Comparison of Safety Factor Approaches for UV and Chemical Disinfection

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INTRODUCTION

The UV Disinfection Guidance Manual (UVDGM) provides test protocols for validating dose delivery and monitoring by UV reactors. Validation involves measuring the dose delivery of the UV reactor under various test conditions of flow, water UV transmittance, and lamp output, and verifying the ability of the reactors monitoring system to indicate that dose delivery. The test conditions should span the operating range of these variables expected at the water treatment plant (WTP) where the reactor will be installed (USEPA, 2003).

Dose delivery is measured using a technique termed biodosimetry. With biodosimetry, the UV reactor is installed in a test train. Water carrying a challenge microbe is passed through the reactor at a controlled flow and UV transmittance. Log inactivation of the challenge microbe by the UV reactor is measured. The UV dose-response of the challenge microbe also is measured using a bench-scale collimated beam apparatus. The UV dose-response is used to relate the log inactivation measured through the reactor to a dose value termed the Reduction Equivalent Dose (RED) (Figure 1).

The validation protocol in the UVDGM provides two approaches, termed Tier 1 and Tier 2, for relating RED measured during validation to the log inactivation of the target pathogens, namely *Cryptosporidium*, *Giardia*, and viruses. With both approaches, a "safety factor," which accounts for systematic and random error in dose monitoring and validation, is derived and multiplied by the regulatory pathogen dose requirements to give the RED that should be demonstrated by validation. The Tier 1 approach specifies RED values needed to demonstrate different levels of target pathogen inactivation based on a safety factor calculated for a UV reactor that meets specific criteria on dose monitoring and validation. Any UV reactor that meets those criteria can use the Tier 1 RED values to demonstrate pathogen inactivation. The Tier 2 allows the user to calculate the safety factor and target RED values specific to their reactor and its validation. The Tier 2 approach allows the use of UV reactors that do not meet Tier 1 criteria and allows the user to apply smaller safety factors if justified.

SAFETY FACTOR

The safety factor is determined using the following equation:

$$S.F. = B_{RED} B_{poly} \left(1 - e_T\right)$$

where B_{RED} is the RED bias, B_{poly} is the polychromatic bias, and e_T is the total random uncertainty.

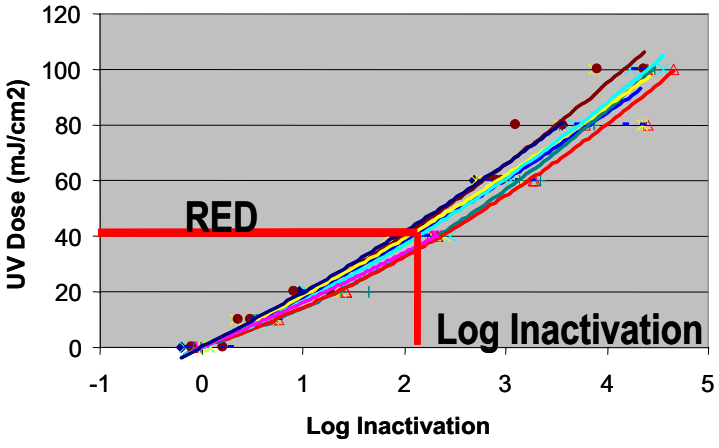

Figure 1. *UV dose-response of the challenge microbe, measured using a bench-scale collimated beam apparatus, is used to relate log inactivation measured through the reactor to RED.*

RED BIAS

The RED bias accounts for an important error that occurs when the challenge microbe used during validation and the target pathogen have different inactivation kinetics. If the challenge microbe is more resistant to UV light than the target pathogen, the RED measured with the challenge microbe will be greater than that of the pathogen (Cabaj et al, 1996; Wright and Lawryshyn, 2000; Petri and Olson, 2003). The magnitude of the error depends on the dose distribution delivered by the reactor – the wider the dose distribution, the larger the error.

In the UVDGM, the Tier 2 approach provides a method for determining the RED bias based on the UV dose-response of the challenge microbe observed during validation, the UV dose-response of the target pathogen as defined by the regulatory dose requirements, and a dose distribution representing commercial UV reactors. The Tier 1 RED values for *Cryptosporidium* were determined using an RED bias of 2.14. This value was determined assuming MS2 phage with a UV sensitivity of 25 mJ/cm2 per log inactivation unit was used during validation. How the RED bias used for Tier 1 compares with the bias that actually would occur with commercial UV reactors is uncertain, because there is little published data on the dose distribution delivered by those reactors. However, Petri and Olson (2003), modeling dose delivery by medium-pressure (MP) reactors, report a factor ranging from 1.3 to 2.0 for a "good" 8-lamp reactor design and 2 to 4 for a "poor" 2-lamp design. This data indicates that the Tier 1 value may be reasonable for good reactor designs and optimistic for poorer designs.

