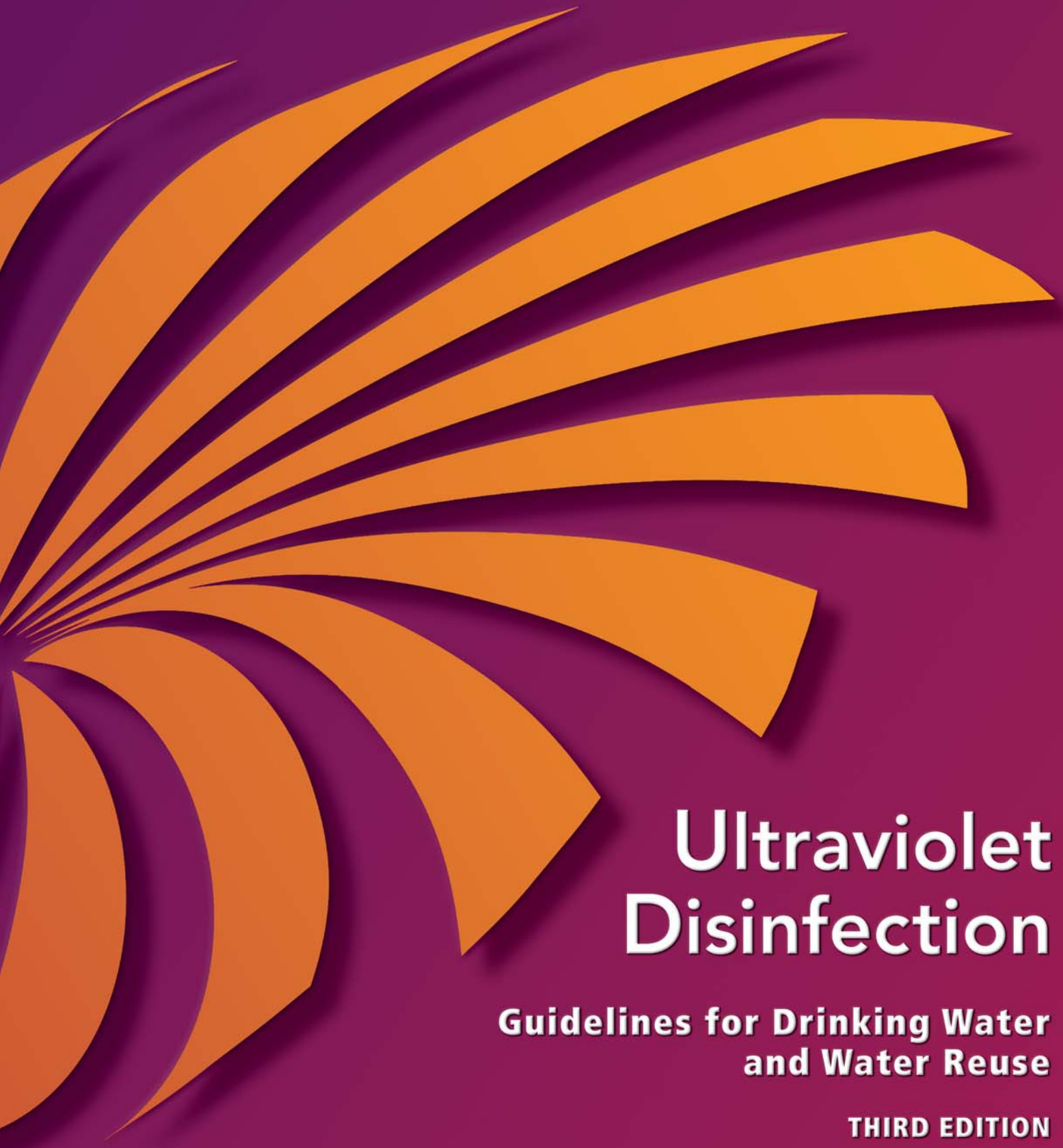

Ultraviolet Disinfection

Guidelines for Drinking Water and Water Reuse

THIRD EDITION

Published by
NATIONAL WATER RESEARCH INSTITUTE
in collaboration with
WATER RESEARCH FOUNDATION

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About NWRI

A 501c3 nonprofit organization, the National Water Research Institute (NWRI) was founded in 1991 by a group of California water agencies in partnership with the Joan Irvine Smith and Athalie R. Clarke Foundation to promote the protection, maintenance, and restoration of water supplies and to protect public health and improve the environment. NWRI's member agencies include Inland Empire Utilities Agency, Irvine Ranch Water District, Los Angeles Department of Water and Power, Orange County Sanitation District, Orange County Water District, and West Basin Municipal Water District.

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Third Edition Revisions

The intent of the revisions of the third edition of the *Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse* was to (1) document the current practice of "spot-checking" performance bioassays for the validation of full-scale performance in lieu of conducting velocity profiles, and (2) standardize the assignment of UV dose when conducting MS-2 based viral assays by making use of a standard dose-response relationship. An appendix was also added to illustrate the computations discussed in Chapter 3. In the future, it is anticipated that a revision will be undertaken that will address ongoing technological advances and other issues.

Foreword

These guidelines are a third revision of the *Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse* published by the National Water Research Institute (NWRI). They are intended to provide guidance to state and federal regulatory agencies who review applications for the use of ultraviolet (UV) disinfection systems in drinking water and water reuse, and to water utilities who are interested in using UV for disinfection purposes. NWRI would like to note that these guidelines have no binding regulatory effect unless promulgated by a federal, state, county, or local authority as official regulations. Although NWRI funded the development of these guidelines, it assumes no responsibility for the content of the work reported or for the opinions or statements of fact expressed herein.

More specifically, the following qualifications apply to these guidelines:

- These guidelines are largely based on the current practice of the California Department of Public Health (CDPH) in their review and approvals of UV disinfection systems. It is the intent that should a full-scale installation be tested at any time for its reduction equivalent dose (RED), measured values match or exceed the RED reported by the system. Thus, these guidelines have not been developed to describe average UV disinfection performance, but rather the minimum performance expected of a UV disinfection system.
- These guidelines have not been developed for applications such as disinfection of secondary effluents or where virus inactivation is not warranted. The general concepts are largely applicable, but the dose objectives will differ and some regulatory objectives may not be achieved with UV disinfection if adequate filtration is not first performed.
- These guidelines are intended to encourage research (including new methods of analysis), improved operational procedures, and new technological developments. These guidelines are intended to be dynamic and will be revised as new information becomes available.
- The present guidelines are based on the application of biodosimetry for reactor characterization using MS-2 bacteriophage as the default organism. It is recognized that a number of alternative approaches have been proposed, including multi-organism bioassay techniques and the ability to design UV disinfection systems for the target pathogen or indicator rather than MS-2 (the default organism). If MS-2 is not an appropriate biological indicator for a specific project, other documents (e.g., EPA, 2006) should be consulted for guidance regarding use of the alternate biological indicator. The target pathogens and their corresponding inactivation requirements for drinking water have been identified by the U.S. Environmental Protection Agency (EPA) and are described in EPA (2006). These Guidelines can be used to support the dose objectives described by EPA. It differs with regards to specific details associated with testing (e.g., use of a standard MS-2 dose-response curve, use of bioassays for full-scale commissioning tests, etc). For any drinking water project, the appropriate regulatory agency should be consulted prior to conducting any testing to assure use of the most appropriate testing protocols for the specific installation.
- In the present guidelines, the focus is on testing the UV disinfection systems directly. Although the importance of computational fluid dynamics in the analysis and design of UV systems is acknowledged, performance predictions based on computational fluid dynamics are not allowed in these guidelines.
- Finally, it is important to note that these guidelines are not meant to serve as a design manual for the planning and installation of UV disinfection systems. The final design of a UV disinfection system remains the responsibility of the design engineer and the UV equipment manufacturer.

Preface

This document had its origin in 1993 when the National Water Research Institute (NWRI) collaborated with the California Department of Public Health (CDPH) to convene a group of experts and, through diligent effort, create the *Ultraviolet Disinfection Guidelines for Wastewater Reclamation in California and UV Disinfection Research Needs Identification* (1993). Over 5,000 copies of the 1993 guidelines were distributed throughout the United States and overseas. Eventually, a number of regulatory agencies within the United States adopted the ultraviolet (UV) disinfection guidelines when reviewing applications for the use of UV systems in water reuse projects.

In January 2000, NWRI and the NWRI Corporate Associates convened *UV 2000: A Technical Symposium* to address the technological advancements and regulatory changes that had occurred since the publication of the 1993 guidelines. The product of the symposium was the *UV 2000 Abstracts*, which had topics ranging from "The Status of UV Technology in Europe" to "Standardizing UV Equipment Performance Validation." More importantly, *UV 2000* focused on the need to revise and expand the 1993 guidelines. This revision would include applying UV disinfection to both water reuse and drinking water purification processes.

Following the symposium, the Water Research Foundation (formerly AwwaRF) approached NWRI to help assist in revising the 1993 guidelines. Over the next 10 months, NWRI and the Water Research Foundation organized several workshops that brought together international experts to rethink and rewrite the guidelines. The resulting document was the *Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse*, which was published in December 2000.

Revisions to the UV guidelines were made to reflect experience gained from the application of the guidelines in a variety of situations. A second edition was released in 2003 to clarify application issues and provide additional guidance on UV lamp storage. This third edition was released in 2012 to reflect revisions to "Chapter 3: Protocols."

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Acronyms

ATCC	American Type Culture Collection
CDPH	California Department of Public Health
EPA	United States Environmental Protection Agency
GFI	Ground fault interruption
MF	Microfiltration
MPN	Most probable number
NF	Nanofiltration
ntu	Nephelometric turbidity unit
QA/QC	Quality Assurance/Quality Control
RED	Reduction equivalent dose
RO	Reverse osmosis
TSB	Tryptic soy broth
TSS	Total suspended solids
UF	Ultrafiltration
UPS	Uninteruptable power supply
UV	Ultraviolet
WRC	Water Recycling Criteria

Abbreviations

a.u./cm	Absorbance units per centimeter
cm	Centimeter
G	Gravity
g	Gram
g/L	Grams per liter
gpm	Gallons per minute
kW	Kilowatt
L	Liter
m	Meter
mg/L	Milligram per liter
mJ/cm^2	Millijoules per square centimeter
mL	Milliliter
mm	Millimeter
mW/cm^2	Milliwatts per square centimeter
$mW{\cdot}s/cm^2$	Milliwatt second per square centimeter (equivalent to mJ/cm^2)
nm	Nanometer
pfu/mL	Plaque forming unit per milliliter
pfu/plate	Plaque forming unit per plate
rpm	Revolutions per minute
µm	Micrometer

Chapter One: Drinking Water

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1. Introduction

These guidelines will facilitate the minimum acceptable design requirements and commissioning of UV disinfection systems subject to the limitations set forth in the Foreword. They will also provide a methodology that can be used to validate UV disinfection system performance. However, these guidelines are not based on specific pathogen or inactivation dose requirements; therefore, regulatory agencies will be responsible for establishing the pathogen of concern and the corresponding UV dose requirement.

UV disinfection can be used as an effective barrier for the inactivation of many waterborne pathogens. The use of UV technologies in a multi-barrier treatment train can provide an effective barrier against specific pathogens (e.g., *Cryptosporidium* and *Giardia*) and help minimize disinfection byproducts. These UV guidelines apply to the disinfection of drinking-water supply sources, which include filtered surface water, unfiltered surface water, and groundwater. For filtered surface waters, water treatment processes prior to UV disinfection could include granular or synthetic medium filtration, membrane filtration (microfiltration [MF], ultrafiltration [UF], nanofiltration [NF], and reverse osmosis [RO]), diatomaceous earth filtration, or slow sand filtration.

Performance Testing of UV Disinfection Systems

These guidelines are meant to provide a common basis for evaluating and implementing UV disinfection technologies. As a minimum, manufacturers are required to demonstrate the efficacy of their equipment[1] as outlined in Chapter Three. When testing is complete, the results shall be summarized in a report. This performance-based testing approach is directed toward quantifying the inactivation of target microorganisms (i.e., MS-2 bacteriophage) by UV equipment.

Organization of the Drinking-Water Guidelines

The drinking-water guidelines are organized into the following sections:

1. Introduction
2. UV Dose
3. Reactor Design
4. Reliability Design
5. Monitoring and Alarm Design
6. Field Commissioning Test
7. Performance Monitoring
8. Engineering Report

The topics in Sections 2 to 7 deal specifically with the key elements involved in designing, operating, and monitoring a UV disinfection system. These topics must be addressed in the required Engineering Report (Section 8).

1. The performance-based testing outlined in these guidelines is not intended to cover the use of UV for photochemical or advanced oxidation processes.

2. UV Dose

The UV dose is expressed, for practical purposes, as the product of UV intensity, expressed in milliwatts per square centimeter (mW/cm^2), and the exposure time of the fluid or particle to be treated, expressed in seconds (s). The units of UV dose are expressed as millijoules per square centimeter (mJ/cm^2), which is equivalent to milliwatt seconds per square centimeter ($mW \cdot s/cm^2$). Currently, it is only possible to accurately characterize the UV dose when using a collimated-beam apparatus because both the intensity reaching the fluid elements and the exposure time can be accurately quantified. Non-ideal hydraulics and non-uniform intensity profiles result in a distribution of doses being applied in continuous-flow reactors.

For continuous-flow reactors, the terms "reduction equivalent dose," "design UV dose," and "operational UV dose" will be used hereafter and are defined as follows:

- *Reduction equivalent dose (RED).* The dose that is assigned to the UV test reactor based on reactor validation testing. The RED is equivalent to that measured with the collimated-beam apparatus for the same degree of inactivation of the target microorganism.
- *Design UV dose.* The RED required for a specific log inactivation of the target microorganism. The design UV dose is used for sizing UV disinfection systems.
- *Operational UV dose:* The UV dose that is established based on the results of the equipment validation testing. The operational UV dose, a useful index of reactor behavior, can be used to make most efficient use of the UV disinfection system (e.g., reduce power demand, reduce the number of reactors or reactor trains on-line) while maintaining the design UV dose.

The design UV dose will depend on the target microorganism and the quality of the water-supply source prior to UV disinfection. The target microorganism and the required inactivation levels must be established by the regulatory agency. Water-supply sources, as discussed in section 1, include filtered surface water, unfiltered surface water, and groundwater. Ultraviolet disinfection equipment validation for different water qualities should be as follows:

Filtered Surface Waters and Groundwaters

A reactor that has been validated in accordance with the equipment validation protocol (see Chapter Three) can be used for all filtered surface waters and all groundwaters. A spot-check commissioning test is warranted to ensure proper installation of the validated reactor and construction of appurtenant facilities.

Unfiltered Surface Waters

To address potential construction deficiencies and seasonal variations in turbidity and transmittance, the equipment used for the disinfection of unfiltered surface water shall be validated with the specific water supply in accordance with the protocols outlined in Chapter Three.

Rationale

Reactor performance, in terms of the inactivation of any particular microorganism, is governed by the UV dose distribution and the intrinsic kinetics of microbial inactivation (i.e., dose-response behavior). While dose-response behavior can be measured using a collimated-beam system and appropriate microbial assays, methods available for characterizing and quantifying UV dose

distributions are not well-defined. Although numerical methods are available for predicting UV dose distribution, these methods are neither standardized nor widely adopted for practical applications. As a result, these guidelines are based on biodosimetry methods for testing and validating UV reactors.

Establishing the RED involves determining the UV inactivation of a selected microorganism under controlled batch conditions (e.g., collimated-beam petri dish). For UV equipment performance validation, MS-2 is recommended for REDs exceeding 20 mJ/cm^2. The benefits of MS-2 include:

- High resistance to UV.
- Nearly first order inactivation kinetics over the range of UV dose typically used for disinfection.
- Ease of seeding and enumeration.
- Consistent and reproducible assay results.
- Non-pathogenicity to humans.
- Inability to photoreactivate.

For the purpose of standardization, the RED is defined as achieving the same degree of MS-2 inactivation in a continuous flow reactor that is achieved in a collimated-beam apparatus reactor equipped with a low-pressure, non-ozone producing mercury lamp. Details are provided in Chapter Three.

For filtered surface waters and groundwaters, the impact of particulate matter on UV disinfection is minimized. For these water supplies, the RED correlations developed for the UV equipment validated in accordance with the protocols in Chapter Three can be used in the design of the UV disinfection system. A spot-check commissioning test is warranted to ensure proper installation of the validated reactor and construction of appurtenant facilities.

Particulate matter in unfiltered surface waters and variations in transmittance can shield microorganisms from UV disinfection. For these water supplies, site-specific equipment validation is recommended to assess the impact of variations in water quality.

Design Conditions

UV disinfection systems for drinking-water applications should be designed to deliver, under the peak flow and minimum UV transmittance, a design UV dose based on the following design conditions:

1. The UV lamp output at 50 percent of nominal (new) UV lamp output (after an appropriate burn-in period), unless the manufacturer establishes the lamp age factor for the time period that corresponds to the lamp change-out time intervals specified in the Engineering Report. The lamp age factor shall be verified in accordance with the protocols in Chapter 3.
2. Eighty-percent transmittance through the quartz sleeve for manually cleaned systems, excluding the transmittance characteristics of the quartz sleeve.
3. Eighty-percent transmittance through the quartz sleeve for automatic mechanical or chemical cleaning systems, excluding the transmittance characteristics of the quartz sleeve, unless test data are provided to substantiate a higher value in accordance with the protocols in Chapter 3. The cleaning frequency will be based on the manufacturer's recommendation.

4. The minimum UV transmittance used in the design of UV disinfection systems is defined as the 5-percentile UV transmittance value, which is based on a minimum of 12 months of UV transmittance data (a minimum of three samples per day spaced equally over the operating period). If 12-month monitoring data are not available, a minimum UV transmittance value of 80 percent shall be used. The UV transmittance measurements shall be at 254 nanometer (nm) wavelength.

5. Shelf life of the lamps should be considered for stocking the replacement lamps. Storage shelf life should be in accordance with the manufacturer's recommendations.

Rationale

Based on lamp testing data, it appears that the operating conditions for water reuse UV disinfection systems result in an accelerated decrease in UV lamp intensity when compared to those tested in air. The decrease in UV lamp intensity in drinking water is expected to be similar to water reuse. The lamp age factor of 0.5 is representative of conventional low-pressure lamps after 1 year of service. Further, reduced lamp output has been observed for replacement lamps stored for extended time periods. This age value is recommended for all lamp systems unless data are collected in accordance with protocols in Chapter 3 to substantiate a different design value. For polychromatic lamps, the impact of lamp age and fouling on lamp output characteristics and individual wavelengths emitted are not known. Therefore, the same factors are assumed for polychromatic lamps until additional data are available.

3. Reactor Design

Because of the numerous system configurations that are available (e.g., open channels, closed conduits, various lamp orientations, etc.), UV facilities will have different scale-up, layout, and mechanical redundancy requirements. The following terms are used consistently throughout this document:

- *Module.* The basic building block of a UV disinfection system. It is comprised of one or more UV lamps with a common electrical feed.
- *Bank.* One or more UV modules that the entire flow for a given reactor train must pass through.
- *Reactor.* An independent combination of single or multiple bank(s) in series with a common mode of failure (e.g., electrical, cooling, cleaning system, etc.).
- *Reactor train.* A combination of reactors in series, including inlet, outlet, and level controlling arrangements (if applicable).
- *UV disinfection system.* The combination of reactor trains with associated controls and instrumentation.

Reactor trains should be designed with approach, inlet, and outlet conditions that promote plug flow (i.e., minimal longitudinal mixing, effective lateral mixing) within the irradiated zone. There must be reliable flow distribution among multiple reactor trains proportional to reactor train flow capability. Inlet approach conditions should allow sufficient distance to establish a uniform velocity field upstream of the first reactor in a reactor train, unless an alternate velocity field can be measured and demonstrated to provide satisfactory performance in accordance with the protocols in Chapter Three. The outlet condition should ensure that hydraulic behavior within the last reactor is not adversely affected by any outlet fluid-level control device or pipefittings.

Regardless of the equipment utilized, the standby equipment and reliability features that are described in Section 4 must be integrated into the design of the UV disinfection system.

Hydraulic Constraints

The designs of the reactor train(s) inlet and outlet are the responsibility of the UV manufacturer and design engineer. Hydraulic testing must be performed as part of UV validation testing (see Chapter Three). In all cases, the reactor train shall be designed to operate with the same approach velocity ranges used for equipment validation (see Chapter Three).

For drinking-water applications, scale-up from pilot-scale equipment is not allowed. Only full-scale reactors validated in accordance with the protocols in Chapter Three can be used. Modular arrangements of the validated reactors can be implemented in full-scale application.

In the layout of the UV disinfection system, the following hydraulic factors (based on the equipment validation test results) must be addressed:

1. The required approach length and conditions prior to the first reactor.
2. The downstream length following the last reactor before the fluid-leveling device (if applicable) or other piping elements (e.g., valves, bends).
3. The spacing between multiple UV reactors. The spacing must allow for maintenance and access in addition to adequate hydraulic performance.
4. Any device, reactor component, or other feature that is used to accomplish or enhance effective uniform velocities.
5. The presence and operation of any cleaning device/mechanism.

