VALIDATION TESTING OF UV REACTORS BASED ON EPA'S DRAFT *UV DISINFECTION GUIDANCE MANUAL* (2003)

UV reactors must be validated for the operational conditions that they will experience. The operational conditions include water quality (UVT), flow rate, and inlet and outlet arrangements. EPA's draft *UV Disinfection Guidance Manual* (USEPA, 2003) presents the recommended approach to validation and is summarized below.

On-site vs off-site validation. Validation should have oversight by an independent professional engineer and can be performed either on-site or off-site. Off-site validation could be performed at the equipment manufacturer's facility for the specific operating conditions expected at a particular facility or for a range of conditions and target doses. This has the advantage that a utility can use a UV reactor that is already pre-validated for their conditions rather than going through on-site validation. On-site validation is complex and requires attention to many details including proper introduction and mixing of chemicals and challenge organisms, accurate operation of sensors, and testing under the full range of expected water quality and hydraulic conditions. On-site validation does offer the advantage of customizing and optimizing the UV reactor for a specific installation.

Validation Procedure

The EPA draft *UV Disinfection Guidance Manual* proposes two validation options, Tier 1 and Tier 2. Tier 1 is less complex than Tier 2 but yields a more conservative design. The steps in the validation process are similar in either case and are described below:

Biodosimetry. The experimental procedure for validating a UV reactor is called biodosimetry. Biodosimetry determines the inactivation of a challenge microorganism, typically non-pathogenic, in a full scale reactor. The steps include:

- Collimated beam (CB) testing: Batch tests expose a surrogate ("challenge") microorganism to varying UV doses using a collimated beam bench top test to develop a dose-response curve, i.e., a curve of UV dose vs log inactivation. (NOTE: Log inactivation = $\log(N_o/N)$ where N is the concentration of microorganism in the sample after receiving treatment and N_o is the concentration of microorganism in sample without treatment.) Some of the details of test include:

  - A sample of the challenge microorganism is exposed in a petri dish to a known intensity of UV light from a low pressure mercury arc lamp producing UV light at 254 nm. The challenge microorganism sample is collected from the influent going into the test UV reactor being validated.

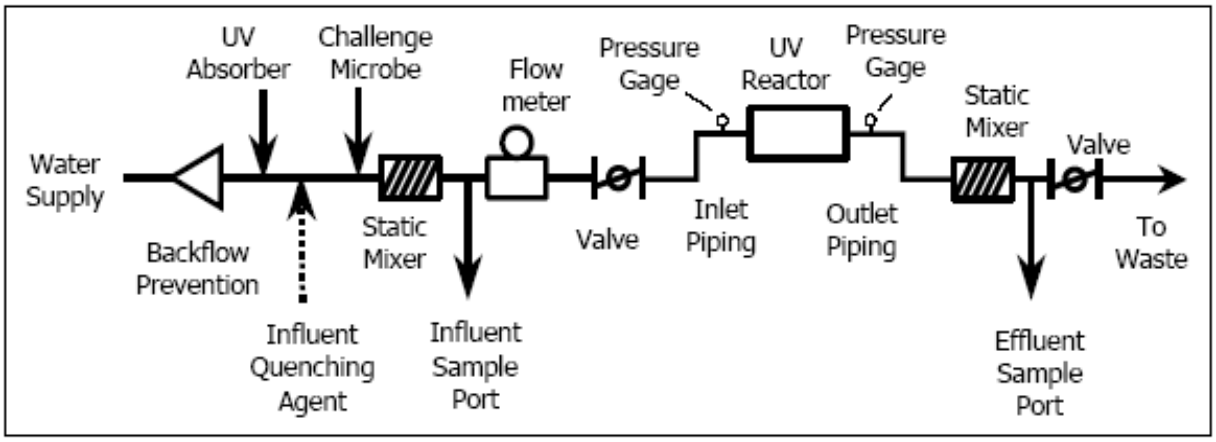
  - The exposure time is varied to produce varying UV doses that achieve about 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 log inactivation.

- At a minimum, tests are conducted for the highest and lowest expected UVT. The dose-response curves should be statistically the same for the two conditions and can be combined into one dose-response curve, otherwise the causes of any differences need to be identified.

