Yikes! What the UVDGM Does Not Address on UV Disinfection

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This paper was presented at the IUVA World Congress on Ultraviolet Technologies held in Paris, France, in 2011.

The USEPA UV Disinfection Guidance Manual (UVDGM) provides guidance for the design, validation and operation of UV systems in the United States for disinfection under the Long Term 2 Enhanced Surface water Treatment Rule. The UVDGM was prepared over six years with drafts released in 2001 and 2003 and a final version released in 2006 (USEPA, 2006). The preparation of the UVDGM was challenged by the limited experience in the US with full scale UV system implementation and validation. During the drafting of the UVDGM and over the course of a decade of full-scale experience, there has been considerable evolution in the understanding of UV disinfection. This paper describes eight issues not fully addressed by the UVDGM that impact UV dose delivery and monitoring by installed systems. Solutions to each issue are proposed.

1. The collimated beam UV dose calculation does not account for UV light reflected from the walls of the vessel.

During UV validation testing, the UV dose response curve of the microbe is used to relate the log inactivation measured through the UV reactor to a UV dose value referred to as the Reduction Equivalent Dose (RED). The UV dose response of microbe is typically measured using a collimated beam apparatus, whereby a stirred microbial suspension is exposed to UV light at 254 nm emitted by a low-pressure mercury lamp. The UVDGM specifies that the UV dose delivered to the sample is calculated using:

$$D = I_0 \times P_f \times (1-R) \times \frac{L}{d+L} \times \frac{1-10^{-Ad}}{Ad\ln(10)} \qquad [1]$$

where D is the UV dose, I_0 is the UV intensity measured using a radiometer at a location corresponding to the center of the surface of the sample, P_f is the Petri factor defined as the ratio of the UV intensity measured at the center of the sample surface to the average intensity measured across the sample surface, $1 - R$ is the reflection factor, where R is the reflection of UV light at 253.7 nm at the air-surface interface (typically $R = 0.025$), $L/(d+L)$ is the divergence factor where L is the distance (cm) from the lamp centerline to the sample surface and d is the sample depth (cm), and $(1 - 10^{-ad})/[a\, d \ln(10)]$ is the absorbance factor where a is the absorption coefficient (cm^{-1}) at 253.7 nm of the suspension. (For reference, see the Low Pressure Collimated Beam Protocol published in the Summer 2015 issue of *IUVA News*.)

The standard dose calculation does not take into account the impact of the reflection of UV light from the side walls of the glass vessel containing the suspension (Figure 1). The reflected light increases the UV dose delivered to the suspension. Figure 2 shows the UV dose-response of T1UV phage measured with and without these effects. In this example, reflection off the walls of the glass irradiation vessels (8.54 cm across, 4.9 cm tall) caused a 12% error when determining the UV dose-response.

Estimations suggest that this error could exceed 20%, depending on the size of the irradiation vessel. The error is minimized by using a vessel height that does not significantly exceed the suspension depth.