Rationale

Based on currently available information, excessive longitudinal mixing in the irradiated zone promotes the broadening of dose distribution. Similarly, inadequate lateral mixing can promote a wide dose distribution where some fluid elements may receive an inadequate UV dose. A properly designed inlet structure and approach will help ensure that uniform flow conditions are imposed on the first reactor in a UV reactor train. Concurrently, a properly designed outlet structure or piping will ensure that outlet conditions do not adversely affect fluid behavior within the last reactor. Uniform flow distribution is typically desirable, but does not guarantee adequate hydrodynamic behavior in the irradiated zone. When inlet and outlet conditions are not identical with respect to geometry, placement of diffusers, and/or flow conditioning devices, velocity measurements will be required.

Reactor Train Layout Constraints

The number of reactor trains included must consider the hydraulic limitations and turndown ratios for the given UV disinfection system. Multiple reactor trains may be required to accommodate large variations from low-flow to peak-flow conditions. The sizing and layout of reactor trains must ensure that the reactor train velocities are within the velocity range that the equipment was validated for. Critical design elements include:

1. Reactor walls shall be consistent with the manufacturer's recommendations.

2. It must be possible to isolate each reactor train during maintenance.
3. All materials used in constructing or coating the reactors and in contact with water shall be in compliance with the NSF International Standard 61 Drinking Water System Components – Health Effects and other applicable codes. All material exposed to UV radiation shall be UV resistant. Concrete channels shall be adequately lined or coated to ensure that organisms do not become embedded within crevices.
4. Any chemicals used to clean the quartz sleeves should be certified and listed in accordance with the NSF Standard 60 Drinking Water Treatment Chemicals – Health Effects.
5. The upstream and downstream portions of the UV reactor and the sections between reactors must be water and light tight (e.g., covered) and must prevent external runoff or other materials from entering the UV reactor train.

Rationale

Extreme flow conditions (i.e., low and peak flow), which may exceed the velocity ranges acceptable for a given reactor, can be mitigated by the use of multiple reactor trains. Because lamps may break during maintenance, the ability to isolate a reactor train during maintenance would aid in containing contaminated water. Variations in reactor walls can result in regions of low UV intensity that would aid in passing inadequately disinfected fluid elements. Lining of concrete channels would aid in preventing microorganisms from growing within crevices of the channel, which could adversely affect disinfection performance. Reactor train(s) must be sealed or covered to avoid the growth of algae containing biofilms and to protect the health of personnel.

Cleaning System Constraints

As part of the UV disinfection system, the cleaning system must deal effectively with site-specific water-quality effects (e.g., precipitation and fouling due to iron, calcium, aluminum, manganese, and other inorganic and organic constituents). Site-specific testing is recommended when iron, calcium, aluminum, manganese, and magnesium are present at high concentrations relative to saturation limits. The fouling test can be done on a scale sufficient to include the smallest modular size of the commercial cleaning device.

Rationale

The effectiveness of a UV disinfection system is, in part, maintained by the performance of the cleaning system. Iron, calcium, aluminum, manganese, and magnesium have been observed to impact the effectiveness and frequency of cleaning requirements. Site-specific testing is recommended when any of these constituents are present at concentrations that can result in the fouling of quartz sleeves.

4. Reliability Design

Special attention must be devoted to the reliability of any proposed UV disinfection system installed to disinfect drinking water, including: standby equipment, water-quality reliability, operation and maintenance, power-supply reliability, electrical safety, and design for seismic loads.

Standby Equipment

The UV disinfection system should be designed to convey the design UV dose (see Section 2) under worst-case operating conditions (e.g., flowrate, water quality) to the pathogen passing through the reactor train. For systems requiring continuous flow treatment, a minimum of one standby reactor train shall be provided. If the UV system can be taken off-line, one reactor train can be used. Standby UV equipment must be available by providing either a complete standby UV reactor train or an additional UV reactor in each reactor train. The standby UV equipment shall be at a minimum equivalent to 20 percent of the UV equipment required for the disinfection of peak flows. Additionally, the configuration and level of standby equipment that is provided should be consistent with the configuration and redundancy available in upstream processes.

The UV disinfection system must be capable of applying the required design UV dose with any failed or out-of-service reactor. Failure can be due to any number of conditions including, but not limited to, failure of the power supply, cleaning mechanism, and cooling system for electrical components. In addition to the minimum requirements for standby equipment described in this section, a contingency plan should be developed for the possibility of total UV disinfection system failure. The provision and configuration of standby equipment, as well as contingency planning in the event of total UV disinfection system failure, must be described in the required Engineering Report.

In case of train failure, the UV system should automatically activate the standby train and isolate the failed trains.

Rationale

System component failure can be expected with any treatment process. The UV disinfection system must be capable of producing disinfected water during any component failure prior to distribution. For continuous flow treatment, a minimum of one standby reactor train is required to isolate one reactor train from the flow stream during maintenance and repair or in case of failure of an on-line train.

Feed Water Quality Reliability

In the event that changes in water quality or upset of the upstream treatment process produce water unsuitable for UV disinfection (e.g., excessive turbidity, low transmittance), the contingency plan addressed in the required Engineering Report shall be implemented.

Rationale

UV feed water of poor quality may not be properly disinfected.

Operation and Maintenance

The operation and maintenance procedures for the UV disinfection system shall be included in the Engineering Report. Operators should receive specific training on the operation of UV disinfection systems.

Lamp breakage and the resulting release of mercury into the water stream is a concern with UV disinfection systems using mercury vapor lamps. A reactor train shall be isolated from the flow stream during maintenance and repair. A contingency plan must be developed as a part of the Engineering Report to address lamp breakage issues and must be implemented upon lamp breakage.

Rationale

Reliable operation requires proper training and the timely maintenance, replacement, and calibration of system components. The presence of mercury is of concern because it can be detrimental to public health and aquatic life.

Power Supply Reliability

To ensure a continuous supply of power, the UV disinfection system must be provided with standby power and a looped power-distribution system (should one of the power supply lines fail). The UV disinfection system components of the same type (i.e., reactors) must be divided among two or more power-distribution panel boards or switchboards to prevent a common mode of failure.

The UV disinfection system design must account for the technology being utilized. Special consideration must be provided for:

1. *Short-term power interruptions.* If the UV disinfection system cannot be immediately restarted upon a short-term power interruption, an uninteruptable power supply (UPS) must be considered with the design. If UPS facilities are not provided, a contingency plan (i.e., storage) must be provided.
2. *Ambient temperature.* The facility design must provide for the effect of ambient temperature on ballast cooling and other electrical components.
3. *System harmonics.* The facility must address the impact of electrical harmonics generated by the UV disinfection on the plant power supply and other electrical systems.

Rationale

Because the UV disinfection system cannot operate without electrical power, reliable power supply and backup power are essential to ensure continuous disinfection (unless the water treatment plant has alternative reliability provisions or disinfection capabilities). Using multiple panel boards or switchboards would allow part of the system to remain on-line, even if one of the power-distribution panel boards or switchboards should fail.

Electrical Safety Design

All UV disinfection systems shall be provided with ground fault interruption (GFI) circuitry.

Rationale

GFI circuitry is required to minimize hazard to personnel in the event of lamp breakage or any other circumstance that could create direct electrical contact with water.

Seismic Design

The UV disinfection facilities (e.g., buildings, structures, piping) should be designed in accordance with the seismic design requirements applicable for the seismic load characteristic of the region in which the system is used. These same seismic design standards shall apply to structures where UV replacement equipment is stored on-site.

Rationale

Seismic design considerations are particularly important for UV disinfection systems because of the fragile components (especially lamps and quartz sleeves) used in the systems. The seismic safety design of the UV disinfection system should be at least equivalent to the design of the water treatment facilities prior to disinfection. This provision will ensure that whenever the plant is capable of generating product, the UV disinfection system will provide adequate disinfection at all times.

5. Monitoring and Alarm Design

The ability to monitor operating parameters continuously is important in the operation of a UV disinfection system to ensure that adequate disinfection is provided. The continuous monitoring of parameters used to adjust the operational UV dose, UV disinfection system components, and proper calibration of on-line monitoring equipment are critical to maintaining the effectiveness of UV disinfection systems.

Continuous Monitoring

The following parameters must be monitored continuously:

1. Flowrate.
2. UV intensity.
3. UV transmittance.
4. Turbidity.
5. Operational UV dose.

UV Disinfection System

Monitoring of the following UV disinfection system components shall be provided:

1. Status of each UV reactor, on/off.
2. Status of each UV lamp, on/off.
3. UV intensity measured by at least one probe per reactor and at least one per 5 kilowatts (kW) power consumption, not to exceed one probe per two lamps.
4. Lamp age in hours.
5. Cumulative number of reactor on/off cycles.
6. Cumulative UV disinfection system power consumption.
7. Reactor power setting (for systems with variable power input to lamps).
8. Liquid level in UV disinfection reactor trains (for all UV disinfection systems with free water surfaces and for installations where UV lamps can be exposed to air).
9. GFI.

Verification and Calibration of Monitoring Equipment

UV intensity probe readings shall be verified (and calibrated, as necessary) at least monthly, using a reference UV intensity probe (see Chapter Three). The location of the on-line intensity probe(s) and the reference probe must be identical to those in the UV reactor used for performance validation. The calibration of turbidity and UV transmittance monitoring equipment shall be in accordance with manufacturers' recommendations. In addition, laboratory measurements of the UV transmittance of grab samples shall be used to verify the accuracy of on-line transmittance monitoring equipment on a weekly basis.

Rationale

Flowrate, UV transmittance, and UV intensity measurements are needed to establish the operational UV dose. Continuous determination of the operational UV dose is technologically feasible and is consistent with the current requirement for continuous chlorine residual monitoring. The procedure for establishing the operational UV dose shall be included in the Engineering Report (Section 8). Turbidity and UV transmittance monitoring data can be used to initiate responses to deteriorating UV influent quality. The depth of water in the reactor train must be carefully controlled to prevent the depth of water above the top UV lamps from exceeding a predetermined design maximum value (for UV disinfection systems with free water surface), which could result in inadequate disinfection, and to prevent lamps from being out of the flow and losing the effect of their UV radiation due to low water levels. The status of each UV reactor and UV lamp is needed to provide on-line monitoring of the operation of the UV disinfection system. UV intensity and lamp age are used to determine the need for cleaning and/or change-out of the lamps. GFI can be caused by a number of factors, including lamp breakage.

Alarms

To protect public health, both high-priority and low-priority alarms are required for the operation of a UV disinfection system. If left unattended, high-priority alarm conditions will compromise the performance of the UV disinfection system. Although low-priority alarm conditions will not compromise the performance of the UV disinfection system, corrective measures must be instituted before high-priority conditions occur. The set point for these alarms will vary as a function of specific site conditions. The set point should allow for an adequate response time based on the importance of the alarm and subsequent consequences. The settings for the alarms shall be specified in the Engineering Report. As a minimum, the following high-priority and low-priority alarms are required:

High-Priority Alarms

- Adjacent lamp failure – when two or more adjacent lamps fail.
- Multiple lamp failure – when more than 5 percent of the lamps in a reactor fail.
- Low-low UV intensity – when the intensity probe reading drops below the predetermined set point.
- Low-low UV transmittance – when the water transmittance drops below a predetermined set point.
- Low-low operational UV dose – when the operational UV dose drops below the predetermined set point.

- High-high turbidity – when the influent water turbidity exceeds a predetermined set point.
- High water level – when the water level in the UV reactor train exceeds a predetermined water level (for UV disinfection systems with free water surface).
- Low water level – when the water level in the reactor or reactor train falls below a predetermined water level.
- GFI.

Rationale

The low-low operational UV dose, low-low UV intensity, and high-high turbidity alarm shall activate the contingency plan response, regardless of the cause. For other high-priority alarms, the operational UV dose should be increased by activating a standby reactor(s) or reactor train(s) (i.e., when the UV disinfection performance is being compromised).

Low-Priority Alarms

- Individual lamp failure (if a single lamp is less than 5 percent of the total lamps in a reactor) – the location of the lamp is to be indicated by reactor and lamp sequence.
- Low UV intensity – when the intensity probe reading drops below the predetermined set point.
- Low operational UV dose – when the operational UV dose drops below the predetermined set point.
- Low UV transmittance – when the influent UV transmittance drops below a predetermined set point.
- High turbidity – when the influent water turbidity exceeds a predetermined set point.

Rationale

For the low operational UV dose and low UV intensity alarms, the UV dose should be increased by the automatic decrease of flowrate, increase of lamp output, or activation of reactor(s) or reactor train(s). The operator then needs to investigate and address the cause for the alarm. Other low-priority alarms indicate that maintenance is required. For example, a low UV transmittance alarm causes a low-priority alarm, requiring the operator to investigate the problem. The operator may activate a standby reactor(s) or reactor train(s) during investigation or repair, as appropriate.

UV Alarm Records

All high- and low-priority alarm conditions shall be automatically recorded.

6. Field Commissioning Test

The following items shall be tested and verified before UV disinfected water is produced and distributed:

1. Electrical components.
2. Water level.

3. Flow split between reactor trains.
4. Controls and alarms.
5. Instrument calibration.
6. Spot-check commissioning tests (see Chapter 3).

A report documenting and detailing the final field-commissioning test results shall be submitted for review to the appropriate water-utility personnel and regulatory authority.

Rationale

The commissioning test is critical to ensure the proper operation of the UV disinfection system and its conformance with design.

7. Performance Monitoring

Performance monitoring for UV disinfection systems will include microorganism sampling and the continuous on-line measurements delineated in Section 5.

Microorganism Sampling

The microorganism type and sampling frequency shall be in accordance with regulatory agency requirements.

Rationale

The required sampling program for performance compliance shall be consistent with the sampling requirements specified by the regulatory agency.

Monitoring of Operational UV Dose

The operational UV dose delivered by the UV disinfection system is to be determined and monitored continuously as described in Section 5.

Rationale

Continuous determination of the operational UV dose, in conjunction with the other continuous monitoring data, is comparable to monitoring chlorine residual in chlorine disinfection systems. The operational UV dose can be used to make the most efficient use of the UV disinfection system while maintaining the design UV dose. As with residual chlorine monitoring, it should be noted that operational UV dose is not a deterministic parameter for reactor-performance characterization.

8. Engineering Report

For water treatment facilities that have not submitted an Engineering Report, a complete Engineering Report shall be prepared by a registered engineer and submitted to the appropriate regulatory agency prior to the implementation of a UV disinfection system.

For existing water treatment facilities for which an Engineering Report acceptable to the regulatory agencies has been submitted and for which UV is proposed for disinfection, the following types of reports may be required:

1. A complete, updated Engineering Report may be required if, since submission of the last Engineering Report, changes or modifications have occurred in the production of treated water (e.g., raw or treated water quality, treatment processes, plant reliability features, monitoring, or operation and maintenance procedures). The necessity to submit a complete, updated Engineering Report in lieu of an abbreviated report that addresses only the UV disinfection system will be at the discretion of the regulatory agencies.
2. An abbreviated Engineering Report in which only the UV disinfection system and related treatment and reliability features is addressed is acceptable only if the proposed modifications solely involve disinfection processes (e.g., replacing or enhancing existing disinfection facilities with UV disinfection facilities); however, the Engineering Report should provide an evaluation of how well the UV disinfection system will integrate into the treatment process train based on variations in source water quality from upstream treatment processes.

Elements of an Engineering Report

Topics addressed in an Engineering Report should include, but not be limited to, the following:

Water Purveyors

Identify the public or private entities that will be responsible for the production of potable (drinkable) water. When more than one entity is involved in the production of potable water, the responsibilities of each entity must be described.

Raw Water

State the source(s) and the expected range of the water-quality parameters that can affect UV disinfection system performance (e.g., variable transmittance).

Treatment Processes

Provide a schematic diagram of the complete water treatment facilities (including monitoring locations). State the expected range of water-quality parameters for the water that will be subject to UV disinfection.

UV Disinfection System Design Basis

Provide a schematic and detailed description of the UV disinfection system. Provide sufficient detail to clearly show that the design and operational requirements conform with validation protocol and scale-up requirements, when applicable. As a minimum, the following information should be provided:

1. Reactor and reactor train layout and dimensions, inlet and outlet configuration, reactor train velocity range, and any devices used to modify the flow within the pipes or channels.
2. Description of the UV reactor; number, manufacturer and type of UV lamps (including arc length); ballast; modules; banks; and electrical facilities.
3. Sleeve configuration and characteristics (e.g., sleeve material, sleeve diameter, sleeve thickness, and spacing).

4. Monitoring and controls, including the number, location, and function of monitoring equipment.
5. The water level relative to the UV lamps and level control device.
6. The anticipated number of reactor trains in operation under low- and peak-flow conditions and the corresponding inlet and outlet velocity ranges.
7. Details of the bioassay experiments and the procedure used to derive the operational UV dose.
8. Applicable seismic design codes.
9. Spot-check commissioning test results (see Chapter 3).

The equipment validation report shall be appended along with a description of how the information contained within the validation report was used in the layout and design of the UV disinfection system. A certificate shall be provided by the manufacturer to verify that the equipment supplied with respect to lamp spacing, type of lamp, quartz sleeve characteristics, and ballasts (as required above) is identical to the technology used in the validation testing.

Monitoring

The Engineering Report must describe a monitoring program. Where continuous analyses and recording equipment are used, the method and frequency of calibration must be stated. Items to be described in the monitoring section include:

1. The monitoring system used to determine and record the operational UV dose, including equipment and procedures used to monitor and record flow, UV intensity, and UV transmittance.
2. The method of monitoring the water level for open channel systems.
3. The method of monitoring lamp outages.
4. The sampling location and frequency for collecting microbial samples.

Reliability

The proposed UV disinfection system reliability features must be described in detail. When alarms are used to indicate system failure, the report must state where the alarm will be received, how the location is staffed, and who will be notified. The report must also state the hours that the plant will be staffed and operated.

Contingency Plan

The Engineering Report must contain a contingency plan that delineates the actions to be taken for the following conditions:

1. Lamp breakage (mercury release).
2. Low-low operational UV dose, low-low UV intensity, or high-high turbidity alarms.
3. Failure of the upstream treatment processes or the UV disinfection system.
4. Power supply interruptions.
5. Activation of standby equipment, including system and lamp start-up times.

The person or persons responsible for implementing the contingency plan must be identified along with the methods used to notify them.

Operator Certification and Training

The operator certification required for the operation of UV disinfection systems will depend on the requirements of the individual states. A description of the program to be implemented for training water treatment plant personnel in the operation and maintenance of the UV disinfection system must be defined.

Operation and Maintenance

The Engineering Report must include an operations plan for system operation and maintenance. This plan should include a description of the control system, alarm functions, records, and reports. The plan should outline procedures and the frequency for sleeve cleaning, lamp replacement, maintenance of system components, and the frequency for calibrating monitoring equipment. The location, access, and quantity of a backup supply of lamps and other critical components should be identified.

9. References

State of California (2000). "Water Recycling Criteria." California Code of Regulations, Title 22, Division 4, Chapter 3, Section 60301 et seq.

Chapter Two: Water Reuse

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1. Introduction

Unless otherwise indicated, these UV guidelines apply to the disinfection of wastewater meeting the definition of "filtered wastewater" in California's Water Recycling Criteria (WRC), Title 22, Division 4, Chapter 3, of the California Code of Regulations. After disinfection, the filtered wastewater is defined herein as "disinfected filtered reclaimed water" and is essentially pathogen-free (i.e., 5-$\log_{10}$ poliovirus inactivation and a 7-day median total coliform of 2.2 most probable number [MPN]/100 milliliters [mL]). Disinfected filtered reclaimed water in California is suitable for the irrigation of food crops (including all edible root crops), parks, playgrounds, school yards, residential landscaping, unrestricted access golf courses, non-restricted recreational impoundments, cooling towers, flushing toilets and urinals, industrial process water, structural firefighting, decorative fountains, commercial laundries, and commercial car washes as well as for the production of artificial snow, priming of drain traps, and consolidation of backfill around potable (drinkable) water pipelines.

The U.S. Environmental Protection Agency (EPA) published *Guidelines for Water Reuse* in 1992. The EPA's guidelines feature a level of treatment and disinfection that is similar to California's requirements. This includes recommendations for the filtration and disinfection of secondary effluent to achieve turbidity less than 2 nephelometric turbidity units (ntu) (24-hour average, with a maximum of 5 ntu) and a median fecal coliform concentration of less than detection. The EPA recommends that, if total suspended solids (TSS) are used by a state in lieu of turbidity, the average TSS should not exceed 5 milligrams per liter (mg/L). These guidelines are applicable to urban reuse systems, the use of reclaimed water for the irrigation of edible crops, and the use of reclaimed water in recreational impoundments. The UV disinfection criteria contained in these guidelines are applicable to this level of treatment and disinfection recommended by the EPA.

Other states have established water reuse regulations similar to the EPA's *Guidelines for Water Reuse.* For example, Florida requires that reclaimed water used to irrigate public access areas (golf course, parks, others), residential properties, and edible crops must receive secondary treatment, filtration, and high-level disinfection. Florida requires that no TSS sample exceeds 5.0 mg/L and that at least 75 percent of all observations of fecal coliforms be less than detection (Florida Administrative Code, 1999). The UV disinfection criteria contained in these guidelines are also applicable to Florida's high-level disinfection criteria and to other states' reuse criterias, where the states' criterias are consistent with the EPA's *Guidelines for Water Reuse.*

UV disinfection may be applicable to water reuse activities that require less stringent microbiological water-quality criteria; however, the performance-based testing criteria contained herein are based on experience using water-quality conditions that are defined by the term, "filtered wastewater." While it may be appropriate to use UV disinfection on secondary effluents used for water reuse, performance-based studies need to be conducted and presented to the appropriate regulatory authorities before such applications are accepted. These guidelines will facilitate the design and commissioning of UV disinfection systems subject to the limitations set forth in the Foreword.