POLYCHROMATIC BIAS

The polychromatic bias accounts for errors in dose delivery and monitoring that can occur with polychromatic UV systems (MP or pulsed UV systems). The error does not occur with monochromatic UV systems [LP (low-pressure) or LPHO (low-pressure high output) UV). This error can occur for three reasons:

First, there can be a significant difference between the UV absorbance spectrum of the additive used during reactor validation and the UV absorbance spectrum of the water at the WTP (water treatment plant). Typically, coffee and lignin sulfonic acid are used during validation. While UV absorbance of WTP waters tends to decrease as wavelength increases from 200 to 400 nm, the UV absorbance spectra of lignin sulfonate and coffee have local minima near 254 nm. Thus, for a given UV absorbance at 254 nm, the UV additives have greater absorbance at other wavelengths than do WTP waters. This difference affects both the RED delivered by the UV reactor and the UV intensity measured by the UV sensor. Both are lower during validation than at the WTP. However, the impact of the difference on the sensor measurement depends on the distance from the lamps to the sensor. If the sensors are relatively close, the impact on the sensor reading is small compared to the impact on RED, and a UV intensity alarm set point established during validation will be a conservative indicator of dose at the WTP. On the other hand, if the sensor is relatively far away, the impact on the sensor reading will be large compared to the impact on RED, and a UV intensity alarm set point established during validation could lead to under-dosing at the WTP.

Second, spectral shifts in the UV output of the lamps, the UV transmittance of the quartz sleeves (aging, internal or external fouling), or the UV transmittance of the UV sensor window could cause a bias error in dose delivery monitoring. Typically, these phenomena have a greater impact at lower wavelengths than at higher wavelengths. The bias error occurs if the UV sensor responds to higher wavelengths more than the microbes. The error is small if the sensors have a germicidal response and are not located too far from the lamps. Minimizing this error is the reason for requiring germicidal sensors for Tier 1.

Third, differences in the wavelength response or action spectra of the challenge microbe used during validation and the target pathogen can cause a polychromatic bias. For example, Petri and Olson (2003) modeled dose delivery by a MP UV reactor and reported that the RED measured with B. subtilis spores can be 10 to 20% higher than the RED measured with MS2 phage. They attribute the difference to the action spectra of the microbes.

The Tier 1 and Tier 2 approaches in the UVDGM account only for the impact of the absorbance spectra on the polychromatic bias. However, the background to the validation protocol describes the potential impact of spectral shifts and differences in the action spectra. Furthermore, an Excel spreadsheet, provided as support to the UVDGM, allows the user to calculate the polychromatic bias using spectral data on the lamp output, sleeve UV transmittance, water UV absorbance, microbe response, and UV sensor response.

TOTAL RANDOM UNCERTAINTY

The total random uncertainty accounts for sources of random error associated with validation and monitoring. Random error is associated with the following:

1. Log inactivation of the challenge microbe measured during validation;
2. UV dose-response of the challenge microbe measured during validation and used to relate log inactivation to RED;
3. Measurement uncertainties of the sensors (flow, UV transmittance, UV intensity) used during validation and at the WTP;

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4. Uncertainty monitoring lamp output if the number of sensors is less than the number of lamps;

5. Interpolation of validation data.

The total random uncertainty is calculated as the square root of the sum of squares of the above mentioned random errors.

COMPARING UV TO CHEMICAL DISINFECTION

The approach used by the UVDGM to relate validation data to target pathogen dose requirements differs from the approach used with chemical disinfection. There is a concern that UV disinfection is being held to a higher standard than chemical disinfection. This concern should be addressed.

The Surface Water Treatment Rule (SWTR) provides concentration x time (CT) or chemical dose requirements for the inactivation of *Giardia* and virus by chlorine, chlorine dioxide, ozone, and conventional chloramination. Many WTPs monitor chemical disinfection by calculating CT as the residual disinfectant concentration multiplied by the 10th percentile of the chemical reactor's residence time distribution (t_{10}).

