UNIFORM PROTOCOL FOR WASTEWATER UV VALIDATION APPLICATIONS

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INTRODUCTION AND BACKGROUND

The treatment objective of an ultraviolet disinfection system used in a wastewater application is to protect aquatic and ecological environments. To ensure this objective is adequately met it is important to validate, or verify equipment performance for a specific application. The widely accepted method for completing this validation is by determining the UV dose delivery performance using biodosimetry. Whilst several protocols exist for completing biodosimetry tests, or bioassays, for different applications, only two methods are in wide scale use in the industry worldwide;

- Ultraviolet Disinfection Guidelines for Drinking Water and Reuse, 2nd Edition, published by the National Water Research Institute (NWRI) in collaboration with the Water Research Foundation (WRF previously AwwaRF). Specifically, chapter two; Water Reuse and chapter three; Protocols. Hereafter referred to as NWRI/AwwaRF.
- Ultraviolet Disinfection Guidance Manual, published by the US EPA. Hereafter referred to as UVDGM.

Both guidelines follow similar formats (**see Table 1**) and are in wide scale use by UV Manufacturers, Engineering Consultants and Regulators. However, neither specifically makes reference to the particular challenges associated with completing bioassays in wastewater applications as defined below. The term wastewater applications means for the purpose of this document a biological treatment plant that is achieving an average effluent quality of less than 30 mg/L BOD/TSS and disinfection requirements of 126 cfu/100 mL E. coli over a 30 day geometric mean or 200 cfu/100 mL fecal coliforms over a 30 day geometric mean. Many stakeholders within the UV industry have called for such a uniform protocol for wastewater UV applications that can be widely adopted by industry and regulatory bodies.

In an effort to provide a positive contribution to the industry in this matter, the International Ultraviolet Association (IUVA) Manufacturers Council formed a task force in 2007.

US EPA UVDGM NWRI/AWWARF GUIDELINES

Table 1: *Format and Equivalency of two Key UV Validation Protocols*

US EPA UVDGM	NWRI/AwwaRF Guidelines
Planning and Preparation	Introduction
	Test Facilities Requirements and Set-up
Testing	Microbiological Testing
	Testing and Sampling Requirements
Validation Data Analysis	Data Analysis and Reporting
Compare Reactor Hydraulics Using CFD	
Reporting	

The objectives of this group were to:

- Evaluate the existing protocols to identify aspects that could be of use for a uniform wastewater protocol.
- Facilitate discussion with both regulators and engineering consultants on the issue of a uniform wastewater protocol.
- Outline a position on a potential solution for uniform wastewater protocol.

After undertaking reviews and discussions with interested parties, this document represents the final portion of the task force objectives.

A proposed protocol format is detailed in **Table 2**, following a similar format to that used in the UVDGM.

Table 2: *Proposed Format for Uniform Wastewater UV Validation Protocol*

Section Number	
1.0	Planning and Preparation
2.0	Microbiological Testing
3.0	Validation Data Analysis
4.0	Additional Analysis using Advanced Tools and Existing Data
5.0	Reporting

The treatment objectives for the wastewater and the UV dose or fluence that is required must be determined before this bioassay method can be used to size the UV equipment. This may be done through long term measurements of the flow rate, UVT, TSS etc., as suggested in NWRI/AwwaRF protocol. The UV dose requirements may also be determined by doing studies with a collimated beam to determine the required UV dose or fluence with the lowest quality of wastewater.

1.0 PLANNING AND PREPARATION

In all cases it is important to understand clearly what are the goals of the testing, how they will be completed and within what limitations. This section describes the key elements of the planning and preparation stage of validation testing. The details of the test plan (in addition to the final validation report) must be reviewed by a third party so that they conform with the bioassay protocol or regulatory requirements. Validation testing of UV equipment for wastewater applications can be conducted at a Wastewater Treatment Plant (WWTP) or a dedicated testing facility (manufacturer owned, or third party).

1.1 TEST UV SYSTEM CHARACTERISTICS

A typical wastewater bioassay test stand is shown in **Figure 1.** In general the following criteria should be followed in relation to the test equipment configuration:

- The test unit must be equivalent in configuration and operation to the commercial unit, both in terms of components, i.e. lamp, ballast, quartz sleeve, sensor, control systems, and automatic cleaning device and other fixed or moving devices, that is, baffle, support bars, etc.
- The test unit must be hydraulically scale able or a commercially available full-scale module as per the NWRI/AwwaRF recommendations. However, it is recognized that additional analysis using field measurements and/or advanced tools described in Section 4.0, could be used to justify operational variations. Closed vessel UV systems may not be hydraulically scaled.
- A single reactor can be used (equivalent to one bank) for validation.