Performance Testing of UV Disinfection Systems

These guidelines are meant to provide a common basis for the evaluation and implementation of UV disinfection technologies. As a minimum, manufacturers are required to demonstrate the

efficacy of their equipment[2] as outlined in Chapter Three. When testing is complete, the results shall be summarized in a report. This performance-based testing approach is directed toward quantifying the inactivation of target microorganisms (i.e., MS-2 bacteriophage) by UV equipment.

Organization of the Water Reuse Guidelines

The water reuse guidelines are organized into the following sections:

1. Introduction
2. UV Dose
3. Reactor Design
4. Reliability Design
5. Monitoring and Alarm Design
6. Field Commissioning Test
7. Performance Monitoring
8. Engineering Report

The topics in Sections 2 to 7 deal specifically with the key elements involved in the design, operation, and monitoring of a UV disinfection system. These topics must be addressed in the required Engineering Report (Section 8).

2. UV Dose

The UV dose is expressed, for practical purposes, as the product of UV intensity, expressed in milliwatts per square centimeter (mW/cm^2), and the exposure time of the fluid or particle to be treated, expressed in seconds (s). The units of UV dose are expressed as millijoules per square centimeter (mJ/cm^2), which is equivalent to milliwatt seconds per square centimeter ($mW \cdot s/cm^2$). Currently, it is only possible to accurately characterize the UV dose when using a collimated-beam apparatus because both the intensity reaching the fluid elements and the exposure time can be accurately quantified. Non-ideal hydraulics and non-uniform intensity profiles result in a distribution of doses being applied in continuous-flow reactors.

For continuous-flow reactors, the terms "reduction equivalent dose," "design UV dose," and "operational UV dose" will be used hereafter and defined as follows:

- *Reduction equivalent dose (RED).* The dose that is assigned to the UV test reactor based on reactor validation testing. The RED is equivalent to that measured with the collimated-beam apparatus for the same degree of inactivation of the target microorganism.
- *Design UV dose.* The RED required for a specific log inactivation of the target microorganism. The design UV dose is used for sizing UV disinfection systems.
- *Operational UV dose:* The UV dose that is established based on the results of the equipment validation testing. The operational UV dose, a useful index of reactor behavior, can be used to make most efficient use of the UV disinfection system (e.g., reduce power demand, reduce number of reactors or reactor trains on-line) while maintaining the design UV dose.

2. The performance-based testing outlined in these guidelines is not intended to cover the use of UV for photochemical or advanced oxidation processes.

The design of a UV disinfection system for the water reuse applications discussed in Section 1 depends on the type of filtration technologies preceding it. The following minimum criteria shall be used for these three types of filtration: media filtration, membrane filtration, and reverse osmosis (RO).

Media Filtration

When using non-membrane filtration (e.g., granular, cloth, or other synthetic media) as part of the treatment process train upstream of UV disinfection, the following performance criteria shall apply:

- The design UV dose shall be at least 100 mJ/cm^2 under maximum day flow.
- The filtered effluent UV transmittance shall be 55 percent or greater at 254 nm.
- The effluent quality as defined by turbidity or TSS should be similar to the standards applicable in California or Florida. In California, the 24-hour average effluent turbidity shall be no greater than 2 ntu, not to exceed 5 ntu more than 5 percent of the time, and never to exceed 10 ntu (California WRC, 2000). In Florida, the TSS limit is 5 mg/L as a single sample maximum (Florida Administrative Code, 1999). Although an average value is not specified, most Florida facilities will reject filtrate as being unacceptable if the turbidity exceeds a set point generally in the range of 2 to 3 ntu.

Collimated-beam apparatus testing on site-specific filtered wastewater, in accordance with the equipment validation protocol (see Chapter Three), shall be conducted to confirm compliance with the indigenous indicator microorganism (e.g., total or fecal coliform bacteria). The minimum design UV dose under the maximum day flow condition shall be either 100 mJ/cm^2 or a RED corresponding to the collimated-beam apparatus dose required for achieving indigenous indicator microorganism inactivation, whichever is greater.

Membrane Filtration

When using membrane filtration (e.g., MF and UF) as part of the treatment process train upstream of UV disinfection, the following performance criteria shall apply:

- The design UV dose shall be at least 80 mJ/cm^2 under maximum day flow.
- The effluent turbidity shall be equal to or less than 0.2 ntu 95 percent of the time, not to exceed 0.5 ntu.
- The filtered effluent UV transmittance shall be 65 percent or greater at 254 nm.

Reverse Osmosis (RO)

When using RO as part of the treatment process train upstream of UV disinfection, the following performance criteria shall apply:

- The design UV dose shall be at least 50 mJ/cm^2 under maximum day flow.
- The effluent turbidity shall be equal to or less than 0.2 ntu 95 percent of the time, not to exceed 0.5 ntu.
- The permeate UV transmittance shall be 90 percent or greater at 254 nm.

Rationale

Reactor performance, in terms of the inactivation of any particular microorganism, is governed by the UV dose distribution and the intrinsic kinetics of microbial inactivation (i.e., dose-response behavior). While dose-response behavior can be measured using a collimated-beam system and appropriate microbial assays, methods available for characterizing and quantifying UV dose distributions are not well-defined. Although numerical methods are available for predicting UV dose distribution, these methods are neither standardized nor widely adopted for practical applications. As a result, these guidelines are based on biodosimetry methods for testing and validating UV reactors.

Establishing the UV dose involves determining the UV inactivation of a selected microorganism under controlled batch conditions. For equipment performance validation, MS-2 is recommended. The benefits of MS-2 include high resistance to UV, nearly first order inactivation kinetics over the range of UV doses typically used for disinfection, ease of seeding and enumeration, consistent and reproducible assay results, non-pathogenicity to humans, and the inability to photoreactivate. For the purpose of standardization, the RED is defined as achieving the same degree of MS-2 inactivation in a continuous flow reactor that is achieved in a collimated-beam apparatus reactor equipped with a low-pressure, non-ozone producing mercury lamp. Details are provided in Chapter Three.

Based on experience, when UV disinfection systems are used with granular medium filtration, it has been found that coliform bacteria inactivation often governs the design requirements. Particulate matter shields bacteria from UV light to various degrees. While the RED of 100 mJ/cm^2 is typically adequate to inactivate total coliform to less than 2.2 MPN/100 mL, in light of variability that has been observed in reuse systems, collimated-beam testing with actual filtered effluent is required to confirm the impact of particle-associated coliform on UV disinfection effectiveness. Identifying and establishing target pathogens and log inactivation requirements are beyond the intent and scope of this manual; however, based on available laboratory studies, a 5-log_{10} inactivation of poliovirus can be achieved with a UV dose of 50 mJ/cm^2; therefore, the design UV dose of 100 mJ/cm^2 is suggested to account for variability in the effluent quality.

When using MF or UF, the impact of particles is eliminated and viruses are the pathogen of concern. Five-log_{10} inactivation of poliovirus can be achieved with a UV dose of 50 mJ/cm^2; therefore, the design UV dose of 80 mJ/cm^2 is suggested to account for variability in the effluent quality.

When using RO for filtration, at least 2 log_{10} of viruses will be removed through the RO process. Three-log_{10} inactivation of poliovirus can be achieved with a UV dose of about 30 mJ/cm^2; therefore, the design UV dose of 50 mJ/cm^2 is suggested to account for variability in the effluent quality.

The UV transmittance and turbidity requirements represent experience from a number of operating facilities. This does not preclude the use of UV in systems with water-quality characteristics outside these limits. To use UV in these instances, the performance of the UV reactor must be validated under poor water-quality conditions.

Design Conditions

The design UV dose must be based on the following design conditions:

1. The UV lamp output at 50 percent of nominal (new) UV lamp output (after an appropriate burn-in period), unless the manufacturer establishes the lamp age factor for the time period

that corresponds to the lamp change-out time intervals specified in the Engineering Report. The lamp age factor shall be verified in accordance with the protocols in Chapter 3.

2. Eighty percent transmittance through the quartz sleeve for manually cleaned systems, excluding the transmittance characteristics of the quartz sleeve.

3. Eighty percent transmittance through the quartz sleeve for automatic mechanical or chemical cleaning systems, excluding the transmittance characteristics of the quartz sleeve, unless test data are provided to substantiate a higher value in accordance with the protocols in Chapter 3. The cleaning frequency will be based on the manufacturer's recommendation.

4. If transmittance data (a minimum of three samples per day spaced equally over the operating period) have been collected for a minimum period of 6 months, including wet weather periods, the 10-percentile UV transmittance value can be used. The UV transmittance measurements shall be at 254 nm wavelength.

5. Shelf life of the lamps should be considered for stocking the replacement lamps. Storage shelf life should be in accordance with the manufacturer's recommendations.

Rationale

Based on lamp testing data, it appears that the operating conditions for water reuse UV disinfection systems result in an accelerated decrease in UV lamp intensity when compared to those tested in air. The lamp age factor of 0.5 is representative of conventional low-pressure lamps after 1 year of service. Further, reduced lamp output has been observed for replacement lamps stored for extended time periods. This age value is recommended for all lamp systems unless data are collected in accordance with the protocols in Chapter 3 to substantiate a different design value. For polychromatic lamps, the impact of lamp age and fouling on lamp output characteristics and individual wavelengths emitted are not known; therefore, the same factors are assumed for polychromatic lamps until additional data are available.

3. Reactor Design

Because of the numerous system configurations that are available (e.g., open channels, closed conduits, various lamp orientations, etc.), UV facilities will have different scale-up, layout, and mechanical redundancy requirements. The following terms are used consistently throughout this document:

- *Module.* The basic building block of a UV disinfection system. It is comprised of one or more UV lamps with a common electrical feed.
- *Bank.* One or more UV modules that the entire flow for a given reactor train must pass through.
- *Reactor.* An independent combination of single or multiple bank(s) in series with a common mode of failure (e.g., electrical, cooling, cleaning system, etc.).
- *Reactor train.* A combination of reactors in series, including inlet, outlet, and level controlling arrangements (if applicable).
- *UV disinfection system.* The combination of reactor trains with associated controls and instrumentation.

Reactor trains should be designed with approach, inlet, and outlet conditions that promote plug flow (i.e., minimal longitudinal mixing, effective lateral mixing) within the irradiated zone. There must be reliable flow distribution among multiple reactor trains proportional to reactor train flow capability. Inlet approach conditions should allow sufficient distance to establish a uniform velocity field upstream of the first reactor in a reactor train. The outlet condition should ensure that hydraulic behavior within the last reactor is not adversely affected by any outlet fluid-level control device or pipefittings. Regardless of the equipment utilized, the standby equipment and reliability features that are described in Section 4 must be integrated in the design of the UV disinfection system.

Hydraulic Constraints

The design of the reactor train(s) inlet and outlet are the responsibility of the UV manufacturer and design engineer. Hydraulic testing must be performed as part of the UV validation testing (see Chapter Three). In all cases, the reactor train shall be designed to operate with the same approach velocity range used for equipment validation (see Chapter Three) and with all appurtenant equipment that affects hydraulic behavior (e.g., diffuser plates).

In the layout of the UV disinfection system, the following hydraulic factors (based on the equipment validation test results) must be addressed:

1. The required approach length and conditions prior to the first reactor.
2. The downstream length following the last reactor before the fluid-leveling device (if applicable) or other piping elements (e.g., valves, bends).
3. The spacing between multiple UV reactors. The spacing must allow for maintenance and access in addition to adequate hydraulic performance.
4. Any device, reactor component, or other feature that is used to accomplish or enhance effective uniform velocities.
5. The presence and operation of any cleaning device/mechanism.

Rationale

Based on currently available information, excessive longitudinal mixing in the irradiated zone promotes the broadening of dose distribution. Similarly, inadequate lateral mixing can promote a wide dose distribution where some fluid elements may receive an inadequate UV dose. A properly designed inlet structure and approach will help ensure that uniform flow conditions are imposed on the first reactor in a UV reactor train. Concurrently, a properly designed outlet structure or piping will ensure that outlet conditions do not adversely affect fluid behavior within the last reactor. Uniform flow distribution is typically desirable, but does not guarantee adequate hydrodynamic behavior in the irradiated zone. When inlet and outlet conditions are not identical with respect to geometry, placement of diffusers, and/or flow conditioning devices, velocity measurements will be required.

Reactor Train Layout Constraints

The number of reactor trains included must consider the hydraulic limitations and turndown ratios for the given UV disinfection system. Multiple reactor trains may be required to accommodate large variations from low-flow to peak-flow conditions. The sizing and layout of

reactor trains must ensure that the reactor train velocities are within the velocity range that the equipment was validated for. Critical design elements include:

1. Reactor walls shall be consistent with the manufacturer's recommendations.
2. It must be possible to isolate each reactor train during maintenance.
3. Concrete channels shall be adequately lined or coated to ensure that organisms do not become embedded within crevices. All material exposed to UV radiation shall be UV resistant.
4. The upstream and downstream portions of the UV reactor and the sections between reactors must be water and light tight (e.g., covered) and must prevent external runoff or other materials from entering the UV reactor train.

Rationale

Extreme flow conditions (i.e., low and peak flow), which may exceed the velocity ranges acceptable for a given reactor design, can be mitigated by the use of multiple reactor trains. Because lamps may break during maintenance, the ability to isolate a reactor during maintenance would aid in containing contaminated water. Variations in reactor walls can result in regions of low UV intensity that would aid in passing inadequately disinfected fluid elements. Lining of concrete channels would aid in preventing microorganisms from growing within crevices of the channel, which could adversely affect disinfection performance. Reactor train(s) must be sealed or covered to avoid the growth of algae containing biofilms and to protect the health of personnel.

Cleaning System Constraints

As part of the UV disinfection system, the cleaning system must deal effectively with site-specific water-quality effects (e.g., precipitation and fouling due to iron, calcium, aluminum, manganese, and other inorganic and organic constituents). Site-specific testing is recommended when iron, calcium, aluminum, manganese, and magnesium concentrations are present at high concentrations relative to saturation limits. The fouling test can be done on a scale sufficient to include the smallest modular size of the commercial cleaning device.

Rationale

The effectiveness of a UV disinfection system is, in part, maintained by the performance of the cleaning system. Iron, calcium, aluminum, manganese, and magnesium have been observed to impact the effectiveness and frequency of cleaning requirements. Site-specific testing is recommended when any of these constituents are present at concentrations that can result in the fouling of quartz sleeves.

4. Reliability Design

Because regulatory standards associated with unrestricted water reuse are stringent, special attention must be devoted to the reliability of any proposed UV disinfection system, including: standby equipment, water-quality reliability, operation and maintenance, power-supply reliability, electrical safety, and design for seismic loads.

Standby Equipment

The UV disinfection system should be designed to convey the design UV dose (see Section 2) under worst-case operating conditions (e.g., flowrate, water quality) to the pathogen passing through the reactor train. At a minimum, two reactors must be simultaneously operated in any on-line reactor train. Standby UV equipment must be provided by one of the following options:

- A standby reactor per reactor train.
- A standby reactor train.

As an alternative to standby equipment, adequate storage[3] or other contingency arrangements can be provided to deal with the flow during UV disinfection system failure and must be described in the required Engineering Report.

The UV disinfection system must be capable of applying the required design UV dose with any failed or out-of-service reactor. Failure can be due to any number of conditions including, but not limited to, failure of the power supply, cleaning mechanism, and cooling system for electrical components.

Rationale

System component failure can be expected with any treatment process. The UV disinfection system must be capable of producing disinfected reclaimed water during any component failure prior to distribution. A minimum of two operating reactors per train ensures that some disinfection occurs until the standby reactor is brought on-line in the event that one of the on-line reactors fails.

Feed Water Quality Reliability

In the event that the upstream treatment process produces water unsuitable for UV disinfection (e.g., excessive turbidity, low transmittance), the contingency plan addressed in the Engineering Report shall be implemented.

Rationale

UV influent of poor quality may not be properly disinfected.

Operation and Maintenance

The operation and maintenance procedures for the UV disinfection system shall be included in the Engineering Report. Operators should receive specific training on the operation of UV disinfection systems.

Lamp breakage and the resulting release of mercury into the water stream is a concern with UV disinfection systems using mercury vapor lamps. A reactor train shall be isolated from the flow stream during maintenance and repair. A contingency plan must be developed as a part of the Engineering Report to address the lamp breakage issues and must be implemented upon lamp breakage.

Rationale

Reliable operation requires proper training and the timely maintenance, replacement, and calibration of system components. The presence of mercury is of concern because it can be detrimental to public health and aquatic life.

3. California regulations require one of the following: (1) 24-hour storage if standby equipment replacement is available on-site, (2) appropriate long-term alternate storage (e.g., 20 days) or disposal provisions, or (3) other reliability mechanisms, if approved by the appropriate regulatory agencies.

Power Supply Reliability

To ensure a continuous supply of power, the UV disinfection system must be provided with standby power and a looped power-distribution system (should one of the power supply lines fail). The disinfection system components of the same type (i.e., banks) must be divided among two or more power-distribution panel boards or switchboards to prevent a common mode of failure. Storage or alternate disposal methods of improperly treated or disinfected water must be available if a continuous power supply, including standby power, is not provided.

The UV disinfection system design must account for the technology being used. Special consideration must be provided for:

1. *Short-term power interruptions.* If the UV disinfection system cannot be immediately restarted upon a short-term power interruption, a UPS must be considered with the design. If UPS facilities are not provided, a contingency plan (i.e., storage) must be provided.
2. *Ambient temperature.* The facility design must provide for the effect of ambient temperature on ballast cooling and other electrical components.
3. *System harmonics.* The facility must address the impact of electrical harmonics generated by the UV disinfection on the plant power supply and other electrical systems.

Rationale

Because the UV disinfection system cannot operate without electrical power, reliable power supply and backup power are essential to ensure continuous disinfection (unless the reclamation plant has alternative reliability provisions or disinfection capabilities). Using multiple panel boards or switchboards would allow part of the system to remain on-line, even if one of the power-distribution panel boards or switchboards should fail.

Electrical Safety Design

All UV disinfection systems shall be provided with GFI circuitry.

Rationale

GFI circuitry is required to minimize hazard to personnel in the event of lamp breakage or any other circumstance that could create direct electrical contact with water.

Seismic Design

The UV disinfection facilities (e.g., building, structures, piping) should be designed in accordance with the seismic design requirements applicable for the seismic loads characteristic of the region in which the system is used. These same seismic design standards shall apply to structures where UV replacement equipment is stored on-site.

Rationale

Seismic design considerations are particularly important for UV disinfection systems because of the fragile components (especially lamps and quartz sleeves) used in the systems. The seismic safety design of the UV disinfection system should be at least equivalent to the design of the reclamation facilities prior to disinfection. This provision will ensure that whenever the plant is capable of producing effluent, the UV disinfection system will provide adequate disinfection.

5. Monitoring and Alarm Design

The ability to monitor operating parameters continuously is important in the operation of a UV disinfection system to ensure that adequate disinfection is provided. The continuous monitoring of parameters used to adjust the operational UV dose, UV disinfection system components, and proper calibration of on-line monitoring equipment are critical to maintaining the effectiveness of UV disinfection systems.

Continuous Monitoring

The following parameters must be monitored continuously:

1. Flowrate.
2. UV intensity.
3. UV transmittance.
4. Turbidity.
5. Operational UV dose.

UV Disinfection System

Monitoring of the following UV disinfection system components shall be provided:

1. Status of each UV reactor, on/off.
2. Status of each UV lamp, on/off.
3. UV intensity measured by at least one probe per reactor.
4. Lamp age in hours.
5. Cumulative number of reactor on/off cycles.
6. Cumulative UV disinfection system power consumption.
7. Reactor power set point (for systems with variable power input to lamps).
8. Liquid level in the UV disinfection reactor trains (for all UV disinfection systems with free water surfaces and for installations where UV lamps can be exposed to air).
9. GFI.

Verification and Calibration of Monitoring Equipment

UV intensity probe readings shall be verified (and calibrated, as necessary) at least monthly, using a reference UV intensity probe (see Chapter Three). The location of the on-line intensity probe(s) and the reference probe must be identical to those in the UV reactor used for performance validation. The calibration of turbidity and UV transmittance monitoring equipment shall be in accordance with manufacturers' recommendations. In addition, laboratory measurements of the UV transmittance of grab samples shall be used to verify the accuracy of on-line transmittance monitoring equipment on a weekly basis.

Rationale

Flowrate, UV transmittance, and UV intensity measurements are needed to establish the operational UV dose. Continuous determination of the operational UV dose is technologically feasible and is consistent with the current requirement for continuous chlorine residual monitoring. The procedure for establishing the operational UV dose shall be included in the Engineering Report (Section 8). Turbidity and UV transmittance monitoring data can be used to initiate responses to deteriorating UV influent quality. The depth of water in the reactor train must be controlled carefully to prevent the depth of water above the top UV lamps from exceeding a predetermined design maximum value (for UV disinfection systems with free water surface), which could result in inadequate disinfection, and to prevent lamps from being out of the flow and losing the effect of their UV radiation due to low water levels. The status of each UV reactor and UV lamp is needed to provide on-line monitoring of the operation of the UV disinfection system. UV intensity and lamp age are used to determine the need for cleaning and/or change-out of the lamps. GFI can be caused by a number of factors, including lamp breakage.