DOSE REQUIREMENTS

CT requirements in the SWTR were determined by applying a conservative statistical analysis or a safety factor to pathogen inactivation data obtained using bench-scale studies. With chlorine inactivation of *Giardia*, the CT requirements were determined by interpolating the 99 percent confidence interval of the CT needed for 4-logs inactivation to other levels of inactivation using first order kinetics. Because the dose-response data demonstrated curvature, the interpolation was considered conservative, especially at mid-range levels of CT. For example, for 0.5- and 3-logs inactivation of *Giardia*, this approach gives a CT value 2 and 1.5 times higher, respectively, than the mean predicted CT at pH 6 and 5°C using 2 mg/L as Cl2 (USEPA, 1991, Appendix F, Figure 1). With other disinfectants, safety factors were applied as shown in Table 1.

With the UVDGM, the UV dose requirements for *Giardia*, *Cryptosporidium*, and virus were obtained by fitting 80 percent credible intervals to the dose-response data. The UV dose requirements for 3-logs *Cryptosporidium* and *Giardia* inactivation, respectively, are 2.6 and 4.4 times the median UV doses. The UV dose requirement for 4-logs virus inactivation is 1.2 times the median UV dose. In summary, the approach used by UVDGM is comparable to the approach used by the SWTR to develop dose requirements for the inactivation of *Giardia* by chlorine. Both approaches account for the reported variability in dose-response data obtained using bench-scale studies.

T10 AND MS2

While MS2 commonly is used to measure dose delivery by UV reactors, the product of residual chemical concentration and T10 often is used to indicate dose delivery by chemical systems. To compare the relative factor of safety applied to UV and chemical disinfection under the UVDGM and SWTR guidance, hypothetical examples of disinfection performance were simulated for each technology. The simulation involves calculating the log inactivation achieved with a given UV dose distribution for a given microbe and relating that inactivation to a RED.

Figure 2 presents the UV dose distribution of the simulated UV system operating to achieve 3-logs *Cryptosporidium* inactivation. Figure 2 also includes the UV dose distribution of a simulated chlorine contact chamber operating to achieve 0.5-log *Giardia* inactivation. Both UV dose distributions represent relatively challenging hydraulics through the reactors.

Figure 3 presents the UV dose-response of *Cryptosporidium* and virus, taken from proposed regulatory UV dose requirements, and the UV dose response of MS2 phage with a UV sensitivity of 25 mJ/cm2. Figure 3 also presents the chlorine dose-response for *Giardia* and virus at pH 6 and 0.5°C using 0.4 mg/L as Cl2, taken from SWTR guidance. The log inactivation of a given microbe by each reactor was calculated by numerically integrating the inactivation achieved by each UV dose in the UV dose distribution. The log inactivation then was converted into an RED using the UV

Table 1. *Safety Factors Incorporated into SWTR CT Requirements*

Disinfectant	Pathogen	Safety Factor Used to Determine SWTR CT Requirements
Chlorine	Virus	Safety factor of 3 applied to the highest CT for a given inactivation
ClO_2	*Giardia*	Safety factor of 1.5 applied to the mean CT for 2 log inactivation
	Virus	Safety factor of 2 applied to the average CT needed at pH 6
Ozone	*Giardia*	Safety factor of 2 applied to the highest CT for 2 log inactivation
	Virus	Safety factor of 3
Chloramines	*Giardia*	No safety factor applied to bench-scale data obtained with preformed chloramines because conventional chloramination is more effective than preformed chloramines
	Virus	

