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ULTRAVIOLET DISINFECTION GUIDANCE MANUAL

Note on the Ultraviolet Disinfection Guidance Manual, June 2003 Draft

Purpose: The purpose of this guidance manual, when finalized, is solely to provide technical information on the application of ultraviolet light for the disinfection of drinking water by public water systems. EPA is developing this manual to support two upcoming drinking water regulations: the Long Term 2 Enhanced Surface Water Treatment Rule, which would require certain systems to provide additional treatment for *Cryptosporidium*, and the Stage 2 Disinfection Byproducts Rule, which would place more stringent limits on certain disinfection byproducts. Chapter 1 of this manual contains additional information about these regulations.

This guidance is not a substitute for applicable legal requirements, nor is it a regulation itself. Thus, it does not impose legally-binding requirements on any party, including EPA, states, or the regulated community. Interested parties are free to raise questions and objections to the guidance and the appropriateness of using it in a particular situation. Although this manual covers many aspects of implementing a UV system, it is not comprehensive in terms of all types of UV systems, design alternatives, and validation protocols that may provide satisfactory performance. The mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Request for comments: EPA is releasing this manual in draft form in order to solicit public review and comment. The Agency would appreciate comments on the content and organization of technical information presented in this manual. A list of topics for comment pertaining to specific chapters and appendices is provided later in this manual. Please submit any comments no later than 90 days after publication of the Long Term 2 Enhanced Surface Water Treatment Rule proposal in the *Federal Register*. Detailed procedures for submitting comments are stated below.

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Glossary

The following definitions were derived from existing UV literature, standard physics textbooks, and/or industry standards and conventions. Some concepts have more than one acceptable term or definition, but for consistency within the document, only one term is used.

Absorption – the transformation of UV light to other forms of energy as it passes through a substance.

Action Spectrum – the relative efficiency of UV energy at different wavelengths in inactivating microorganisms. Each microorganism has a unique action spectrum.

Ballast – provides the proper voltage and current required to initiate and maintain the gas discharge within the UV lamp.

Bioassay – a procedure used to determine the response of a specific microorganism after exposure to UV light, usually in UV reactors. Bioassay is a term typically utilized in toxicology, describing the testing of the bio-toxicity of a contaminant. Bioassay has been used in the UV disinfection literature in the same context as "biodosimetry" (see **biodosimetry**).

Biodosimeter – the challenge microorganism used to measure UV inactivation and ultimately calculate the reduction equivalent dose (RED; see **UV dose**) in a UV reactor.

Biodosimetry – a procedure used to determine the reduction equivalent dose (RED) of a UV reactor. Biodosimetry involves measuring the inactivation of a challenge microorganism after exposure to UV light in a UV reactor and comparing the results to the known UV dose-response curve of the challenge microorganism (determined using collimated beam testing) to determine the RED (see **UV Dose**).

Challenge Organism – a microorganism used in UV reactor biodosimetry testing.

Collimated Beam Test – a carefully controlled bench-scale test that is used to determine the UV dose-response of a microorganism. Both time and UV light intensity are accurately measured, resulting in a specific calculation of delivered UV dose for the microorganism being tested. Collimated beam tests are described in detail in Appendix C.

Dark Repair – an enzyme-mediated microbial process that removes and regenerates a damaged section of deoxyribonucleic acid (DNA), using an existing complimentary strand of DNA. Dark repair refers to all microbial repair processes not requiring reactivating light.

Delivered UV Dose – see **UV Dose**

Dose Control Strategy – the technique used by a UV system to control the delivered dose that typically involves adjusting the lamp power or turning "on" or "off" banks of UV lamps to respond to changes in UV absorbance, lamp intensity, and flow. Typically, the dose control strategy is different for LP/LPHO and MP systems.

Dose Distribution – see **UV Dose, Delivered UV Dose Distribution**.

Emission Spectrum – the relative light power emitted by a lamp as a function of wavelength.

Fluence – see **UV Dose**

Fluence Rate – see **UV Intensity**

Gas Discharge – a mixture of non-excited atoms, excited atoms, cations, and free electrons formed when a sufficiently high voltage is applied across a volume of gas. Most commercial UV lamps use mercury gas discharges to generate UV light.

Germicidal Effectiveness – the relative inactivation efficiency of each UV wavelength in a polychromatic emission spectrum. This value is usually approximated by the relative absorbance of DNA at each wavelength, although individual microorganisms may respond differently. By convention, germicidal effectiveness of the 254 nm emission line by LP UV lamps is considered to be unity. The germicidal effectiveness is typically used to weight a polychromatic, MP UV lamp output to reflect the germicidal energy of that specific source.

Germicidal Range – the range of UV wavelengths responsible for microbial inactivation in water (200 to 300 nm).

Lamp Envelope – the exterior surface of the UV lamp, which is typically made of quartz.

Lamp Sleeve – the quartz tube that surrounds and protects the UV lamp. The exterior is in direct contact with the water being treated. There is typically an air gap (approximately 1 cm) between the lamp envelope and the quartz sleeve.

Light Pipe – a quartz cylinder that transmits light from the interior of the UV reactor to the photodetector of a UV intensity sensor.

Lignin Sulfonate – a commercially available reagent grade chemical that can simulate the UV absorbance spectrum of natural waters and be used to adjust UV transmittance during validation testing.

Low Pressure (LP) Lamp – a mercury vapor lamp that operates at an internal pressure of 0.001 to 0.01 torr (2×10^{-5} to 2×10^{-4} psi) and electrical input of 0.5 watts per centimeter. This results in essentially monochromatic light output at 254 nanometers.

Low Pressure High Output (LPHO) Lamp – a low pressure mercury vapor lamp that operates under increased electrical input (1.5 to 10 W/cm), resulting in a higher UV intensity than LP lamps. It also has essentially monochromatic light output at 254 nanometers.

Medium Pressure (MP) Lamp – a mercury vapor lamp that operates at an internal pressure of 100 to 10,000 torr (2 to 200 psi) and electrical input of 50 to 150 W/cm. This results in a polychromatic (or broad spectrum) output of UV and visible light at multiple wavelengths, including the germicidal range.

Monochromatic – light output at only one wavelength. For example, because low pressure and low pressure high output lamps only significantly emit light at 254 nanometers, they are considered monochromatic UV light sources.

Monitoring Window – a quartz disc that transmits light from the interior of the UV reactor to the photodetector of a UV intensity sensor.

Offline Chemical Clean (OCC) – a process to clean lamp sleeves where the UV reactor is taken off-line and a cleaning solution (typically an acid) is manually pumped into the reactor. After the foulant has dissolved, the reactor is drained, rinsed, and returned to service. Also called flush-and-rinse systems.

Online Mechanical Clean (OMC) – a process to clean lamp sleeves where an automatic mechanical wiper (e.g., O-ring, brush) wipes the surface of the lamp sleeve at a prescribed frequency.

Petri Factor – a ratio used in collimated beam testing that is equal to the average intensity measured across the surface of a suspension in a petri dish divided by the intensity at the center of a petri dish. The petri factor is used to help calculate delivered UV dose as described in Appendix C.

Photodetector – a device that produces an electrical current proportional to the UV light intensity at the detector's surface.

Photoreactivation – a microbial repair process where enzymes activated by light in the near UV and visible range (310 to 490 nm) split pyrimidine dimers, thereby repairing UV induced damage. Photoreactivation requires the presence of light.

Polychromatic – light energy output at several wavelengths such as with MP lamps.

Quartz Sleeve – see **lamp sleeve**

Radiometer – an instrument used to measure UV irradiance

Reduction Equivalent Dose (RED) – see **UV Dose, RED**.

Reflection – the change in direction of light propagation when deflected by an interface or surface.

Refraction – the change in direction of light propagation as it passes through one medium to another.

Scattering – the change in direction of light propagation caused by interaction with a particle.