Alarms

To protect public health, both high-priority and low-priority alarms are required for the operation of a UV disinfection system. If left unattended, high-priority alarm conditions will compromise the performance of the UV disinfection system. Although low-priority alarm conditions will not compromise the performance of the UV disinfection system, corrective measures must be instituted before high-priority conditions occur. The set point for these alarms will vary as a function of specific site conditions. The set point should allow for adequate response time based on the importance of the alarm and subsequent consequences. The settings for the alarms shall be specified in the Engineering Report. As a minimum, the following high-priority and low-priority alarms are required:

High-Priority Alarms

- Adjacent lamp failure – when two or more adjacent lamps fail.
- Multiple lamp failure – when more than 5 percent of the lamps in a reactor fail.
- Low-low UV intensity – when the intensity probe reading drops below a predetermined set point.
- Low-low UV transmittance – when the influent water reuse UV transmittance drops below a predetermined set point.
- High-high turbidity – when the influent turbidity to the disinfection unit exceeds a predetermined set point.
- Low-low operational UV dose – when the operational UV dose drops below the predetermined set point.
- High water level – when the water level in the UV reactor train exceeds a predetermined water level (for UV disinfection systems with free water surface).
- Low water level – when the water level in the reactor or reactor train falls below a predetermined water level.
- GFI.

Rationale

The low-low operational UV dose, low-low UV intensity, and high-high turbidity shall activate the contingency plan response, regardless of the cause. For other high priority alarms, the operational UV dose should be increased by activating a standby reactor(s) or reactor train(s) (i.e., when the UV disinfection performance is being compromised).

Low-Priority Alarms

- Individual lamp failure (if a single lamp is less than 5 percent of the total lamps in a reactor) – the location of the lamp is to be indicated by reactor and lamp sequence.
- Low UV intensity – when the intensity probe reading drops below a predetermined set point.
- Low UV transmittance – when the influent UV transmittance drops below a predetermined set point.
- High turbidity – when the influent turbidity exceeds a predetermined set point.
- Low operational UV dose – when the operational UV dose drops below the predetermined set point.

Rationale

For the low operational UV dose and low UV intensity alarms, the UV dose should be increased by automatically activating a standby reactor(s) or reactor train(s). The operator then needs to investigate and address the cause for the alarm. Other low-priority alarms indicate that maintenance is required. For example, a low UV transmittance alarm causes a low-priority alarm, requiring the operator to investigate the problem. The operator may activate a standby reactor(s) or reactor train(s) during investigation or repair, as appropriate.

UV Alarm Records

All high- and low-priority alarm conditions shall be automatically recorded.

6. Field Commissioning Test

The following items shall be tested and verified before initiating the production of reclaimed water:

1. Electrical components.
2. Inlet/outlet velocity distribution (if full-scale reactors use more lamps than the reactors used for validation testing).
3. Water level.
4. Flow split between reactor trains.
5. Controls and alarms.
6. Instrument calibration.
7. Spot-check commissioning tests (see Chapter 3).

A report documenting and detailing the field-commissioning test results shall be submitted for review to the appropriate water-utility personnel and regulatory authority.

Rationale

The commissioning test is critical to ensure the proper operation of the UV disinfection system and its conformance with design.

7. Performance Monitoring

Performance monitoring for UV disinfection systems will include microorganism sampling and the continuous on-line measurements delineated in Section 5.

Microorganism Sampling

Routine monitoring based on representative samples should include the following:

- Coliform bacteria and/or
- Other microorganisms, as required.

The representative samples for coliform bacteria and other microorganisms shall be collected downstream of the UV disinfection system at a time when water reuse characteristics are most demanding on the treatment and disinfection facilities. The sampling frequency shall be consistent with permit requirements.

Rationale

The required sampling program for performance compliance shall be consistent with the sampling requirements specified by the regulatory agency.

Monitoring of Operational UV Dose

The operational UV dose delivered by the UV disinfection system is to be determined and monitored continuously as described in Section 5.

Rationale

Continuous determination of the operational UV dose, in conjunction with the other continuous monitoring data, is comparable to monitoring chlorine residual in chlorine disinfection systems. The operational UV dose can be used to make most efficient use of the UV disinfection system while maintaining the design UV dose. As with residual chlorine monitoring, it should be noted that operational UV dose is not a deterministic parameter for reactor-performance characterization.

8. Engineering Report

For water reuse facilities that have not submitted an Engineering Report, a complete Engineering Report shall be prepared by a registered engineer and submitted to the appropriate regulatory agency prior to the implementation of a UV disinfection system.

For existing water reuse facilities for which an Engineering Report acceptable to the regulatory agencies has been submitted and for which UV is proposed for disinfection, the following types of reports may be required:

1. A complete, updated Engineering Report may be required if, since submission of the last Engineering Report, changes or modifications have occurred in the production of reclaimed water (e.g., treatment processes, plant reliability features, monitoring, or operation and maintenance procedures), reclaimed water transmission and distribution system, or reclaimed water use area (e.g., type of reuse, use area controls, or use area design). The necessity to submit a complete, updated Engineering Report in lieu of an abbreviated report that only addresses the UV disinfection system will be at the discretion of the regulatory agencies.
2. An abbreviated Engineering Report in which only the UV disinfection system and related treatment and reliability features is addressed is acceptable only if the proposed modifications solely involve disinfection processes (e.g., replacing or enhancing existing disinfection facilities with UV disinfection facilities); however, the Engineering Report should provide an evaluation of how well the UV disinfection system will integrate in the treatment process train.

Elements of an Engineering Report

Topics addressed in an Engineering Report should include, but not be limited to, the following:

Producer

The producer is the public or private entity that will treat the wastewater used in the project. Where more than one agency is involved in the treatment, the responsibilities of each agency must be described.

Purveyor

The person, party, or agency responsible for the water reuse distribution system.

Raw Wastewater

State the physical, chemical, and biological characteristics of the wastewater and identify any unusual characteristics that may affect the UV disinfection system (e.g., variable transmittance). State the proportion and type of industrial waste.

Reclaimed Water

Identify the reclaimed water uses and the corresponding water-quality and treatment requirements.

Treatment Processes

Provide a schematic diagram of the complete water reuse treatment facilities (including monitoring locations). State the existing or expected quality of the treated wastewater that will be subject to UV disinfection.

UV Disinfection System Design Basis

Provide a schematic and detailed description of the UV disinfection system. Provide sufficient detail to clearly show that the design and operational requirements conform with validation protocol and scale-up requirements, when applicable. As a minimum, the following information should be provided:

1. Reactor and reactor train layout and dimensions, inlet and outlet configuration, reactor train velocity range, and any devices used to modify the flow within the pipes or channels.

2. Description of the UV reactor; number, manufacturer, and type of UV lamps (including arc length); ballast; modules; banks; and electrical facilities.
3. Sleeve configuration and characteristics (e.g., sleeve material, sleeve diameter, sleeve thickness, and spacing).
4. Monitoring and controls, including the number, location, and function of monitoring equipment.
5. The water level relative to the UV lamps and level control device.
6. The anticipated number of reactor trains under low- and peak-flow conditions and the corresponding inlet and outlet velocity ranges.
7. Details of the bioassay experiments and the procedure used to derive the operational UV dose.
8. Applicable seismic design codes.
9. Spot-check commissioning test results (see Chapter 3)

The equipment validation report shall be appended along with a description of how the information contained within the validation report was used used in the layout, scale-up, and design of the the UV disinfection system. A certificate shall be provided by the manufacturer to verify that the equipment supplied with respect to lamp spacing, type of lamp, quartz sleeve characteristics, and ballasts (as required above) is identical to the technology used in the validation testing.

Monitoring

The Engineering Report must describe a monitoring program. Where continuous analyses and recording equipment are used, the method and frequency of calibration must be stated. Items to be described in the monitoring section include:

1. The monitoring system used to determine and record the operational UV dose, including equipment and procedures used to monitor and record flow, UV intensity, and UV transmittance.
2. The method of monitoring the water level for open channel systems.
3. The method of monitoring lamp outages.
4. The sampling location and frequency for collecting microbial samples.

Reliability

The proposed UV disinfection system reliability features must be described in detail. When alarms are used to indicate system failure, the report must state where the alarm will be received, how the location is staffed, and who will be notified. The Engineering Report must also state the hours that the plant will be staffed and operated.

Contingency Plan

The Engineering Report must contain a contingency plan that delineates the actions to be taken for the following conditions:

1. Lamp breakage (mercury release).
2. Low-low operational UV dose, low-low UV intensity, or high-high turbidity alarms.

3. Failure of the upstream treatment processes or the UV disinfection system.
4. Power supply interruptions.
5. Activation of standby equipment, including system and lamp start-up times.

The person or persons responsible for implementing the contingency plan must be identified along with the methods used to notify them. A plan for notifying the reclaimed water users, the responsible regulatory agencies, and other agencies, as appropriate, of any treatment failures that could result in the delivery of inadequately treated wastewater to the use area should be included as part of the contingency plan.

Operator Certification and Training

The operation certification required for the operation of UV disinfection systems will depend on the requirements of the individual states. A description of the program to be implemented for training treatment plant personnel in the operation and maintenance of the UV disinfection system must be defined.

Operation and Maintenance

The Engineering Report must include an operations plan for system operation and maintenance. This plan should include a description of the control system, alarm functions, records, and reports. The plan should outline procedures and the frequency for sleeve cleaning, lamp replacement, maintenance of system components, and the frequency for calibrating the monitoring equipment. The location, access, and quantity of a backup supply of lamps and other critical components should be identified.

9. References

State of California (2000). "Water Recycling Criteria." California Code of Regulations, Title 22, Division 4, Chapter 3, Section 60301 et seq.

Florida Department of Environmental Protection (1999). *Reuse of Reclaimed Water and Land Application.* Florida Administrative Code, Chapter 62-610.

United States Environmental Protection Agency (EPA) and United States Agency for International Development (USAID) (1992). *Guidelines for Water Reuse,* EPA-625-R-92-004. United States Environmental Protection Agency, Washington, D.C.

Chapter Three: Protocols

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1. Introduction

This revision to Chapter Three: Protocols of the NWRI UV Guidelines provides a common ground for testing and validating UV equipment performance. It is based on the current practices of the California Department of Public Health (CDPH) for reviewing testing protocols and commissioning tests for UV disinfection systems. It was written in consideration of other currently available UV validation protocols, including the German UV equipment-performance validation protocol (DVGW W294); "Generic Verification Protocol for High-Rate, Wet-Weather Flow Disinfection" (HydroQual, Inc., 2000); "Standardizing UV Equipment Performance Validation" (Emerick et. al., 2000); and EPA's *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule* (EPA, 2006).

The intent of this revision is to (1) document the current practice of performing "spot-check" performance bioassays for validation of full-scale performance in lieu of conducting velocity profiles, and (2) standardize the assignment of UV dose when conducting MS-2 based viral assays by making use of a standard dose-response relationship. The fundamental difference between this testing protocol and others is its use of a standard MS-2 coliphage-based dose-response relationship. A standard MS-2 dose-response is based on the assumption that the bacteriophage used for any testing can and should be traceable to a standard virus maintained by the American Type Culture Collection (ATTC) with constant UV dose-response. This requirement provides for repeatability in results among different laboratories or when system testing is repeated over time. Use of project or site-specific dose response curves is inherently based on the assumption that MS-2 inactivation behavior can differ at different locales or over time and is likely to result in differing capacity assessments whenever the testing is repeated.

Any project-specific protocol (e.g., UV disinfection equipment validation, on-site system commissioning tests) should first be submitted to the appropriate regulatory agency for review and approval prior to implementation.

Organization of the UV Validation Protocols

The protocols are organized into the following sections:

1. Introduction
2. Test Facilities Requirements and Set-up
   Addresses the performance standards, equipment, documentation, and personnel qualifications needed at UV test facilities
3. Microbiological Testing
   Addresses how to prepare and use the bioassay organism, MS-2 bacteriophage, for UV reactor validation.
4. Testing and Sampling Requirements
   Addresses how to test and evaluate the performance of UV reactors.
5. Data Analysis and Reporting
   Addresses the procedure needed to analyze and organize data into a standardized report.
6. References

2. Test Facilities Requirements and Set-up

The following criteria pertain to test facilities used to carry out the validation protocol described herein, as well as UV reactors tested under the protocol. These criteria address:

- Performance standards for critical components of both the test facility and UV reactor.
- Necessary equipment to carry out the protocol.
- Necessary documentation.
- Standards for the use of equipment.
- Qualifications for personnel who conduct or oversee the test.

These criteria are intended to reasonably ensure the validity of evaluations conducted with this protocol.

Collimated-Beam Apparatus

To establish the UV susceptibility of the microorganisms used in the UV reactor validation test, it is necessary to determine a dose-response relationship for the microorganisms under standard conditions in a laboratory collimated-beam apparatus. The criteria for such a device are described in this section.

UV Source. The lamp must be low-pressure and non-ozone generating, with primary monochromatic output at 254 nm (such as GT5VL). The configuration of the UV lamp(s) should ensure a uniform intensity field at the surface of the sample. The irradiation field in the sample vessel must be perpendicular to the plane surface of the sample. The UV intensity must be monitored and recorded before and after each sample exposure. The UV intensity must be determined at the surface of the sample with a calibrated UV sensor or actinometer. Documentation for the calibration of all UV sensors used in the test must be provided. The shutter time to initiate and terminate exposure of the samples to UV radiation must be less than 2 percent of the shortest irradiation time. To achieve constant output, the lamp in the collimated-beam apparatus should be turned on for at least 30 minutes before testing is initiated. Both temperature and power supply voltage for UV lamp(s) must be monitored and should remain constant during the test.

Sample Container. The petri dish dimensions, sample volume, sample depth, stirring speed, and stirrer bar dimensions must be specified and must remain the same for all tests to achieve reproducible results. A separate sample aliquot and petri dish must be used for each UV exposure.

Rationale

To achieve accurate and reproducible results in laboratory-scale dose-response tests, radiation imposed on an aqueous suspension of microorganisms should be uniform, collimated, and constant. To achieve these conditions, the lamp temperature and power-supply voltage must be constant. The UV intensity at the sample surface must be quantified accurately, which requires the use of a well-calibrated sensor, as well as a uniform UV intensity field. The experimental parameters listed above must be specified fully to achieve reproducible and meaningful results.

Testing Requirements

Water Supply. The performance validation bioassay can be conducted making use of the chlorine-free water supplies discussed under "Water Quality Matrix for Validation Testing." The spot-check

bioassays must be conducted using water that has passed through the filtration step of the full-scale facility. The facility used to test the UV reactor must have an adequate supply of test water to allow testing of the selected flow range in a single pass. Recirculation is acceptable, provided the entire dose undergoing assay occurs within a single pass. The water-supply system must be equipped with a flowrate control system and a backflow preventer. The water used for testing must not contain any disinfectant residuals. Over the testing period, the water temperature must not change by more than plus or minus 2°C of the target temperature, and the UV transmittance must not change by more than plus or minus 2 percent from the target UV transmittance.

Additives. Dosing of additives (e.g., test organisms and/or UV absorbing solution) may be done either in-line with a mixer or in a batch mixing-tank prior to the UV reactor. If in-line mixing is used, then the input solutions must be fed continuously. The mixing must achieve a uniform concentration within the pipe. Proper mixing must be demonstrated by showing that the UV transmittance in the test solution remains constant, as measured by an on-line transmittance monitor, following the dosing of additives.

Sampling and Monitoring. Influent monitoring can be conducted either via an influent sampling point that allows a representative sample of the water entering the reactor train to be collected or at the effluent collection point while the UV disinfection system is in the OFF position. The influent sampling point must be situated after any mixing devices for additives and before the UV reactor train. It can also serve for testing the efficiency of the mixing device. There must also be an effluent sampling point that allows a representative sampling of the water leaving the UV reactor. There must be a mixing device following the UV reactor train, but prior to the effluent sampling point. Collection of the effluent sample as it passes over a weir is sufficient to constitute adequate mixing. All mixing devices shall be located outside the inlet and outlet zones of the UV reactor train. Sample points shall be located outside of the UV exposure field and away from the pipe or channel wall.

The test facility must have instrumentation for the continuous monitoring and recording of the following:

- Flowrate.
- UV transmittance.
- Electrical supply voltage.
- Power input to the UV lamps.
- UV sensor signals.

Water temperature, pressure (closed pipe reactors), water level, and headloss across each UV reactor must be measured and reported at each flowrate investigated.

Installation Configuration. The inlet and outlet piping or channel configurations for the UV reactor are not prescribed by this protocol; however, these conditions must be recorded and will constitute conditions under which the test results are valid. For example, the following test items must be documented:

- The length of the straight pipe or channel entering and exiting the reactor.
- Pipe diameter or channel dimensions.
- Inlet and outlet configuration and dimensions (as well as any devices used to modify the flow within the pipes).

Rationale

For test results to be valid and meaningful, the water quality and dosing of additives for any given set of conditions must be constant. The water quality entering the UV reactor should be homogeneous and constant, which requires effective mixing. The reactor effluent samples must be representative of the water exiting the reactor, which also requires mixing. The test facility instrumentation must be able to record all parameters related to water quality and UV reactor performance that are monitored during the test. The influent and effluent piping configurations and any flow modification devices can have a significant impact on reactor performance.

UV Reactor Equipment and Documentation

Reactor Scale. For drinking-water applications, full-scale reactors must be tested. For reclaimed water, the only allowable scale-up is the modular arrangement of the validated reactors, as described in Section 5 of this chapter.

All reactors must undergo bioassay validation prior to full-scale implementation and must also undergo spot-check validation during full-scale commissioning. It is acceptable to conduct bioassay validation on a modular arrangement that can be expanded for full-scale implementation.

General Documentation. The manufacturer must provide the following documentation for each UV reactor tested:

- A technical description of the UV reactor that includes dimensions, maximum pressure rating, working flow range, head loss, internal fixtures, spare part specifications, circuit diagram, power consumption, ballast information, and the number and type of UV lamps and sleeves.
- Assembly and installation instructions (with all the necessary information on electrical and mechanical installation).
- An operation and maintenance manual.
- Cleaning procedures and instructions (including any special cleaning equipment).

Sensor Documentation. The UV reactor must have UV sensors that monitor UV intensity within the reactor continuously. The sensors must be sufficiently sensitive to detect changes in UV transmittance, ballast output, sleeve fouling, and lamp aging. It must be demonstrated during the commissioning test that the sensors can detect changes in UV transmittance and ballast output. Sensors that appear saturated during the commissioning test (e.g., report the same value at different ballast settings or water transmittance values) cannot be used to demonstrate compliance with sleeve fouling or lamp aging design factors. The manufacturer must specify the number and location of UV sensors within the reactor and must provide the methodology used for selecting the sensor location and monitoring positions.

The manufacturer must provide reference sensors that can be used to verify the accuracy of the reactor sensors. The UV reactor shall be designed with a monitoring window that allows reproducible determination of the UV intensity by reference and system sensors. During testing, the reactor sensors must be checked by comparison with the reference sensors. If the reading of a reactor sensor deviates from the reference sensor by more than the measurement uncertainty, as specified below, then the cause of the deviation must be identified or the reactor sensors must be recalibrated or replaced.

Documentation (e.g., the manufacturer specifications) must be provided to verify that UV reactor sensors and reference sensors conform to these performance standards:

- The working range of sensors must correspond to the UV intensity expected at the monitoring position(s) in the UV reactor.
- The measurement uncertainty of reactor sensors must be less than 10 percent of the working range. Uncertainty of reference sensors must be less than 5 percent of the working range.
- The selectivity of the reactor sensors must be greater than 90 percent for the germicidal range (i.e., wavelengths between 200 and 300 nm). The selectivity of reference sensors must be greater than 95 percent.
- The linearity of reactor and reference sensors in the working range must be within 5 percent.
- The stability of sensors must be such that sensitivity does not deviate by more than 5 percent within the specified working temperature range and over a specified operating period of at least 5,000 hours.
- The acceptance angle of all reactor and reference sensors must be uniform.

UV Lamps and Sleeves. The manufacturer must specify the type and manufacturer of the lamps used in the UV reactor, including the emission spectrum and the characteristics of radiant power. The UV lamps must be subject to a burn-in period (e.g., 100 hours) sufficient to produce nearly constant emission during the test period. For UV lamp sleeves and sensor monitoring windows, the manufacturer must specify the dimensions, transmission spectrum, and pressure rating. For medium-pressure lamps, the reactor must be equipped against overheating with a safety cut-off switch. Instrumentation must be provided to monitor ballast power. The manufacturer must also supply all necessary facilities to allow testing at reduced UV output. The reduced UV output testing is intended to simulate old and fouled lamp conditions.

It is acceptable to make use of equivalent "generic" lamps in the full-scale system only after a full-scale spot-check bioassay has been conducted demonstrating that the use of generic lamps results in performance equal or greater than that described by the underlying design curve, including aging impacts. Use of generic lamps must be approved by the regulating authority.

