ABSTRACT

ZHAO, XI. Analysis of a Low Pressure UV reactor under Multiple Upstream Elbow Configurations using UV Sensitive Fluorescent Microspheres. (Under the direction of Dr. Joel Ducoste.)

Upstream piping configuration has been known to impact the UV reactor validation using biodosimetry tests. However, the influence of upstream configuration on the UV dose distribution has not been experimentally investigated. This research was performed to evaluate the UV reactor dose distribution under multiple upstream configurations using UV sensitive fluorescent microspheres. The upstream hydraulics configurations included two kinds of 90- degree bends and one straight pipe configuration. Experimental tests were performed at 51 gpm flow rate, 91% UV transmittance (UVT) on a single lamp low-pressure high-output (LPHO) UV reactor. The UV irradiation kinetics of the photo-chemically active fluorescent microspheres was quantified with bench-scale collimated beam experiments. The correlation with microspheres' fluorescence intensity distribution to UV fluence distribution was achieved by a statistical process involving Bayesian and Markov chain Monte Carlo integration techniques. The results of this study showed that the straight pipe configuration produced a shift in UV fluence distribution to a higher UV fluence range compared to the two elbow configurations. No significant difference was observed between the two elbow configurations. The fluorescent microspheres Bayesian method can serve as an additional test to the traditional biodosimetry for UV reactor validation and added confidence in the experimental results by providing unbiased UV dose behavior.
Analysis of a Low Pressure UV reactor under Multiple Upstream Elbow Configurations using UV Sensitive Fluorescent Microspheres

By

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Introduction

Ultraviolet (UV) disinfection for drinking water and wastewater treatment is increasingly becoming a popular disinfection treatment alternative since it can inactivate chlorine resistant pathogenic microorganisms such as Cryptosporidium and Giardia without forming regulated disinfection byproducts (DBPs) (USEPA 2006). Under the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), UV disinfection is one of the options for public water systems (PWSs) to further reduce microbial contamination of drinking water (USEPA 2006). Currently, PWS must ensure the required log inactivation credit through a dose monitoring program that has been validated over a range of UV transmittances, flow rates, and UV intensities as mandated by the Stage 2 Disinfectants and Disinfection Byproducts Rule (S2DBPR) (Wright and Machey 2003).

UV reactors can be validated through on-site or off-site testing. Most equipment manufactures choose off-site validation as the first option since a broader range of flows and water quality conditions can be tested compared to limited on-site testing conditions (Kelly et al. 2004). In order to effectively validate future UV installations, it is essential for the off-site validation protocol to set up hydraulic configurations that cover the possible on-site requirements. The flexibility required, however, for the piping gallery to accommodate all possible treatment plant UV installations at validation facilities may be too costly. For this reason, the US EPA’s Ultraviolet Disinfection Guidance Manual (UVDGM) provides three recommendations for inlet and outlet piping configurations during the off-site validation test. One of the three recommendations is using a worst case
hydraulic condition, which is assumed to be met by placing a single 90-degree bend, a “T” bend, or an “S” bend upstream from the reactor inlet (USEPA 2006). However, the validation of this “worst case” scenario has come under question by researchers who have utilized computational fluid dynamics (CFD) models to simulate UV reactor performances and showed that not all influent bend configurations lead to a reduction in the log inactivation compared to the straight pipe configuration (Ducoste et al., 2005). Limited studies have shown a reduction in the log inactivation when a single 90-degree or T-bend has been placed upstream from a UV reactor compared to a straight pipe configuration (Ducoste and Linden, 2006).

Photochemically active fluorescent microspheres as non-biological surrogates have been investigated as a tool to measure the actual fluence distribution of a UV reactor rather than biodosimetry and chemical actinometry that only provide a measure of the average UV fluence. Previously, microspheres have been investigated as indicators for pathogen inactivation in ozone reactors (Marinas et al. 1999), filtration experiments (Dai and Hozalski 2003), and sequential disinfection processes with ozone and chlorine (Baeza and Ducoste 2004). For UV disinfection, fluorescent microspheres were selected to use as a photobleachable probe of UV fluence in a reactor (Anderson et al. 2003) but without comparison to other conventional methods or modeling.

Dyed microspheres were used to measure the cumulative UV fluence distribution together with such parallel methods as biodosimetry and numerical simulation to give a comprehensive assessment of a UV reactor (Blatchley et al. 2006). While the cumulative UV fluence distribution displayed differences between the flow conditions tested, it is
difficult to examine what individual UV fluence was impacted by the operational change. A stochastic hierarchical process involving Bayesian statistics and the Markov chain Monte Carlo integration technique was used to correlate the microspheres’ fluorescence intensity distribution to the UV fluence distribution (Bohrerova et al. 2005). In Bohrerova et al., the results were compared with the fluence distribution predicted using a CFD model at multiple flow rates. However, no designs on upstream configuration were performed by any of these previous studies. The advantage of using dyed microspheres to assess the impact of the upstream hydraulic configuration on the UV reactor performance is that it provides more detailed information about changes in the fluence distribution compared to just the average fluence. In addition, the direct quantification of the UV fluence distribution using fluorescent microspheres measurement can help improve the validation of CFD models, which is currently the only other approach for assessing the UV fluence distribution.

The objective of this study was to provide insight into the impact of upstream hydraulic configuration changes on the UV reactor performance with UV sensitive fluorescent microspheres. A pilot-scale closed-vessel UV reactor housing a single low-pressure high output (LPHO) mercury vapor lamp located at the reactor center line and emitting principally at 254nm, was used for the test. Fluorescent microspheres were injected into the main flow under three different upstream configurations that included a straight pipe and two alternate 90-degree bends.
**Materials and Methods**

**UV Reactor**

The reactor subjected to the validation test was a closed-vessel reactor, which was made with a 12” diameter schedule 80 PVC pipe that is 3 ft long. Water flows through a 6” PVC pipe from one side of the reactor to another side and parallel to the lamp arc (Figure 1). The reactor has only one LPHO UV germicidal lamp installed axially inside the reactor center line. The LPHO UV lamp was operating at 87 Watts with 28 Watts UV output at 254nm (catalog number 05-0264 GHO36T5/L/4PSE, Atlantic Ultraviolet Corp.)