Spectral UV Absorbance – the determination of UV Absorbance (A) over a range of wavelengths (e.g. 200 to 400 nm)

State – the agency of the state, tribal, or federal government that has jurisdiction over public water systems.

UV absorbance (A) – a measure of the amount of UV light that is absorbed by a substance (e.g., water, microbial DNA, lamp envelope, quartz sleeve) at a specific wavelength (e.g., 254 nm). This measurement accounts for absorption and scattering in the medium (e.g., water). Typically the absorbance is measured on a per centimeter (cm) basis in a 1 cm quartz cuvette. Standard Method 5910B details this measurement method. However, for UV disinfection applications, the sample should not be filtered or adjusted for pH as described in Standard Methods.

UV Dose – the energy per unit area incident on a surface, typically in units of mJ/cm^2 or J/m^2 (older literature also used the units $mW\text{-}s/cm^2$ where 1 $mW\text{-}s/cm^2$ = 1 mJ/cm^2). The UV dose received by a waterborne microorganism in a reactor vessel accounts for the effects on UV intensity of the absorbance of the water, absorbance of the quartz sleeves, reflection and refraction of light from the water surface and reactor walls, and the germicidal effectiveness of the UV wavelengths. This guidance also uses the following terms related to UV dose:

- **Delivered UV dose distribution** – the probability distribution of delivered UV doses that microorganisms receive in a flow-through UV reactor; typically shown as a histogram. An example is shown in Figure 2-7.

- **Reduction Equivalent Dose (RED)** – a calculated dose for a flow through UV reactor that is based on **biodosimetry** (i.e., measuring the level of inactivation of a challenge microorganism with a known UV dose-response). The RED is set equal to the UV dose in a **collimated beam test** that achieves the same level of inactivation of the challenge microorganism as measured for the flow-through UV reactor during biodosimetry testing.

UV Dose-Response – the relationship indicating the level of inactivation of a microbe as a function of UV dose. Inactivation is often plotted as $\log_{10}(N_0/N)$ where N_0 is the number of microbes present prior to UV light exposure and N is the number of microbes present after UV light exposure. Examples are shown in Figure 2-8.

UV Installation – all of the components of the UV disinfection process, including (but not limited to) UV reactors, control systems, piping, valves, and building or enclosure.

UV Intensity – the power per unit area passing through an area perpendicular to the direction of propagation. UV intensity is used in this guidance manual to describe the magnitude of UV light in a UV reactor and in bench-scale UV experiments.

UV Intensity Sensor – a photosensitive detector used to measure the UV intensity at a point within the UV reactor.

UV Irradiance – the power per unit area incident to the direction of light propagation at all angles, including normal.

UV Light – electromagnetic radiation with wavelengths from 200 to 400 nm.

UV Reactor – the vessel or chamber where exposure to UV light takes place, consisting of UV lamps, quartz sleeves, UV intensity sensors, quartz sleeve cleaning systems, and baffles or other hydraulic controls. The UV reactor also includes additional hardware for controlling UV dose; typically comprised of (but not limited to): UV intensity sensors, UV transmittance monitors, ballasts, and control panels.

UV Reactor Validation – a process by which a UV reactor's disinfection performance is determined relative to operating parameters that can be monitored. Reactors are validated to indicate that they achieve a certain delivered UV dose for a range of flow, UV intensity, and water quality conditions (e.g., UV transmittance). Appendix C details the protocol for validating UV reactors.

UV Transmittance (UVT) – a measure of the fraction of incident light transmitted through the water column. The UV transmittance is the ratio of the light entering the water to that exiting the water. The UVT is usually reported for a pathlength of 1 cm. In an alternate pathlength is used, it should be specified. UVT is often represented as a percentage and is related to the UV absorbance by the following equation: $\%UVT = 100 \times 10^{-A}$. As the UV absorbance increases, the UV transmittance decreases.

List of Acronyms and Abbreviations

A_{254}	ultraviolet absorbance at 254 nanometers
AC	alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
ACS	Automatic cleaning system
ANSI	American National Standards Institute
AOC	assimilable organic carbon
APHA	American Public Health Association
ATCC	American Type Culture Collection
atm	atmospheres
AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation
BDL	below detectable limits
BDOC	biodegradable dissolved organic carbon
°C	degrees Centigrade
CCPP	calcium carbonate precipitation potential
CF	cumulative frequency
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
cfu	colony forming unit
CIP	clean-in-place
cm	centimeter
CPEL	ceiling level permissible exposure limit
CSI	Construction Specifications Institute
CT	residual disinfectant concentration (mg/L) x time (min)
CWS	community water system
DBP	disinfection byproduct
DBPR	disinfection byproduct rule
DC	direct current
D/DBP	disinfectants/disinfection by-product
DNA	deoxyribonucleic acid
DOC	dissolved organic carbon
DVGW	Deutsche Vereinigung des Gas- und Wasserfaches (German Association for Gas and Water)
e	exponent of the base of the natural logarithm
EPA	United States Environmental Protection Agency
°F	degrees Fahrenheit
ft	feet
g	gram
GAC	granular activated carbon

gal	gallon
GFI	ground fault interrupt
gpm	gallons per minute
GWR	ground water rule
GWUDI	ground water under the direct influence [of surface water]
h	hour
HAA	haloacetic acid
HDPE	high-density polyethylene
HGL	hydraulic grade line
hp	horsepower
HPC	heterotrophic plate count
HSP	high service pump
Hz	hertz
I	UV intensity
IDLH	Immediately Dangerous to Life or Health
IDSE	initial distribution system evaluation
IESWTR	Interim Enhanced Surface Water Treatment Rule
IT	UV intensity x time
J	joule
kW	kilowatt
kW-hr	kilowatt-hour
ln	natural logarithm
LP	low pressure
LPHO	low pressure high output
LRAA	locational running annual average
LSI	Langlier Saturation Index
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
λ	wavelength
m	meter
mA	milliamp
MCL	maximum contaminant level
mg	milligram
mgd	million gallons per day
min	minutes
mJ	millijoule
mL	milliliter
mm	millimeter
MP	medium pressure
MS2	male specific-2 bacteriophage
μg	microgram
μm	micrometer, micron

NEL	National Electric Code
nm	nanometer
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NOM	natural organic matter
NSF	National Science Foundation
NTNCWS	non-transient non-community water system
NTU	nephelometric turbidity units
NWRI	National Water Research Institute
O&M	operation and maintenance
OCC	offline chemical clean
OMC	online mechanical clean
ÖNORM	Österreichisches Normungsinstitut (Austrian Standards Institute)
OSHA	Occupational Safety and Health Administration
PAC	powdered activated carbon
PEL	permissible exposure limit
%	percent
PER	preliminary engineering report
pfu	plaque forming unit
pH	negative logarithm of the effective hydrogen ion concentration
PHA	process hazard analysis
PLC	programmable logic controller
POE	point of entry
psi	pounds per square inch
psig	pounds per square inch gauge
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
r	radial distance from center
r^2	correlation coefficient
RAA	running annual average
RCRA	Resource Conservation and Recovery Act
RED	reduction equivalent dose
RMS	root-mean-square
RNA	ribonucleic acid
rpm	revolutions per minute
RPZ	reduced pressure zone
s	second
SARA	Superfund Amendments and Reauthorization Act
SCADA	supervisory control and data acquisition
SDWA	Safe Drinking Water Act
SMCL	secondary maximum contaminant level
SMP	standard monitoring program

SOP	standard operating procedure
SSS	system-specific study
SUVA	specific ultraviolet absorbance
SWTR	Surface Water Treatment Rule
T_{10}	time at which ten percent of water has passed through the reactor
TCLP	toxic characteristic leaching procedure
TCR	total coliform rule
TDH	total dynamic head
TDS	total dissolved solids
THM	trihalo methane
TLV	threshold limit values
TNTC	too numerous to count
TOC	total organic carbon
TOX	total organic halides
TSA	tryptic soy agar
TSB	tryptic soy broth
TSS	total suspended solids
TTHM	total trihalomethane
UPS	uninterruptible power supply
UV	ultraviolet
UVT	ultraviolet transmittance
VFD	variable frequency drive
W	watt
WTP	water treatment plant

Requested Feedback on the UV Disinfection Guidance Manual

Chapter or Appendix Title

Specific Issues for Comment

Glossary

1. Are there additional terms that should be defined?
2. Is each definition accurate and clearly presented?

1. Introduction

1. Does this chapter provide the appropriate amount of information on the relevant regulations?

2. Overview Of UV Disinfection

1. Is the level of detail appropriate?
2. Is there additional information that should be provided?

3. Planning And Design Aspects For UV Installations

1. Is the overall UV installation design flowchart realistic? Is the chapter organization reader-friendly?
2. Is the issue of off-specification operation and its implications on the UV installation design clearly described?
3. Are the recommendations on developing design criteria helpful? Are there other approaches that should be discussed?
4. Is the power quality information clear? Is more information needed?
5. Are there additional planning or design issues that should be discussed?