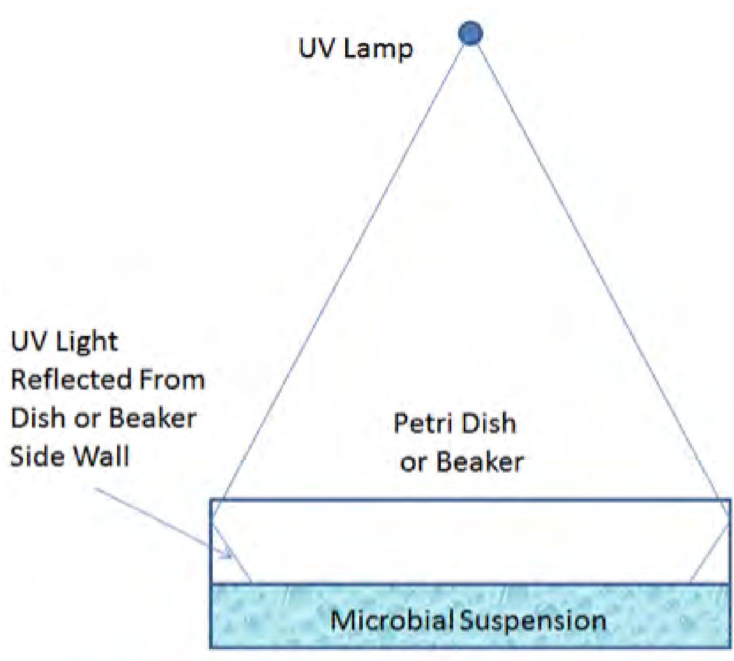

Figure 1. Reflection of UV light from the side walls of the dish into the microbial suspension increases the UV dose delivered by the collimated beam apparatus.

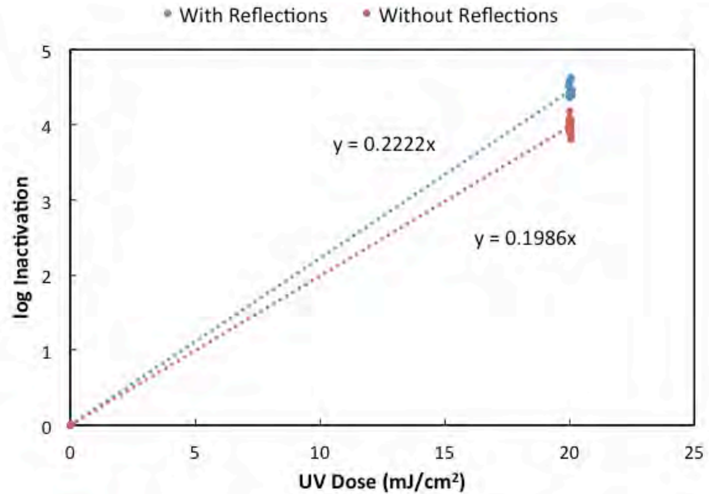

Figure 2. UV dose response of T1UV with and without the effects of side wall reflection.

2. Defining the zero dose calculation using a fit to the UV dose-response curve can bias the relationship between log inactivated and RED.

The UV dose-response curve, measured using the collimated beam apparatus, defines the relation between UV dose, calculated using Equation 1, and log inactivation of the microbe. Typically, the concentration of the microbes is measured as a function of UV dose, typically at 6 or 8 discrete UV dose levels. The UVDGM recommends that the log inactivation with the UV dose-response curve is calculated as:

$$\log I = \log N_0 - \log N \qquad [2]$$

where log I is the log inactivation, log N is the logarithm of the concentration of the microbes remaining after exposure to a known UV dose, and log N_0 is the logarithm of the concentration of the microbes with zero dose. The UVDGM recommends that the value of log N_0 should be defined using regression analysis as the y-intercept of a mathematical fit to log N versus UV dose. For example, the UV dose-response of MS2 phage is often fit using a polynomial function:

$$\log N = A + B \times D + C \times D^2 \qquad [3]$$

and log N_0 is therefore defined as the value A.

An alternate approach to the UVDGM recommendation is to define log N_0 as the average of the log concentrations measured with a zero UV dose. Figure 3 compares the UV dose-response curve of MS2 phage obtained using these approaches. The value of log N_0 calculated using the fit was 5.94 whereas the log N_0 value calculated as the average of the measured log concentration was 6.03. As shown, the RED that would be predicted for a given log inactivation through the reactor would depend on which approach was used to analyze the collimated beam data. In many cases, the bias with the UVDGM approach is random. However, there are validations where the UVDGM approach results in a notable bias that increases the RED assigned to the UV reactor. This bias is eliminated if the log N_0 is calculated as the average of the measured log concentrations obtained with a zero dose. It is recommended that validation data be inspected for this bias. If the bias is presented, the data should be reanalyzed to eliminate the bias.