Rationale

Currently, it is not possible to ensure that UV testing results from pilot-testing will be present at full-scale given differences in construction tolerances and the potential for the introduction of human error during construction. Even closed pipe systems have been observed to perform poorly if air is inadvertently introduced into the system (e.g., following membrane bioreactor treatment), if the wrong sensors are installed, etc. Many of these concerns are not readily apparent. Viral indicators are typically not present in the water being disinfected, so it is essential that the RED reported by the UV disinfection system under field conditions accurately mimic design expectations. Consequently, full-scale spot-check testing of UV reactors is required for both drinking water and recycled water systems to demonstrate that the full-scale system operates according to the underlying design curve.

The entity testing the UV reactor must have full documentation on all aspects related to operation and performance to verify adequacy. The performance of the UV sensors is critical in monitoring the performance of the reactor during operation. Results of the validation protocol are only effective at ensuring performance when used in combination with well-performing sensors because, at minimum, the sensors are used to detect impacts due to lamp aging and sleeve fouling,

and (with many systems) also detect changes in water transmittance and lamp intensity. The output of the UV lamps, along with the transmission characteristics of the lamp sleeves and sensor monitoring windows, are important information for documenting the reactor performance.

Test Facilities Qualification

The facilities and set-up must be acceptable to the appropriate regulatory agency. The validation must be conducted by a qualified party (other than the manufacturer) who is accepted by the regulatory agency. A registered engineer, who is independent from the manufacturer and has experience or training in UV equipment testing, must witness the test program.

Rationale

The test facility, entity conducting the test, and test results must be acceptable to the appropriate regulatory agency for a given application. Witnessing of the test by a registered independent engineer provides a degree of accountability for the test results.

3. Microbiological Testing

The microbiological testing procedure and requirements, assay and enumeration, and quality assurance/quality control (QA/QC) for the surrogate microorganism are described in this section. MS-2 bacteriophage (ATCC 15597 B1) has been selected as the bioassay organism outlined in these guidelines. Other test organisms are acceptable if more appropriate for the dose range under consideration. The QA/QC described in this section pertains only to the use of MS-2 bacteriophage. Use of a different viral indicator to demonstrate reactor performance will require additional documentation that the dose-response observed is typical of that observed by other researchers. In addition to the procedures outlined in this protocol, there is also Havalaar's ISO protocol to consider (International Standards Organization, 1995).

Collimated-Beam Apparatus Quality Assurance/Quality Control (QA/QC)

Because no means exist to measure the UV dose delivered to a microbe in a UV reactor, the primary purpose of the bioassay is to assess the disinfection efficacy of the UV reactor; however, such a goal cannot be attained without the proper controls to ensure the integrity of the microbial cultures used to test the reactor. Since manufacturers will test equipment at different times and under different conditions, it is important to reduce the variability inherent in the biological component of the bioassay to gain some degree of comparability between test results of the different UV reactors. There must be some assurance that the propagation, harvesting, and preparation of the microbial stock results in the production of a homogenous, monodispersed suspension of microorganisms before the material is introduced into the UV reactor. Attaining this goal will provide better comparability of bioassay results.

Molecular techniques to assay organism cultures for purity have not been developed. Although it has been suggested by a few researchers, adding antibiotics to prevent the growth and propagation of hosts that support the growth and propagation of other bacteriophage has not been adequately demonstrated to be effective. Consequently, the purity of the seed stock shall be checked by a smaller bioassay (dose response) of the seed stock using a collimated-beam apparatus.

Any method used to produce a homogenous, monodispersed culture of MS-2 is acceptable as long as the resulting dose-response curve has the following characteristics:

The QA/QC of the data shall be conducted by plotting the dose-response data on a graph of the UV dose (mJ/cm^2) (x-axis) versus the log inactivation (y-axis). The linear regression through the data must fall in the area bound by Equations 3.1 and 3.2.

$$-\log_{10}(N/N_o) = (0.040)\ (\text{UV dose, } mJ/cm^2) + 0.64 \quad (3.1)$$

$$-\log_{10}(N/N_o) = (0.033)\ (\text{UV dose, } mJ/cm^2) + 0.20 \quad (3.2)$$

Where:

N = Concentration of infective MS-2 after UV exposure.

N_o = Concentration of infective MS-2 at dose zero.

The UV dose is not to exceed 150 mJ/cm^2 and should not fall below 20 mJ/cm^2. One method of propagating, harvesting, and preparing the seed stock has been included at the end of this section. Any other protocol or deviation from this protocol must be documented. Any protocol or change in the appended protocol that still produces a dose-response curve that meets the aforementioned criteria can be used to prepare the MS-2 seed stock.

In addition to meeting the aforementioned criteria, at least 80 percent of the data points should lie inside the area defined by Equations 3.1 and 3.2. The remaining can lie in the region outside the area defined by Equations 3.1 and 3.2. All data points in the dose range of 20 to 150 mJ/cm^2 shall be included in the conduct of a regression analysis. The regression analysis is not to include the "zero dose" point. The final regression line must lie within the area bounded by Equations 3.1 and 3.2.

Once the quality of the MS-2 stock has been assured, the standard MS-2 dose-response relationship shall be used to define disinfection performance in both the validation and spot-check bioassays. The standard MS-2 equation to be used to assign the RED is:

$$\text{x (UV dose)} = \frac{\text{y (log inactivation)} - 0.5464}{0.0368} \quad (3.3)$$

where the units of UV dose are mJ/cm^2.

Rationale

Wright and Lawryshyn (2000) discuss the importance of the sensitivity of microorganisms to UV and how such information should be used in conjunction with a bioassay as a measure of the effectiveness of any UV reactor. Their contention is that if the organism used in the bioassay is less resistant than the target pathogen, then the degree of inactivation of the target pathogen will be less than or equal to the log inactivation attained by the inactivation of the bioassay organism. Unfortunately, the bioassay will not be able to establish the inactivation efficacy of the UV reactor with respect to the target pathogen as the impact of the variables on UV reactor performance is not linear. Whereas, if the organism used in the bioassay is more resistant to UV than the target pathogen, then one is assured of at least achieving a similar degree of inactivation on the less resistant organism. The collimated-beam apparatus test dose range was limited to greater than 20 mJ/cm^2 so that there was assurance that inactivation behavior was log-linear and at least 1 log of MS-2 inactivation would be achieved. If the dose-objective is less than 20 mJ/cm^2 for a

site-specific installation, inactivation of MS-2 bacteriophage is not likely the appropriate viral indicator and other protocols should be consulted (e.g., EPA, 2006).

The "zero dose" point is not to be included in the regression analysis because MS-2 dose-response is not linear all the way to a dose of zero. The linear regression must only be applied to the linear portion of the dose-response curve.

A standard MS-2 dose response curve is used when assigning REDs to minimize the impact of experimental variability on RED assignment. Different researchers, different laboratories, and the variance inherent in biological systems will affect the regression equation even with replicates of a single sample. Use of the site-specific regression equation is intended only to demonstrate the integrity of the MS-2 titer used for testing. Because the revised methodology for assigning REDs in this chapter during both pilot validation and spot-check testing will minimize errors in dose-assignment, and because the target design doses for granular medium filtration, membrane filtration, and RO have already accounted for variability in effluent quality (See Chapter 2, Section 2, UV Dose), no further accounting for experimental variability is warranted.

The standard MS-2 dose-response relationship was developed by comparing the dose-response relationship for MS-2 reported by three different laboratories that routinely conduct MS-2 viral assays. The data used to generate the standard curve from the three laboratories is illustrated in Figure 1. There was considerable variability even within a single laboratory. However, on an average basis, all of the laboratories reported similar dose-response. The entire dataset derived from the three laboratories was used to develop the standard MS-2 dose-response curve. The intent of making use of a standard curve is to eliminate as much experimental variability as is possible to prevent unnecessary facility de-rating upon comparing the design equation to the site-specific spot-check validation assays conducted as part of facility commissioning.

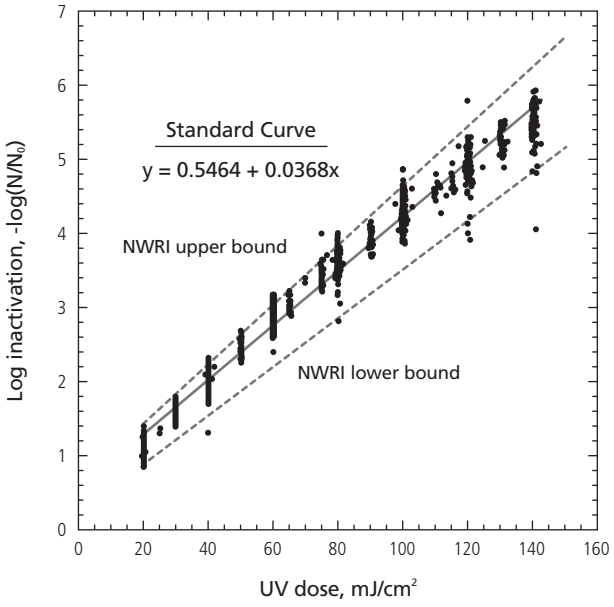

Figure 1: Dose-response relationship data from three laboratories was compared and used to develop the standard MS-2 dose-response curve.

Assay and Enumeration of the MS-2 Bacteriophage

After the seed has been harvested, it must be titered and prepared for extended storage (e.g., frozen), if necessary. Dose-response validation with a collimated-beam apparatus must be completed within 24 hours. The collimated-beam apparatus dose-response curve must meet the specifications described under the QA/QC procedures. A method for the enumeration of MS-2 is contained in the twentieth edition of *Standard Methods for the Examination of Water and Wastewater* (American Public Health Association et al., 1998). Method 9211D is used for MS-2 detection. The host bacterium for Method 9211D is *E. coli* ATCC 13706, which differs from the host bacterium specified in the enumeration assays listed below (*E. coli* ATCC 15597).

The EPA is in the process of establishing standard protocols (*Method 1601: Male-specific [F+] and Somatic Coliphage in Water by Two-Step Enrichment Procedure* [EPA, 2000a] and *Method 1602: Male-specific [F+] and Somatic Coliphage in Water by Single Agar Layer [SAL] Procedure* [EPA, 2000b]) for the enumeration of coliphage. The host *E. coli* specified in the EPA methods is identified as *E. coli* HS(pFamp)R and not ATCC 15597. Either of the EPA methods can be used (substituting *E. coli* ATCC 15597 for *E. coli* HS[pFamp]R) to enumerate MS-2.

Quality Assurance/Quality Control (QA/QC)

An influent sample to the test unit undergoing verification shall be used to produce a minimum five-point dose-response curve using a collimated-beam apparatus (each dose should be assayed in triplicate) that meets the criteria outlined above. MS-2 stock cultures that do not respond to UV disinfection cannot be used in the bioassay to validate or spot-check UV reactor performance. The results from tests or assays not used to validate the reactor performance must still be reported, but will not be used to determine the bioassay dose-response curve.

Rationale

It is generally recognized that the propagation of the seed organism depends on good laboratory practice and sterile techniques to maintain the purity of the stock cultures. However, good laboratory practices and sterile techniques alone do not guarantee that some other bacteriophage will not enter the cultures and successfully compete against the MS-2, resulting in a different composition of the stock culture. An improper microorganism might be used if quality-control measures are not in place. Consequently, the results from the bioassay may lead to an incorrect evaluation of the UV reactor performance. For example, if the seed organism is more susceptible to UV, then the UV reactor may appear to be more efficient at delivering the desired UV dose because a higher log removal is achieved at a lower dose. Thus, a contaminated culture can provide an unjustified competitive advantage to a manufacturer. Because the bioassay is the primary means of validating the performance of a UV reactor, the purity of the cultures must be maintained or erroneous results can produce an inadequately designed UV disinfection system (i.e., one that is delivering less operational dose than assumed). Without testing the seed stock cultures under strictly controlled conditions, it is impossible to distinguish between UV reactor performance and improper seeding materials.

Preparing the MS-2 Bacteriophage Seed

Host Bacterium:

Escherichia coli (ATCC 15597 Preceptol™ Culture "C3000" derived from *E. coli* strain K-12; Strauss and Sinsheimer [1963]).

Bacteriophage:

MS-2 (ATCC 15597-B1): icosahedral symmetry, f-specific, linear single-stranded RNA, 28 nm. Family: Leviviridae. Genus: *Levivirus*. Type species: Enterobacteria phage MS-2.

Begin by starting an overnight culture of the *E. coli* host bacteria (ATCC 15597). Inoculate fresh tryptic soy broth (TSB) with an aliquot of frozen host bacteria and grow overnight at 35 to 37°C. For example, inoculate the host bacterium culture, *E. coli*, into 10-mL TSB (Difco) and incubate for 18 to 24 hours at 35 to 37°C.[4]

Propagation Option 1. The following day, inoculate 100 mL of fresh TSB with *E. coli* (a ratio of 1 to 100 dilution of the bacteria) and incubate at 35 to 37°C with continuous shaking at approximately 75 revolutions per minute (rpm). Allow the culture to grow for 3 to 4 hours until it is visibly turbid (indicative of log-phase growth) and add 2 mL of MS-2 at a concentration of 10^9 plaque forming unit per milliliter (pfu/mL). After the MS-2 is added to the log-phase bacteria, the culture is left in the incubator (shaking at 35 to 37°C) overnight (about 16 hours).

Recover the phage from the broth culture on the following day by centrifuging at 8,600 gravity (G) for 15 minutes to remove cells and cellular debris. The supernatant is centrifuged again at 17,000 G for 15 minutes. After the second centrifugation, the supernatant is filtered through a 0.45-micrometer (μm) low protein-binding filter that is normally used for tissue culture sterilization.

Serial dilutions of filtered MS-2 stock solution 10^{-1} to 10^{-12} are prepared. The stock dilutions are assayed by an overlay agar assay technique (Adams, 1959; Yahya et al., 1992) to determine the titer of purified phage stock. The prepared seed should be used for seeding the UV inactivation experiment within a month.

Propagation Option 2. Transfer 1 mL of a 24-hour *E. coli* culture into 50 mL TSB and incubate for 4 to 6 hours at 35 to 37°C with continuous shaking at 100 rpm. The MS-2 culture is diluted serially using 2.5 grams per liter (g/L) Tris buffer, pH 7.3 (Trizma base, Sigma Chemical) to an approximate concentration of 10^5 pfu/mL (stock MS-2). A 1-mL volume of the stock solution (10^5 pfu/mL) is transferred into each 50 mL, 3- to 6-hour *E. coli* culture and incubated overnight at 35 to 37°C.[5]

The bacteriophage is recovered from the culture suspension by centrifugation at 8,000 G for 10 minutes at 4°C. Filter the resulting supernatant through a 0.45-μm low protein-binding filter that is normally used for tissue culture sterilization.

Serial dilutions of filtered MS-2 stock solution 10^{-1} to 10^{-12} are prepared. The stock dilutions are assayed by overlay agar assay technique (Adams, 1959; Yahya et al., 1992) to determine the titer of purified MS-2 stock. The prepared seed should be used for seeding the UV inactivation experiment within the month.

Recovery Option:

1. Add 2-mL chloroform to 700-mL broth and shake vigorously for 5 to 10 minutes.
2. Centrifuge the broth (5,000 G) at maximum speed for 20 minutes.

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4 Use relative volumes of cultures, inoculum, and phage stock solutions to scale-up the phage preparation procedure. For example, add 10 mL 24-hour culture to 500-mL TSB and 10 mL of 10^5 pfu/mL MS-2 stock to a 3- to 6-hour culture to prepare a 500-mL MS-2 stock solution.

5 Once the laboratory has established and checked their procedure to verify that 3 to 4 hours of incubation places the culture in log phase, it is not necessary to routinely check the optical density of the cultures. Previous documented experience should be sufficient to demonstrate that a ratio of 1 to 100 dilution of bacteria followed by 3-to-4 hour growth puts the culture in log phase.

3. Decant the supernatant (make sure to leave chloroform behind [it will sink to bottom]), and filter the supernatant through a 0.45-μm membrane filter into a sterile container.

Tris Buffer. Tris (hydroxymethyl) — aminomethane (Trizma base, Sigma Chemical) for the preparation of serial dilutions. Dissolve 2.5-grams (g) Tris (Trizma hydrochloride, Sigma Chemical) in 1 liter (L) of ultrapure water and adjust the pH to 7.3. Autoclave as above. Store at room temperature. Dispense 2.7 mL each into sterile glass culture tubes for serial dilutions.

Rationale

The broth culture propagation procedures[6] are taken from the protocols submitted by the Los Angeles County Sanitation Districts (Thompson, 1999) and Orange County Sanitation District (CH2M Hill, 1999). Another protocol, received from the University of California, Davis, was also included in the review. These respective laboratories propagate and harvest MS-2 for use in UV inactivation studies. While the growing procedures are not the same, the differences would not impact the MS-2 response to UV disinfection significantly. Both protocols used the same host and bacteriophage, and both started with growing a flask of host organisms. The protocols then diverge slightly in how the MS-2 is recovered from the *E. coli* culture. Consequently, these protocols present two options, with an additional option for recovering the bacteriophage from the *E. coli* culture. Once the MS-2 solutions have been centrifuged and filtered, they are assayed to determine the titer.

4. Testing and Sampling Requirements

The testing and evaluation of the performance of UV reactors using surrogate dose-response and reactor-validation testing are described in this section. Standard test methods and procedures should be used whenever possible or feasible (e.g., Standard Methods, appropriate EPA methods, etc.).

Collimated-Beam Apparatus Dose

The collimated-beam apparatus results for each test shall be presented in both tabular and graphical form. The table shall include the UV transmittance and turbidity for each sample, initial MS-2 concentration, MS-2 concentration and log-inactivation at each subsequent test, measured UV intensity before and after each test, exposure time, and calculated UV dose. The UV dose shall be calculated as follows:

$$D = I_o t[(1 - e^{-kd})/kd] \quad (4.1)$$

Where:

- D = UV dose at 254 nm (mJ/cm^2).
- I_o = Incident intensity at the surface of the sample at 254 nm (mW/cm^2).
- t = Exposure time (seconds).
- k = Absorbance coefficient (cm^{-1}) (note that this is base e).
- d = Depth of the sample (cm).

The incident intensity shall be corrected for reflectance at the surface of the sample. Surface reflectance is approximately 2.5 percent of the measured incident intensity (HydroQual, Inc., 2000). Thus, the value of I_o should be approximately 0.975 times the measured intensity at the surface of the sample. The absorbance coefficient is given in base e with units cm^{-1}. Absorbance

6 Use the method supplied by ATCC to derive an initial titer from a freeze-dried culture.

units per centimeter (a.u./cm) measured with spectrophotometers can be converted to the absorbance coefficient as follows:

$$\text{Absorbance coefficient, } k = (2.3)\ (\text{a.u./cm}) \tag{4.2}$$

Transmittance can be calculated from absorbance measurements by the relationship:

$$T, \% = [10^{-(\text{a.u./cm})}]\ 100 \tag{4.3}$$

The total MS-2 log inactivation shall be calculated as follows:

$$-\log(N/N_o) \tag{4.4}$$

Where:

N = Concentration of infective MS-2 after UV exposure.

N_o = Concentration on infective MS-2 at dose zero.

The collimated-beam apparatus data shall be plotted and compared to the QA/QC equations presented in Section 3 of this chapter. The collimated-beam apparatus data shall be plotted on a graph of the UV dose (mJ/cm^2) (x-axis) versus the log inactivation (y-axis). If it is found not possible to develop a dose-response relationship that is within the bounds described by Equations 3.1 and 3.2, the integrity of the coliphage may be in doubt or the conduct of the collimated-beam test may be in error. The test should be repeated with a different source of MS-2 coliphage traceable to ATCC 15597-B1, or EPA guidance (EPA, 2006) should be consulted to determine if errors are present in the conduct of the collimated-beam test.

Rationale

Establishing the UV dose involves determining the UV inactivation of a selected microorganism, MS-2, under controlled batch conditions. MS-2 inactivation follows first order kinetics over the range of UV doses proposed for collimated-beam apparatus testing, and the results are consistent and reproducible. When similar MS-2 seed and assay techniques are used (per Section 3 of this chapter), the results should be comparable; therefore, QA/QC of the results can be accomplished by comparing the results for a given test to the QA/QC equations presented in Section 3 of this chapter.

Collimated-Beam Apparatus Dose-Response Curve

To establish a dose-response curve, collimated-beam apparatus tests shall be carried out with seeded feed water used in reactor testing within 24 hours of the reactor test. The exposed samples shall be plated on the same day as the collimated-beam apparatus test. In general, the initial concentration of MS-2 should be about 2-logs higher than the number of logs of inactivation that are to be achieved. For example, if 4 logs of inactivation are to be achieved, the initial concentration should be 6 logs (10^6 pfu/mL).

UV Exposures: A series of sub-samples (five minimum) shall be exposed for a range of times calculated to achieve a range of UV doses from 20 to 150 mJ/cm^2, with a minimum interval of 25 mJ/cm^2. The exposed sample shall be plated in triplicate at dilutions appropriate to give 20 to 200 plaque forming unit per plate (pfu/plate).

The seeded test water shall be mixed thoroughly and pipetted into the petri dishes.

The contents of the petri dish shall be stirred thoroughly (e.g., a minimum of 10 seconds) prior to the initiation of UV exposure. To establish the initial concentration of MS-2, a separate sample shall be prepared and tested.

Instrument Calibration

The radiometer and sensor used in the collimated-beam apparatus test shall be calibrated in accordance with the manufacturer's specifications.