1.1.1 Challenge Organism

It is critical that the challenge microorganism have the following properties:

- Is non pathogenic to humans.
- Should be easy to grow in high concentrations and simple to enumerate.
- Demonstrates repeatable results and stability over long time periods.

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Figure 1*: Typical layout of wastewater bioassay test stand*

- Has a known action spectrum that correlates to the target pathogen or indicator organism.
- Is pre-defined, to ensure valid comparisons between bioassays.
- Is analyzed only within the linear region of the UV dose-response curve.
- Must have UV inactivation kinetics that are similar to the indicator organisms or pathogens or two organisms must be used that span the UV inactivation kinetics of the indicator organisms or pathogens.
- Must not be an indigenous organism since the UV inactivation kinetics vary from site to site.

Based on the above criteria the following challenge microorganisms are permissible and it is preferable to use two that span the UV inactivation kinetics of the indicator organisms or pathogens of concern:

- T1
- Q phage
- MS2 phage

The microorganisms must be prepared and used in accordance with the NWRI/AwwaRF and UVDGM procedures.

1.1.2 Water Source

Key Characteristics:

- Finished water supply (potable water) and/or filtered (cloth or granular) wastewater treatment plant effluent (secondary or tertiary), or a blend of both.
- Turbidity < 2 NTU or < 5 mg/L total suspended solids in all cases. Since suspended solids are different in every wastewater treatment plant a filtered effluent should be used or potable water.
- Must not contain any disinfectant residuals that could affect the microorganisms used for the testing of the UV dose.
- Any quenching agents or their byproducts should not impact UV transmittance in the 200 to 300 nm range,and the quenching agent should not affect the challenge organism.
- The water supply must be de-chlorinated (e.g. with thiosulfate or biosulfite) before being used for the bioassay with residual chlorine levels non-detectable with a 0.05 mg/L detection limit.
- pH after UVT and de-chlorination adjustment should be within ± 0.5 pH units of the initial pH; otherwise buffering is required.
- Impact of additives on polychromatic absorbance shall be measured and documented. It is recommended not to use additives that may have an adverse effect on the polychromatic absorbance.

1.1.3 Absorbing Chemical

Where a UV absorbing chemical is used to simulate the range of UVT values defined in the test plan, it is critical that it have the following properties:

- An absorbance spectrum similar to the background filtered effluent/water used for validation. (Note a full UVC spectral scan is required if polychromatic lamps are used.)
- Known and uniform impact on all relevant parameters.
- Not be toxic to the bio-surrogate ('challenge microorganism'; see note above).
- Known spectral absorbance in the UVC wavelength range.
- Solubility should not be affected by lamp heat dissipation.

Based on the above criteria the following UV absorbing compounds are permissible:

- Coffee
- Lignin Sulfonic Acid (LSA)
- Humic Acids such as Superhume™

MSDS sheets should be included in the report for these compounds.

1.1.4 Mixing and Sampling

It is critical that any UV absorbing chemical or challenge microorganism injected into the flow stream be uniformly dispersed at both the influent and effluent sampling points, therefore the following guidance is provided:

- The effluent sampling point must be far enough downstream of the reactor exit, so that all fluid streamlines exiting the reactor have had the opportunity to fully mix/disperse with each other,

so that the effluent samples are representative of the bulk of the post-reactor effluent.

- In-line mixing, with one mixer before the influent sample point and one mixer before effluent sample point is required for closed vessel systems. The same is preferred for open channel systems; however, if a mixer is only used before the bank of UV lights then sampling must take place after the level control device.
- The effluent sample point, particularly for open channel systems, should be in such a location so as to eliminate free surfaces and wall edge effects.

Verification of mixing should be completed in accordance with the method described in the UVDGM and be fully documented in the final validation report.