! Full reactor scale tests (biodosimetry tests): Log inactivation data are collected from tests on the full scale UV reactor using the same microorganism in the collimated beam tests and using the range of flow rates, water transmittances, and lamp power combinations expected in the actual installation(s). The challenge microorganisms used for the collimated beam and the biodosimetry tests should be from the same batch of microorganisms grown. Three to five influent and five effluent samples need to be collected for each test condition and the standard deviation of the microorganism cncentrations must be less than 0.20 log units

! RED calculation: Because the actual UV dosage can not be measured directly in the full scale UV reactor, the reduction equivalent dose (RED) for the reactor is calculated indirectly by using the log inactivation results from the full scale reactor tests and the UV dose response curves from the CB tests.

A typical UV reactor validation testing facility is shown below.



Biodosimetry test facility (USEPA, *UV Disinfection Guidance Manual*, 2003)

Safety factor. Because of the uncertainties in the experimental measurements and the UV reactor itself and associated hydraulics, the target dosage to be shown in validation is the required UV dose times a safety factor. The equation for the safety factor is:

$$SF = B_{RED} \cdot B_{Poly} \cdot (1 + e)$$

where:

SF = safety factor

B_{RED} = The RED bias corrects for the difference between the dose response curves of the challenge organism used in validation and the target pathogen

B_{Poly} = The polychromatic bias accounts for "spectral differences in the lamp output, lamp sleeve UV transmittance, water UV transmittance, and action spectrum between validation and operation of a UV reactor."

e = Expanded uncertainty expressed as a fraction which accounts for the uncertainty in measurements during validation and associated with the equipment used to monitor the dose delivered

A Tier 1 approach uses pre-determined safety factors based on validation testing of that UV reactor while a Tier 2 approach uses more detailed knowledge of the reactor and testing conditions.

Further considerations for validation testing. Many aspects of UV reactor validation must be considered and the reader is referred to the draft *UV Disinfection Guidance* Manual (EPA, 2003), especially Appendix C & D, for more details. To summarize, these considerations include:

- Inlet and outlet hydraulics: Inlet and outlet configurations need to reflect the same or worst case conditions for UV dose delivery than in the actual installation. Computational fluid dynamics can be used as part of modeling the UV dose but the uncertainty in predictions warrant a 20% safety factor in delivered dose.

- Control strategies for monitoring dose delivery: Test conditions need to reflect the control strategy that will be used. Possible control strategies include:

  - UV intensity setpoint: UV intensity measurement and flow rate are used to confirm that the UV reactor is delivering an adequate dose. The system is in compliance if the UV intensity is greater than the setpoint for that flow rate.
  - UV intensity/UVT setpoint: UVT, UV intensity and flow rate measurements are used to confirm dose delivery. The system is in compliance if the UV intensity and UVT are greater than the setpoint for that flow rate.
  - Calculated dose: A dose is calculated based on an algorithm incorporating UV intensity, UVT (in some cases), lamp power and flow rate.

- Sensor calibration and number: The sensor calibration must be properly checked to ensure it is properly calibrated. For Tier 1 criteria, reactors with MP lamps should have 1 sensor per lamp while LP and LPHO reactors should have 1 sensor per bank of lamps. (Note: the sensor used during routine operation is called the 'duty sensor.')

- Lamp aging: Lamps need 100 hours of burn-in to stabilize their output. If aged lamps reduce their UV light output or change their spectral output, the validation testing needs to be done with aged and new lamps.

- Challenge microorganism: The challenge microorganism needs to have inactivation characteristics closely matching the target pathogen and must be reproducibly cultured at high enough concentrations. Typically MS2 phage and *Bacillus subtilis* are used which are actually more resistant to UV disinfection than *Cryptosporidium*.

- UV absorbing substances: If the potential UV reactor application is for waters with significant UV light absorbers which lower the UVT, then the validation testing needs to test waters with similar UVT's. Coffee and lignin sulfonate and sometimes sodium thiosulfate and fluoroscein have been used to simulate UV light absorbers and the expected UVT, although these will not exactly match absorbing properties of the actual UV light absorbers in any specific water.

The draft *UV Disinfection Guidance Manual* also gives criteria for proper placement of sensors, the spectral response of sensors, accuracy and calibration, uncertainty in measurement of a UVT monitor, standard deviation of UV lamp output for LP and LPHO lamps, uncertainty in flow measurement, uncertainty in dose in collimated beam apparatus, sensitivity and characteristics of the dose-response curve for the challenge microorganism, and minimum UVT values for MP lamps during validation for the given the UV reactor configuration.