**Hydraulic Configurations**

The UV reactor was tested with three inlet configurations to simulate different approach hydraulic conditions. Configuration A was composed of a 4” diameter schedule 40 PVC pipe at a length of 40” (10 pipe diameters) to achieve the straight pipe hydraulic condition. Configurations B and C were achieved using the same construction components but oriented in different ways. As illustrated in Figure 2, configuration B was equipped with 3 sections of 4” diameter schedule 40 PVC pipe at the length of 40”, respectively. These three sections were connected by three 4” 90 bends and a 6” 90 bend to allow final connection to the reactor. Configuration C was identical to configuration B but installed at a right angle to configuration B. Configurations were connected to the main pipe line by true unions, which made the switch between different configurations feasible.
In a previous study, a numerical simulation of a UV reactor with similar inlet/outlet configurations showed that an upstream elbow configuration (configuration C) may produce a higher log inactivation compared to the elbow configuration B or the straight pipe configuration in Figure 2 (Ducoste et al., 2005). Although the model used in Ducoste et al. (2005), was validated using experimental data for one of the elbow conditions, no experimental biodosimetry tests were performed for the other configurations. Moreover, none of the experimental tests in Ducoste et al. (2005), utilized fluorescent microspheres to measure the fluence distribution.

Based on the CFD results in Ducoste et al. (2005), configuration B in the present study is hypothesized to be the worst case scenario, which causes additional mixing and possibly short-circuiting and a decrease UV disinfection performance. According to Ducoste et al. (2005), configuration C is speculated to be the best case scenario. Ducoste et al. (2005) hypothesized that configuration C will provide longer particle path lengths due to the change in direction of the core fluid in the elbow away from the outlet and in a rotating motion around the lamp. Due to this rotating motion, configuration C may result in an increase UV disinfection performance compared to the straight pipe configuration.

**Fluorescent Microspheres and Flow Cytometry**

Experiments were performed using Fluorescent 14 polystyrene microspheres that were obtained commercially from PolyMicrospheres, a Division of Vasmo, Inc. (Indianapolis, IN). The microspheres have an average diameter of 1.6 μm, with raw concentration of \(7 \times 10^8\) microspheres mL\(^{-1}\), an excitation maximum at 340 nm, and an
emission maximum at 380 nm. The commercial microspheres were arrived from the manufacturer stored in an aqueous solution of 0.2% solids content.

Flow cytometry was used to measure the fluorescence output of the microspheres. The flow cytometer used in this study was a DakoCytomation MoFLo that included Sortmaster, three lasers, and ten fluorescence detectors (DakoCytomation Ft. Collins, Colorado), located at the Flow Cytometry and Cell Sorting Facility at North Carolina State University College of Veterinary Medicine. A Coherent I90K Kryton tunable laser was set to a wavelength of 350nm to individually detect fluorescent microspheres. The fluorescence intensity emitted by each microsphere was detected by a photomultiplier detector after passing through a 405/30nm band-pass filter. Summit v4.3 (Dako Colorado, Inc.) was used as the software platform for the flow cytometer and the results were recorded on an arbitrary 405 MN linear scale of fluorescence intensity from 0 to 1023. Each sample was used to obtain at least 10,000 microspheres to determine the fluorescence distribution with gating applied to the boundary fluorescence to eliminate background noise. Histogram results were extracted into txt. file by Summit v4.3 for future analysis (Appendix A).

Pilot Test

Pilot system operation include an 11000 gallon storage tank filled with tap water, a submersible pump that provides up to 108 gpm at 42ft head (Model 292 ½ H.P., Zoeller Pump Co., Inc.), a turbine flow meter installed downstream of the pump with flow range capacity of 15-225gpm (±0.50%) (HO2X2-15-225-B-1MX-F1SS, Hoffer Flow Controls),
a 4L spiking dark container for mixing microspheres into the main water flow, a peristaltic pump (7518-10, Masterflex L/S) for microspheres injection, several 3 inch PVC ball valves to control the flow, a sample controller, and a test LPHO UV reactor.

The three inlet configurations were individually tested under identical conditions. For each configuration test, the pilot was operated at 50 (±1) gpm, which provides a theoretical residence time of 21s in the reactor. UV lamp was given 30 minutes to warm up before each configuration test. After stabilization of the flow at 50 gpm, Microspheres were spiked into the main flow at a rate of 0.5 gpm to provide a concentration of $1 \times 10^5$ microspheres mL$^{-1}$. Effluent sample valve was set to full open at the commencement of spiking the flow with microspheres. After three residence times (63 seconds) given to ensure the reactor has reached steady state, a 1L sample was collected from the effluent sample point.

2mL of 0.1 N sodium thiosulfate was added to the sample to quench any residual free and combined chlorine. Preliminary bench scale experiments with the microspheres in contact with the residual free and combined chlorine found in the tap water after two hours showed no reduction in fluorescence. The quenching procedure was used as an added level of quality control to eliminate any other possible source of fluorescence decay. Once quenched, three 3 mL sub samples were collected and stored in 12×75 mm$^2$ Falcon (B.D. Lab Ware) tubes at 4 °C before analysis. Along with the reactor lamp turned on, a dark test (i.e., lamp turned off) was conducted and effluent samples were collected for bench-scale quasi-collimated beam experiments, water analyses, and for controls. The influent was also sampled for control and complete mix conditions.
**Water Analyses**

Absorbance at 254nm and pH were measured according to standard methods for examination of water and wastewater (APHA 1992). Both influent and effluent dark test samples were analyzed for free chlorine and total chlorine using the DPD Pocket Colorimetric Method, Hach Co. (Loveland, Co.) for both raw and quenched samples.

**Quasi-Collimated Beam Settings**

Bench-scale experiments were performed with the quasi-collimated beam apparatus to provide the calibration curve for the microspheres’ fluorescence intensity decay for known UV fluence values. The collimated beam, which contains 4 low pressure (LP) UV mercury lamps, was calibrated by measuring the Petri dish factor, which achieved a value of 0.96 (Bolton and Linden, 2003). Experiments were performed in completely mixed Petri dishes with 15mL samples from the dark test effluent sample. Samples were exposed to UV fluences of 5, 10, 15, 20, 30, 40, 60, 80, 100, and 120 mJ/cm\(^2\). UV fluence was calculated as the average irradiance multiplied by the exposure time. The incident UV irradiance (mW/cm\(^2\)) was measured at the surface center of the liquid suspension by radiometer (UVX Digital radiometer E 27987/ UVP, Inc.). The radiometer was calibrated with potassium iodide actinometry method (Rahn, 1997) (Appendix B). The average UV irradiance was determined according to Bolton and Linden (2003) as

\[
I_{\text{avg}} = I_{\text{incident}} \times \text{Petri Factor} \times \text{Reflection Factor} \times \text{Water Factor} \times \text{Divergence Factor}
\]  

(1)
Computation of the UV Fluence Distribution from Microspheres’ fluorescence

Intensity Measurements

In this study, the statistical approach developed by Bohrerova et al. (2005) was used to compute UV fluence distribution from the microspheres’ fluorescence distribution. A detailed discussion of this approach is provided in Bohrerova et al. (2005) and summarized here. The UV fluence probability distribution function (UV-PDF) in the reactor was determined using a Markov chain-Monte Carlo (MCMC) integration of the Bayes theorem. The computed UV-PDF was based on the effluent measurements of microspheres’ fluorescence of the continuous-flow tests and on measurements of the fluorescence intensities decay of the microspheres’ fluorescence in the bench-scale quasi-collimated beam experiments.