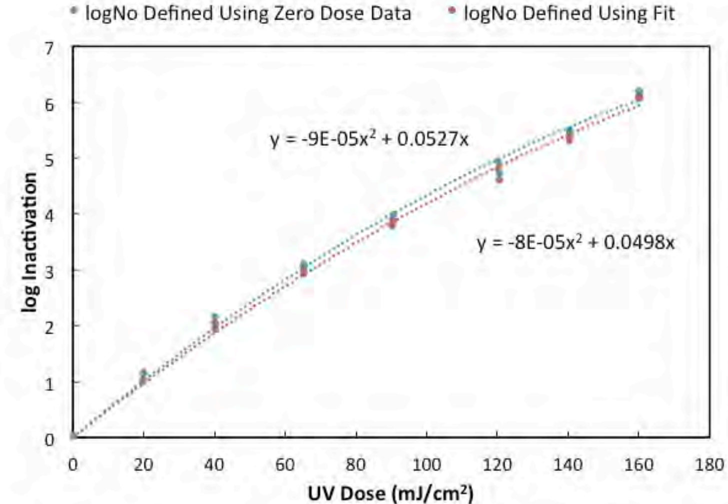

Figure 3. Comparison of UV dose-response where log N_0 was defined using the intercept of a polynomial fit (Equation 3) and as the average of the measured log N values obtained with zero UV dose.

3. MS2 is not a good surrogate for *Cryposporidium* at wavelengths below 240 nm.

Section D.4.1 of the 2006 UVDGM (USEPA, 2006) describes approaches for evaluating the action spectra of the test microbes used for validation. Ideally, the action spectra of the test microbes should match that of the target pathogen. The UVDGM states that the relative impact of the action spectra can be assessed by calculating the germicidal output of the UV lamps using:

$$P_G = \sum_{\lambda=200nm}^{320} P(\lambda)G(\lambda)\Delta\lambda \qquad [4]$$

where P_G is the germicidal output of the lamps, $P(\lambda)$ is the UV output of the lamp as a function of the wavelength λ, and $G(\lambda)$ is the action spectra of the microbe. The UVDGM states that the ratio of the germicidal output of the UV lamps calculated using the action spectra of MS2 to that calculated using the action spectra of *Cryptosporidium* is 1.04. While the 2006 UVDGM

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does not provide details on the action spectra and lamp output used to determine this ratio, the 2003 draft UVDGM did (EPA 815-D-03-007). This ratio was determined using the MS2 action spectra from 225 to 320 nm as shown in Figure F.9 of the 2003 draft UVDGM and lamp output data given in Figure F.12 of the 2003 UVDGM. The UV output of the lamp used to calculate this ratio had negligible output below 240 nm. In contrast, MP lamps used today by UV vendors have significant output at wavelengths down to 200 nm. Furthermore, UV reactors are using synthetic quartz sleeves that transmit low wavelength UV light.

Figure 4 compares the action spectra of MS2 and *Cryptosporidium*. The *Cryptosporidium* action spectra data was measured by Linden et al. (2001) and is provided in Figure 2.9 of the 2006 UVDGM (USEPA, 2006). The MS2 action data was measured by Rauth (1965) and is provided in Figure D.8 of the 2006 UVDGM. Below 240 nm, the action spectra data shows that MS2 phage is much more sensitive to UV light than is *Cryptosporidium*. If the MP UV lamp used during validation emits UV light below 240 nm, the REDs measured using MS2 overstate *Cryptosporidium* inactivation credit. The magnitude of the differences will depend on the UVT spectra of the quartz sleeves housing the lamp and the UVT spectra of the water used during validation.

