67 | 101 | 106 |
| Batch - 2 | 27 | 27 | 32 | 25 | 54 | 69 | 81 |
| Batch - 3 | 15 | 9 | 14 | 9 | 36 | 54 | 60 |
| | **Geosmin concentration ng/L** | | | | | | |
| Batch - 0 | | | | 166 | 61 | 79 | 102 |
| Batch - 1 | | | | 56 | 49 | 61 | 70 |
| Batch - 2 | | | | 10 | 36 | 52 | 51 |
| Batch - 3 | | | | <2 | 22 | 29 | 41 |

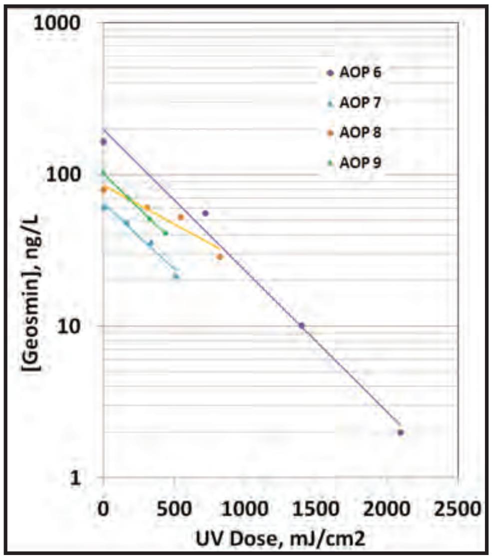



**Figure 4.** *Geosmin concentration vs. UV Dose in Bench Tests*

of the target contaminant in each cell, and hence in the reactor as a whole.

### *CFD Design Conditions*

Computational Fluid Dynamic Modeling (CFD) was performed for each test to predict the performance at the following design conditions (See **Table 4** below):

### *Full Scale Fluence Rate Calculations*

The fluence rate at every point in the reactor was calculated as follows:

- The spectral lamp output between 200 and 300 nm was divided into 5 nm bands, and the fluence rate at each wavelength was determined using the UVCalc Fluence model (Bolton Photosciences Inc., Edmonton, AB, Canada).

**Table 4.** *CFD design conditions*

| Test ID | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| **UVT at 254 nm** | 94.5% | 95.0% | 88.6% | 94.9% | 89.6% | 89.6% | 83.2% |
| **No. of lamps per reactor** | 18 | 18 | 18 | 9 | 18 | 18 | 18 |
| **$H_2O_2$ concentration, mg/L** | 4.5 | 4.2 | 9.3 | 4.6 | 9.8 | 4 | 15.2 |
| **Influent MIB conc. , ng/L** | 92 | 191 | 143 | 244 | 88 | 127 | 152 |
| **Influent geosmin conc. , ng/L** | | | | 173 | 68 | 91 | 103 |

- The fluence rate was multiplied by the $H_2O_2$ absorption factor (absorbance relative to that at 254 nm) to give the $H_2O_2$ weighted fluence rate in each wavelength band normalized to 254 nm.
- Summing this from 200 to 300 nm gives the total $H_2O_2$ weighted fluence rate at each point in the reactor.

This procedure is the same as the accepted technique used to calculate the germicidal fluence rate for the inactivation of microorganisms using broad spectrum UV. New lamps (after 100 hour burn-in) were used with a combined end-of-lamp-life and fouling factor (CAF) of 1.0.

### *CFD Program*

The CFD analysis was performed using CFX software (ANSYS Inc., Canonsburg, PA). The reactor geometry was divided into a mesh of approximately 3 million-volume elements, and the fluid-dynamics and photo-statics were calculated in each cell with the CFD program reading the fluence rate at the mesh points. The program calculates the destruction of the target compound in each mesh cell as the water flows through the reactor. The following formula was used to calculate the destruction in each volume element:

$$\frac{\Delta C}{\Delta t} = \frac{-E'C}{D_L \, x \log e}$$

where: C is the concentration of MIB or Geosmin in the volume element

$E'$ is the $H_2O_2$ weighted fluence rate in that volume element ($mW/cm^2$)

$D_L$ is the dose required for 1-log reduction ($mJ/cm^2$/log) for each contaminant derived from the bench test.

**Table 5** shows the dose/log-reduction of the targeted organism used in the CFD analysis.

### *Illustration of the CFD results*

The following analysis shows the CFD plots for Test ID #4.