MCMC integration over the range of observed fluorescence distributions is an important step to determine the corresponding fluence level distribution since a fluorescence intensity distribution was generated for a known fluence level instead of a single fluorescence value. As a result, the fluorescence distribution displayed overlaps between each fluence level used in the calibration procedure with the collimated beam apparatus. Therefore, a single fluorescence distribution can be attributed to a continuous range of corresponding exposure fluences.

Two separate statistical models were built for the reactor results and the bench-scale calibration results to resolve the unknown and known fluorescence distributions, respectively. For the bench-scale experiments, the purpose was to determine the parameters and variability of the relationship between the microsphere fluorescence and
UV fluence. Based on Bayes’ theorem, the statistical model can be shown as (Bohrerova et al., 2005):

\[
\text{Fl}_{UV_{cb}} = \left\{ \begin{array}{l}
\mu_d = B_{\mu} + A_{\mu} UV_d \\
\sigma_d = B_{\sigma} + A_{\sigma} UV_d \\
UV_d = \{UV_{cb}\}_d
\end{array} \right.
\]  

(2)

In Equation 2, Fl\(_{UV_{cb}}\) is the UV fluences for the collimated beam experiments and Fl\(_d\) is the microsphere fluorescence for a known single fluence level (UV\(_d\)). Fl\(_d\) can be characterized as either a normal or log normal distribution and is represented generically by Dist(). According to Bohrerova et al. (2005), Fl\(_d\) was expressed as a Log-Normal distribution due to the range and shape of the microsphere fluorescence distribution. On the other hand, these distributions were described in the past as Gaussians (Anderson et al. 2003), and Weibull (Blatchley et al. 2006) distributions for different dyed microspheres. In order to assess a better fluorescence distribution model for the specific microspheres used in this research, the commonly used statistical technique quantile-quantile (QQ) plot was investigated with Matlab to help determine which distribution best describes the microspheres’ fluorescence data.

Figure 6 illustrates a representative QQ plot result for one of the continuous-flows microsphere fluorescence distribution. The linear relationship between the normal distribution theoretical quantiles and the experimental data quantiles suggests that the microsphere fluorescence data can be characterized under the normal distribution. Due to the fluorescence results gating technique, which manually truncates the fluorescence distribution tails to avoid ambient noise from flow cytometry analysis, a few points from
the very ends of the QQ plot did not follow the hypothetical linear line well. However, the impact of those tail points was negligible since the majority population, which had reached at least 10,000 observations, provided an $R^2$ greater than 0.99 with the linear relationship.

In Equation 2, a linear correlation was assumed between the averages ($\mu$) and the standard deviations ($\sigma$) of the normal distribution for each fluence level tested in the collimated beam experiments. $B_\mu$, $A_\mu$, $B_\sigma$, $A_\sigma$ was the set of fitting parameters from the bench-scale collimated beam experiments statistical model. $A_\mu$ and $A_\sigma$ were the slopes of the linear fit lines between UV fluences and the corresponding fluorescence average and standard deviation, while $B_\mu$ and $B_\sigma$ were the intercept of those two lines.

$B_\mu$, $A_\mu$, $B_\sigma$ and $A_\sigma$ were then used as the average and standard deviation values for the reactor microsphere fluorescence data. Equation 3 displays the statistical model used for the UV LPHO reactor fluorescence data (Bohrerova et al., 2005).

$$\begin{align*}
F_{UV_R} & = \begin{cases} 
Fl_R & \approx Dist\left(\mu_R,\sigma_R\right) \\
\mu_R & = B_\mu + A_\mu UV_R \\
\sigma_R & = B_\sigma + A_\sigma UV_R \\
UV_R & \approx Gamma\left(\alpha,\rho\right)
\end{cases}
\end{align*}$$

The UV fluence distribution in the reactor ($UV_R$) was assumed to take the shape of a Gamma distribution since it can produce a broad range of shapes that includes log-normal and Weibull distributions. A review of the literature of studies that performed UV reactor modeling showed that UV fluence distributions will have shapes consistent with log-normal, Weibull, and Gamma distributions (Bohrerova et al., 2005; Ducoste and Linden, 2006). For the Gamma distribution, shape parameter ($\alpha$) was assumed as a prior
Pareto distribution (with $c_1=1$ and $c_2=5$) and defines a decreasing distribution between $c_2$ and $\infty$. The rate parameter ($\rho$) was assumed as an exponential distribution (with $\lambda_2=0.001$). Exponential prior distributions were assigned to $B_\mu$, $A_\mu$, $B_\sigma$ and $A_\sigma$ with a decay rate of $\lambda_2$, which defines it as a slowly decaying distribution between 0 and $\infty$.

$$\begin{cases} 
\{
\alpha \\
\rho
\end{cases} = \left\{ \begin{array}{c} 
Pareto (c_1, c_2) \\
Exp (\lambda_2)
\end{array} \right\} \quad (4)$$

As in Bohrerova et al. (2005), a range of $c_2$ values were tested to explore its sensitivity to the results and no difference was found beyond a value of 5. R. 2.5.0 statistical software was used to generate the best estimate for $B_\mu$, $A_\mu$, $B_\sigma$, $A_\sigma$ and initial data input for WINBUGS 1.4, which was used to generate the best estimates for $\alpha$ and $\rho$ using MCMC integration. 1000 pairs of $\alpha$ and $\rho$, generated by WINBUGS, were resampled by R. 2.5.0 to generate the reactor UV fluence distribution based on the total of 200,000 values of UV fluence in the reactor (Appendix A).

**Results and Discussions**

**Collimated-beam Results**

Measurements of microspheres’ fluorescence intensity distribution for bench-scale collimated beam experiments displayed a clear trend in the applied UV fluence. Figure 7 displays only three representative UV fluence levels to demonstrate the microspheres’ fluorescence reduction trend and the appearance of overlapping regions between the distributions. Although each of the samples was exposed to a single fluence value, variation in the resulting fluorescence distribution was likely due to intrinsic
heterogeneity among the microspheres’ size, shape, and surface characteristics (Blatchley et al. 2006) as well as the amount of dye contained in each microsphere. Discussions with fluorescence microspheres manufactures revealed that of these variables that impact the fluorescence, the amount of dye contained on each microsphere is the most difficult to control and would require more research into the dye application technique.