4. Overview of Validation

1. Are the elements of validation clearly presented?
2. Is there other information from the detailed validation protocol (Appendix C) that should be described here?

5. Start-Up And Operation Of UV Installations

1. Are there other elements of the UV installation start-up that should be discussed?
2. Are the organization of the chapter and presentation of information appropriate?
3. Are the operational requirements examples clearly described?
4. Are there other operation and maintenance issues that should be discussed?
5. Are the operational challenges described realistic, and are the solutions helpful?

6. References

1. Are there any references that were overlooked that should be added to help clarify any points made in the UVDGM?

A. Fundamentals of UV Disinfection

1. Is the level of detail appropriate?
2. Is there additional information that should be provided?

B. Derivation of UV Dose-Response Requirements

1. Are there published or unpublished data available that are not included in this analysis?

C. UV Validation Protocol Testing

1. Is the description of the testing methods clear?
2. Are the distinctions between Tier 1 and 2 clearly described?
3. To provide a better assessment of the RED bias, please provide dose distributions for UV reactors you have modeled at UVTs of 95, 90, 85, and 80%.
4. Are the Tier 1 criteria acceptable? If not, please provide data and rational to support alternative criteria.
5. During validation, the uncertainty of some measurements will not be random. In particular, errors associated with measurements made by the radiometer will likely be a systematic error (i.e., the radiometer will always read high or read low for the duration of the validation testing). Other such errors could occur with the intensity sensors or the reference sensor used to calibrate the duty sensors. Currently, the UVGM combines these sources of uncertainty with other random sources of uncertainty to define an expanded uncertainty. Because these sources of error are not random during a given validation, should the following approach be used:

   If the error of a measurement during validation is constant and systematic, should the uncertainty of the measurement be used to define a bias error that is applied to the validation results?
   Under the current approach, this would apply to the uncertainty of the radiometer and move it from the expanded uncertainty to its own bias error. For example, if the uncertainty of the radiometer is 8 %, a safety factor of 1.08 is added to the RED bias, polychromatic bias, and expanded uncertainty. This will increase RED targets for Tier 1 and 2.

6. The expanded uncertainty is calculated for an 80 percent confidence interval to ensure at least nine out of ten cases of UV system operation meet target dose values. Should the expanded uncertainty calculation be based on a 90 or 95 percent confidence interval to ensure a higher percentage of UV systems meet requirements?

D. Validation Microbial Methods

1. The bounds provided for the MS2 and *B. subtilis* data come from an analysis of data published in the literature. Should these bounds be used? If not, please provide data to support using alternative bounds? Should any of the literature data used to develop these bounds not be included? If yes, please provide a rational for not including that data.
2. Are the methods for analyzing the collimated beam data and subsequent UV dose-response curve clearly stated and appropriate? Are there other options that should be considered?

E. Collimated Beam Apparatus – Measuring Challenge Microbe UV Dose-Response

1. Is the collimated beam testing description clear?

F. Validation Background

1. The following is an alternate approach for monitoring dose delivery that is not included in the manual because it has not been applied or referenced.

   Calculate the percent UV output from the lamp to the water based on the sensor readings using the formula:

$$P_L = \frac{S}{S'(UVT)} * 100$$

   where
   P_L = UV output from the lamp to the water (%)
   S = Sensor reading
   S'(UVT) = Sensor reading expected with a new lamp operating with unfouled sleeves at a given UVT
   UVT = UVT of the water at 254 nm

   The calculated lamp power and measured UVT should be above setpoint values established during validation. The relation S'(UVT) is measured during validation as opposed to being calculated.

   This approach has the following potential benefits:

   - No requirement on sensor position
   - Could measure S'(UVT) with NOM and compare with LSA or coffee as an experimental approach for reducing the Polychromatic Bias to one.

   Should this approach be discussed in the manual?

G. Issues for Unfiltered Systems

1. Is the level of detail appropriate?
2. Is there additional water quality related design or operational concerns for unfiltered systems that should be addressed?

H. Issues for Ground Water Systems

1. Are there design or operational issues with UV disinfection of groundwater that are not addressed?

I. Issues for Small Systems

1. Is the level of detail appropriate?
2. Are the design concerns facing small systems adequately addressed?
3. Design information is presented in Chapter 3, and this appendix only includes areas where small system design differs from the design issues discussed in Chapter 3. Is this approach effective?

J. Pilot-Scale and Demonstration-Scale Testing

1. Is the level of detail appropriate?
2. Were all of the recommended testing methods clearly explained?
3. Are there any other example testing protocols that should be included in this appendix?

K. Preliminary Engineering Report

1. Are there any elements of this report that would benefit from more detail?
2. Is there any information missing from this report that you would like to see included in a standard template (i.e., in this example Design Engineering Report)?

L. Regulatory Timeline

1. Is this appendix helpful for UV installation planning?
2. Are the time allocations for the tasks listed in the timeline appropriate?

M. Compliance Forms

1. Are the example compliance forms well organized and easy to complete?
2. Are there other forms that would be helpful to the utility or the State?

N. UV Lamp Breakage Issues

1. Considering available information, are the major issues surrounding lamp breakage adequately presented in this appendix? Are there additional issues or sources of information to be discussed?
2. Are there additional methods for the prevention or mitigation of on-line lamp breaks that should be presented?

O. Case Studies

There are no questions related to this appendix because it is not included in this draft.

P. Validation Protocol Calculator Tool

There are no questions related to this appendix.

1. Introduction

There is growing interest among public water systems in using ultraviolet (UV) light to disinfect drinking water, based on its ability to inactivate certain microorganisms without forming harmful disinfection byproducts (DBPs). Some pathogens, such as *Cryptosporidium*, are resistant to commonly used disinfectants, whereas UV light has proven effective against these microorganisms.

The United States Environmental Protection Agency (EPA) is developing the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) to further control microbial contamination of drinking water. The rule requires additional treatment for some systems based on their source water *Cryptosporidium* concentrations. UV disinfection is one of the options utilities have to comply with the treatment requirements.

UV light has been widely used to disinfect effluent from wastewater treatment facilities, particularly those that reuse effluent for irrigation. Until recently, the use of UV treatment for drinking water applications was primarily limited to small ground water systems, due to the belief that it was not effective for inactivating protozoa and was not cost-effective for large systems. In 1998, however, research demonstrated that UV light could effectively inactivate *Cryptosporidium* at low dosages (Buhkari et al. 1998), prompting more research to better understand its potential for widespread application.

UV disinfection design, operation, and maintenance needs differ from those of traditional chemical disinfectants used in drinking water applications. EPA is therefore developing this guidance manual to familiarize States[1] and utilities with these important issues as well as regulatory requirements. Areas of particular design and operational importance include hydraulic control, reliability, redundancy, lamp cleaning and replacement, and lamp breakage. Regulatory requirements are addressed through UV reactor validation, monitoring, and reporting.