Reactor Evaluation and Validation

If the reactor is intended to be operated solely via its intensity sensor readings, the performance of the reactor will be evaluated at the minimum sensor reading over the specified flowrate operating range. There must be assurance that the minimum sensor level represents minimum inactivation potential due either to UV absorbance or low lamp output. The minimum sensor reading will be achieved in the following two ways:

1. The sensor reading will be lowered by reducing the UV transmittance of the test water while lamps operate at full output.
2. The sensor reading will be lowered by reducing the lamp output with full UV transmittance specified in Section 2 of Chapters 1 and 2 of these guidelines or the UV transmittance specified by the manufacturer for equipment validation.

The log inactivation achieved by these two methods will be compared. The test condition that results in the least MS-2 inactivation will be deemed the limiting factor for sensor sensitivity and will be employed in subsequent reactor testing.

The above described procedure is not required during spot-check commissioning tests. However, the series of tests investigated during the spot-check must include both high and low ballast settings and high and low transmittance values.

Rationale

By using these two different methods to reduce sensor readings, the relative sensitivity of the sensor location is evaluated. The sensor reading measured using the reduction method, which gives lower inactivation, is assumed to reflect the true minimum UV intensity.

Revalidation of the equipment is not an objective of the spot-check commissioning tests. Rather, the focus of the spot-check commissioning tests is to verify that operation matches design intent. Investigating various ballast settings and water transmittance values during the spot-check commissioning tests is sufficient to verify fulfillment of design intent.

Water-Quality Matrix for Validation Testing

The water-quality matrix used for collimated-beam apparatus testing and UV reactor validation shall be identical. Test water for validation shall have characteristics of the intended application as defined in the outline below:

Intended Application Water	*Test Water*
Drinking waters	
Unfiltered surface water	Site-specific water
RO-treated or microfiltered water	Any finished drinking water
Filtered surface water or groundwater	Any finished drinking water
Reclaimed waters	
RO-treated or microfiltered water	Any finished drinking water
Granular, synthetic, or cloth media filtered water	Granular media filtered reclaimed water (1-ntu minimum turbidity)

For all waters, the UV transmittance will be adjusted to the minimum level determined in "Reactor Evaluation and Validation." The additives used to adjust UV transmittance shall have a uniform effect across the 200- to 300-nm range and shall be applied uniformly to the reactor stream.

Prior to testing, the absence of chemical disinfectants shall be verified. Any quenching agents or their byproducts used should not significantly impact the UV transmittance in the 200- to 300-nm range or harm MS-2.

Rationale

As indicated in the guidelines, the impact of particles on UV disinfection is minimized for waters with significant levels of pretreatment or high-quality groundwaters. Reactors that are to be applied to such waters may be tested with similar high-quality water. As the water quality of the intended application decreases, test water reflecting this lower quality should be used. Any chemicals used to alter the physical or chemical characteristics of the water should have a known and uniform impact on all relevant parameters.

Reactor Validation Tests

Reactor validation tests shall be conducted over a range of operating flowrates, including lowest and highest, at which the unit is proposed to be operated and at a minimum of two intermediate flowrates. If the system is to be controlled solely via the use of intensity sensors, the least effective of the sensor evaluation test conditions, as discussed above, shall be incorporated in these tests. The maximum interval between two tested flowrates shall not exceed 150 percent of the lower of the two rates.

Testing at each flow condition shall be conducted three times. Three samples shall be collected from the inlet and outlet over the course of each test. The mean of the three influent samples will be used as the UV reactor influent concentration for that test. The inactivation value shall be established as follows:

- *For drinking water:* At each test condition (e.g., flowrate, transmittance, ballast setting), the average inactivation result shall be determined from the three replicates. The RED shall then be assigned making use of the standard MS-2 dose response curve. The overall predictive model used for design and operation shall be derived using the lower 90-percent confidence prediction interval, making use of all of the inactivation results.
- *For reclaimed water:* At each test condition (e.g., flowrate, transmittance, ballast setting), the average inactivation result shall be determined from the three replicates. The RED shall then be assigned making use of the standard MS-2 dose response curve. The overall predictive model used for design and operation shall be derived using the lower 75-percent confidence prediction interval, making use of all of the inactivation results.

Rationale

By establishing the inactivation of MS-2 across a range of flowrates (and at minimum sensor readings, if the reactor is controlled solely via intensity sensor measurements), the acceptable operating range of the reactor can be determined. The prediction interval is used because the procedure is used in an attempt to predict full-scale performance. The lower 90 percent (for drinking water) or 75 percent (for reclaimed water) prediction interval over the entire data set is most applicable when using the results to develop a model useful for system operation.

Reactor Spot-Check Commissioning Tests

Eight test conditions shall be investigated in a manner similar to conducting the validation tests as part of the full-scale commissioning test. Whereas the validation tests required the inclusion of the entire operational range of transmittance values, flowrates, and ballast settings in its conduct, the spot-check commissioning test only needs to show performance at eight different operational conditions. The operational conditions do not need to account for the entire range of expected operation.

Any eight test conditions can be investigated as part of the spot-check validation test. The tests should include changes to the largest possible number of operational parameters. Operational parameters include:

- Bank placement (inlet, middle, outlet).
- Ballast setting.
- Flowrate.
- UV transmittance.

The RED for each test condition will be assigned making use of the same methodology used during validation testing.

The commissioning test report will present a comparison of the intended RED values for each test derived from the operational equation that was developed from the reactor validation tests to the dose values observed during the spot-check commissioning test.

The RED values for each test condition shall be compared to the intended design values. If new lamps are used as part of the system commissioning tests, the results should be compared to the design curve prior to the application of lamp aging or fouling factors. If aged lamps are used as part of the system commissioning tests, the results should be compared to the design curve with the aging factor in place. Only clean systems should be tested. Thus, the lamp fouling factor is not to be included when comparing spot-check performance to the design equation.

The performance ratio for each test condition shall be calculated as the ratio between spot-check performance and predicted performance (from the operational model derived from the validation testing). There must be seven passing tests out of the eight conducted (i.e., the performance ratio must equal or exceed 1.0 on seven of the eight test conditions). If necessary, the design equation can be reduced or a site-specific dose goal shall be developed that assures that the performance ratio is always greater than or equal to 1.0 for seven of the eight tests. An example illustrating the spot-check commissioning tests and analysis is provided in Appendix A.

If, upon system commissioning, it is found that system de-rating is required to ensure seven passing tests out of eight, it is permissible to undertake system modification to aid in returning system performance to design intent. Examples include modifying hydraulic performance, modifying channel geometry, altering weir height, etc. After system modification is complete, the entire suite of eight tests must be re-performed and analyzed per the guidance above.

Rationale

It is not necessary to define the eight spot-check test conditions because it is not the intent of the spot-check commissioning tests to revalidate the UV disinfection system. Full-scale facilities are inherently limited in their operational flexibility. Considerable discretion must be afforded the research team to complete the commissioning tests within the system operation constraints.

The lower 90-percent confidence values (for drinking water applications) or lower 75-percent confidence values (for recycled water) are compared to the design equation because the lower 90-percent prediction interval (for drinking water) or lower 75-percent prediction interval (for recycled water) was used for equation development. Comparison in this manner assures the realization of design intent and maintenance of a desired level of public protection in the application of a RED.

Sample Collection and Handling

Sample Collection: Sample points shall be located away from the pipe or channel wall and outside the UV exposure field. For open channels, effluent samples shall be collected downstream of the effluent weir. Sampling shall be initiated after the flowrate is established and a minimum time period corresponding to five empty-bed contact times has passed.

Sample Handling: Sample bottles shall be sterile and of volumes appropriate to the anticipated dilutions to be analyzed. Samples shall be chilled immediately to 4°C and delivered to the laboratory and analyzed within 24 hours. Samples shall not be held for longer than 24 hours before analysis.

Rationale

Attention to proper sample collection and handling will ensure that the analytical results accurately reflect the effect of UV intensity on the sampled organisms by the tested reactor.

Lamp Age Factor Testing

Ideally, aged lamps are to be used during validation testing so that the impacts of lamp aging are integrated into the model used for design and operation directly. If new lamps must be used for validation testing, it is recommended that design engineers make use of the default lamp age factor unless the manufacturer provides a test report documenting that an alternative value is more accurate. Alternative lamp age factors shall be developed by comparing spot-check bioassays performed on a single full-scale facility with similar test conditions making use of (1) new lamps and (2) aged lamps. The spot-check bioassays shall be conducted on a system with a minimum of 10 lamps selected from two different lamp batches. The manufacturer must specify the maximum number of on/off cycles and intervals that the lamps will be operated (with a minimum of four on/off cycles per day). The full-scale UV disinfection system shall be designed to automatically limit the number of on/off cycles and intervals to the number of cycles used for validation testing.

Rationale

The impacts of lamp aging are best determined via operation in a full-scale facility undergoing exposure to typical lamp starts and stops and wastewater temperature variability. Comparing full-scale spot-check results observed in a full-scale facility will allow for calculating population performance rather than individual lamp performance.

Cleaning Mechanism Testing

The design engineer is free to make use of any desired fouling factor to account for sleeve fouling (i.e., reduction in dose resulting from sleeve fouling). The design assumption shall be tested during the spot-check commissioning test to establish a cleaning frequency that ensures compliance with design intent. The cleaning frequency will be developed by noting the intensity sensor reading

under clean conditions, allowing the system to operate for a defined time period, and then noting sensor intensity at the fully fouled condition. The fully fouled condition is not to exceed the assumed sleeve fouling safety factor.

Rationale

A standard safety factor for sleeve fouling cannot be developed on one water type and then applied to another water type. A fouling factor suggested by the system manufacturer can be used, but the cleaning frequency must be adjusted for the site-specific water to maintain system effectiveness. The design engineer is responsible for conducting the due-diligence necessary to ensure use of an appropriate fouling factor for any specific UV disinfection system installation.

Instrument Calibration

The flow meter readings shall be verified across the operating range of the reactor prior to testing. The on-line turbidity meter and the UV transmittance monitor, as well as the on-line and reference sensor, shall be calibrated per manufacturer recommendations. The performance of the additive dosing equipment shall be verified. The calibration results or certificates shall be provided with the equipment validation results.

5. Data Analysis and Reporting

The analysis and reporting of the data requires calculating the UV dose and the QA/QC of the collimated-beam apparatus results, determining the RED for the reactor, and statistically analyzing the results (see Appendix A). The reporting format and tabular and graphical presentation of the data must also be standardized to accommodate the review and analysis of the test results. If pilot-scale reactors are validated, the data analysis and reporting shall also present the scale-up considerations from the pilot-scale to full-scale facilities.

UV Reactor Dose Assignment

For the validated reactor, the total MS-2 log inactivation shall be calculated as follows:

$$-\log_{10}(N/N_o) \qquad (5.1)$$

Where:

N = Concentration of infective MS-2 exiting the disinfection system after exposure to UV.

N_o = Concentration of infective MS-2 in the reactor influent.

The UV inactivation values and operational doses for water and reclaimed water applications shall be determined as described in Section 4 of this chapter and illustrated in Appendix A. Results shall be reported in terms of flow per lamp (e.g., gallons per minute per lamp [gpm/lamp], liters per minute per lamp [Lpm/lamp]). The per-lamp RED shall be calculated as the ratio of flow for each assigned RED to the number of lamps in the test reactor (at the tested minimum sensor reading, if operated according to sensor intensity values). Interpolation of performance between flowrates and transmittance values will be permitted only within the conditions investigated during validation testing. REDs can not be mathematically assigned to different sensor readings or alternative lamp spacing arrangements (i.e., extrapolation). The UV equipment performance shall be validated for alternate sensor reading or lamp spacing.

The UV equipment manufacturer shall provide the procedure for establishing the operational UV dose for the range of flows the UV reactor is validated for (i.e., the operational model) and shall constitute the basis of the system validation (refer to Appendix A for an example). The operational UV dose cannot be mathematically assigned to different sensor readings or UV transmittances. Validation testing shall be conducted to demonstrate the impact of changes in UV transmittance, ballast settings, and/or sensor readings on the UV equipment performance and operational UV dose.

The UV equipment validation results shall be presented in tabular and graphical forms and summarized by the design and operation equation. The data summary table shall include:

- UV transmittance.
- Temperature and turbidity of the test water.
- Influent and effluent MS-2 concentration.
- MS-2 log inactivation.
- RED.
- On-line sensor readings.
- Ballast power output for each test point.

The report shall include a comparison of reference and on-line sensor readings before and after each test run, with the reactor filled with the test water. All data collected during the equipment validation test (i.e., MS-2 replicates, lamp age, ballast power set, actual ballast output, on-line and reference sensor readings, test water quality and temperature) shall be included in tabular form in the report. Instrument calibration results or certificates (i.e., turbidity meter, on-line UV transmittance monitor, on-line and reference sensors) shall also be included in the report.

The graphical representation of the data shall present the following:

1) The log inactivation of MS-2 as a function of flow per lamp.

2) The RED as a function of flow per lamp.

Each test condition (i.e., minimum sensor reading, UV transmittance, lamp spacing) shall be presented as a separate curve. All data points shall be clearly shown on the plot. If in-line dosing of the additives and bacteriophage is used, test results shall be presented to show that proper mixing is achieved. The reactor is considered validated for the continuous flow range that meets or exceeds the required target inactivation. An example of an acceptable validation test is provided in Appendix A.

Rationale

For the purpose of standardization, the RED is defined as achieving the same degree of MS-2 inactivation in a continuous flow reactor as is achieved in a collimated-beam apparatus reactor equipped with a low-pressure, non-ozone producing mercury lamp. Experimental validation of dose delivery by UV technologies is necessary because of the uncertainties associated with calculating UV dose from limited information available for the lamp technology (i.e., different wavelengths emitted and their associated intensities) and the limited tools available for complete characterization of hydraulic behavior within the reactor. Even the more sophisticated tools available for dose calculation, such as those based on computational fluid dynamics, require validation against empirical data.

Reactor intensities increase as UV transmittance increases. This phenomenon alters the dose distribution within the reactor; however, at higher UV transmittances, more flow can be passed through a given reactor for a constant RED. Changes in flowrate typically alter the hydraulics through a system in a manner that normally cannot be predetermined. Additional pilot testing for higher UV transmittances (higher sensor settings) is required to demonstrate changes in the system's hydraulic behavior.

The use of flow per lamp for a specific log inactivation and the corresponding RED at a set sensor reading will contribute to predictable UV dose delivery of full-scale facilities by ensuring that similar hydraulic behavior is present for both the validated test reactors and full-scale facilities. Similarly, changes in lamp spacing alter the dose distribution and hydraulics of the UV reactor and need to be validated.

Scale-Up Considerations

Scale-up may involve as many as three characteristics of the system:

- The number of lamps in a reactor.
- The number of reactors in a reactor train
- The number of reactor trains in a UV disinfection system.

For all UV systems, the equipment performance validation can be conducted with a reactor train consisting of one or more multiple reactors; however, the minimum number of reactors for full-scale application shall be the same as the number of reactors used for equipment validation. For drinking-water and water-reuse applications, as discussed below, the scale-up is allowed by the addition of identical reactors to a reactor train, where hydraulic independence can be demonstrated, or by addition of reactor trains using reactors identical to those used in validation testing.

In addition, for reclaimed-water applications only, spot-check validation testing during system commissioning can be used to verify design intent and allow larger reactors to be used in full-scale applications. The full-scale and test reactors shall have identical lamp spacing and water depth. The full-scale reactor shall be operated at the same velocity range and flow per lamp used for performance validation. There is no limit to scale-up for a given reactor. The UV equipment manufacturer shall establish and present how the inlet and outlet configuration and dimensions used in pilot-scale reactors will be modified to the full-scale reactors as a function of flow rate. For UV disinfection systems with free water surface, the total system headloss shall not exceed those measured in equipment validation testing.

For the reactor trains where reactors are hydraulically independent,[7] the RED per reactor shall be calculated as the total RED for the reactor train, divided by the number of on-line reactors. For full-scale applications, if the reactors are hydraulically independent, additional reactors can be added to each reactor train. The RED for the reactor train shall be the RED per reactor, multiplied by the number of on-line reactors in the reactor train (excluding the stand by reactor). For UV disinfection systems with free water surface, the total system headloss shall not exceed those measured in equipment validation testing. UV equipment manufacturers shall supply testing protocols and test reports, conducted by a qualified third party that establishes that the reactors are hydraulically independent. If the reactors are not hydraulically independent, then full-scale reactor trains shall be validated.

7 For these systems, hydraulic independence may be assumed if it is possible to verify that the inlet particle position in one reactor is independent of inlet particle positions in subsequent reactors.

Regarding the number of parallel reactor trains, scale-up is allowed when the reactor trains are identical and independent and the flow is equally distributed among the reactor trains. Similar approach and exit velocity profiles to and from the reactor trains and lamp output characteristics shall be maintained in all reactor trains.

Rationale

For drinking-water applications, there are no convenient indicator organisms, like total coliforms, available for the routine monitoring of UV disinfection system performance; therefore, it is important that the full-scale reactor be validated to ensure delivery of the design UV dose selected for target pathogen inactivation.

In theory, if sequential reactors in a reactor train are hydraulically independent and identical,[8] the process behavior (e.g., dose distribution) delivered by each bank will be identical and can be assumed to be additive. If the test organism displays first-order dose-response behavior, additivity will also apply to "log" inactivation. If these conditions are not met, it is not valid to assume additivity in sequential reactors. In the absence of information to support the assumptions of independence and identical behavior, it is necessary to validate reactor trains that have the same number of reactors as those intended for full-scale application.

Variability in lamp output represents a potentially serious issue for reactor scale-up. UV lamps are commonly assumed to be identical; however, when measurements of lamp output are conducted, substantial variations in lamp output are observed. These variations in lamp output can have a substantial effect on the performance of UV reactors, particularly when small numbers of lamps are involved. In larger systems, it is expected that lamp output variability will have a less profound effect on process performance. These arguments point out another level of uncertainty in scaling up from pilot-scale reactors (where small numbers of lamps are the norm) to full-scale systems.

The practice of conducting a spot-check bioassay eliminates concerns regarding scale-up because the actual performance of the full-scale facility will be investigated and documented.

8 Identical process behavior in UV reactors will be accomplished when inlet and outlet hydraulic behavior, reactor/lamp geometry, and lamp output spectra are identical.

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Appendix A: UV Computational Examples

The purpose of this appendix is to illustrate the computations involved in the application and evaluation of UV disinfection systems. The following example computations are addressed:

1. Verification of laboratory procedures for bacteriophage MS-2 response.
2. Conduct a pilot test to validate UV disinfection system performance.
3. Conduct a spot-check bioassay to validate the performance of a full-scale UV disinfection system.

Example 1 is provided to illustrate the steps involved in the development of a dose-response for a microorganism of concern (MS-2 bacteriophage, in this example). The procedure used to develop a validation equation for a UV reactor, based on the 75-percent prediction interval, is illustrated in Example 2. Evaluating the performance of an installed UV system using the spot-check method of validation and developing a site-specific safety factor, if needed, are illustrated in Example 3.

Example 1: Verification of laboratory procedures for bacteriophage MS-2 response

The collimated-beam test results in Table A-1 were obtained for a stock solution of bacteriophage MS-2, which is to be used to test a UV reactor. Verify that the laboratory test results are acceptable.

Table A-1: Collimated-Beam Test Results

Dose[a] (mJ/cm^2)	**Surviving Concentration (phage/mL)**	**Log Survival (log [phage/mL])**	**Log Inactivation (log [phage/mL])**
0	1.00×10^7	7.0	0.0
20	1.12×10^6	6.05	0.95[b]
40	6.76×10^4	4.83	2.17
60	1.95×10^4	4.29	2.71
80	4.37×10^3	3.64	3.36
100	1.20×10^3	3.08	3.92
120	7.08×10^1	1.85	5.15
140	1.48×10^1	1.17	5.83

[a]UV dose was computed using Equation 4.1 (Chapter 3).
[b]Sample calculation: Log inactivation = 7.00 – 6.05 = 0.95 log (phage/mL).

Solution

1. Plot the collimated-beam test results and compare to the quality control range expressions provided in the Chapter 3 (Equations 3.1 and 3.2). The results are plotted in Figure A-1.

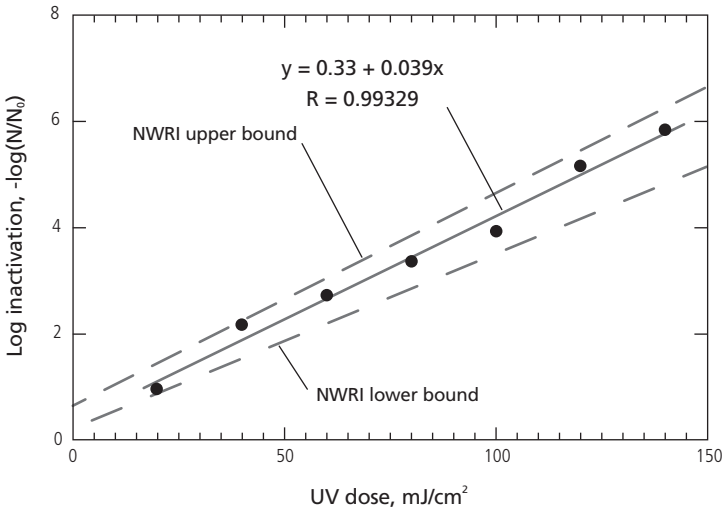

Figure A-1: Results of plotted collimated-beam results as compared to quality control range expressions.