The linear relationship obtained from the mean of the fluorescence distributions for collimated beam experiments (Figure 8) also illustrates that increasing the UV fluence level will lead to a decrease in the microspheres’ fluorescence. The fluorescence intensity decay rate constant was \(-1.76 \text{ cm}^2\text{mJ}^{-1}\), which was higher than \(-0.27 \text{ cm}^2\text{mJ}^{-1}\) found in Bohrerova et al. (2005). The higher decay rate is likely due to the settings of the flow cytometer that were different from Bohreroval et al. (2005) as well as differences in the dye quantity with each microsphere used in the present study. However, the higher decay rate constant has the added benefit of improving the results accuracy by indicating a higher sensitivity and better separation between fluorescence distributions. Figure 8 also displays the change in fluorescence standard deviation for each of the distributions. The decay rate constant \((-0.16 \text{ cm}^2\text{mJ}^{-1})\) indicates that the microspheres’ fluorescence distribution had a broader variance for lower fluence level than that for the higher fluence. A narrowing of the fluorescence distribution is expected with increasing UV fluence since more of the dye is reaching the limit of zero fluorescence. Finally, the high \(R^2\) values displayed in Figure 8 suggest that a linear relationship for the mean fluorescence and standard deviation with the applied UV fluence is reasonable for the microspheres used in this study.
**Pilot Results**

Figure 9 displays the control microspheres’ fluorescence intensity distribution result along with the UV reactor data with the straight pipe inlet configuration at 51gpm. The results in Figure 9 displays a significant reduction in the mean fluorescence intensity along with a broader distribution for the straight pipe UV reactor data compared to the control data ($\mu_{\text{reactor}} = 649$, $\sigma_{\text{reactor}} = 98$, $\mu_{\text{control}} = 801$, $\sigma_{\text{control}} = 87$). The broader variance was attributed to the microspheres exposure to a wide range of fluences that occurred from the infinite number of paths that can be taken in the continuous-flow reactor. As discussed earlier, the broad UV reactor fluorescence distribution tends to overlap with several fluorescence distributions created at known fluence levels during the collimated beam experiments. Consequently, the statistical models (Equations 2 and 3) were used to resolve the UV reactor fluence distribution from the fluorescence distribution in Figure 9.

Figure 10 displays a comparison between the UV fluence distributions computed by the Bayesian model analysis for three pilot continuous-flows tests under the ambient conditions summarized in Table 1. In Figure 10, the UV fluence distribution curves for the two elbow configurations overlap with the same mean value (48 mJ/cm$^2$; 95%CI: 47-49 mJ/cm$^2$) and the same standard deviation (21 mJ/cm$^2$). The result for the straight pipe inlet configuration demonstrates a higher UV fluence mean value (56 mJ/cm$^2$; 95%CI: 54-56 mJ/cm$^2$) and the distribution curve shifts to a higher UV fluence region. The higher UV fluence distribution for the straight pipe configuration indicates that this configuration produced a better hydraulic condition for UV disinfection compared to the elbow inlet conditions. As can be seen in Figure 10, the presence of the upstream elbow
seems to reduce the fraction of UV fluence between 55 and 140 mJ/cm$^2$ and increase the fraction of UV fluence between 10 and 50 mJ/cm$^2$. The greatest change in the fraction occurred between 20 and 40 mJ/cm$^2$.

The UV fluence distributions were used to compute the log inactivation and reduction equivalent fluence (REF) for microorganisms used in Bohrerova et al. (2006) (two MS-2 and two Bacillus Subtilis spores) and Cryptosporidium from Qian et al. (2004). Two Cabaj models (Cabaj and Sommer, 2000) were applied to replicate UV fluence-response kinetics for the two surface batches of the Bacillus Subtilis spores experimental kinetics data used in Bohrerova et al. (2006). A first order model was used to capture the kinetics of the MS-2 data from Bohrerova et al. and Cryptosporidium from Qian et al. A least squares fit was used to optimize the model constants. The kinetics are displayed in Figure 11. Table 2 displays the computed REF results. The two kinds of MS-2 and Cryptosporidium experimental data followed the log-linear UV fluence-response kinetics while Bacillus Subtilis spores followed a log-non-linear UV fluence-response kinetics based on the Cabaj-Sommer model, which includes a shoulder in the low UV fluence region and a tail in the high UV fluence region quite well. As can be seen in Table 2, both MS-2 kinetics, Cryptosporidium kinetics, and B. Subtilis 2 kinetics predicted similar REF values for the three configurations as with the average UV fluence value computed by the Bayesian model. However, B. Subtilis 1 was not as sensitive as the other biological indicators in detecting the difference in performance between the elbow configurations and the straight pipe configuration and predicted a lower overall REF for all three configurations. Although both B. Subtilis followed log-non-linear kinetics, B. Subtilis 2
kinetics was log-linear in the UV fluence region (20 to 40 mJ/cm²) where the greatest change in the UV fluence distributions between the elbows and straight configuration occurred. Therefore, the log-non-linear UV fluence-response kinetics did not impact the sensitivity of *B. Subtilis* 2 in detecting the impact of the design change on the UV reactor performance.

These results seem to support some of the experimental biodosimetry data in the literature that displayed a decrease in the REF with the presence of an upstream elbow compared to the straight pipe configuration for a pilot-scale single lamp LP UV reactor (Ducoste et al., 2005). Ducoste et al. also reported CFD modeling results for their single lamp reactor and showed that the predicted UV fluence distribution for the straight pipe configuration also shifted to a higher UV fluence fluence range compared to the elbow configuration UV fluence distribution. However, the results displayed in Figure 10 did not reveal an elbow configuration that was better than the straight pipe configuration as predicted by Ducoste et al. (2005) for a full-scale multilamp medium pressure (MP) UV reactor. Ducoste et al. (2005) theorized that a perpendicular elbow configuration similar to Figure 2C would produce a rotating flow that may enhance the log reduction through longer path lengths in the reactor. However, the results in Figure 10 suggest that whether a rotating flow enhances the log reduction may be a strong function of the reactor design. A single LPHO lamp located at the center of the reactor diameter may not be as sensitive to a rotating flow compared with a reactor that contains four MP lamps located off center. In addition, the UV reactor lamp in this study has an arc length that is not long enough to cover the entire reactor length (Arc length = 29.7 inch, Reactor length = 36 inch). A
longer arc length UV lamp was not selected in this reactor design to reduce any chance of significant reactor wall degradation since the reactor is made of PVC pipe. Consequently, a small dark zone exists in the influent region.