1.1 Guidance Manual Objectives

This manual provides guidance to utilities, States, manufacturers, and other interested parties on the disinfection of drinking water with UV light, including the regulatory requirements associated with UV disinfection. The LT2ESWTR requirements do not cover all aspects of the disinfection process. In the areas not directly addressed by the rule, the manual provides

[1] Throughout this document, the terms "State" or "States" are used to refer to all types of primacy agencies, including U.S. Territories, Indian Tribes, and EPA Regions.

recommendations to assist utilities and regulatory agencies in assessing the disinfection capability and performance of UV installations. The manual's objectives are as follows:

- Provide public water systems and designers with technical information and guidance on the selection, design, and operation of UV installations and the UV-related requirements for compliance with the LT2ESWTR.

- Provide States with guidance and the necessary tools to assess UV installations at the design, start-up, and routine operation phases.

- Provide manufacturers with testing and performance standards for UV components and systems for treating drinking water.

1.2 Organization

This manual consists of six chapters and appendices:

- Chapter 1 – Introduction. The remainder of this chapter summarizes the LT2ESWTR and Stage 2 DBPR and discusses regulatory requirements for disinfection of drinking water with UV light.

- Chapter 2 – Overview of UV Disinfection. This chapter describes the principles of disinfection with UV light including inactivation mechanisms, dose-response relationships, water quality impacts, and UV reactors.

- Chapter 3 – Planning and Design Aspects for UV Installations. This chapter discusses the key design features for UV disinfection facilities and presents some common approaches to facility design. Key design features include treatment goals, existing infrastructure, water quality, hydraulics, and operation and control strategies.

- Chapter 4 – Overview of UV Reactor Validation. This chapter describes the LT2ESWTR requirements for validating UV reactors and provides an overview of validation protocol presented in Appendix C.

- Chapter 5 – Start-up and Operation of UV Installations. This chapter discusses start-up and operation issues of UV disinfection facilities as well as required monitoring for regulatory compliance.

- Chapter 6 – References. This chapter lists the full references from Chapters 1-5.

- The appendices and their titles follow:

Appendix A. Fundamentals of UV Disinfection
Appendix B. Derivation of UV Dose-Response Requirements
Appendix C. Validation of UV Reactors
Appendix D. Microbiological Methods
Appendix E. Collimated Beam Apparatus: Measuring Challenge Microorganism UV Dose-Response
Appendix F. Background to the UV Reactor Validation Protocol
Appendix G. Issues for Unfiltered Systems
Appendix H. Issues for Ground Water Systems
Appendix I. Issues for Small Systems
Appendix J. Pilot-Scale and Demonstration Scale Testing
Appendix K. Preliminary Engineering Report
Appendix L. Regulatory Time Line
Appendix M. Compliance Forms
Appendix N. UV Lamp Breakage Issues
Appendix O. Case Studies [This appendix will be included in the final draft at which time EPA anticipates more information being available.]
Appendix P. Validation Protocol Calculator Tool

1.3 Regulations Summary

This section summarizes the drinking water regulations for microbial and DBP control. The Stage 2 Disinfectants and Disinfection Byproduct Rule (DBPR) aims to reduce peak DBP concentrations in the distribution system by modifying the Stage 1 DBPR monitoring requirements and procedures for compliance determination. The LT2ESWTR and Stage 2 DBPR are to be promulgated together to address the risk-risk trade off between microbial disinfection and the byproducts formed by commonly used disinfectants. Consequently, when a utility assesses its disinfection strategy, not only the disinfection of target pathogens is important, but also the DBP formation from each disinfectant. Table 1.1 summarizes the microbial treatment requirements and DBP maximum contaminant levels (MCLs) from the Surface Water Treatment Rule (SWTR), Interim Enhanced Surface Water Treatment Rule (IESWTR), Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR), LT2ESWTR, Stage 1 DBPR, and Stage 2 DBPR.

Table 1.1 Summary of Microbial and Disinfection Byproduct Rules

Surface Water Treatment Rules - Minimum Treatment Requirements				
Regulation	***Giardia***	**Virus**	***Cryptosporidium***	
SWTR	3 log removal and inactivation	4 log removal and inactivation	Not addressed	
IESWTR and LT1ESWTR	No change from SWTR		2 log removal	
LT2ESWTR	No change from SWTR		0-2.5 log additional treatment[1]	
			2-3 log treatment[2]	
Disinfection Byproduct Rules - MCLs Based on Running Annual Averages (RAAs)				
Regulation	**Trihalomethanes (TTHM) (µg/L)**	**Haloacetic Acids (HAA5) (µg/L)**	**Bromate (µg/L)**	**Chlorite (µg/L)**
Stage 1 DBPR	80 as RAA	60 as RAA	10	1000
Stage 2A DBPR[3]	120 as LRAA	100 as LRAA	No change from Stage 1	
Stage 2B DBPR[4]	80 as LRAA	60 as LRAA	No change from Stage 1	

[1]Requirement for filtered systems is in addition to removal achieved by conventional treatment complying with the IESWTR and LT1ESWTR. Specific requirements for each plant depend on source water monitoring results (40 CFR 141.720).

[2]Unfiltered systems must provide 2-3 log inactivation; specific requirements for each plant depend on source water monitoring results (40 CFR 141.721(b)).

[3]Stage 2A bases compliance on a locational running annual average (LRAA) at the Stage 1 monitoring locations. Stage 1 RAAs must still be met during this time. Stage 2A begins [3 years after rule promulgation] for all systems.

[4]Stage 2B bases compliance on an LRAAs at revised monitoring locations identified during the Initial Distribution System Evaluation. Stage 2B begins [6 years after rule promulgation] for large systems and [7.5-8.5 years after rule promulgation] for small systems dependent on their LT2ESWTR requirements.

1.3.1 Long Term 2 Enhanced Surface Water Treatment Rule

The LT2ESWTR applies to all public water systems that use surface water or ground water under the direct influence of surface water (GWUDI), except those that purchase all their surface and GWUDI water. It builds on the SWTR, IESWTR, and the LT1ESWTR by improving control of microbial pathogens, specifically the contaminant *Cryptosporidium*. Unlike the previous rules, the LT2ESWTR bases treatment requirements on a system's source water *Cryptosporidium* concentration and type of treatment provided. This section describes the rule requirements for filtered and unfiltered systems.

1.3.1.1 Filtered Systems

The LT2ESWTR requires systems that use a surface water or GWUDI source (referred to collectively in this manual as surface water systems) to conduct source water monitoring to determine average *Cryptosporidium* concentrations, unless they have historical *Cryptosporidium* data equivalent to what is required under the LT2ESWTR (40 CFR 141.701(a)). Based on its average source water *Cryptosporidium* concentration, filtered systems will be classified in one of four possible bins. A system's bin assignment determines the extent of any additional *Cryptosporidium* treatment requirements. The rule requires systems to comply with additional treatment requirements by using one or more management or treatment techniques from a toolbox of options (40 CFR 141.720(b)). The process is described in more detail below; the full monitoring requirements are described in the *Source Water Monitoring Guidance Manual for Public Water Systems for the Long Term 2 Enhanced Surface Water Treatment Rule* (USEPA 2003).

Bin Classification

Table 1.2 presents the bin classifications and their corresponding additional treatment requirements for all filtered systems (40 CFR 141.709 and 40 CFR 141.720). Systems with average *Cryptosporidium* concentrations of less than 0.075 oocysts per liter are placed in Bin 1, for which no additional treatment is required. For concentrations of 0.075 or more, additional treatment is required on top of that required by existing rules. The additional treatment required for each bin, specified in terms of log removal, depends on the type of treatment already in place by the system.