### *Fluence*

**Figures 5 and 6** are plots of the peroxide weighted Fluence Rate and velocity profile through the reactor.

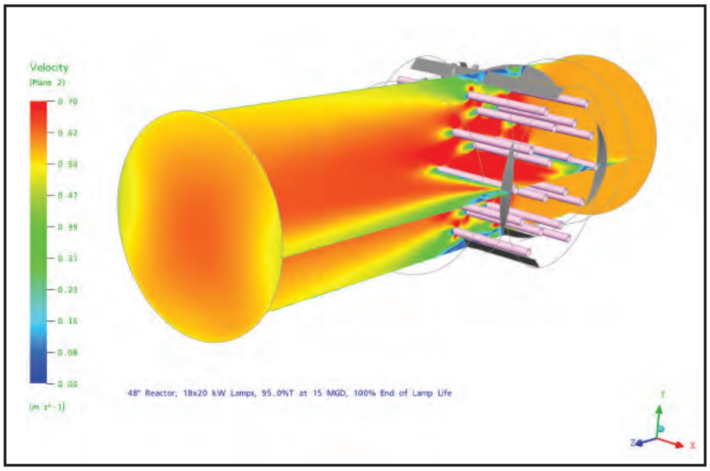



**Figure 6.** *Velocity profile through the UV reactor. Flow direction is right to left.*

### *MIB and geosmin destruction*

CFD plots of the MIB and Geosmin destruction through the reactor are shown in **Figures 7 and 8**.

### *Results of Full-Scale CFD Prediction*

The CFD analysis predicted the following performance for the 48" 18 x 20 kW Chevron Sentinel® reactor for the seven AOP tests:

**Table 5.** *Dose per log-reduction of target compound*

| Test ID | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| **Dose/Log-Reduction of MIB** | 1228 | 1209 | 960 | 1411 | 1333 | 2178 | 1079 |
| **Dose/Log-Reduction of Geosmin** | | | | 1084 | 1065 | 1704 | 1061 |

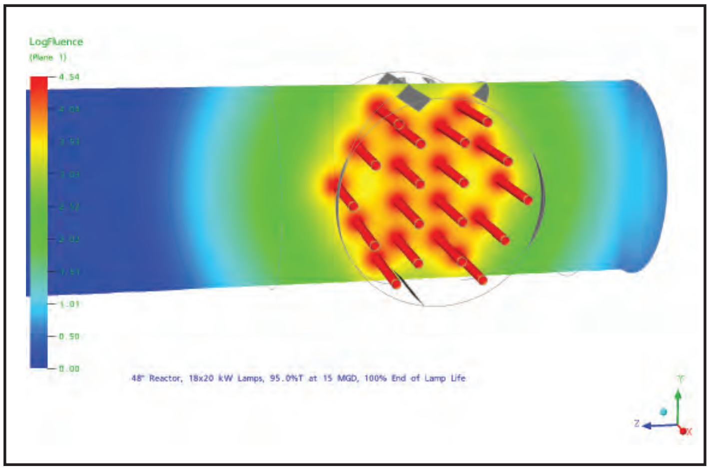



**Figure 5.** *$H_2O_2$ weighted fluence field in the 48" Chevron Sentinel® UV reactor at 95%T with 18 lamps on.*

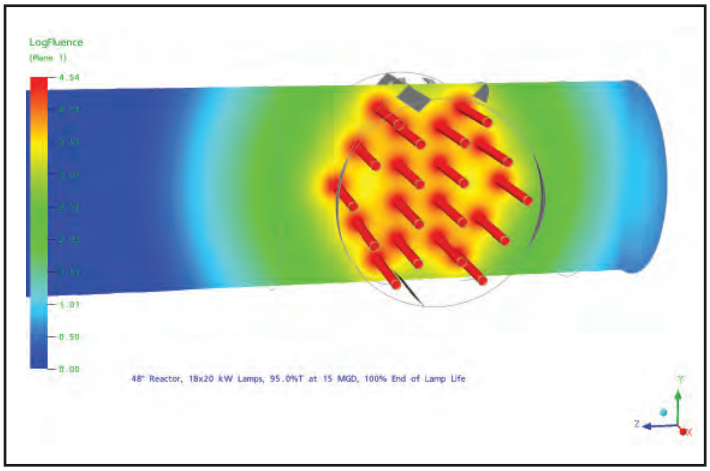



**Figure 7.** *Log MIB Destruction showing even dose distribution in bulk of flow and a predicted 1.02-log MIB inactivation at design conditions*