These subtle changes in reactor design can influence how the reactor behaves under the influence of different upstream hydraulic configurations. The results in Figure 10 may further suggest that the possible occurrence of an上游 elbow configuration that performs better than an upstream straight pipe configuration may be very limited. Although the UV fluence results for elbow 1 and elbow 2 look the same, it is possible that either the Bayesian model or the fluorescent microspheres may not be sensitive enough to capture subtle difference between the two elbow hydraulic conditions. In order to test the sensitivity of the Bayesian model, an ideal normal fluorescence distribution had been developed to mimic the reactor microspheres’ fluorescence distribution.

**Bayesian Model Sensitivity**

In this sensitivity analysis, a UV fluence distribution had been computed using the Bayesian model by 1) keeping a constant average of the ideal normal fluorescence distribution and changing the standard deviation and 2) changing the average value but keeping a constant standard deviation. A mid level UV fluence region (around 50 mJ/cm\(^2\)) and a low level UV fluence region (around 20 mJ/cm\(^2\)) had been explored in Table 3.

Based on the results in Table 3, the Bayesian model does not seem to display a strong sensitivity in detecting a change in the standard deviation of the microspheres’ fluorescence distribution. When the standard deviation was changed from 49 to 109
fluorescence units (Fl), there was only a corresponding change in the mean of UV fluence of ±1 mJ/cm$^2$ and 1 mJ/cm$^2$ change in the standard deviation. The only exception is when the microspheres’ fluorescence standard deviation went down to 29 (Fl), the UV fluence distribution displayed a significant change in standard deviation (8 mJ/cm$^2$) and distribution shape although the UV fluence average still remained within 1 mJ/cm$^2$ of the other values.

In contrast with standard deviation sensitivity, the Bayesian model was quite sensitive to changes in the average of the microspheres’ fluorescence distribution. A change in the average of 10 fluorescence units (637 to 647 Fl) produced a corresponding change in the average of 5 mJ/cm$^2$. However, this corresponding change between fluorescent units and UV fluence seems to decrease in the low fluence range since a change in the average of 10 fluorescence units (714 to 724 Fl) produced a change in the average UV fluence of 3 mJ/cm$^2$. Consequently, the sensitivity of fluorescence microspheres for detecting subtle changes in the design configuration or operating condition in the low fluence region may be limited due to the overlapping nature of the microspheres’ fluorescence data with known UV fluences in the collimated beam experiments.

The experimental continuous-flow microspheres’ fluorescence distribution statistics are compared in Table 4 for the three configurations. The results in Table 4 display similar agreement with the Bayesian model sensitivity conclusion. Compared with the two elbow configuration tests, the straight pipe inlet configuration test had different average fluorescence value, which led to a significant change in the UV fluence
using the Bayesian model. However, the two elbow configuration tests had the same average fluorescence value and similar standard deviation. In this case, the results for the experimental microspheres indicate identical performance between the two elbow conditions.

**Relationship with Biodosimetry**

The performance of a UV reactor is currently validated using biodosimetry, which measures the log inactivation of a non-pathogenic surrogate through a UV reactor and back-calculates the reduction equivalent fluence (REF) from a known UV fluence-response curve (Qualls and Johnson 1983). The non-pathogenic surrogates that have been commonly used for validating UV reactor treatment efficiency are MS-2 coliphage and *Bacillus subtilis* spores. However, there are some challenges of computing the REF predicted by biodosimetry. These challenges include the following:

1. REF predicted by MS-2 and *Bacillus subtilis* is not consistent (a maximum of 30% difference) for the same UV reactor under certain conditions (Bohrerova et al. 2006).

2. It has been shown that only microbial surrogates with similar sensitivity to the target pathogen can detect the reactor hydraulic inefficiencies from the REF value (Mackey et al. 2002).

3. *Bacillus subtilis* does not have the same sensitivity in the whole range of UV fluence due to its complex UV inactivation kinetics. The kinetics of UV inactivation of *Bacillus subtilis* contain a shoulder in the limit of low fluences, followed by roughly first-order inactivation, then followed by tailing (Nicholson and Galeano 2003; Bohrerova et al. 2006).
The results in Table 2 did show that the REF predicted using *Bacillus subtilis* 1 could significantly deviate from other biological surrogates. However, this deviation was a strong function of the kinetics since another batch of *Bacillus subtilis* (2) had similar REF results compared to other biological surrogates in Table 2. Furthermore, the results in Table 2 seem to contradict in part the concept that the UV response kinetics of the biological surrogate had to be similar to the target pathogen. In Table 2, *Cryptosporidium* UV response was 3.8 times greater than MS-2-1 and 4.4 times greater than MS-2-2. Yet, the MS-2 REF values were similar to *Cryptosporidium* REF value for both the elbow configurations and the straight pipe configuration. Based on the predicted REF similarity between MS-2 and *Cryptosporidium*, the requirement should be that the biological surrogate should have the same shape in the UV response kinetics over the fluence region being tested.

The challenges described with the biodosimetry method make the current UV reactor validation not comprehensive and inconsistent. In order to improve the UV reactor validation process, fluorescent microspheres using the Bayesian approach could be used as an additional test since a) it provides consistent results for the same reactor configuration; and b) the fluorescent microspheres kinetics due to exposure to UV irradiation follows a linear relationship, which provides the same UV sensitivity in the total UV fluence region.
Conclusions

A study has been performed to evaluate the UV reactor fluence distribution under multiple upstream configurations using UV sensitive fluorescent microspheres. Experimental tests were performed at 51 gpm flow rate, 91% UV transmittance (UVT) on a single lamp low-pressure high-output (LPHO) UV reactor with two kinds of 90-degree bends and one straight pipe configuration. The results illustrated that the fluorescent microspheres using the Bayesian approach was able to characterize the change in UV reactor performance due to changes to upstream hydraulic configurations. The result for the straight pipe inlet configuration demonstrated a higher UV fluence mean value and the distribution curve shifted to a higher UV fluence region. Compared to the fluence distributions from both elbow configurations, the UV fluence distribution curves of the two elbow configurations overlapped each other and produced the same mean value and standard deviation. The results also showed that the Bayesian approach was quite sensitive to changes in the average of the microspheres’ fluorescence distribution although it did not display a strong sensitivity in detecting a change in the standard deviation for the microspheres’ fluorescence distribution. Overall, the fluorescent microspheres Bayesian approach can serve as an additional test to biodosimetry for UV reactor validation by providing unbiased UV fluence distribution assessment of design changes or operational changes.
References