Table 1.2 Bin Requirements for Filtered Systems[1]

If your *Cryptosporidium* concentration (oocysts/L) is...	Your bin classification is...	And if you use the following filtration treatment in full compliance with existing regulations, then your *additional* treatment requirements are...			
		Conventional Filtration Treatment (includes softening)	Direct Filtration	Slow Sand or Diatomaceous Earth Filtration	Alternative Filtration Technologies
< 0.075	**1**	No additional treatment	No additional treatment	No additional treatment	No additional treatment
≥ 0.075 and < 1.0	**2**	1 log treatment[2]	1.5 log treatment[2]	1 log treatment[2]	As determined by the State[2,4]
≥ 1.0 and < 3.0	**3**	2 log treatment[3]	2.5 log treatment[3]	2 log treatment[3]	As determined by the State[3,5]
≥ 3.0	**4**	2.5 log treatment[3]	3 log treatment[3]	2.5 log treatment[3]	As determined by the State[3,6]

[1] (40 CFR 141.709 and 40 CFR 141.720)
[2] Systems may use any technology or combination of technologies from the microbial toolbox.
[3] Systems must achieve at least 1 log of the required treatment using ozone, chlorine dioxide, UV disinfection, membranes, bag/cartridge filters, or bank filtration.
[4] Total *Cryptosporidium* treatment must be at least 4.0 log.
[5] Total *Cryptosporidium* treatment must be at least 5.0 log.
[6] Total *Cryptosporidium* treatment must be at least 5.5 log.

1.3.1.2 Unfiltered Systems

All existing requirements for unfiltered systems under the SWTR (40 CFR 141.71 and 141.72(a)) remain in effect. This includes disinfection to achieve at least 3 log inactivation of *Giardia* and 4 log inactivation of viruses and to maintain a disinfectant residual in the distribution system (e.g., free chlorine or chloramines). The IESWTR and LT1ESWTR did not change the disinfection requirements for unfiltered systems. The LT2ESWTR requires 2 log or 3 log inactivation of *Cryptosporidium*, depending on the source water concentration of *Cryptosporidium* (40 CFR 141.721(b)).

The arithmetic mean concentration of all *Cryptosporidium* samples taken is used to determine the amount of treatment required, as shown in Table 1.3 (40 CFR 141.721(a)). If the mean concentration is less than or equal to 0.01 oocysts/L, the system must provide 2 log inactivation of *Cryptosporidium* (40 CFR 141.721(b)). If the mean concentration of *Cryptosporidium* exceeds 0.01 oocysts/L, the system must provide at least 3 log inactivation of *Cryptosporidium* (40 CFR 141.721(b)).

Table 1.3 Bin Requirements for Unfiltered Systems

Bin Number	Average *Cryptosporidium* Concentration (oocysts/liter)	Additional *Cryptosporidium* inactivation requirements
1	≤ 0.01	2 log[1]
2	> 0.01	3 log[1]

[1] Overall disinfection requirements must be met with a minimum of two disinfectants (40 CFR 141.721(d)).

1.3.1.3 UV Disinfection Requirements for Filtered and Unfiltered Systems

To receive disinfection credit for a UV reactor, the LT2ESWTR requires utilities to demonstrate through validation testing that the reactor can deliver the required UV dose (40 CFR 141, Subpart W, Appendix D). EPA developed dose requirements for *Cryptosporidium*, *Giardia*, and virus as presented in Table 1.4 and described in Appendix B of this guidance manual. These dose requirements account for uncertainty associated with the dose-response of the microorganisms in controlled experimental conditions. In practical application, other sources of uncertainty are introduced due to the hydraulic effects of the UV installation, UV reactor equipment, and monitoring approach (e.g., UV intensity sensors). Therefore, the validation protocol (described in Chapter 4 and Appendix C of this guidance manual) applies a safety factor to the Table 1.4 dose requirements to account for these areas of uncertainty and variability.

Table 1.4 UV Dose Requirements Used During Validation Testing[1]

	Log Inactivation							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	-	-
Giardia	1.5	2.1	3.0	5.2	7.7	11	-	-
Virus	39	58	79	100	121	143	163	186

[1] 40 CFR 141.729(d)

The LT2ESWTR (40 CFR 141, Subpart W, Appendix D) specifies the following with respect to reactor validation:

- Validation testing must determine a range of operating conditions that can be monitored by the system and under which the reactor delivers the required UV dose.
- Operating conditions must include flowrate, UV intensity, and lamp status, at a minimum.

- Validated conditions determined by testing must account for UV absorbance of the water, lamp fouling and aging, measurement uncertainty of on-line UV intensity sensors, UV dose distributions arising from the velocity profiles through the reactor, failure of UV lamps or other critical installation components, and inlet and outlet piping or channel configurations of the UV reactor.

Using the above requirements as a basis, Appendix C provides guidance for several possible approaches to reactor validation. States may approve modifications to these approaches or alternative approaches at their discretion.

Monitoring Requirements (40 CFR 141.729(d))

The LT2ESWTR requires utilities to monitor their reactors to demonstrate that they are operating within the range of conditions that were validated for the required UV dose. At a minimum, utilities must monitor each reactor for flowrate, lamp outage, UV intensity as measured by a UV intensity sensor, and any other parameters required by the State. UV absorbance should also be measured where it used in a dose control strategy. Systems must check the calibration of UV intensity sensors and must recalibrate sensors in accordance with a protocol approved by the State. The LT2ESWTR does not specify monitoring frequency (section 5.4 of this guidance describes the monitoring requirements with recommended frequencies).

Reporting Requirements (40 CFR 141.730)

The LT2ESWTR requires utilities to report the following items:

- Initial reporting - Validation test results demonstrating operating conditions that achieve the UV dose required for the inactivation credit desired for compliance with the LT2ESWTR.

- Routine reporting - Volume of water entering the distribution system that was not treated by the UV reactors operating under validated conditions on a monthly basis.

For the purposes of this guidance manual, when a UV reactor is operating outside of its validated limits, it is considered "off-specification."

Additional Requirement for Unfiltered Systems (40 CFR 141.721(c)(2))

For unfiltered systems using UV disinfection to meet the LT2ESWTR requirements, the required *Cryptosporidium* log inactivation by UV disinfection must be achieved in at least 95 percent of the water delivered to the public during each calendar month.

1.3.2 Stage 2 DBPR

The requirements of the Stage 2 DBPR will apply to all community water systems (CWSs) and nontransient noncommunity water systems (NTNCWSs)—both ground and surface water systems—that add a disinfectant other than UV light, or that deliver water that has been treated with a disinfectant other than UV light.

Initial Distribution System Evaluations

The Stage 2 DBPR is designed to reduce DBP occurrence peaks in the distribution system by changing compliance monitoring requirements. Compliance monitoring will be preceded by an initial distribution system evaluation (IDSE) to identify compliance monitoring locations that represent high TTHM and HAA5 levels. The IDSE consists of either a standard monitoring program (SMP) or a system-specific study (SSS). NTNCWSs serving fewer than 10,000 people are not required to perform an IDSE, and other systems may receive waivers from the IDSE requirement.

Compliance Determination and Schedule

The Stage 2 DBPR changes the way sampling results are averaged to determine compliance. The determination for the Stage 2 DBPR is based on a LRAA (i.e., compliance must be met at *each* monitoring location) instead of the system-wide RAA used under the Stage 1 DBPR.

The Stage 2 DBPR will be implemented in two phases, Stage 2A and Stage 2B. Under Stage 2A, all systems must comply with TTHM/HAA5 MCLs of 120/100 µg/L measured as LRAAs at each Stage 1 DBPR monitoring site, while continuing to comply with the Stage 1 DBPR MCLs of 80/60 µg/L measured as RAAs. Under Stage 2B, systems must comply with TTHM/HAA5 MCLs of 80/60 µg/L at locations identified under the IDSE.

Significant Excursion Evaluations

Because Stage 2 DBPR MCL compliance is based on an annual average of DBP measurements, a system could from time to time have DBP levels significantly higher than the MCL (referred to as a significant excursion) while still being in compliance. This is because the high concentration could be averaged with lower concentrations at a given location. If a significant excursion occurs, a system must conduct a significant excursion evaluation and discuss the evaluation with the State no later than the next sanitary survey.