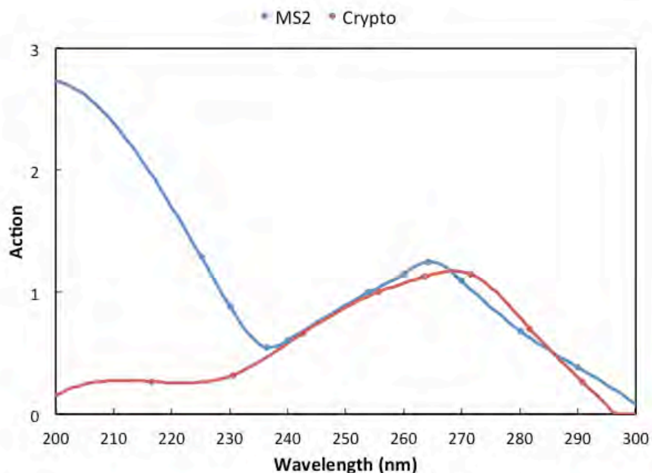

Figure 4. Comparison of the action spectra of MS2 and *Cryptosporidium* shows large differences below 240 nm.

4. While UV light at wavelengths below 240 nm can have a big impact on UV dose delivery, current UV sensor technologies used by medium-pressure systems do not respond to those wavelengths.

While *Cryptosporidium* is less sensitive to UV light at wavelengths below 240 nm than MS2 phage, adenovirus is much more sensitive. As indicated in Figure 2.9 of the UVDGM (USEPA, 2006), the ratio of the action of adenovirus to that of MS2 at 230 nm is approximately a factor of 5.3, while the ratio of the action of MS2 to that of *Cryptosporidium* is approximately a factor of 2.1. If a UV lamp emits UV light at wavelengths below 240 nm, the inactivation of adenovirus will be greater than indicated by MS2 REDs, by a factor of two or more.

However, this performance benefit only applies if the water does not absorb the UV light at those wavelengths (Petri et al., 2009). Lamps and sleeves may also preferentially age and foul at lower wavelengths, reducing the benefits (Wright et al., 2007). If the UV sensors do not respond to wavelengths below 240 nm (example shown in Figure 5), the UV dose monitoring system will not capture these affects. Instead, the UV dose monitoring algorithm will indicate an MS2 dose greater than is actually delivered to the water.

One solution for this issue would be to validate UV systems using Type 219 quartz sleeves, which block UV light below 240 nm. Alternatively, the UV system needs to monitor the UV output of the lamps and the UVT of the water below 240 nm and include those parameters as inputs to the UV dose monitoring algorithm.

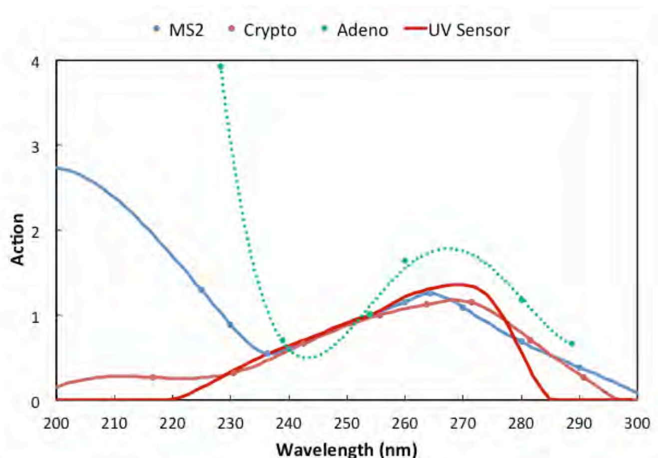

Figure 5. Comparison of the spectral response of UV sensors to the action spectra of adenovirus, MS2 phage and *Cryptosporidium*.

5. Empirical UV dose algorithms can provide poor interpolation of UV dose if they use the wrong functional relationship between UV dose and the dependent variables.