Data analysis. The goal of analyzing the data collected from the collimated beam and biodosimetry tests is to determine the log inactivation credit given to a specific UV reactor. Data analysis steps include:

- The UV dose-response curves from the collimated beam experiments are usually statistically fitted to a linear or quadratic equation although higher order polynomials can be used in certain situations to give dose as a function of log inactivation, e.g., Dose, $mJ/cm^2 = 15.5 \cdot (\text{Log inactivation}) - 6.0$. The fitted equation coefficients should be significant at a 95% confidence level and the 80% confidence interval for fitted equation should be determined.

- The mean and standard deviation of the log of the influent and log of the effluent challenge microorganism concentration is calculated for each test condition in reactor. From these log of influent and effluent microorganism concentrations, the log inactivation of influent compared to effluent is calculated, i.e., $\log(N_o/N)$, where again N_o is the influent and N the effluent microorganism concentration. Note that the calculated standard deviations are used in safety factor calculations for a Tier 2 approach while a Tier 1 uses an assumed standard deviation limit.

- The log inactivation found from biodosimetry for a specific set of test conditions is used in the dose-response curve or equation to find the RED, i.e., the UV dose in the collimated beam experiments that achieved that log inactivation. Multiple RED's can be determined based on the multiple conditions tested, i.e., varying flow rates, UVT, and lamp output. The monitoring approach used for a UV reactor will effect the appropriate RED to use and in turn the log inactivation credit given to a reactor. The monitoring approaches discussed in the EPA draft *UV Disinfection Guidance Manual* (2003) and corresponding reactor ratings are:

- "UV intensity setpoint approach: The UV reactor should be rated at the lowest inactivation observed for each setpoint condition tested."
- "UV intensity and UVT setpoint approach: The UV reactor should be rated at the inactivation observed with UV reactor operation under setpoint conditions."
- "Calculated dose approach: The UV reactor should be rated at lowest inactivation observed for each calculated dose setpoint evaluated."

It is also possible to develop a fitted equation for biodosimetry results that gives the RED as a function of inverse flow rate, UVT, or UV intensity. Importantly, one can not extrapolate outside the range of data.

Determining log inactivation credit. A Tier 1 approach uses specified safety factors to determine the log inactivation credit assigned to a reactor based on the validation test data. Tier 2 is calculated by more complex methods and the reader is referred to the draft *UV Disinfection Guidance Manual* (2003) for details. For a Tier 1 approach, the log inactivation credit is found from the tables below for LP or LPHO and MP lamps respectively. Each table gives the log inactivation credit assigned for three microorganisms, *Cryptosporidium*, *Giardia* and viruses. The values in the table are derived by multiplying the doses required by LT2ESWTR by the Tier 1 safety factors. The RED for the reactor must be greater than that given in table in order to achieve the given credit.

Example problem of determining log inactivation credit. Assume that an LP reactor is being considered at a water utility and will be validated using Tier 1 criteria. From the log inactivation data collected for the range of conditions tested during validation testing, the lowest RED obtained from the dose-response curve for the challenge microorganism was 27 mJ/cm^2. Since this RED is greater than the minimum RED of 21 mJ/cm^2 to achieve a log inactivation credit of 2.0 for *Cryptosporidium* but is less than the minimum of 28 mJ/cm^2 needed to achieve a credit of 2.5, the UV reactor would be assigned a log inactivation credit of 2.0 for *Cryptosporidium*. Similarly, it would be assigned a log inactivation credit of 2.5 for *Giardia* and no credit for viruses.

Tier 1 RED Targets for UV Reactors with LP or LPHO Lamps

Log Inactivation Credit	RED Target (mJ/cm^2)		
	Cryptosporidium	*Giardia*	*Virus*
0.5	6.8	6.6	55
1.0	11	9.7	81
1.5	15	13	110
2.0	21	20	139
2.5	28	26	169
3.0	36	34	199
3.5	-	-	227
4.0	-	-	259

Tier 1 RED Targets for UV Reactors with MP Lamps

Log Inactivation Credit	RED Target (mJ/cm^2)		
	Cryptosporidium	*Giardia*	*Virus*
0.5	7.7	7.5	63
1.0	12	11	94
1.5	17	15	128
2.0	24	23	161
2.5	32	30	195
3.0	42	40	231
3.5	-	-	263
4.0	-	-	300