1.4 Alternative Approaches for Disinfecting with UV Light

This manual provides technical information about using UV disinfection for drinking water treatment. Although it covers many aspects of implementing a UV installation, from design and validation to operation, it is not comprehensive in terms of all types of UV installations, design alternatives, and validation protocols that may provide satisfactory

performance. For example, pulsed UV and eximer lamps are two types of UV technologies not included in this manual, but they may provide effective disinfection. Currently, a significant level of research is being conducted surrounding UV disinfection and its applications in various industries. As more information becomes available, other UV equipment or methods of operation, design, and validation will evolve. States may recognize alternatives in UV installation design, operation, and validation that are not described in this manual.

2. Overview of UV Disinfection

Chapter 2 provides an overview of UV disinfection. The material ranges from an explanation of the process in terms of basic chemical and physical principles to a description of the components of a UV installation and performance monitoring. Appendix A, Fundamentals of UV Disinfection, serves as a companion to this chapter by providing more detailed information on each of the topics discussed. The corresponding appendix sections are noted throughout the text. The organization of this chapter is presented below, including the key question each section addresses.

- What are the fundamental characteristics of UV light, and what happens to UV light as it propagates through water? ..... Section 2.2
- How does UV light inactivate microorganisms? .....Section 2.3.1
- Can microorganisms undergo repair and become infectious after inactivation by UV light? .....Section 2.3.2
- How are UV dose and microbial response determined? ..... Sections 2.3.3 and 2.3.4
- How does UV dose vary in a UV reactor? .....Section 2.3.3
- What affects a microorganism's response to UV light? ..... Sections 2.3.4 and 2.3.5
- What do UV reactors look like and how do the key components function? ..... Section 2.4
- What are the differences between low pressure and medium pressure lamps?.....Section 2.4.2
- How do the utility and the State know the UV reactor is delivering the required UV dose? .....Section 2.4.9
- How does water quality affect UV reactor performance? .....Section 2.5.1
- Do any disinfection byproducts form as a result of UV disinfection?.....Section 2.5.2

2.1 History of UV Light for Drinking Water Disinfection

UV disinfection is an established technology supported by decades of fundamental and applied research and practice in North America and Europe. Downes and Blunt (1887) discovered the germicidal properties of sunlight. The development of mercury lamps as artificial UV light sources in 1901 and the use of quartz as a UV transmitting material in 1906 was soon

followed by the first drinking water disinfection application in Marseilles, France in 1910. In 1929, Gates identified a link between UV disinfection and absorption of UV light by nucleic acid. The development of the fluorescent lamp in the 1930s led to the production of germicidal tubular lamps. Considerable research on the mechanisms of UV disinfection and the inactivation of microorganisms occurred during the 1950s (Dulbecco 1950; Kelner 1950; Powell 1959; Brandt and Giese 1956).

While there was substantial research on UV disinfection during the first half of the 20th century, the low cost of chlorine and operational problems with early UV disinfection systems limited the growth of UV disinfection as a drinking water treatment technology. The first reliable applications of UV light for disinfecting municipal drinking water occurred in Switzerland and Austria in 1955 (Kruithof and van der Leer 1990). By 1985, the number of installations in these countries had risen to approximately 500 and 600, respectively. With the discovery of chlorinated disinfection byproducts (DBPs), UV disinfection became popular in Norway and the Netherlands with the first installations occurring in 1975 and 1980, respectively.

As of 1996, there were over 2000 UV disinfection systems treating drinking water in Europe (USEPA 1996), primarily treating flows less than 1 million gallons per day (MGD). A survey conducted in 2000 found that UV disinfection is currently being used to treat larger flows, including two installations treating a combined flow of 76 MGD in Helsinki, Finland (Toivanen 2000), and that the number of installations is increasing (USEPA 2000). Several large installations across the United States are currently under design. Because of the susceptibility of *Cryptosporidium* to UV disinfection and the emphasis in recent regulations on controlling *Cryptosporidium*, the number of utilities using UV disinfection is expected to increase significantly over the next decade.

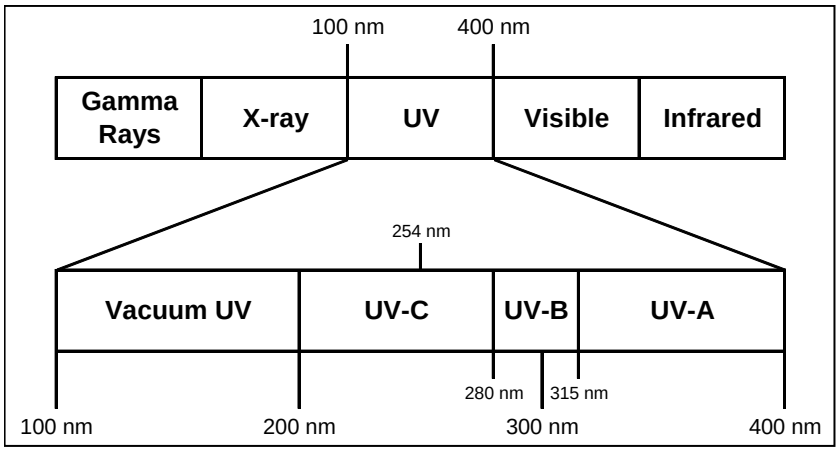
2.2 Fundamental Aspects of UV Light

The use of UV light to disinfect drinking water involves (1) the generation of UV light with the desired germicidal properties and (2) the delivery (or transmission) of that light to pathogens. This section provides a basic description of how UV light is generated and the environmental conditions that affect its delivery to pathogens.

2.2.1 Nature of UV Light

UV light is the region of the electromagnetic spectrum that lies between x-rays and visible light (Figure 2.1). The UV spectrum is divided into four regions as shown in Figure 2.1: vacuum UV (100 to 200 nm), UV-C (200 to 280 nm), UV-B (280 to 315 nm), and UV-A (315 to 400 nm) (Meulemans 1986). UV disinfection occurs due to the germicidal action of UV-B and UV-C with microorganisms. The germicidal action of UV-A is small relative to UV-B and UV-C and therefore needs very long exposure times to be effective as a disinfectant. Light in the vacuum UV range is very effective in disinfecting microorganisms (Munakata et al. 1991). However, it is impractical for water disinfection applications because it rapidly attenuates over very short distances in water. For the purposes of this manual, the practical germicidal wavelength for UV light ranges between 200 and 300 nm.

Figure 2.1 UV Light in the Electromagnetic Spectrum



Typically, UV light is generated by applying a voltage across a gas mixture, resulting in a discharge of photons. The specific wavelengths of light emitted from photon discharge depend on the elemental composition of the gas and the power level of the lamp (section A.1.1). Nearly all UV lamps designed for water treatment use a gas mixture containing mercury vapor. Mercury is an advantageous gas for UV disinfection applications because it emits light in the germicidal wavelength range, as discussed in section 2.3.5. The light output depends on the concentration of mercury atoms, which is directly related to the mercury vapor pressure. Mercury at low vapor pressure (near vacuum; 0.001 to 0.01 torr, 2×10^{-5} to 2×10^{-3} psi) and moderate temperature (40 ºC) produces essentially monochromatic UV light at 253.7 nm. At higher vapor pressures (100 to 10,000 torr, 2 to 200 psi) and higher operating temperatures (600 to 900 ºC), the frequency of collisions between mercury atoms increases, producing UV light over a broad spectrum (polychromatic) with an overall higher intensity. Mercury vapor pressure between 0.01 and 100 torr does not efficiently produce UV light.