The UVDGM states that validation data can be analyzed to define a UV dose monitoring equation that expresses RED as a function of flow rate, UV absorbance of the water, UV sensor readings, and banks of lamps, if applicable. The UVDGM (USEPA, 2006) states that the following empirical equation provides a good fit to validation data:

$$RED = 10^{a} \times UVA^{b} \times \left(\frac{S}{S_0}\right)^{c} \times Q^{d} \times B^{e} \quad [5]$$

where RED is the Reduction Equivalent Dose, *UVA* is the UV absorbance of the water, *Q* is the flow rate through the UV reactor, *B* is the number of banks of operating lamps, and S/S_0 is the relative lamp output calculated as the measured UV intensity (S) divided by the UV intensity (S_0) predicted for new lamps operating at 100% ballast power in new and clean quartz sleeves and being monitored by a calibrated UV sensor through a new, clean UV sensor port window. With MP UV systems, the UV sensor equation used to predict S_0 has the form:

$$S = 10^{A} \times \exp\left(B \times UVT\right) \times P^{C} \quad [6]$$

where *UVT* is the UV transmittance of the water, *P* is the ballast power setting, and *A*, *B* and *C* are constants obtained by fitting the equation to validation data. With LPHO UV systems, the UV sensor equations typically has the form:

$$S = 10^{A} \times \exp\left(B \times UVT\right) \times \exp\left(C/P\right) \quad [7]$$

The UVDGM (USEPA, 2006) states that the exact form of the UV dose monitoring equation will depend on the reactor and the functional relations between the RED and each variable. One approach for identifying the functional relations is to plot RED against one variable holding the others constant. For example, as shown in Figure 6, at a fixed UVA and bank configuration, RED can be expressed as a function of a combined variable $(S/S_0)/Q$ using:

$$RED = a' \times \left(\frac{S/S_0}{Q}\right)^{b'} \quad [8]$$

where a' and b' are constants obtained from regression analysis. The values of a' and b' often vary as a function of UVA. The relation between a' and UVA can be expressed as:

$$a' = 10^{a} \times UVA^{b} \quad [9]$$

while the relation between b' and UVA is expressed as:

$$b' = c + d \times UVA + e \times UVA^{2} \quad [10]$$

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Equation 10 accounts for the curvature in the relation between RED and $(S/S_0)/Q$, which increases at lower UVT. The curvature reflects the impact of the UV dose distribution on the RED. At high UVTs, the UV dose distribution is narrow and the relation is almost linear (i.e. $b' \rightarrow 1.0$). At low UVTs, the UV dose distribution is relatively wide, and the relation shows significant curvature (i.e. $b' < 1$).

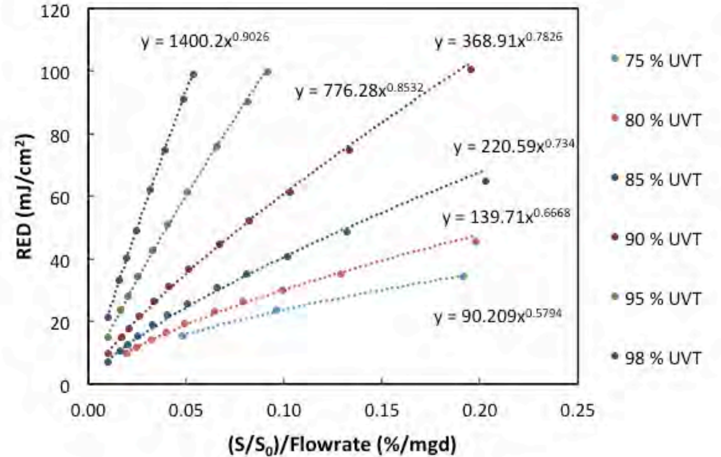

Figure 6. Relation between RED and $(S/S_0)/Q$ predicted using CFD-based UV dose models.