**Table 6.** *CFD predictions of MIB and geosmin log reductions*

| Test ID | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| **UVT at 254 nm** | 94.5% | 95.0% | 88.6% | 94.9% | 89.6% | 89.6% | 83.2% |
| **No. of lamps per reactor** | 18 | 18 | 18 | 9 | 18 | 18 | 18 |
| **$H_2O_2$ concentration, mg/L** | 4.5 | 4.2 | 9.3 | 4.6 | 9.8 | 4 | 15.2 |
| **Predicted MIB log reduction** | 0.47 | 1.02 | 0.52 | 1.27 | 0.27 | 0.29 | 0.3 |
| **Predicted geosmin log reduction** | | | | 1.61 | 0.33 | 0.37 | 0.31 |

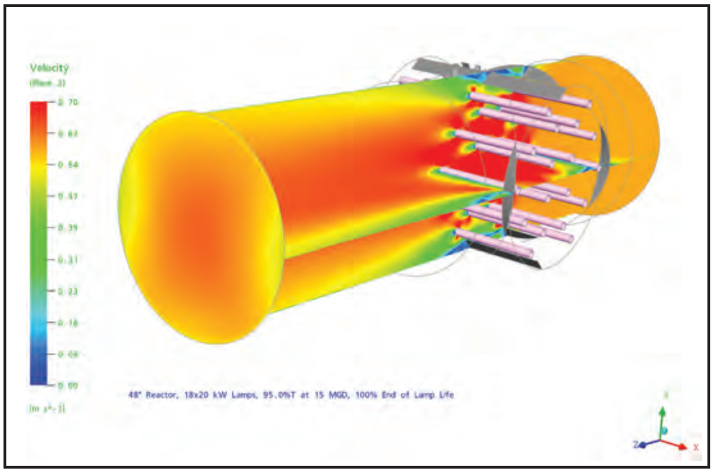



**Figure 8.** *Log geosmin destruction. Flow is from right to left.*

# FULL-SCALE AOP TESTING

The validated UV reactor was a Sentinel® Chevron 48 inch reactor with 18 x 20 kW lamps with lamp arrangement as shown in **Fig. 9**. The reactor is very flexible in operation as 18, 9, or 5 lamps can be run in AOP mode, and in addition, 4, 3, and 2 lamps (all operating as individual banks) can be run in disinfection mode. Furthermore, the individual lamps can be turned down to 40% of full power.

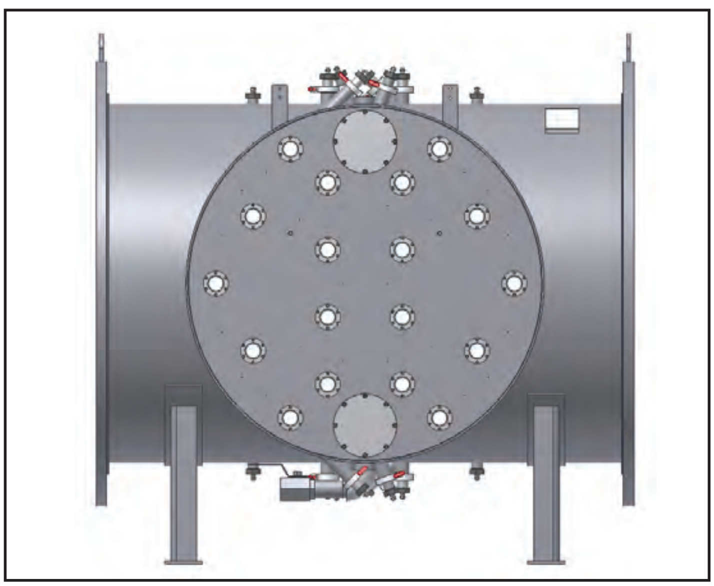


**Figure 8.** *Side view of Sentinel® Chevron 48" Reactor showing lamp arrangement*

## *IUVA and IWA Collaborate in Mexico City*

Join IUVA in a pre-conference workshop on November 25, 2012, in Mexico City. The workshop will focus on the "Basics of UV Disinfection for Water, Wastewater and Reuse Applications."

This workshop will be held in conjunction with the IWA (International Water Association) meeting from November 26 – 29, 2012, which is titled, "Disinfection of Water, Wastewater and Biosolids." The IWA's Disinfection Group is organizing the Mexico City meeting.

Sponsorship opportunities are available for the workshop.