2. As shown in Figure A-1, the regression curve for the site-specific virus falls within the acceptable range. Therefore, the virus is considered adequate for assay testing. The standard MS-2 dose response curve will be used for all subsequent data analysis to minimize experimental errors between the validation exercise and any spot-check assays to be conducted as part of individual field commissioning tests.

Comment

As noted above, the RED assignment will make use of Equation 3.3 (Chapter 3). Use of a standardized dose-response curve, based on the statistical analysis of many individual dose-response curves from a number of laboratories, will make it possible to compare the performance of UV systems from different manufacturers on a uniform basis.

Example 2: Conduct a pilot test to validate UV disinfection system performance

The manufacturer has supplied a pilot-scale UV disinfection system to be tested for the assignment of UV doses as a function of lamp hydraulic loading rate. The manufacturer has requested that an operational curve be developed to allow automated system operation, based on flowrate and transmittance. Because the UV disinfection system will be used for filtered secondary effluent, it is desired to determine the range of flows, expressed as L/min•lamp, over which the UV disinfection system will deliver a dose of 50 mJ/cm^2 at a prediction interval level of 75 percent. The manufacturer has specified that the UV disinfection system should be tested for hydraulic loading flowrates varying from about 30 to 300 L/min-lamp. The steps involved in the UV validation process are delineated below.

Solution

1. Set up a pilot testing facility.
   a. The manufacturer chose to make use of a four-lamp-per-bank pilot facility. Three banks were provided to account for impacts related to inlet hydraulics, outlet hydraulics, and internal hydraulics. Because each bank is considered hydraulically independent, the actual bank location is not delineated explicitly in the data analysis, but rather is included so that overall model variance is adequately characterized.
   b. New lamps were placed in the pilot facility. To simulate the performance of the UV lamps at the end of their warranted life and to account for fouling, correction factors will be applied to the final design equation. New lamps were used because it would take at least a year if aged lamps were used before the UV reactor could be validated.
   c. Testing was conducted on tertiary effluent from a local wastewater reclamation facility. Normal transmittance of the tertiary effluent is 75 percent. Transmittance reducing agent (e.g., instant coffee, Super Hume™) was injected into the process stream until the transmittance was lowered to 55 percent. Testing on water with different transmittance values will allow for development of an operational equation that accounts for changes in transmittance.
2. Test the UV reactor.
   a. The test organism was MS-2 bacteriophage.
   b. Each flowrate was tested randomly with respect to order. The actual low and high flowrates tested were 31.4 and 283.9 L•min/lamp, respectively. Three distinct replicate samples were collected per flowrate per transmittance condition. An inlet sample (i.e., that containing the concentration of phage prior to any inactivation) was collected with each process replicate.
   c. The inlet and outlet phage concentration was determined for each test condition. The test results at a transmittance of 55 percent are provided in Table A-2 (columns 1 through 5 and 8). Test results at a transmittance of 75 percent are provided in Table A-3 (columns 1 through 5 and 8).
3. Analyze the test data and determine the UV dose.
   a. Calculate the logarithm of the inlet and outlet phage concentrations (columns 6 and 9 in Tables A-2 and A-3).
   b. Compute the arithmetic average of the three logarithmic concentrations (columns 7 and 10 in Tables A-2 and A-3).
   c. Determine the average log inactivation by subtracting the values in column 10 from the values in column 7 (the average log inactivation is given in column 11 in Tables A-2 and A-3).
   d. Determine the UV dose using the standard MS-2 dose-response relationship (presented in Chapter 3).

$$x\ (\text{UV dose}) = \frac{y\ (\log \text{inactivation}) - 0.5464}{0.0368} \qquad (3.3)$$

For the first log inactivation value given in column 11 in Table A-2, the corresponding UV dose is equal to:

$$\text{UV dose} = \frac{3.49 - 0.5464}{0.0368} = 79.9\ \text{m/cm}^2$$

The computed UV dose is shown in column 12. The other values given in column 12 were computed in the similar manner.

Table A-2: UV Reactor Test Data at 55-Percent Transmittance

Normalized Flowrate (L/min-lamp)	Bank	Transmittance (%)	Replicate	Inlet Phage			Outlet Phage			Average Log Inactivation (phage/mL)	UV Dose Assignment (mJ/cm^2)
				Measured Concentration (phage/mL)	Log (Conc.) (phage/mL)	Average Log (Conc.) (phage/mL)	Measured Concentration (phage/mL)	Log (Conc.) (phage/mL)	Average Log (Conc.) (phage/mL)		
1	2	3	4	5	6	7	8	9	10	11	12
31.4	inlet	55	1	5.80E+06	6.76		1.40E+03	3.15			
31.4	inlet	55	2	6.50E+06	6.81	6.74	1.60E+03	3.20	3.26	3.49	79.9
31.4	inlet	55	3	4.50E+06	6.65		2.60E+03	3.41			
63.2	inlet	55	1	6.70E+06	6.83		3.30E+04	4.52			
63.2	inlet	55	2	7.40E+06	6.87	6.86	3.30E+04	4.52	4.57	2.29	47.4
63.2	inlet	55	3	7.70E+06	6.89		4.70E+04	4.67			
110.5	inlet	55	1	2.60E+06	6.41		5.10E+04	4.71			
110.5	inlet	55	2	2.90E+06	6.46	6.45	5.70E+04	4.76	4.79	1.66	30.3
110.5	inlet	55	3	2.90E+06	6.46		7.80E+04	4.89			
157.9	inlet	55	1	3.30E+06	6.52		3.80E+05	5.58			
157.9	inlet	55	2	5.40E+06	6.73	6.66	3.20E+05	5.51	5.54	1.12	15.6
157.9	inlet	55	3	5.50E+06	6.74		3.50E+05	5.54			
31.4	middle	55	1	4.40E+06	6.64		1.30E+03	3.11			
31.4	middle	55	2	4.30E+06	6.63	6.62	8.20E+02	2.91	2.99	3.63	83.8
31.4	middle	55	3	3.80E+06	6.58		8.70E+02	2.94			
63.2	middle	55	1	1.50E+06	6.18		9.60E+03	3.98			
63.2	middle	55	2	1.40E+06	6.15	6.17	1.10E+04	4.04	4.03	2.13	43.1
63.2	middle	55	3	1.50E+06	6.18		1.20E+04	4.08			
110.5	middle	55	1	2.30E+06	6.36		8.90E+04	4.95			
110.5	middle	55	2	2.50E+06	6.40	6.41	7.30E+04	4.86	4.95	1.46	24.7
110.5	middle	55	3	2.90E+06	6.46		1.10E+05	5.04			
157.9	middle	55	1	1.90E+06	6.28		2.10E+05	5.32			
157.9	middle	55	2	1.20E+06	6.08	6.15	7.80E+04	4.89	5.05	1.10	15.0
157.9	middle	55	3	1.20E+06	6.08		8.40E+04	4.92			
31.4	outlet	55	1	4.10E+06	6.61		4.50E+02	2.65			
31.4	outlet	55	2	4.20E+06	6.62	6.59	2.20E+02	2.34	2.48	4.11	96.9
31.4	outlet	55	3	3.40E+06	6.53		2.70E+02	2.43			
63.2	outlet	55	1	2.20E+06	6.34		2.00E+04	4.30			
63.2	outlet	55	2	1.90E+06	6.28	6.33	1.80E+04	4.26	4.30	2.03	40.2
63.2	outlet	55	3	2.40E+06	6.38		2.20E+04	4.34			
110.5	outlet	55	1	1.90E+06	6.28		9.20E+04	4.96			
110.5	outlet	55	2	2.00E+06	6.30	6.29	6.20E+04	4.79	4.90	1.39	22.9
110.5	outlet	55	3	1.90E+06	6.28		8.60E+04	4.93			
157.9	outlet	55	1	2.10E+06	6.32		1.70E+05	5.23			
157.9	outlet	55	2	2.80E+06	6.45	6.39	1.60E+05	5.20	5.23	1.16	16.8
157.9	outlet	55	3	2.60E+06	6.41		1.80E+05	5.26			

Table A-3: UV Reactor Test Data at 75-Percent Transmittance

Flowrate (L/min-lamp)	Bank	Transmittance (%)	Replicate	Inlet Phage			Outlet Phage			Average Log Inactivation (phage/mL)	UV Dose Assignment (mJ/cm^2)
				Measured Concentration (phage/mL)	Log (Conc.) (phage/mL)	Average Log (Conc.) (phage/mL)	Measured Concentration (phage/mL)	Log (Conc.) (phage/mL)	Average Log (Conc.) (phage/mL)		
1	2	3	4	5	6	7	8	9	10	11	12
63.2	inlet	75	1	4.50E+05	5.65		1.20E+01	1.08			
63.2	inlet	75	2	8.00E+05	5.90	5.85	3.80E+01	1.58	1.34	4.51	107.8
63.2	inlet	75	3	1.00E+06	6.00		2.30E+01	1.36			
110.5	inlet	75	1	5.30E+05	5.72		1.00E+03	3.00			
110.5	inlet	75	2	4.80E+05	5.68	5.70	8.40E+02	2.92	2.94	2.76	60.2
110.5	inlet	75	3	5.00E+05	5.70		7.90E+02	2.90			
157.9	inlet	75	1	1.30E+06	6.11		2.20E+03	3.34			
157.9	inlet	75	2	1.00E+06	6.00	6.03	2.10E+03	3.32	3.32	2.71	58.7
157.9	inlet	75	3	9.30E+05	5.97		2.00E+03	3.30			
283.9	inlet	75	1	2.40E+06	6.38		6.50E+04	4.81			
283.9	inlet	75	2	2.30E+06	6.36	6.35	4.10E+04	4.61	4.68	1.67	30.6
283.9	inlet	75	3	2.00E+06	6.30		4.00E+04	4.60			
63.2	middle	75	1	1.10E+06	6.04		3.90E+01	1.59			
63.2	middle	75	2	1.10E+06	6.04	6.01	2.20E+01	1.34	1.47	4.54	108.4
63.2	middle	75	3	8.90E+05	5.95		3.10E+01	1.49			
110.5	middle	75	1	6.00E+05	5.78		6.20E+02	2.79			
110.5	middle	75	2	6.00E+05	5.78	5.76	2.30E+02	2.36	2.57	3.19	71.8
110.5	middle	75	3	5.20E+05	5.72		3.60E+02	2.56			
157.9	middle	75	1	2.40E+05	5.38		1.40E+03	3.15			
157.9	middle	75	2	2.40E+05	5.38	5.36	8.50E+02	2.93	3.02	2.34	48.7
157.9	middle	75	3	2.10E+05	5.32		9.90E+02	3.00			
283.9	middle	75	1	1.50E+05	5.18		7.80E+03	3.89			
283.9	middle	75	2	1.90E+05	5.28	5.19	5.60E+03	3.75	3.86	1.33	21.2
283.9	middle	75	3	1.30E+05	5.11		8.90E+03	3.95			
63.2	outlet	75	1	1.30E+06	6.11		1.00E+02	2.00			
63.2	outlet	75	2	1.40E+06	6.15	6.11	2.90E+01	1.46	1.78	4.33	102.9
63.2	outlet	75	3	1.20E+06	6.08		7.60E+01	1.88			
110.5	outlet	75	1	9.60E+05	5.98		5.10E+02	2.71			
110.5	outlet	75	2	8.80E+05	5.94	5.95	2.40E+02	2.38	2.54	3.41	77.8
110.5	outlet	75	3	8.10E+05	5.91		3.30E+02	2.52			
157.9	outlet	75	1	4.40E+05	5.64		1.60E+03	3.20			
157.9	outlet	75	2	6.80E+05	5.83	5.75	8.50E+02	2.93	3.14	2.60	55.9
157.9	outlet	75	3	5.90E+05	5.77		2.00E+03	3.30			
283.9	outlet	75	1	5.00E+05	5.70		6.40E+03	3.81			
283.9	outlet	75	2	4.60E+05	5.66	5.70	3.80E+03	3.58	3.73	1.97	38.7
283.9	outlet	75	3	5.60E+05	5.75		6.50E+03	3.81			

4. Develop the operational design equation.

   a. Use a multi-linear regression analysis to develop an operational equation based on water flowrate and transmittance. Other equations are possible, depending on the control strategy.

   b. To complete a regression analysis, the flowrate, transmittance, and UV dose data must first be log transformed. The data are log transformed to develop a linear relationship that can be used with the linear dose response curve developed using the collimated-beam (see Example 1). The log transformed data are presented in columns 4, 5, and 6 in Table A-4.

Table A-4: Data Analysis

Normalized Flowrate (L/min-lamp)	Transmittance (%)	Bioassay UV Dose (mJ/cm^2)	Log Transformed		
			Flowrate (Log [L/min-lamp])	Transmittance (Log [%])	UV Dose (Log [mJ/cm^2])
1	**2**	**3**	**4**	**5**	**6**
31.4	55	79.9	1.497	1.740	1.903
63.2	55	47.4	1.801	1.740	1.676
110.5	55	30.3	2.043	1.740	1.481
157.9	55	15.6	2.198	1.740	1.193
31.4	55	83.8	1.497	1.740	1.923
63.2	55	43.1	1.801	1.740	1.634
110.5	55	24.7	2.043	1.740	1.393
157.9	55	15.0	2.198	1.740	1.176
31.4	55	96.9	1.497	1.740	1.986
63.2	55	40.4	1.801	1.740	1.606
110.5	55	22.9	2.043	1.740	1.360
157.9	55	16.8	2.198	1.740	1.225
63.2	75	107.8	1.801	1.875	2.033
110.5	75	60.2	2.043	1.875	1.780
157.9	75	58.7	2.198	1.875	1.769
283.9	75	30.6	2.453	1.875	1.486
63.2	75	108.4	1.801	1.875	2.035
110.5	75	71.8	2.043	1.875	1.856
157.9	75	48.7	2.198	1.875	1.688
283.9	75	21.1	2.453	1.875	1.324
63.2	75	102.9	1.801	1.875	2.012
110.5	75	77.8	2.043	1.875	1.891
157.9	75	55.9	2.198	1.875	1.747
283.9	75	38.7	2.453	1.875	1.588

c. Using the UV dose (column 6) as the dependent variable and the flowrate (column 4) and transmittance (column 5) as the two independent variables, the results in Table A-5 are obtained using the multi-linear regression analysis add-in program XLSTAT for Microsoft Excel (other statistical packages can be used).

Table A-5:
Results Obtained from Multi-Linear Regression Analysis Add-In Program XLSTAT

Summary Output	
Regression Statistics	
R Square	0.953
Adjusted R Square	0.948
Standard Error	0.063
Observations	24
Analysis of Variance (ANOVA) (degrees of freedom [df])	
Regression	2
Residual	21
Total	23
Model Coefficients	
Intercept	-2.451
X Variable 1	-0.952
X Variable 2	3.328

d. Using the values given above the equation for UV dose as a function of flowrate and transmittance, based on the regression analysis, is

$$\log(\text{UV dose}) = -2.451 - 0.952(\log \text{flowrate}) + 3.328\ (\log \text{transmittance})$$

or

$$\text{UV dose} = (10^{-2.451})\ [(\log \text{flowrate})^{-0.952}][(\log \text{transmittance})^{3.328}]$$

5. Develop the operational design equation based on the lower 75-percent prediction interval.

   a. The statistical analysis program XLSTAT can be used to obtain the lower 75-percent prediction interval for corresponding predicted values from the regression analysis. The lower 75-percent prediction interval and the ratio between the two numbers for each of the experimental conditions are reported in Table A-6.

   b. The ratio between the lower 75-percent prediction interval and the predicted value is termed the confidence ratio. Making reference to Column 6 in Table A-6, the lowest confidence ratio of the dataset is 0.831. Therefore, the results of the multi-linear regression based prediction model will be multiplied by 0.831 to develop a design curve based on the lower 75-percent prediction interval.

6. Compute the predicted UV dose design values and correct for lamp aging and fouling.

   a. The predicted UV dose design values are given in Table A-7.

   b. To account for lamp aging and fouling, a correction factor of 0.8 will be applied, based on the manufacturers recommendation. Note the design engineer must decide what additional factor of safety may be required. The UV dose based on lamp aging and fouling is given in column 5 in Table A-7.

Table A-6: Lower 75-Percent Confidence Ratio Calculations

Normalized Flowrate (L/min-lamp)	Transmittance (%)	Bioassay UV Dose (mJ/cm^2)	Predicted UV Dose (mJ/cm^2)	Lower 75% Prediction Interval Dose (mJ/cm^2)	Confidence Ratio
1	2	3	4	5	6
31.4	55	79.9	82.4	68.4	0.831[a]
63.2	55	47.4	42.3	35.4	0.837
110.5	55	30.3	24.9	20.8	0.836
157.9	55	15.6	17.7	14.8	0.833
31.4	55	83.8	82.4	68.4	0.831
63.2	55	43.1	42.3	35.4	0.837
110.5	55	24.7	24.9	20.8	0.836
157.9	55	15.0	17.7	14.8	0.833
31.4	55	96.9	82.4	68.4	0.831
63.2	55	40.4	42.3	35.4	0.837
110.5	55	22.9	24.9	20.8	0.836
157.9	55	16.8	17.7	14.8	0.833
63.2	75	107.8	118.8	98.9	0.833
110.5	75	60.2	69.8	58.4	0.837
157.9	75	58.7	49.7	41.6	0.837
283.9	75	30.6	28.4	23.7	0.833
63.2	75	108.4	118.8	98.9	0.833
110.5	75	71.8	69.8	58.4	0.837
157.9	75	48.7	49.7	41.6	0.837
283.9	75	21.1	28.4	23.7	0.833
63.2	75	102.9	118.8	98.9	0.833
110.5	75	77.8	69.8	58.4	0.837
157.9	75	55.9	49.7	41.6	0.837
283.9	75	38.7	28.4	23.7	0.833

[a] Example calculation: 68.4 mJ/cm^2 divided by 82.4 mJ/cm^2 equals 00.831.

7. Prepare a plot of the predicted UV dose in mJ/cm^2 versus the flowrate in L/lamp•min based on (1) the predicted design equation based on the lower 75-percent prediction interval and (2) the design equation corrected for lamp aging and fouling. The required plot is presented in Figure A-2 at 55-percent and 75-percent UV transmittance conditions.

Comment

As noted in Step 4a, a number of different linear regression relationships are possible, depending on the control strategy. Factors that could be considered in the development of the control strategy include UV absorbance or transmittance readings, flowrate, relative sensor intensity, lamp aging, and ballast output (among others).

The underlying design equation used to develop the plot was not a step function; it is applicable at all transmittance values between those tested (e.g., 55 percent and 75 percent). The two conditions illustrated were chosen to illustrate the expected relationship between the design equation and the dataset underlying its development.

Table A-7: Design UV Dose

Normalized Flowrate (L/min-lamp)	Transmittance (%)	Bioassay UV Dose (mJ/cm^2)	Design UV Dose (mJ/cm^2)	UV Dose Corrected for Lamp Aging and Fouling (mJ/cm^2)
1	2	3	4	5
31.4	55	79.9	68.4	54.8[a]
63.2	55	47.4	35.4	28.3
110.5	55	30.3	20.8	16.5
157.9	55	15.6	14.8	11.8
31.4	55	83.8	68.4	
63.2	55	43.1	35.4	
110.5	55	24.7	20.8	
157.9	55	15.0	14.8	
31.4	55	96.9	68.4	
63.2	55	40.4	35.4	
110.5	55	22.9	20.8	
157.9	55	16.8	14.8	
63.2	75	107.8	98.9	79.1
110.5	75	60.2	58.4	46.7
157.9	75	58.7	41.6	33.3
283.9	75	30.6	23.7	19.0
63.2	75	108.4	98.9	
110.5	75	71.8	58.4	
157.9	75	48.7	41.6	
283.9	75	21.1	23.7	
63.2	75	102.9	98.9	
110.5	75	77.8	58.4	
157.9	75	55.9	41.6	
283.9	75	38.7	23.7	

[a] Example calculation: 68.4 mJ/cm^2 multiplied by 0.8 equals 54.8 mJ/cm^2. The number 0.8 is a manufacturer-recommended number, but is subject to engineering judgment.

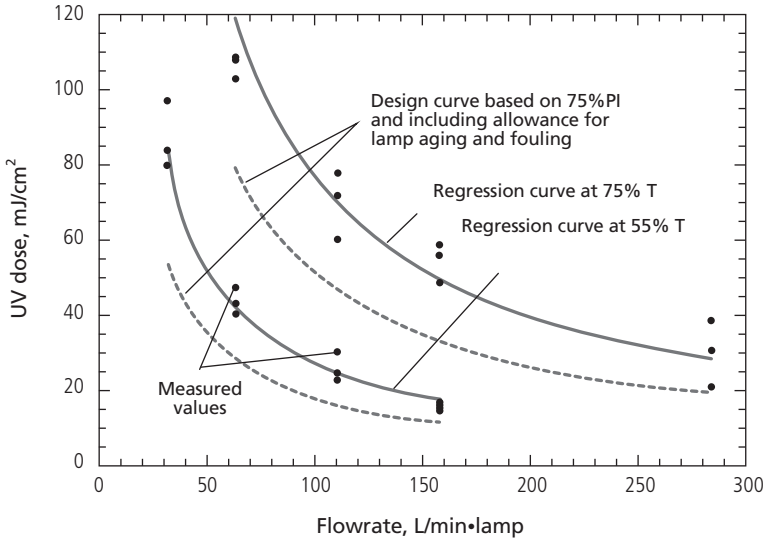

Figure A-2: Plot of the predicted UV dose versus the flowrate.