Substitution of Equations 9 and 10 into Equation 8 gives:

$$RED = 10^a \times UVA^b \times \left(\frac{S/S_0}{Q} \right)^{c+d\times UVA+e\times UVA^2} \quad [11]$$

In some cases, the relation between a' and UVA is better fit using:

$$a' = 10^a \times UVA^{b\times UVA} \quad [12]$$

whether or not the terms S/S_0 and Q can be combined into a single variable can be determined by fitting the data to:

$$\text{RED} = 10^a \times UVA^b \times \left(\frac{S/S_0}{Q} \right)^{c+d\times UVA+e\times UVA^2} \times Q^{f+g\times UVA+h\times UVA^2} \quad [13]$$

If S/S_0 and Q have independent impacts on RED, the constants f, g and/or h will be statistically significant, with a p-statistic < 0.05. In many cases, the terms f, g and h are not statistically significant, justifying the use of a combined variable. If the reactor operates with banks of lamps in series, the data can be fit to:

$$\text{RED} = 10^a \times UVA^b \times \left(\frac{S/S_0}{Q} \right)^{c+d\times UVA+e\times UVA^2} \times Banks^{f+g\times UVA+h\times UVA^2} \quad [14]$$

Typically, the impact of *Banks* on RED is independent of the impact of the combined variable $(S/S_0)/Q$, and these terms cannot be combined.

The overall approach described in Equations 8 to 14 leads to a UV dose equation that is functionally different from Equation 5 given in the UVDGM (USEPA, 2006). Both equations can be fitted to validation data with relatively high R-squared values; however, Equation 11 (or Equation 14 if the reactor validation includes banks) always provides a higher R-squared value. Typically, all the terms of Equation 5 are statistically significant, whereas most if not all of the terms of Equation 11 (or Equation 14) are statistically significant. However, because Equation 5 does not account for dependence of the curvature of RED vs. $(S/S_0)/Q$ on UVT, Equation 5 can provide biased predictions of UV reactor performance by as much as 25 or 30%. Given the potential for such errors, validation reports should provide a rationale for the equations used to fit the biodosimetry data, showing that the functional relations used are appropriate for the underlying data and demonstrating that the coefficients are statistically significant.

6. The optimal UV sensor location for UV intensity setpoint monitoring can result in significant under-dosing.

The UVDGM (USEPA, 2006) specifies two approaches for UV dose monitoring: the calculated dose approach (see Equation 5) and the UV intensity setpoint approach. The UV intensity setpoint approach is also specified by the German DVGW and Austrian ONORM UV disinfection rules.

With the UV intensity setpoint approach, the UV reactor delivers a specified UV dose when the UV sensor reading is equal to or greater than an alarm setpoint value that is defined as a function of flow rate. The UVDGM, DVGW and ONORM protocols specify that the UV intensity setpoint approach should be validated using two test conditions. With the first test condition, the reactor operates at the maximum ballast power (typically 100%) and a decreased UVT until the UV sensor reads at the alarm level. With the second test condition, the reactor operates at the maximum UVT (typically 98%), and the lamp power is lowered until the UV sensor reads at the alarm level. The RED measured under these conditions depends on the placement of the UV sensor relative to the lamps. If the UV sensor is located relatively close to the lamps, the RED measured with the first test condition will be lower than that measured with the second test condition. If the UV sensor is located relatively far from the lamps, the RED measured with the second test condition will be lower than that

measured with the first test condition. At some intermediate UV sensor location, the REDs measured with the two test conditions will have the same value. The UVDGM, DVGW and ONORM protocols state that the UV reactor is rated based on the lowest RED measured with the two test conditions. As such, UV vendors are motivated to locate their UV sensors at the intermediate position where the two REDs have a similar value.

An underlying assumption with the two test conditions is that at UVT and ballast power combinations that result in UV sensor readings at the setpoint value, the RED will have a value that lies between the two values measured with test conditions 1 and 2. However, as shown in Figure 7, this assumption does not hold true. Figure 7 shows a plot of RED as a function of UV sensor reading divided by the flow rate observed during UV reactor validation. As shown, the relationships at low UVT (70%) and high UVT (97%) overlap such that an RED of 40 mJ/cm^2 is associated with an *S*/*Q* of 220 mW/cm^2 per mgd. However, at UVT values between 70 and 97%, the REDs associated with an *S*/*Q* of 220 mW/cm^2 per mgd range from 40 down to 24 mJ/cm^2. This issue is addressed if the UV intensity setpoint validation includes a third test point at an intermediate UVT.