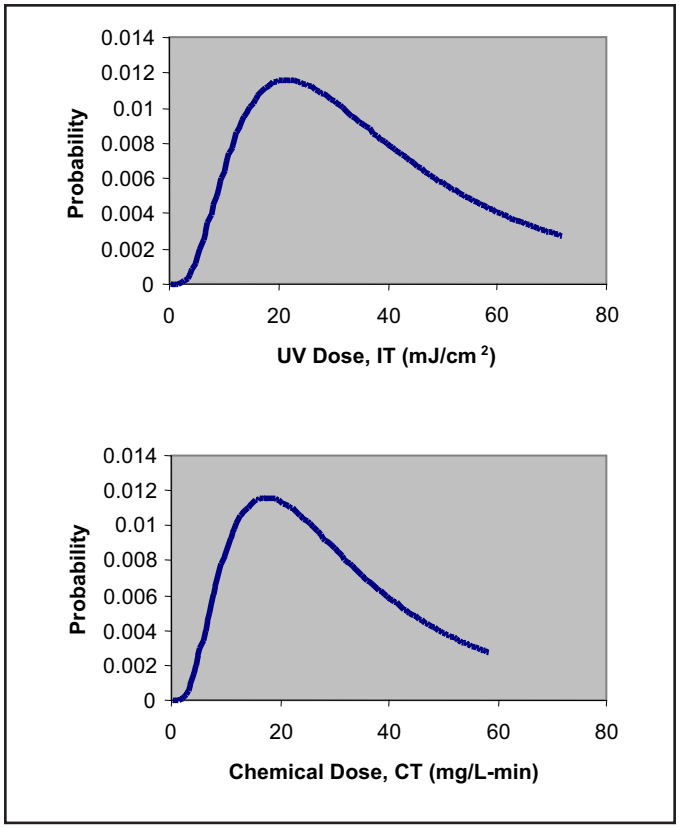

Figure 2. *Dose distributions for a yypothetical UV reactor and chlorine contactor.*

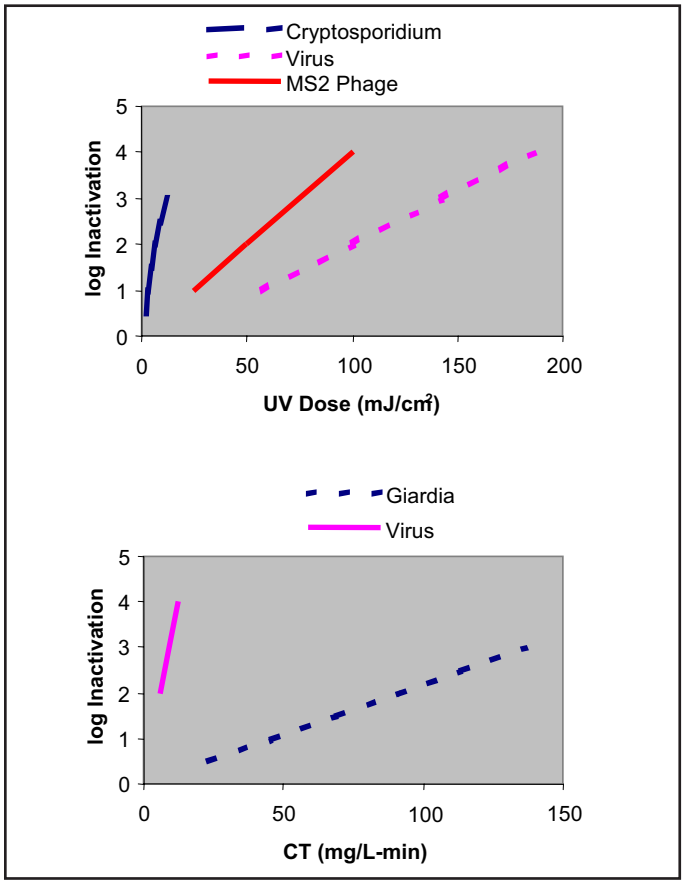

Figure 3*. Inactivation kinetics of target pathogens by chlorine and UV and MS2 phage by UV.*

dose-response curves in Figure 3. Table 2 presents the RED values for the inactivation of *Giardia* and virus by chlorine and the inactivation of *Cryptosporidium*, MS2 phage, and adenovirus by UV. For comparison, Table 2 also provides CT_{10} values for the chlorine dose distribution.

As expected from the relative UV sensitivity of the microbes, MS2 RED is a conservative estimator of RED delivered to adenovirus. However, the MS2 RED is greater than the *Cryptosporidium* RED by a factor of 2 with the UV dose distribution represented. On the other hand, CT10 is a conservative indicator of the *Giardia* RED by chlorine by a factor of 2.5 and is a good indicator of virus RED.

In summary, the use of CT10 to indicate *Giardia* inactivation by chemical disinfection is conservative, while using MS2 phage to indicate *Cryptosporidium* inactivation by UV is not. Therefore, applying the RED bias to account for these errors with UV disinfection does not hold UV to a higher standard. Indeed, in the example shown here, using CT10 to indicate *Giardia* inactivation by chemical disinfection is more conservative than applying the RED bias as a safety factor to UV validation data.