1.1.5 Lamp Variability and UV Sensor Port Window Testing

To account for lamp variability the UV system supplier must include the NWRI/AwwaRF test results for end of lamp life testing. It is recommended that the designer use the average lamp output. Only lamps that have been running in a quartz sleeve under water and tested in the same condition will be acceptable. Air testing is not acceptable. Lamps that have not been tested or run this way should not be grandfathered. Closed vessel systems should follow the UVDGM procedures. UV sensor port window testing should follow the UVDGM.

1.1.6 Measurement Equipment

It is critical that all key process parameters are monitored and recorded. This includes: flow, UVT, electrical power consumption, power input to the lamps if possible but power to the lamps and ballasts can be substituted, UV intensity, water temperature, pressure (for enclosed vessels) and head-loss. The methods described in the UVDGM are comprehensive and should be adopted.

1.2 INLET/OUTLET PIPING

The configuration of the inlet and outlet conditions must be documented in the validation report as per UVDGM for closed vessels and as per NWRI/AwwaRF for open channel systems.

If the site specific installation is shown to be 'different' than the validation testing, then the velocity profile or, preferably the UV dose and or UV dose distribution should be shown to be equivalent or better than that observed for the bioassay validation. This should be completed by one or more of the following methods, as appropriate;

- Velocity profile as described in the NWRI/AwwaRF guidelines
- CFD as per Section 4.0 of this document.
- Check-point bioassay.

1.3 TEST LAMPS

For wastewater applications all UV lamps should be documented to have been seasoned/burnt-in for a period of at least 100 hours. Inlet power and UVT parameters should be adjusted to account for lamp aging and quartz sleeve fouling. Equipment verification protocols for these two variables are discussed in Section 4.2 of this document.

1.4 TEST CONDITIONS AND QA/QC SAMPLES

The validation test conditions should reflect as many variables as possible with respect to the wastewater and UV equipment. Some of these are described in the NWRI/AwwaRF Guidelines and UVDGM. Therefore, the test matrix should be designed to a specified range of water qualities (defined by UVT), flows and powers regardless of the ultimate operating philosophy: UV dose pacing, intensity pacing or confirming existing validation equations (check-point bioassay).

The challenge microorganism should be injected into the flow upstream of the UV reactor under steady state conditions. In general good sampling practices should be followed to collect at least three (3) influent and three (3) effluent samples for each test condition. An example would be three samples over 15 minutes or three volume changes of the UV system. The following process measurements should be taken for each sampling event:

- Flow rate
- UV Intensity from all sensors
- Calculated UV Dose
- Percent Lamp Current or Power
- UV Transmittance
- Electrical power

Where any of the above parameters change in value by more than the error of measurement (See Section 5.5 of UVDGM for error of measurement), over the course of each test condition, the test should be repeated.

The following standard quality control samples should be taken.

- Reactor Controls: With lamps off; Log Inactivation equivalent to RED < 3% of lowest RED tested.
- Reactor Blanks: Without surrogate addition take one sample per day. The measured densities should be negligible.
- Trip Controls: One sample bottle of challenge micro organism stock solution should travel with the stock solution used for validation testing from the microbiological laboratory to the location of reactor testing and back to the laboratory. The change in the log concentration of the challenge microorganism in the trip control should be within the measurement error. (i.e., the change in concentration over the test run should be negligible. This is typically on the order of 3 to 5 percent. e.g., at 1 x 1011, Log = 11. +/- 5% equivalent to ~10.5 to 11.5.
- Method Blanks: Normal laboratory blanks generated by plating with distilled reagent water.
- Stability Blanks: Purpose is to show no degradation

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of the surrogate with time in the UVT and water matrix.

1.5 THIRD PARTY OVERSIGHT

An independent third party must provide oversight to ensure that validation testing and data analyses are conducted in a technically sound manner and without bias. A person independent of the UV reactor manufacturer should oversee validation testing. Individuals qualified for such oversight include engineers experienced in testing and evaluating UV reactors and scientists experienced in the microbial aspects of biodosimetry. Appropriate individuals should have no real or apparent conflicts of interest regarding the ultimate use of the UV reactor being tested. A qualified third party should be present for and direct all testing, analyze data and author a detailed report. The final report should include the names and qualifications of all persons involved in the testing and their role. The independent third party should review the validation report before its release. When appropriate, the third party should rely on additional outside experts to review various aspects of UV validation testing, such as lamp physics, optics, hydraulics, microbiology, and electronics.