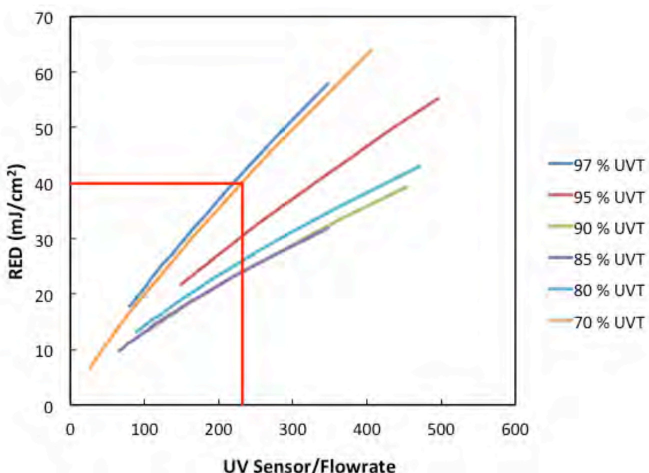

Figure 7. Relationship between RED and UV sensor reading divided by flow rate shows that UV intensity setpoint validation should include test points at intermediate UVT values.

7. The UVT measured during validation with LSA as a UV absorber is strongly impacted by the wavelength accuracy of the spectrophotometer.

Figures 8a and 8b show the UVT spectra of validation test waters adjusted using LSA. Because the LSA spectrum has a significant slope at 254 nm, a 1 nm wavelength error with a spectrophotometer (the wavelength accuracy of many commercial spectrophotometers) will cause a significant error measuring UVT at 254 nm. For example, the UVT at 253, 254 and 255 nm with the spectra shown in Figure 8 is 81.3%, 82.3% and 83.1%, respectively. While the impact appears small over a 1 cm path

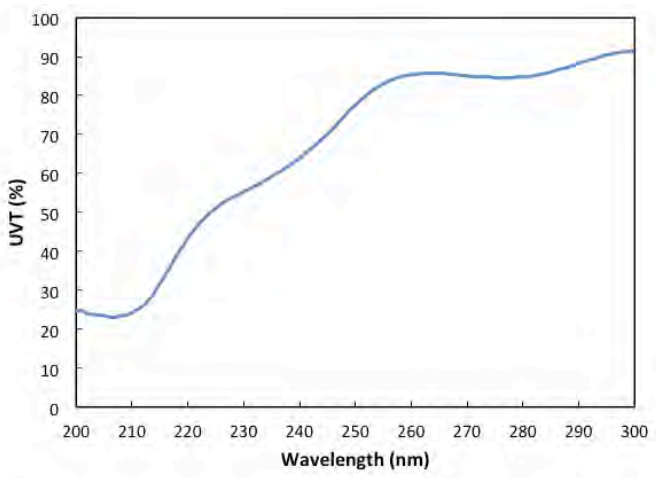

Figure 8a. UVT spectra of validation test waters adjusted using LSA and the impact of a 1 nm wavelength error on measuring UVA.

length in water, the differences are significant over the longer path lengths that occur within a UV reactor, and these errors have a significant impact on the accuracy of RED predictions by the UV dose monitoring algorithm. The errors are eliminated by using a UV photometer equipped with a LP lamp to