Standard Methods for Dose Monitoring and Uncertainty. The SWTR specifies approaches for determining CT delivered by a chemical disinfection system. Standard Methods for the Examination of Water and Wastewater provides standardized approaches for measuring the concentration of ozone, chlorine, chloramines, and chlorine dioxide. Measurement uncertainty with the methods is on the order of 5 to 10% or better.

UV reactor validation protocols from Germany (DVGW) and Austria (ÖNORM) define standards for monitoring UV dose delivery by UV reactors. Both protocols specify the properties and dimensions of the UV sensors used on reactors, the method whereby UV sensor measurements are used to indicate UV dose delivery, and the test protocol for calibrating that method (through biodosimetric testing). Furthermore, both protocols require application of a safety factor to account for sensor measurement uncertainty.

The UVDGM describes three approaches for monitoring UV dose delivery by UV reactors and provides approaches for validating UV dose delivery and monitoring with each approach. The UVDGM provides criteria for the measurement uncertainty, spectral response, and positioning of the UV sensors under Tier 1. The UVDGM does not provide criteria for sensor properties and placement under Tier 2. However, the Tier 2 approach does account for those properties in the determination of the polychromatic bias and the total random uncertainty.

Table 2. *REDs for chemical and UV inactivation.*

Disinfectant	Microbe	Log Inactivation	RED	CT_{10} or MS2 RED	Ratio
Chlorine	*Giardia*	0.50	23 mg/L-min	9.3 mg/L-min	2.5
Chlorine	Virus (HAV)	3.2	9.5 mg/L-min	9.3 mg/L-min	1.0
UV	Cryptosporidium	3.0	12 mJ/cm2	24 mJ/cm2	0.5
UV	Virus (adenovirus)	0.6	28 mJ/cm2	24 mJ/cm2	1.2

Note: RED is calculated from the dose distribution using the equation:

$$RED = -\frac{1}{k}\ln\left[\int_0^{D_{max}} p(D)\exp(-kD)dD\right]$$

where D is the dose, p(D) is the dose distribution, and k is the first order inactivation coefficient of the modeled microbe.

The UVDGM approach was selected for the following reasons:

1. Major UV manufacturers are using monitoring approaches and sensor technologies that do not meet DVGW and ÖNORM requirements.
2. US regulators did not want to restrict monitoring to a single approach.
3. Available performance data on UV sensors and validation are limited, so that specifying performance criteria that are too stringent was a concern.
4. Large measurement uncertainties can occur with relaxed criteria and should be addressed.

In summary, the UVDGM has flexible criteria for UV dose monitoring, but provides checks and balances in the form of safety factors for polychromatic bias and total random uncertainty to account for possible errors that could arise. This differs from chemical disinfection and DVGW and ÖNORM UV standards that specify monitoring approaches with minimal error but provide little flexibility.

CONCLUSIONS

In summary, the UVDGM provides one approach for relating validation data to pathogen UV dose requirements. The approach uses a safety factor that accounts for total random uncertainty and two bias errors associated with UV dose monitoring and validation. A Tier 1 approach specifies the safety factor for UV reactors that meet specific criteria on UV dose monitoring and validation. The Tier 2 approach allows the user to calculate the safety factor and take advantage of technologies that do not fall within Tier 1 criteria or take advantage of improved methods for monitoring and validation that lead to smaller safety factors.

The safety factor approach specified by the UVDGM is comparable if not less conservative than the approaches used with chemical disinfection. Like *Giardia* inactivation by chlorine, UV dose requirements for UV were selected by applying statistical analysis to bench-scale UV dose-response data to define an upper confidence level. On the other hand, dose requirements for other disinfectants in the SWTR were obtained by applying conservative multipliers to limited bench-scale data. The product of residual C and T10 used to indicate dose delivery by a chemical contactor is a good measure of CT delivered to virus and a conservative measure of CT delivered to *Giardia*. However, MS2 RED is a conservative indicator of the UV dose delivered to adenovirus and is notably greater than the UV dose delivered to *Giardia* and Cryptosporidium. Errors in UV dose monitoring that can occur with polychromatic UV systems are unique to those systems and do not have analogy to chemical systems. Last, monitoring with chemical disinfection uses relatively accurate techniques defined by Standard Methods. The DVGW and ÖNORM UV standards also specify standards for UV dose monitoring. The UVDGM, on the other hand, does not restrict monitoring to one approach but does identify potential errors in monitoring that should be accounted for using a safety factor.

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