2.2.2 Propagation of UV Light

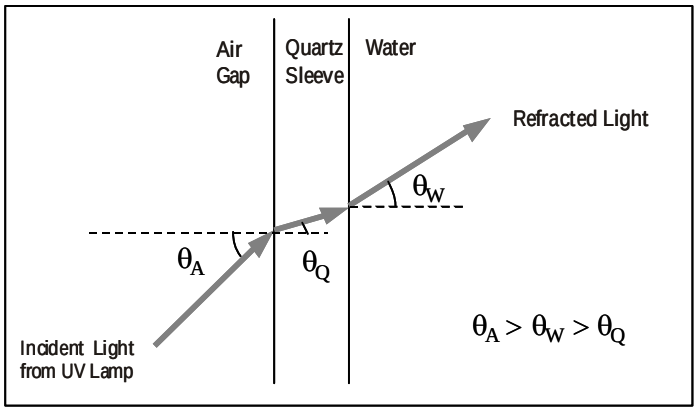
As UV light propagates from its source, it interacts with the materials it encounters through absorption, reflection, refraction, and scattering. In disinfection applications, these phenomena result from interactions between the emitted UV light and UV reactor components (i.e., lamp envelopes, lamp sleeves, and reactor walls) and also the water being treated. When assessing water quality, UV absorbance or UV transmittance is the parameter that incorporates the impact of absorption and scattering. This section briefly describes both the phenomena that influence light propagation and measurement techniques to quantify UV light propagation. More detailed information is provided in sections A.1.2.1 through A.1.2.5.

Absorption is the transformation of light to other forms of energy as it passes through a substance. UV absorption of a substance will vary with the wavelength of the light. The components of the reactor and the water passing through the reactor all absorb UV light to varying degrees, depending on their material composition. When UV light is absorbed, it is no longer available to disinfect microorganisms.

Unlike absorption, the phenomena of refraction, reflection, and scattering change the direction of UV light, but the UV light is still available to disinfect microorganisms.

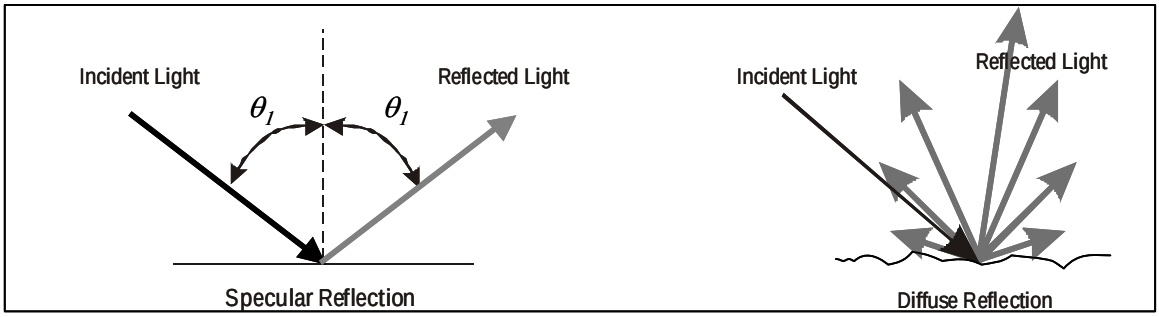
Refraction (Figure 2.2) is the change in the direction of light propagation as it passes from one medium to another. In UV reactors, refraction occurs when light passes from the UV lamp through an air gap, through the lamp sleeve, and through the water. These changes alter the angle that UV light strikes target pathogens.

Figure 2.2 Refraction of Light



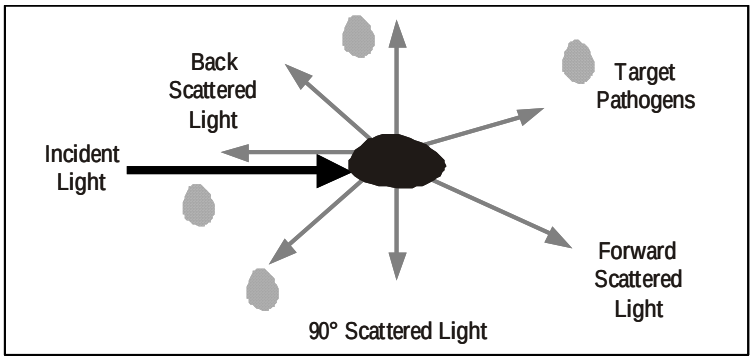
Reflection is the change in direction of light propagation when it is deflected by a surface (Figure 2.3). Reflection may be classified as specular or diffuse. Specular reflection occurs from smooth polished surfaces and follows the Law of Reflection (the angle of incidence is equal to the angle of reflection). Diffuse reflection occurs from rough surfaces and scatters light in all directions with little dependence on the incident angle. In UV reactors, reflection will take place at interfaces that do not transmit UV light (e.g., the reactor wall) and also at UV transmitting interfaces (e.g., the inside of a lamp sleeve). The type of reflection observed and intensity of light reflected from a surface depends on the material of the surface.

Figure 2.3 Reflection of Light



Scattering of light is the change in direction of light propagation caused by interaction with a particle (Figure 2.4). Particles can cause scattering in all directions, including towards the incident light source (back-scattering). Scattering of light caused by particles smaller than the wavelength of the light is called Rayleigh scattering (section A.1.2.4). Particles larger than the wavelength of light scatter more light in the forward direction but also cause some backscattering. Rayleigh scattering depends inversely on wavelength to the fourth power ($1/\lambda^4$) and thus is more prominent at shorter wavelengths. Scattering by particles larger that the wavelength of the light is relatively independent of wavelength.

Figure 2.4 Scattering of Light



UV absorbance (A_{254}) is a commonly used water quality parameter that characterizes the decrease in the amount of incident light as it passes through a water sample over a specified distance or pathlength. Various procedures call for filtering the sample through a 0.45 μm membrane before measuring the absorbance. If the measurement is made according to a modified version of Standard Method 5910B (APHA et al. 1998), the water sample is not pH adjusted or filtered. Since most particles in drinking water are strong absorbers of UV light, it is recommended that absorbance measurements be made without filtering the sample. Therefore, the modified measurement accounts for scattering and some absorption from particles in the water sample that may interfere with UV disinfection. Although Standard Methods identifies this measurement as UV absorption, this manual will refer to it as absorbance since the latter term is widely used in the water treatment industry.

The term **UV transmittance** (UVT) has also been used extensively in the literature when describing the behavior of UV light. UVT is the percentage of light passing through a water sample over a specified distance and is related to UV absorbance by Equation 2.1:

$$\%\ UVT = 100 * 10^{-A_{254}} \qquad \text{Equation 2.1}$$

where

UVT = UV transmittance at specified wavelength (e.g., 254 nm) and pathlength (e.g., 1 cm)

A_{254} = UV absorbance at specified wavelength, based on 1 cm pathlength (unitless; UV absorption as measured by Standard Method 5910B)

2.3 Microbial Response to UV Light

The mechanism of disinfection by UV light differs considerably from chemical disinfectants such as chlorine and ozone. Chemical disinfectants inactivate microorganisms by destroying or damaging cellular structures, interfering with metabolism, and hindering biosynthesis and growth (Snowball and Hornsey 1988). UV light inactivates microorganisms by damaging their nucleic acid, thereby preventing the microorganism from replicating. A microorganism that cannot replicate cannot infect a host.