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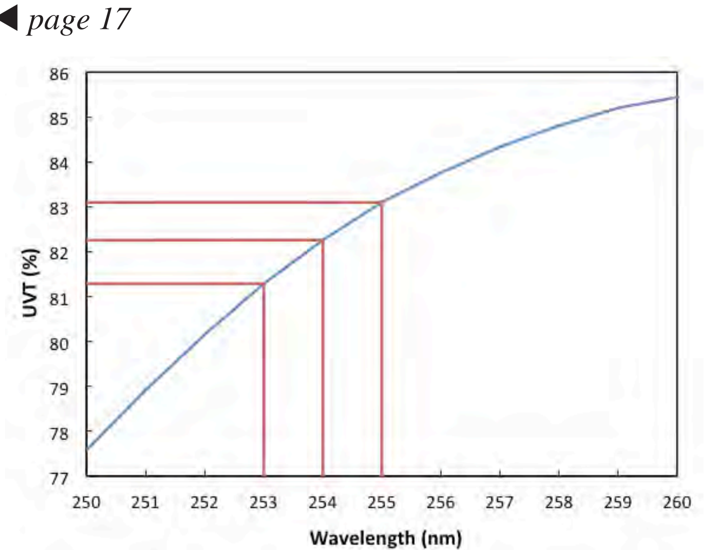

Figure 8b. UVT spectra of validation test waters adjusted using LSA and the impact of a 1 nm wavelength error on measuring UVA.

measure the UVT during validation, since the wavelength of the UV output from the LP lamps is fixed at 253.7 nm.

8. A 2 percent UVT monitoring error with UV system operation can cause large UV dose monitoring errors at high UVTs.

The UVDGM (USEPA, 2006) states that the accuracy of the online UVT monitor should be checked at least weekly by comparison of the online UVT measurements to UVT measurements using a bench-top spectrophotometer. The UVDGM states that the online UVT monitor must not deviate by more than two percent UVT from the spectrophotometer measurements.

The UVDGM does not discuss the magnitude of the RED error than can occur with a 2% UVT monitor error. The RED error, however, can be calculated using the UV dose monitoring equation provided in the validation report. Typically, the UVT monitor error impacts the accuracy of UV dose monitoring in two ways. First, the UVT monitor error impacts the UVA (or UVT) used in the UV dose monitoring equations (see Equations 11 or 14). Secondly, the UVT monitor error impacts the value of S_0 used to calculate the ratio S/S_0 (see Equations 6 and 7). The impact of the UVT monitor on the value of S/S0 depends on the location of the UV sensor relative to the lamps, and is greater when the UV sensor is relatively far from the lamps.

As an example, Figure 9 shows the RED error as a function of true UVT where the online UVT meter read 2% greater than the true UVT. With this particular UV reactor, the error in the calculated RED varies with UVT and ranges from 9 to -42%. These errors can lead to significant under- or overdosing by the

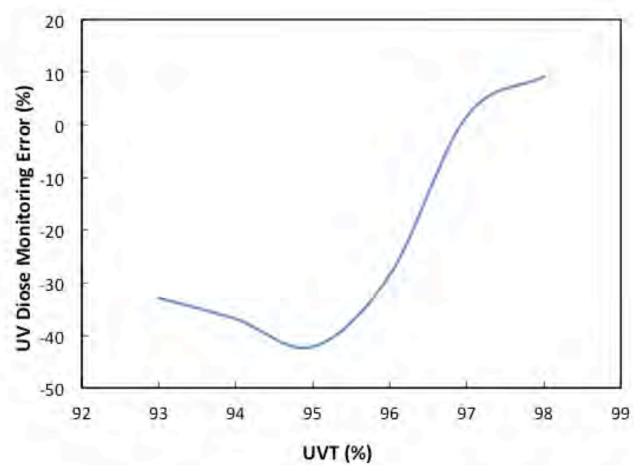

Figure 9. UV dose monitoring error caused by a 2% UVT monitoring error shown as a function of the true UVT.

reactor and can be minimized by specifying tighter criteria for UVT monitor accuracy.

Summary

This paper describes eight issues not fully addressed by the UVDGM that impact UV dose delivery and monitoring by installed UV systems. The impact ranges from a few percent to as much as 50%. Currently, there is no formal mechanism for addressing issues with the UVDGM and future updates of the UVDGM are not anticipated at this time. It is recommended that IUVA develop a working group of stakeholders to address issues with the UVDGM and provide communications on these issues and their solutions. ■

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