- Primary Conference Sponsor .... $3,000
- Luncheon ................................ $1000
- Speakers (travel stipend)........... $500
- Coffee break (a.m. or p.m.)...... $300 each
- Attendee notepad (with Logo) . $500
- Attendee pen........................... $250

For more information or to sponsor an event please contact Deb Martinez at deb.martinez@iuva.org and to view the entire meeting to include the IWA's meeting please click the link

http://eventos.iingen.unam.mx/DisinfConfMex2012/

# FULL-SCALE TEST RESULTS

A total of 7 runs were completed with MIB and Geosmin. The following are the results:

**Table 7.** *CFD predictions of MIB and geosmin log reductions*

| Test ID | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| **UVT at 254 nm, %** | 94.9 | 95.4 | 89.6 | 95.4 | 90.6 | 90.1 | 84.6 |
| **No of lamps operating** | 18 | 18 | 18 | 9 | 18 | 18 | 18 |
| **$H_2O_2$ concentration, mg/L** | 4.53 | 4.22 | 9.35 | 4.56 | 9.82 | 4.02 | 15.22 |
| **Influent MIB conc., ng/L** | 90 | 190 | 143 | 246 | 87 | 123 | 152 |
| **Effluent MIB conc., ng/L** | 31 | 18 | 40 | 14 | 39 | 76 | 75 |
| **Log reduction MIB** | 0.48 | 1.04 | 0.55 | 1.25 | 0.35 | 0.22 | 0.31 |
| **Influent geosmin conc., ng/L** | | | | 170 | 65 | 87 | 102 |
| **Effluent Geosmin conc., ng/L** | | | | 3.7 | 24 | 39 | 45 |
| **Log reduction geosmin** | | | | 1.67 | 0.44 | 0.37 | 0.36 |

These results are compared with the CFD predictions in **Table 8**:

**Table 8.** *Comparison of CFD Predictions with actual test results in the Sentinel® Chevron 48" Reactor*

| Test ID | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| **MIB predicted log reduction** | 0.47 | 1.02 | 0.52 | 1.27 | 0.27 | 0.29 | 0.30 |
| **MIB expl. log reduction** | 0.48 | 1.04 | 0.55 | 1.25 | 0.35 | 0.22 | 0.31 |
| **Deviation, MIB log reduction** | 0.01 | 0.02 | 0.03 | -0.02 | 0.08 | -0.07 | 0.01 |
| **Geosmin predicted log reduction** | | | | 1.61 | 0.33 | 0.37 | 0.31 |
| **Geosmin expl. log reduction** | | | | 1.67 | 0.44 | 0.37 | 0.36 |
| **Deviation, geosmin log reduction** | | | | 0.06 | 0.11 | 0.00 | 0.05 |

# CONCLUSIONS

The prediction of the log inactivation in the full-scale tests was within ±0.04 log on average and ±0.11 log maximum. The performance of a full-scale UV AOP system can therefore be reliably scaled up from the dose per log inactivation ($D_L$) of the target compounds measured in bench testing using the Computational Fluid Dynamic modeling (CFD) coupled with UV intensity modeling (UVI).

# DISCUSSION

A water quality metric that is independent of the UV reactor characteristics is proposed to measure performance in UV/AOP reactors. The $H_2O_2$ weighted fluence (or UV dose) per log inactivation ($D_L$) 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. Using this method, the performance of a full-scale system can be reliably predicted from bench-scale testing of a representative sample of water.

The $D_L$ water quality metric could be used to specify the performance requirements of UV AOP systems and then be checked in performance testing of the installed system, reducing the risk for both purchasers and suppliers of UV AOP systems.

$D_L$ is inversely proportional to the reaction rate constant with the hydroxyl radical for compounds that do not have significant direct photolysis. Therefore, it can be measured for one compound or surrogate in a water matrix and from this derived for all other compounds of interest, provided their reaction rate is constant with •OH is known. In addition, the impact of all hydroxyl radical scavengers such as carbonate/bicarbonate, TOC, $H_2O_2$, etc. can be calculated, and from that the specified or required $D_L$ for a system can be adjusted for design water quality conditions from that of the water tested.

This approach has benefits to all parties in an AOP purchase and installation:

***Reduces risk for Consulting Engineer***

- Can independently measure and specify the $D_L$ associated with specific contaminants
- It is, therefore, not dependent on vendor testing the water

***Reduces risk to Purchaser/Owner***

- $D_L$ can be measured in a performance trial
- UV vendors cannot hide behind nefarious water quality parameters

***Reduces the risk for the Vendor***

- No surprises in unknown $OH^{\cdot}$ scavengers showing up in the water and affecting the performance

## REFERENCES


*Bolton, J. R., Bircher, K. G., Tumas, W. and Tolman. C. A. Figures-of-Merit for the Technical Development and Application of Advanced Oxidation Technologies for both Electric- and Solar-Driven Systems, 2001. Pure Appl. Chem. 73 (4), 627-637.*

*Bircher, K. G., Vuong, M., Crawford, B., Heath, M., Bandy, J.. C. A. Scale Up of UV AOP Reactors from Bench Tests using CFD Modeling, 2011, Proceedings of IOA/IUVA Conference, Toronto, Canada.*