Table 1: Flow conditions and analyses of effluent water spiked with microspheres for continuous-flows tests.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (gal./min)</td>
<td>51</td>
</tr>
<tr>
<td>Water transmittance (%)</td>
<td>91.1</td>
</tr>
<tr>
<td>UV Absorbance (254nm)</td>
<td>0.0403</td>
</tr>
<tr>
<td>pH</td>
<td>7.77</td>
</tr>
<tr>
<td>Quenched chlorine concentration (mg/L)</td>
<td></td>
</tr>
<tr>
<td>Free chlorine</td>
<td>0.02 (Raw water 2.14)</td>
</tr>
<tr>
<td>Total chlorine</td>
<td>0.05 (Raw water 6.06)</td>
</tr>
</tbody>
</table>
Table 2: Reduction equivalent fluence (REF) computed for MS-2, *Bacillus Subtilis* and *Cryptosporidium* with fluence distributions results for three configurations. The average UV fluence predicted by the Bayesian model (Fmean) was also compared.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>MS-2-1</th>
<th>MS-2-2</th>
<th>B.Subtilis 1</th>
<th>B.Subtilis 2</th>
<th>Cryptosporidium</th>
<th>Fmean (mJ/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight</td>
<td>56</td>
<td>55</td>
<td>37</td>
<td>54</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Elbow 1</td>
<td>48</td>
<td>47</td>
<td>34</td>
<td>44</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>Elbow 2</td>
<td>48</td>
<td>47</td>
<td>34</td>
<td>44</td>
<td>48</td>
<td>48</td>
</tr>
</tbody>
</table>
Table 3: UV fluence distribution mean and standard deviation computed using Bayesian model.

<table>
<thead>
<tr>
<th>Fluorescence distributions</th>
<th>Computed fluence distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (Fl units)</td>
<td>Standard deviation (Fl units)</td>
</tr>
<tr>
<td>637</td>
<td>59</td>
</tr>
<tr>
<td>637</td>
<td>109</td>
</tr>
<tr>
<td>642</td>
<td>59</td>
</tr>
<tr>
<td>645</td>
<td>59</td>
</tr>
<tr>
<td>647</td>
<td>29</td>
</tr>
<tr>
<td>&quot;</td>
<td>49</td>
</tr>
<tr>
<td>&quot;</td>
<td>54</td>
</tr>
<tr>
<td>&quot;</td>
<td>59</td>
</tr>
<tr>
<td>&quot;</td>
<td>69</td>
</tr>
<tr>
<td>&quot;</td>
<td>79</td>
</tr>
<tr>
<td>&quot;</td>
<td>109</td>
</tr>
<tr>
<td>714</td>
<td>70</td>
</tr>
<tr>
<td>719</td>
<td>&quot;</td>
</tr>
<tr>
<td>724</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
Table 4: Mean and standard deviation of the experimental continuous-flow microspheres’ fluorescence distribution for the three upstream configurations.

<table>
<thead>
<tr>
<th></th>
<th>Straight</th>
<th>Elbow 1</th>
<th>Elbow 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microspheres’ fluorescence mean (Fl)</td>
<td>649</td>
<td>672</td>
<td>672</td>
</tr>
<tr>
<td></td>
<td>(95% CI: 646-651)</td>
<td>(95% CI: 665-675)</td>
<td>(95% CI: 665-675)</td>
</tr>
<tr>
<td>Microspheres’ fluorescence standard deviation (Fl)</td>
<td>98</td>
<td>98</td>
<td>99</td>
</tr>
</tbody>
</table>
Figure 1: Photograph of LPHO UV reactor
Figure 2: AutoCAD designs of three inlet configurations. A: Straight pipe configuration; B: 90 elbow horizontal configuration (Elbow 2); C: 90 elbow vertical configuration (Elbow 1).
Figure 3: Photograph of pilot test configurations.
Figure 4: Photograph of pilot test that display injection and sampling points.
Figure 5: Photograph of Collimated beam apparatus
Figure 6: QQ-plot for continues-flow microsphere fluorescence distribution data
Figure 7: Comparison of microspheres’ fluorescence intensity distribution for bench-scale collimated beam experiments at 0, 40 and 120 mJ/cm² fluence level.
Figure 8: Mean and standard deviation of the fluorescence intensity distributions obtained from collimated beam experiments.
Figure 9: Measured microspheres’ fluorescence intensity distribution for pilot continues-flow experiment at flow rate of 51gpm with straight pipe configuration inlet. Control is the influent dark sample.
Figure 10: Computed UV fluence distributions of continuous-flows experiments under three different inlet configurations: straight pipe (straight); vertical 90 elbow (elbow 1); horizontal 90 elbow (elbow 2). The mean of UV fluence distribution (Avg) and the standard deviation (Sd) of the respective distribution are illustrated. 95% CI for Straight: 54-56 mJ/cm²; 95% CI for Elbow 1 and Elbow 2: 47-49 mJ/cm².
Figure 11: UV fluence-response kinetics for *Cryptosporidium* (Qian et al. 2004), MS-2 and *Bacillus Subtilis* spores (Bohrerova et al. 2006).
Appendix A: Statistical analysis procedures

1. Extract microspheres fluorescent data using Summit v4.3
   
   (1) Input flow cytometry raw data into Summit v4.3.
   
   (2) Change histogram scale to 1024 for fluorescence value.
   
   (3) Save data as txt file.

2. Use Matlab program to transform txt file into csv files.

Matlab program:

```matlab
cd 'C:\xi\Research\UV\test\06-28\matlab\txt'
a(:,1) = textread('062807B #0 Sample_2_405 NM Lin.txt');
a(:,2) = textread('062807B #1 Sample_3_405 NM Lin.txt');
a(:,3) = textread('062807B #2 Sample_4_405 NM Lin.txt');
a(:,4) = textread('062807B #3 Sample_5_405 NM Lin.txt');
a(:,5) = textread('062807B #4 Sample_6_405 NM Lin.txt');
a(:,6) = textread('062807B #5 Sample_7_405 NM Lin.txt');
a(:,7) = textread('062807B #6 Sample_8_405 NM Lin.txt');
a(:,8) = textread('062807B #7 Sample_9_405 NM Lin.txt');
a(:,9) = textread('062807B #8 Sample_10_405 NM Lin.txt');
a(:,10) = textread('062807B #9 Sample_11_405 NM Lin.txt');
a(:,11) = textread('062807B #10 Sample_11_405 NM Lin.txt');
xlswrite ('CB.xls',a);
```

3. Prepare csv input files for R 2.5.0 alpha
   
   (1) Upload R2WinBUGS package to R 2.5.0 alpha at the start of using R 2.5.0 alpha.
   
   (2) First csv file: collimated-beam fluorescence data transferred from matlab under different UV fluence levels (DataCBWinBUGS.csv).
   