2.0 MICROBIOLOGICAL TESTING

The UVDGM contains a more comprehensive microbiological testing protocol than the NWRI/AwwaRF guidelines and reflects the latest understanding of UV disinfection technology; therefore it is proposed that this guideline be adopted in its entirety for the uniform validation testing of wastewater applications. However, it is recognized that specific unique challenges apply to microbiological testing with wastewater and therefore the following issues should be considered;

- Preparing the Challenge Microorganism
- Stability - Stability should be checked, and consistent recovery from seeded effluent should be confirmed, particularly in a treated wastewater effluent matrix. The challenge microorganism concentrations should be stable over the holding time between sampling and completion of the assays. If they are not stable, the data collected will be unusable because distinguishing the sources of inactivation—exposure to UV light and die-off in holding—will be impossible. Stability verification can help ensure that the bioassay and challenge microorganism samples will be viable and the data useable.
- Refer to Section 1.1.1 for a list of recommended challenge microorganisms.
- Verifying UV Reactor Properties
- The water temperature must be measured during the bioassay. Since the water temperature cannot be varied during the testing the UV manufacturer must submit UV intensity testing by a third party of the same lamp, ballast and quartz sleeve combination at water temperatures from 5 to 30°C.

- For medium-pressure (MP) systems, a temperature sensor and safety cut-off switch to prevent over heating should be provided by the manufacturer.
- UV Intensity Sensors Performance
- Higher variability should be permitted if additional operational safety factors (i.e. set points) are included.
- Measuring UV Dose Delivery
- UVT should be within ± 2 % of the target UVT.
- Water temperature variability shall be within 0.5 °C.
- Sampling shall not proceed until a minimum of 5 × total void volume exchanges have passed. This flush volume is calculated between the microorganism's injection point and the effluent sampling point.
- At least three (3) influent and three (3) effluent samples for each test condition shzould be collected. Influent and effluent samples are not collected at the same time, but collected in an alternating sequence at times that approximate the time of travel across the system. There should be at least one volume exchange between samples.
- Influent sample must be taken from the batch tank, the tap from the feed pipe, or from the channel; effluent sample must be taken from the reactor outflow or the channel after the effluent weir, or a sample tap, which is representative of the entire outflow.
- Plating should be at a minimum of two dilutions, with at least two plates per dilution.
- The following parameters should be measured and recorded: flow rate through the reactor, UV intensity, on-line UVT, calculated UV dose values both before and after the samples are collected, UVT as measured by a UV spectrophotometer with each influent sample electrical power consumed by the lamps and or ballasts, ambient air temperature, water temperature for each test.
- Sampling for UVT measurements should be separate; measurements should be taken within 24 hours of collection.
- The concentrations of the challenge microorganisms before and after exposure to UV light should generally be measured within 24 hours of sample collection unless stability studies indicate that the samples can reliably be considered stable over longer periods of time. Samples that are not assayed immediately should be stored in the dark at 4°C. Exposure of samples to visible light should be avoided.
- Collimated-Beam Testing
- The protocols for collimated beam testing should follow those in Bolton and Linden (2003) and the IUVA Excel spreadsheets.
- The UV sensitivity of the challenge microorganism and shape of each UV dose-response curve should be consistent with expected inactivation behavior for that challenge micro organism; accordingly, confidence bands developed for MS2 and other surrogates as a test of the quality of the UV dose response data should be used.
- Challenge Microorganisms with Shoulders or Tailing – In the case of a challenge micro organism with a shoulder or tailing in the UV dose response curve, the UV sensitivity should be defined as the sensitivity over the region of linear log inactivation that occurs between the shoulder and the onset of tailing. It is recommended that organisms with a shoulder not be used for this bioassay. Refer to Section 1.1.1 for a list of recommended challenge microorganisms.

3.0 VALIDATION DATA ANALYSIS

Validation testing of UV reactors produces the following types of data for each experimental test:

- Concentration of the challenge microorganism in the influent and effluent sample.

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- UVT of water.
- Flow rate.
- UV intensity as measured by the UV sensor.
- Lamp or lamp and ballast power.
- Status (on/off) for each lamp.