Example 3: Conduct a spot-check bioassay to validate the performance of a full-scale UV disinfection system

A spot-check bioassay is to be conducted to validate the performance of a newly installed and operational UV disinfection system at a wastewater treatment plant. The wastewater treatment plant has a design maximum hour flowrate of 20,000 L/min and a design minimum flowrate of 5,500 L/min. The UV system is comprised of four channels, each containing four banks of lamps. Each bank contains 48 UV lamps oriented parallel to flow. The system was designed to provide a UV dose of 100 mJ/cm^2 using three banks of lamps at the maximum hour flowrate, with the fourth bank provided for system redundancy. The design minimum transmittance is 70 percent, though typical operation is at a transmittance as high as 75 percent. The design equation used to size the UV disinfection system is that developed in Example 2.

$$\text{UV dose} = (10^{-2.451})\,[(\log \text{flowrate})^{-0.952}][(\log \text{transmittance})^{3.328}](0.831)(0.8)$$

where 0.831 is the coefficient used to obtain the lower 75-percent prediction interval, and 0.8 is the factor used to account for lamp aging and fouling.

The system was designed such that lamp aging and fouling would reduce the design dose to 80 percent of the new lamp non-fouled condition. The ballast setting can be adjusted to provide a dose between 60 and 100 percent of full ballast output.

Solution

1. Determine the maximum UV lamp hydraulic loading.

   Although it may not be possible to test at the extreme flowrates (e.g., minimum and maximum hydraulic loading rate), every effort should be made to test the maximum possible range of hydraulic loading rates. In some cases, it may be possible to divert more or less flow to a single channel to obtain the desired range in flowrates. The maximum hydraulic loading rate in this example is determined by noting that each bank of UV lamps in each channel is exposed to one-fourth of the total peak flow.

$$\text{Maximum lamp hydraulic loading} = \frac{20{,}000 \text{ L/min}}{(4 \text{ channels})(48 \frac{\text{lamp}}{\text{bank}})} = 104 \text{ L/min•lamp}$$

2. Determine the minimum UV lamp hydraulic loading.

   In this example, two channels cannot be used at the minimum flowrate condition because the resulting velocity would be less than the validated minimum. Thus, at the minimum design flowrate, only a single channel will be used to provide disinfection and maintain the velocity within the validated flow range (see Example 2):

$$\text{Maximum lamp hydraulic loading} = \frac{5{,}500 \text{ L/min}}{(1 \text{ channel})(48 \frac{\text{lamp}}{\text{bank}})} = 115 \text{ L/min•lamp}$$

3. Develop the test conditions.

   A minimum of eight spot-check viral assays must be conducted to demonstrate that full-scale UV reactor performance complies with the design intent.

   a. Four of the tests will be conducted at the (1) maximum flowrate per lamp, (2) minimum transmittance, (3) maximum power setting, and (4) with one operational UV bank in sequence (i.e., 1, 2, 3, and 4). The goal of the first four tests is to determine whether bank placement has an impact on operational performance.

   b. The next four tests will be conducted at (1) ambient transmittance, (2) intermediate ballast output settings (60, 70, 80, and 90 percent), (3) intermediate flowrates, and (4) with one operational UV bank in sequence (i.e., 1, 2, 3, and 4). The goal of this series of tests is to evaluate the performance of the UV system at various intermediate operating conditions.

   c. A description of the eight tests is provided in Table A-8.

   d. The design dose after lamp aging and fouling impacts are accounted for is reported in the last column of Table A-8. For three banks in operation, the total design dose after lamp aging and fouling impacts are accounted for is 100 mJ/cm^2. However, verification of this dose delivery cannot be accomplished unless the system is allowed to operate for its warranted lamp life prior to spot-check validation. Most regulatory agencies prefer that testing be conducted prior to the production and delivery of recycled water; thus, testing will be conducted on new and clean lamps. The spot-check tests must be compared to the correct pilot predicted dose, without the influence of lamp aging or lamp fouling in place.

Table A-8: Bioassay Test Conditions

Test No.	UVT (%)	Number of Operational Banks	Hydraulic Loading Rate (L/min-lamp)	Power Setting (%)	Lower 75% PI Design Dose (mJ/cm^2)	Design Dose after Lamp Aging and Fouling[a] (mJ/cm^2)
1	70	1 (Bank 1 of 4)	115	100	44.5	35.6
2	70	1 (Bank 2 of 4)	115	100	44.5	35.6
3	70	1 (Bank 3 of 4)	115	100	44.5	35.6
4	70	1 (Bank 4 of 4)	115	100	44.5	35.6
5	73[b]	1 (Bank 1 of 4)	50	60	67.7	54.1
6	73	1 (Bank 2 of 4)	65	70	61.5	49.2
7	73	1 (Bank 3 of 4)	75	80	61.3	49.1
8	73	1 (Bank 4 of 4)	90	90	58.0	46.4

[a] The safety factor selected by the design engineer to account for lamp aging and sleeve fouling was 0.8. Thus, it is expected that the system will deliver 80 percent of the dose after lamp aging, and sleeve fouling as would be observed with new and clean lamps.
[b] The background ambient transmittance, without the use of a chemical to alter the transmittance, is 73 percent. Because the ambient transmittance is within the operating range, adjustment of the transmittance for tests 5, 6, 7, and 8 is not necessary.

UVT = UV transmittance.
PI = Prediction interval.

4. Conduct collimated-beam bioassays of the stock MS-2.

   a. Verify the adequacy of the MS-2 stock bacteriophage. A separate sample of the stock solution was collected each day for the conduct of a collimated-beam dose-response curve. The MS-2 bacteriophage collimated-beam data for the samples collected on Days 1 and 2 are presented in Tables A-9 and A-10, respectively.

Table A-9: Collimated-Beam Data for Day 1

UV Dose (mJ/cm^2)	Virus Survival (No./mL)	Log Inactivation
0	5.50E+05	
19.9	4.00E+04	1.14
39.8	4.20E+03	2.12
59.6	5.00E+02	3.04
79.5	9.00E+01	3.79
99.4	1.60E+01	4.54
119.4	3.00E+00	5.26

Table A-10: Collimated-Beam Data for Day 2

UV Dose (mJ/cm^2)	Virus Survival (No./mL)	Log Inactivation
0	2.70E+04	
19.7	1.20E+03	1.14
39.3	2.00E+02	2.12
59.0	2.70E+01	3.04
78.6	4.00E+00	3.79

   b. Compare the collimated-beam data to the QA/QC intervals given in Example 1 to determine whether the data complies with the quality requirements.

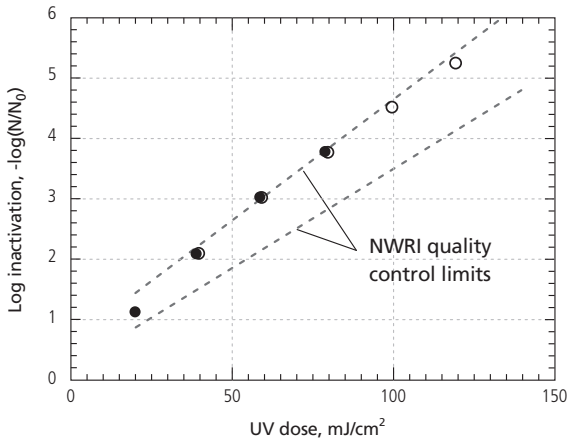

Figure A-3: Comparison of collimated-beam data to QA/QC intervals in Example 1.

As illustrated in Figure A-3, these data points comply with the QA/QC guidelines, demonstrating that the data are useful for use in the spot-check validation exercise. However, any experimental variance between the validation tests and the spot-check tests could result in different dose values being assigned when all factors were identical. To remedy the impact of experimental bias, it is appropriate to make use of the standard MS-2 dose-response relationship for the assignment of the UV doses. The standard MS-2 curve that will be used to assign UV doses (presented in Chapter 3) is as follows:

$$x\ (\text{UV dose}) = \frac{y\ (\log \text{inactivation}) - 0.5464}{0.0368} \qquad (3.3)$$

5. Conduct the on-site viral assays and determine the REDs.

   The data analysis used to determine RED values is presented in Table A-11. A comparison of the predicted and spot-check UV dose values is given in Table A-12.

Table A-11: MS-2 Bacteriophage Inactivation and Dose Assignment Summary[a]

Test[a]	Inlet Replicate (No./mL)	Outlet Replicate (No./mL)	Average Log (Inlet) (Log [No./mL])	Average Log (Outlet) (Log [No./mL])	Log Inactivation (Log [No./mL])	UV Dose[b] (mJ/cm^2)
1	$3.0x10^5$	$4.9\ x10^3$				
1	$3.4\ x10^5$	$5.2\ x10^3$	5.53	3.72	1.81	34.3
1	$3.9\ x10^5$	$5.5\ x10^3$				
2	$3.1\ x10^5$	$5.4\ x10^3$				
2	$4.8\ x10^5$	$9.8\ x10^2$	5.57	3.49	2.08	41.7
2	$3.4\ x10^5$	$5.6\ x10^3$				
3	$3.1\ x10^4$	$2.5\ x10^2$				
3	$2.9\ x10^4$	$2.2\ x10^2$	4.42	2.41	2.01	39.8
3	$2.0\ x10^4$	$3.1\ x10^2$				
4	$4.2\ x10^4$	$2.3\ x10^2$				
4	$4.3\ x10^4$	$9.9\ x10^1$	4.65	2.41	2.24	46.0
4	$4.8\ x10^4$	$7.4\ x10^2$				
5	$2.0\ x10^5$	$9.1\ x10^1$				
5	$1.5\ x10^5$	$9.2\ x10^1$	5.25	1.96	3.29	74.6
5	$1.9\ x10^5$	$8.9\ x10^1$				
6	$1.5\ x10^4$	$2.3\ x10^1$				
6	$1.6\ x10^4$	$2.0\ x10^1$	4.24	1.32	2.92	64.5
6	$2.2\ x10^4$	$2.0\ x10^1$				
7	$1.2\ x10^5$	$1.3\ x10^2$				
7	$1.3\ x10^5$	$1.7\ x10^2$	5.15	2.17	2.98	66.1
7	$1.8\ x10^5$	$1.5\ x10^2$				
8	$1.6\ x10^5$	$1.8\ x10^2$				
8	$2.0\ x10^5$	$2.0\ x10^2$	5.27	2.28	2.99	66.4
8	$2.0\ x10^5$	$1.9\ x10^2$				

[a] See Table A-8 for operating conditions.
[b] The UV dose assignment was made using Equation 3.3.

6. Compare the spot-check results to the design equation.

   A comparison of the predicted dose values to the spot-check validation results are provided in Table A-12. The ratio of the spot-check results to the predicted values is defined as the performance ratio.

Table A-12: Summary of Bioassay Testing Results

Test	UV Dose (mJ/cm^2)		Performance Ratio Spot-Check/ Predicted
	Predicted[a]	Spot-Check	
1	44.5	34.3	0.77
2	44.5	41.7	0.94
3	44.5	39.8	0.89
4	44.5	46.0	1.03
5	67.7	74.6	1.10
6	61.5	64.5	1.05
7	61.3	66.1	1.08
8	58.0	66.4	1.14

[a]Based on field instrumentation reading and excludes lamp aging and lamp fouling factors due to testing on new lamps with clean conditions. An allowance in design must be provided to allow for ongoing lamp aging and fouling.

7. Calculate site-specific dose target setting.

   a. Some agencies prefer that the system dose equation not be modified, but a site-specific dose target set to assure the design dose. If a site-specific dose target is to be developed, at the 75-percent prediction interval, seven out of eight test results must exhibit performance equal to or exceeding the design intent. The seventh lowest ratio was 0.89. Therefore, to be assured that the design dose of 100 mJ/cm^2 is met, the system should be set at a target dose of 112 mJ/cm^2.

$$\text{Target UV dose} = \frac{(100\ mJ/cm^2)}{0.0368} = 112\ mJ/cm^2$$

   b. Some agencies instead prefer that the system equation be modified via the de-rating process (if necessary) so that the design dose and target dose remain the same. The UV system can be de-rated by adjusting the numerical coefficients in the equation used to define the prediction interval curve and the system design curve (which includes the correction factor for lamp aging and fouling). The adjusted UV dose, based on the design equation, is determined as follows.

$$\text{UV dose}_{Adj} = \text{Design equation} \times 7^{th} \text{ lowest 75\% prediction interval spot-check ratio}$$

Discussion

The agency has the option of undertaking system enhancements to improve system performance. Examples of what might be done include modifying channel walls, adjusting the effluent weir height, and eliminating air or standing waves, etc. If improvements are made, the complete spot-check bioassay must be redone.

Glossary

Ambient Temperature: The outside air temperature or the temperature of a given piece of equipment that is operated on a continuous basis.

Ballast: An electromagnetic or electronic device used to provide power to the UV lamps.

Bank: One or more UV modules that the entire flow for a given reactor train must pass through (same as Ultraviolet Lamp Bank).

Bioassay: A biological test used to assess the effectiveness of UV disinfection for the inactivation of microorganisms.

Collimated-Beam Apparatus: A device used to collimate (make parallel) a source of light.

Contingency Plan: An alternative plan that is implemented when an existing plan is not operative.

Design Ultraviolet Dose: The reduction equivalent dose required for a specific log inactivation of the target microorganism. The design UV dose is used for sizing UV disinfection systems.

Disinfection: The selective destruction and/or inactivation of disease-causing (pathogenic) organisms.

Disinfection Byproducts: Compounds formed as a result of a series of complex reactions between disinfectant and organic compounds.

Disinfection Channel: A channel in which either horizontal or vertical arrays of UV lamps are placed for the disinfection of water.

Filtered Surface Water: Water from surface sources, such as rivers and lakes or groundwater under the direct influence of surface water, which has been treated by filtration, in conformance with the requirements of the Surface Water Treatment Rule.

Flowrate: The quantity of liquid that is discharged per unit time relative to a fixed reference point.

Fouling Factor: The reduction in available UV output due to changes in transmittance of the enclosure (i.e., quartz sleeve) separating the UV lamp from the liquid. The reduction in available UV output is determined by comparison to a new enclosure.

Germicidal Wavelength: The germicidal range of the electromagnetic spectrum (i.e., wavelengths between 200 and 300 nm).

Grab Samples: A discrete sample taken under specific circumstances at a given time and location.

Ground Fault Interrupter: A device that measures and trips at low leakage electrical current to ground.

Hardness: A measure of the concentration of the multivalent ions (e.g., aluminum, calcium, and magnesium) in a solution.

Headloss: Loss of energy caused by friction or turbulence induced by appurtenances in pipes and open channels.

Lamp Age Factor: The reduction in available UV output at the end of UV lamp life as compared to a new UV lamp, after the appropriate burn-in period.

Langelier Saturation Index: A measure of the potential for a water to be scale forming. The index only applies to the presence or absence of a calcium carbonate scale.

Level Control Device: Any device, such as weir or counter-balanced level controller, used to maintain the liquid level in the disinfection channel between a minimum and maximum level throughout the complete flow range.

Maximum Week Flow: The maximum 7-day flow based on a running 7-day average. The maximum week flow should be based on a minimum of 1 year's worth of flow data.

Media Filtration: Filtration process using granular, synthetic, or cloth media to remove residual suspended solids.

Microfiltration: A pressure-driven membrane process that separates micrometer-diameter and submicrometer-diameter particles (down to approximately 0.1 micrometer-diameter size) from a feed stream by using a sieving mechanism. The smallest particle size removed is dependent on the pore size rating of the membrane.

Module: The basic building block of a UV disinfection system. It is comprised of one or more UV lamps with a common electrical feed.

Most Probable Number: The results obtained using the multiple-tube fermentation technique for the analysis of bacteria are expressed in terms of MPN/100 mL. The MPN is based on the application of the Poisson distribution for extreme values to the analysis of the number of positive and negative results obtained when testing multiple portions of equal volume and in portions constituting a geometric series.

Nephelometric Turbidity Unit: The unit of measurement used to define the turbidity of a solution.

Operational Ultraviolet Dose: The UV dose that is established based on the results of the equipment validation testing. The operational UV dose can be used to make most efficient use of the UV disinfection system (e.g., reduce power demand, reduce number of the reactors or reactor trains on-line) while maintaining the design UV dose.

Pathogen: Any agent, especially a microorganism, capable of causing disease.

Peak Flow: A flowrate of a given magnitude that is sustained for a specified period of time. Because it is difficult to compare numerical peak flowrate values from different treatment plants, peak flowrate values are normalized by dividing by the long-term average flowrate. The resultant ratio is known as a peaking factor.

Performance Validation Protocol: A procedure whereby the performance of UV equipment is validated.

Quartz Sleeve: An outer jacket of quartz glass used to protect the UV lamp.

Quartz Sleeve Fouling: The formation of material on the quartz sleeve, which causes a reduction in the UV intensity emitted from the quartz sleeve.

Quartz Sleeve Scaling: The formation of a scale on the quartz sleeve that causes a reduction in the UV intensity emitted from the quartz sleeve. Scaling is typically caused by the multivalent metallic ions in solution.

Reactor: An independent combination of single or multiple bank(s) in series with a common mode of failure (e.g., electrical, cooling, cleaning system, etc.).

Reactor Train: A combination of reactors in series, including inlet, outlet, and level controlling arrangements (if applicable).

Reactor Train Inlet: The inlet arrangement used to direct the flow to a UV reactor train.

Reactor Train Outlet: The outlet arrangement used to direct the flow out of a UV reactor train.

Reduction Equivalent Dose: The dose that is assigned to the UV test reactor based on reactor validation testing. The reduction equivalent dose is equivalent to that measured with the collimated-beam apparatus for the same degree of inactivation of the target microorganism.

Registered Engineer: A person who is qualified to practice engineering based on passing the national examination for civil and/or environmental engineers.

Reverse Osmosis: The separation (removal) of particulate, colloidal matter, and dissolved solids from a liquid using a thin membrane. The membrane acts as a barrier that will selectively retain certain constituents found in the liquid.

Seismic Loads: Additional loadings on UV disinfection facilities and buildings caused by earthquakes.

Spot-Check: The performance of a full-scale UV disinfection system is determined via bioassay testing under a limited number of discrete operating conditions and compared to the corresponding design predictions.

Standby Bank: A bank of UV lamps that is used as a standby (substitute) for the operating banks.

Supernatant: The liquid remaining after separating solids from a liquid-solid mixture.

Surface Water Treatment Rule: A rule established by the EPA for the treatment of surface waters before distribution to the public.

Target Pathogen: The microorganism that is of concern with respect to the protection of public health.

Theoretical Average Velocity: The value of the velocity obtained by dividing the flowrate by the cross-sectional area when expressed in consistent units.

Title 22: See Water Recycling Criteria.

Treatment Process Train: The assemblage or grouping of treatment units together to achieve a specified treatment objective.

Turbidity: A measure of the ability of a solution to scatter light. Light scattering is usually caused by the presence of small particles.

Ultraviolet Disinfection: The inactivation of microorganisms by exposure to UV radiation.

Ultraviolet Disinfection System: The combination of reactor trains with associated controls and instrumentation.

Ultraviolet Intensity: The intensity of UV radiation over a wavelength range of 200 to 300 nm.

Ultraviolet Intensity Probe: A device used to measure the intensity of UV radiation striking a UV sensor within a UV reactor.

Ultraviolet Lamp: A germicidal lamp used to produce UV irradiation in the range of 200 to 300 nm.

Ultraviolet Lamp Bank: One or more UV modules that the entire flow for a given reactor train must pass through (same as Bank).

Ultraviolet Radiation: A band of nonionizing electromagnetic radiation having wavelengths from 5 to 400 nm (Wavelengths that are effective for microorganism inactivation are in the range from 200 to 300 nm. The most effective range is between 250 and 275, with the optimum being between 260 and 265 nm).

Ultraviolet Transmittance of Fluid: The ability of a fluid to transmit ultraviolet radiation. Factors known to affect ultraviolet transmittance of a fluid include dissolved organics, dissolved iron, color (i.e., textile dyes), and turbidity. Ultraviolet transmittance is quantified by spetrophometric measurement at a wavelength of 253.7 nm using a 1-cm pathlength.

Ultraviolet 254 Absorbance: The absorbance of electromagnetic radiation at a wavelength 254 nm by a liquid through a 1-cm pathlength.

Unfiltered Surface Water: Water from surface sources, such as rivers and lakes or groundwater under the direct influence of surface water, that has not been treated by filtration prior to disinfection and distribution.

Uninterruptible Power Supply : The means or methods used to provide a continuous power supply to a treatment process.

Velocity Profiles: The velocity profile is a measure of the variability of the flow velocity across a cross-section perpendicular to the flow.

Water Recycling Criteria (Title 22): The section of the California Code of Regulations regarding water reuse. The reuse criteria are set forth in Title 22, Division 4, Chapter 3 of the California Code of Regulations.

Water Reuse: The treatment of wastewater to a quality that makes it suitable for one or more beneficial uses and the subsequent use of the treated water.

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