   (3) Second csv file: continuous-flows reactor test fluorescence data transferred from matlab (DataReactorWinBUGS.csv).
   
   (4) Manually gate noise which was caused from flow cytometer: change noise value of the two boundaries to 0 for both the first and second csv files.
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(5) Third csv file (DataParamsWinBUGS.csv): parameters related to statistical calculation:

- NCB: number of observations in each collimated beam dose level
- UVCB: UV dose in collimated beam that correspondent to NCB
- Gatemin: lowest gated brightness observation
- gatemax: highest gated brightness observation
- Nreactor: number of observations in reactor
- Ntot: total number of observations including collimated beam and reactor
- NCat: number of UV dose levels in collimated beam

4. Calculate best estimate for $B_\mu$, $A_\mu$, $B_\sigma$, $A_\sigma$, and regenerate observations for reactor, and prepare initiate value for MCMC chains with R 2.5.0 alpha.

R program:

```r
CBDat<-read.csv("C:\xi\Research\UV\test\06-28\bugs\straight pipe\normal\DataCBWinBUGS.csv", header = TRUE, sep = ",", quote=""", dec=".",fill=TRUE) ReactorDat<-read.csv("C:\xi\Research\UV\test\06-28\bugs\straight pipe\normal\DataReactorWinBUGS.csv", header = TRUE, sep = ",", quote=""", dec=".",fill=TRUE) ParamDat<-read.csv("C:\xi\Research\UV\test\06-28\bugs\straight pipe\normal\DataParamsWinBUGS.csv", header = TRUE, sep = ",", quote=""", dec=".",fill=TRUE) NCB <- ParamDat[,1]  # num observations in CB UVCB <- ParamDat[,2]  # UV dose in CB gatemin <- ParamDat[1,3] # lowest gated brightness observation gatemax <- ParamDat[2,3] # highest gated brightness observation Nreactor <- ParamDat[1,4] # num observations in reactor NFl <- ParamDat[1,5]  # total # observations NCat <- ParamDat[1,6]  # number of UV dose levels in collimated beam FlCatInd <- vector('numeric',(NCat+1))*0 stdCB <- vector('numeric',(NCat))*0
```
avgCB <- vector('numeric',(NCat))*0
UVreactor <- vector('numeric',Nreactor)*0

maxdose <- 400  # highest possible UV dose in reactor
mindose <- 0
skw <- 5       # minimal skew parameter for Gamma

# calculate cumulative index start points
for (cat in 2:(NCat+1)) {
  FlCatInd[cat] <- sum(NCB[1:(cat-1)])
} # end cat

Fl <- vector('numeric',FlCatInd[NCat+1])*0
FlR <- vector('numeric',Nreactor)*0

# regenerate observations for CB
ind <- 0
for (cb in 1:NCat) {
  for (i in gatemin:gatemax) {
    if (CBDat[i,cb] > 0) {
      Fl[(ind+1):(ind+CBDat[i,cb])] <- i
      ind <- ind+CBDat[i,cb]
    } # end if
  } # end i
  stdCB[cb] <- sd(Fl[(FlCatInd[cb]+1):(FlCatInd[cb]+NCB[cb])])
}

avgCB[cb] <- mean(Fl[(FlCatInd[cb]+1):(FlCatInd[cb]+NCB[cb])])
} # end cb

glmSTD <- glm(stdCB ~ UVCB, family=gaussian)
OmegaSD <- solve(vcov(glmSTD))
meanSD <- coefficients(glmSTD)

glmAVG <- glm(avgCB ~ UVCB, family=gaussian)
OmegaA <- solve(vcov(glmAVG))
meanA <- coefficients(glmAVG)

# regenerate observations for reactor
indR <- 0
for (i in gatemin:gatemax) {
  if (ReactorDat[i,1] > 0) {
    FlR[(indR+1):(indR+ReactorDat[i,1])] <- i
    indR <- indR+ReactorDat[i,1]
  } # end if
} # end i

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MeanReactor <- (mean(FlR)-meanA[1])/meanA[2]

mu1 <- meanA[1]
u2 <- meanA[2]
tau1 <- meanSD[1]
tau2 <- meanSD[2]

bugs.data(c("FlR","mu1","mu2","tau1","tau2","Nreactor","skw"),
dir="C:\\xi\\Research\\UV\\test\\06-28\\bugs\\straight pipe\\normal\\min"),digits = 5)

UVreactor <- vector('numeric',Nreactor)+MeanReactor
gr<- skw+0.1
gmu<-0.05
bugs.data(c("UVreactor","gr","gmu"),dir="C:\\xi\\Research\\UV\\test\\06-28\\bugs\\straight pipe\\normal\\min\\init1"),digits = 5)

UVreactor <- vector('numeric',Nreactor)+MeanReactor+10
gr<- skw+0.8
gmu<-0.001
bugs.data(c("UVreactor","gr","gmu"),dir="C:\\xi\\Research\\UV\\test\\06-28\\bugs\\straight pipe\\normal\\min\\init2"),digits = 5)

bugs.data(c("Fl"),dir="C:\\xi\\Research\\UV\\test\\06-28\\bugs\\straight pipe\\normal\\min\\Fl"),digits = 5)

5. Use WinBUGS 1.4 to iterate over the probable range of the $B_\mu$, $A_\mu$, $B_\sigma$, $A_\sigma$ parameter values and converges to the most probable set of values.

(1) WinBUGS model:

```r
model {

  for (i in 1:Nreactor) {
    FlR[i] ~ dlnorm(mu[i],tau[i])
    mu[i] <- log(mu1+mu2*UVreactor[i])
    tau[i] <- tau1+tau2*UVreactor[i]
    UVreactor[i] ~ dgamma(gr, gmu)
  }
```

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\begin{verbatim}
  gr ~ dpar(1, skw)
  gmu ~ dexp(0.001)
}\end{verbatim}

(2) Procedures:

- In WinBUGS, load model then click (1) model (2) specification (3) check model. A message saying "model is syntactically correct" should appear in the bottom left of the WinBUGS program window.

- Open data file generated by R, then click once with the load data button in the Specification Tool window. A message saying "data loaded" should appear in the bottom left of the WinBUGS program window.

- Type the number 2 in the white box labeled number of chains in the Specification Tool window. In the current approach, only two chains were necessary. Next compile the model by clicking once on the compile button in the Specification Tool window. A message saying "model compiled" should appear in the bottom left of the WinBUGS program window.

- Open “initial value 1” data file generated by R, click once on the load inits button in the Specification Tool window. A message saying "initial values loaded: model contains uninitialized nodes " should appear in the bottom left of the WinBUGS program window. Next open “initial value 2” data file generated by R and repeat this process for the second initial values file. A message saying "initial values loaded: model initialized" should now appear in the bottom left of the WinBUGS program window.