All experimental data should be documented, preferably in tabular format, and included in the Validation Report. The Reduction Equivalent Dose (RED) should be calculated for each experimental test using a combination of reactor testing data and collimated beam results. An additional analysis of RED data depends on the reactor's UV dose-monitoring strategy. For the UV Intensity Set point Approach, RED results are averaged for each test condition and evaluated to identify the minimum value. For the Calculated Dose Approach, all RED values and associated test conditions are used to create a UV dose-monitoring equation.

4.0 ADDITIONAL OPTIONAL ANALYSIS USING ADVANCED TOOLS AND EXISTING DATA

New and emerging technologies are being developed to aid in the validation of UV reactors. Computational Fluid Dynamics and Lagrangian Actinometry with Dyed Microspheres are two such technologies. They are presented here as optional analysis tools to provide greater flexibility and understanding of reactor design, not as alternatives to bioassays.

- Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the millions of calculations required to simulate the interaction of fluids with light and microorganisms in a complex UV system. The results from the CFD model must be calibrated with the results from the bioassay to validate the computer model. Once calibrated, the CFD model can be used to develop a CFD uncertainty factor and this can be used to predict the average and range of UV doses with a UV system CFD can also be used to calculate the UV dose of a system at parameters (e.g. flow rate, and UV Transmittance), which have notbeen bioassayed. For more information on modeling UV reactors with CFD see AwwaRF Project #4107 "Evaluation of Computational Fluid Dynamics (CFD) as a Cost –Effective Tool for Assessing UV System Performance". A comprehensive paper was written on this AwwaRF project titled "Important Factors for Computational Modeling of UV Disinfection Systems"It is in the Proceeding of the AWWA Water Quality Technical Conference 2008.
- Lagrangian Actinometry with Dyed Microspheres (DMS) Lagrangian actinometry is a newly developed test method that uses dyed microspheres to determine the UV dose-distribution of a UV reactor. Microspheres are modified by the attachment of a dye that allows measurement of the UV dose. When subjected to UV radiation, the dye undergoes a photochemical reaction to yield a stable, fluorescent compound that can be easily and accurately differentiated from the non-fluorescent parent compound. By measuring a large population of exposed microspheres, the UV dose-distribution with the reactor can be measured directly.

4.1 GRANDFATHERED PROTOCOLS

It is our recommendation that a similar guideline to that described in the UVDGM is adopted for a uniform wastewater UV validation protocol, namely that UV equipment validated prior to the publication of a uniform wastewater protocol, be recognized within the following limitations:

- The microorganisms used in the previous validation were the same as those recommended in this document.
- QA/QC procedures that are generally inline with this document were followed.
- Data analysis was generally in-line with the methods outlined in this document.
- A qualified third party conducted and certified the results of the bioassay.

4.2 RELATED EQUIPMENT VERIFICATIONS

It should be recognized that in addition to UV dose delivery performance validations, there are other related equipment tests that are used to verify operational performance. These include:

- Lamp output measurement.
- Lamp age factor testing.
- Cleaning mechanism testing (quartz sleeve fouling).

Whilst these verification tests can be completed separately to bioassay testing, it is recognized that they are used in the final equipment sizing design and as such deserve attention.

The IUVA Manufacturers Council has published a protocol for the measurement of the UV output of low pressure lamps, and it is our recommendation that this be adopted. A similar protocol for medium pressure lamps is pending.

Separate, updated, protocols for lamp aging and quartz fouling are required; however, in the short term it is recommended that the existing NWRI/AwwaRF guideline be followed.

5.0 REPORTING

A formal validation report is an important element of any validation testing. Both the NWRI/AwwaRF guideline and the USEPA UVDGM include reporting guidelines. Since the UVDGM details a more comprehensive outline of the key elements of a validation report, together with checklists helpful for review and approval, this guideline should be adopted for a uniform wastewater UV validation protocol.

SUMMARY

To ensure the objective of environmental protection is adequately met when UV light is being used to disinfect wastewater discharges, it is important to verify equipment performance. The widely accepted method for completing this validation is by determining the UV dose delivery performance using biodosimetry. The preceding proposed protocol takes elements of existing protocols for drinking water and reuse water and applies them to the specific application of wastewater as defined in this document.

However, unlike drinking water or reuse water, the wastewater regulatory community looks to effluent disinfection compliance as the sole target for UV disinfection performance and not system design or system testing processes. Therefore, the components of this document are not designed to propose a regulatory standard, but rather as a tool that allows for direct comparisons of UV systems during the design of such systems and to help to properly size a UV systems.

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