- Set gr and gmu as monitoring values during model running process: Select Samples... from the Inference menu; Type gr to be the monitored in the white
box marked node; Click set button once; Repeat for gmu. Type * in the white box then click trace button once to trace both gr and gmu while model running.

- Update model: Select the Update... option from the Model menu. Click once on the update button: the program will now start simulating values for each parameter in the model.

6. Prepare shape (gmu) and rate (gr) parameters generated by WinBUGS: After WinBUGS finished updating, select Samples... from the Inference menu; type “gmu”, “gr” under separate instances in the white box marked node; click once coda for each and copy 1000 “gmu” and “gr” values for each chain into a csv file.

7. Use R 2.5.0 alpha to resample from each Gamma distribution and regenerate the UV fluence distribution in the reactor.

R program:

```R
dat <- read.csv("C:\\xi\\Research\\UV\\test\\06-28\\bugs\\straight pipe\\normal\\output.csv", header = TRUE, sep = ",", quote=""", dec=".", fill=TRUE)

converge <- 50
Ndat <- length(Dat[,1])
N <- Ndat-converge+1

#shape=mu, rate = r
Shape <- vector('numeric',2*N)*0
Rate <- vector('numeric',2*N)*0
Numloop <- 100
result <- vector('numeric',2*Numloop*N)*0

Rate[1:N] <- Dat[converge:Ndat,2]
Rate[(N+1):(2*N)] <- Dat[converge:Ndat,3]
Shape[1:N] <- Dat[converge:Ndat,4]
Shape[(N+1):(2*N)] <- Dat[converge:Ndat,5]

for (j in 1:Numloop) {

```
for (i in 1:(2*N)) {
    result[(j-1)*(2*N)+i] <- rgamma(1, shape=Shape[i], rate=Rate[i])
}

brek <- c(0:1000)*(max(result))/1000
HIST <- hist(result, breaks=brek)
UV_Dose <- HIST$mids[1:1000]
Probability <- HIST$density[1:1000]

write.csv(UV_Dose, file="C:\\xi\\Research\\UV\\test\\06-28\\bugs\\straight pipe\\normal\\min\\R\\data1.csv")
write.csv(Probability, file="C:\\xi\\Research\\UV\\test\\06-28\\bugs\\straight pipe\\normal\\min\\R\\data2.csv")
Appendix B: Experimental protocol for collimated beam calibration and radiometer validation

1. Average fluence (UV dose) determination by radiometer

Correction factors

A. Reflection Factor:

Reflection factor accounts for the reflection when the beam comes from one media to another. For air and water, reflection factor is 0.975, and represents the fraction of the incident beam that enters the water.

B. Petri Factor

Petri factor is defined as the ratio of the incident irradiance average over the Petri dish area to the irradiance at the center of the dish and is used to correct the irradiance reading at the center of the Petri dish to more accurately reflect the average incident fluence rate over the surface area.

Steps:

   a) Vertically scan the radiometer detector over the Petri dish area every 2 grids (2.39mm/grid) on the marked graph paper.

   b) Horizontally scan the radiometer detector over the Petri dish area every 2 grids (2.39mm/grid) on the marked graph paper.

   c) Divide the irradiance at each point by the center irradiance to be the ratio value.

   d) Multiply the vertical ratio value by the horizontal ratio to get the point total ratio.
e) Take the average of the entire total ratio to be the Petri Factor.

In general, a well designed collimated beam apparatus should deliver a Petri Factor greater than 0.9.

C. Water Factor

Water factor accounts for the decrease in irradiance arising from absorption as the beam passes through the water.

$$\text{Water Factor} = \frac{1 - 10^{-a l}}{a l \ln(10)}$$

\(a\): absorbance for a 1 cm path length at 254 nm.

\(\ell\): vertical path length (cm) of the water in the Petri dish.

D. Divergence Factor

$$\text{Divergence Factor} = \frac{L}{L + \ell}$$

\(L\): distance from the UV lamp to the surface of the cell suspension (cm).

\(\ell\): vertical path length (cm) of the water in the Petri dish.

Average Fluence calculation:

$$\text{Fluence}_{avg} = E_0 \times \text{Petri Factor} \times \text{Reflection Factor} \times \text{Water Factor} \times \text{Divergence Factor} \times t$$

\(E_0\): radiometer reading at the center of the Petri dish area.

\(t\): exposure time

2. Fluence determination by iodide/iodate actinometry

Solutions preparation

Solution A: Make a 0.01 M borax / 0.1 M iodate solution by adding 3.81 g of
Na₂B₄O₇•10H₂O and 21.4 g of KIO₃ to 1 L of distilled water.

Solution B: On the day of an experiment, add sufficient iodide to make the concentration of iodide 0.60 M. For example, add 24.9 g of KI to 250 mL of Solution A and stir until dissolved.

**Actinometry Procedure**

a). Add 10 mL of Solution B to a 50 × 35 mm petri dish. Place in position and center under the UV light in the bench scale apparatus and leave for 1 min while UV light off. Using deionized water as baseline to zero the spectrophotometer. Determine the absorbance at 352 nm as blank run.

b). Add 10 mL of Solution B to the 50 × 35 mm petri dish and center under the UV light. Do this three times with targeted irradiation times (for example, 30, 45 and 60 s). After irradiation each solution, determine the absorbance at 352nm.

**Fluence calculations**

\[
\text{Fluence} = \frac{(A_{352} - A_{352,0})W}{\Phi l \varepsilon_{352} A_{cs}} \times E \quad (\text{mJ cm}^{-2})
\]

- \(A_{352,0}\) = absorbance at 352 nm for blank run (unitless)
- \(A_{352}\) = absorbance at wavelength 352nm at time t (unitless)
- \(l\) = pathlength of the spectrophotometer cuvette (cm)
- \(\varepsilon_{352}\) = molar absorption coefficient of actinometer at 352nm (26400 M\(^{-1}\)·cm\(^{-1}\))
- \(\Phi\) = quantum yield at the irradiating wavelength (e.g. 0.64 × [1 + 0.02 × (Temp-20.7)] moles/einstein at 254nm)
Temp = actinometer temperature during irradiation (°C)

V = volume of irradiated actinometer solution (0.01 L)

A_{cs} = cross sectional area (17.20 cm$^2$)

E = constant used to convert einstein into conventional UV fluence units (4.72 \times 10^8 \text{ mJ / Einstein for low pressure UV at 254nm})

3. Plot radiometry fluence versus actinometry fluence, and calculate linear regression and 95% CI as shown below.