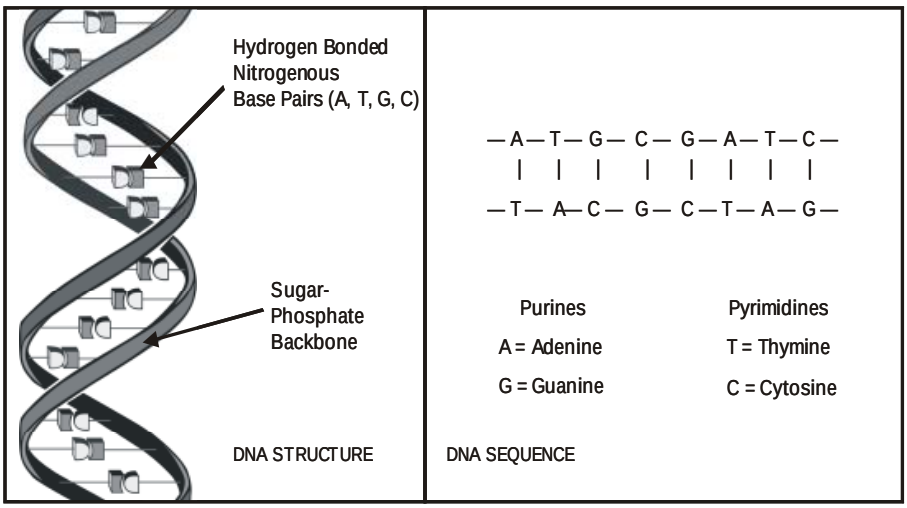
When studying UV disinfection effectiveness, it is important to use microbial assays that measure infectivity, not viability. Until recently, viability assays such as excystation and vital dyes were used to determine inactivation. However, these assays do not evaluate changes in the ability of a microorganism to reproduce and infest a host. The importance of using assays that measure inactivation is highlighted by the history of UV disinfection for *Cryptosporidium.* It was believed that UV disinfection was not effective for *Cryptosporidium* inactivation because results of early *Cryptosporidium* inactivation studies were based on viability assays. The ability of UV light to inactivate *Cryptosporidium* at low doses was revealed when infectivity was assessed by inoculating mice with UV treated water, which showed greater than 4-log inactivation of *Cryptosporidium* at doses less than 20 mJ/cm^2 (Bukhari et al. 1999).

This section discusses the damage that causes microbial inactivation, the ability of microorganisms to repair the damage, methods for determining microbial inactivation, and how wavelength of UV light affects inactivation.

2.3.1 Mechanisms of Microbial Inactivation by UV Light

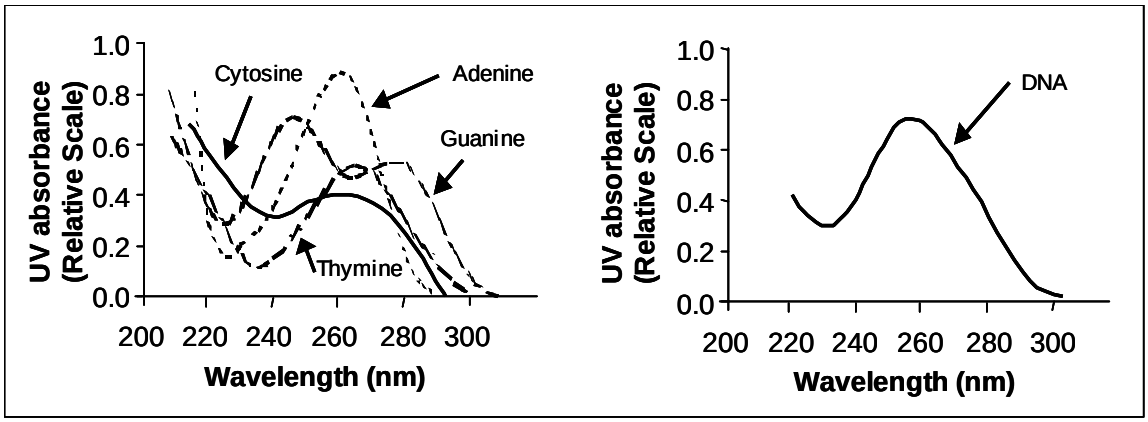
UV light inactivates microorganisms by damaging deoxyribonucleic acid (DNA) or ribonucleic acid (RNA), thereby interfering with replication of the microorganism (section A.2.2). In normal DNA replication, the double helix strand separates allowing the single strands to serve as a template for reconstructing the opposite strand of nucleotides: adenine bonds to thymine and guanine bonds to cytosine (Figure 2.5).

Figure 2.5 Structure of DNA and Nucleotide Sequences Within DNA



Light that is absorbed by a system can induce a chemical reaction. As shown in Figure 2.6, each of the nucleotides absorbs UV light from 200 to 300 nm (section A.2.2). The UV absorption of DNA results from the combination of nucleotides and has a peak near 260 nm and a local minimum near 230 nm. DNA absorbs light in the wavelength range emitted by UV lamps, enabling photobiological effects that lead to nucleic acid damage.

Figure 2.6 UV Absorbance of Nucleotides (left) and Nucleic Acid (right) at pH 7 (adapted from Jagger 1967)



Damage to nucleic acid does not prevent the cell from undergoing metabolism and other cell functions. Although the microbial cell is alive after exposure to UV light, it cannot reproduce, and therefore it is incapable of infecting a host. To kill the microbial cell, the UV dose would need to be increased by orders of magnitude as compared to the UV dose needed to prevent replication.

Variations in DNA content cause microorganisms to absorb UV light differently, thereby contributing to the differences in microorganism susceptibility to UV disinfection. There can be significant disparity in the susceptibility of different strains of bacteria and viruses to UV disinfection (section A.2.7). Among the pathogens of interest in drinking water, viruses are most resistant to UV disinfection followed by bacteria and *Cryptosporidium* oocysts and *Giardia* cysts. Appendix B provides statistical evaluations for dose-response data of *Giardia* cysts, *Cryptosporidium* oocysts, and viruses, and Chapter 1 contains the regulatory requirements for inactivating these pathogens.

2.3.2 Microbial Repair

Because microorganisms that have been exposed to UV light still retain metabolic functions, some are able to repair the damage done by UV light to a limited degree as described in section A.2.3. In some cases, the microorganism regains infectivity. These microorganisms have evolved enzyme-mediated mechanisms for reversing UV damage. Repair of UV light-induced DNA damage includes photoreactivation and dark repair (Knudson 1985). In photoreactivation (or photorepair), enzymes energized by exposure to light between 310 and 490

nm (near and in the visible range) repair damaged sections of DNA. Photoreactivation needs the presence of reactivating light. Dark repair is defined as when a repair process does not need reactivating light. The term is somewhat misleading because dark repair can occur in the presence of light, and therefore does not need dark conditions. Excision repair, a form of dark repair, is an enzyme-mediated process where the damaged section of DNA is removed and regenerated using the existing complimentary strand of DNA.

Knudson (1985) found that bacteria are able to repair in light and dark conditions, suggesting that bacteria may have the enzymes necessary for photorepair and dark repair. Viral DNA lacks the necessary enzymes for repair, but can repair using the enzymes of a host cell (Rauth 1965). Linden et al. (2002a) did not observe photoreactivation or dark repair of *Giardia* at UV doses typical for UV disinfection applications (16 and 40 mJ/cm^2). However, unpublished data from the same study show *Giardia* reactivation in light and dark conditions at very low UV doses (0.5 mJ/cm^2; Linden 2002). Shin et al. (2001) reported *Cryptosporidium* does not regain infectivity after inactivation by UV light. One study has shown that *Cryptosporidium* contains the capability to undergo some DNA repair (Oguma et al. 2001). However, even though the DNA is repaired, infectivity is not restored.

Knudson (1985) demonstrated that photorepair can be overcome by increasing the damage to the DNA through higher UV doses. However, it is unknown if higher UV doses can reduce dark repair because it is more difficult to study experimentally. Research is continuing to evaluate this phenomenon. At the doses typically used in UV disinfection, microbial repair can be controlled and accounted for as discussed in section 3.1.1.

2.3.3 UV Dose and Dose Distribution

UV dose is a measurement of the energy per unit area that is incident on a surface. UV dose is the product of the average intensity acting on a microorganism from all directions and the exposure time. Units commonly used for UV dose are J/m^2, mJ/cm^2, and mWs/cm^2 (10 J/m^2 = 1 mJ/cm^2 = 1 mWs/cm^2) with mJ/cm^2 being the most common units in North America and J/m^2 being the most common in Europe.

In a batch system such as a bench scale collimated beam test (described in Appendix E), the average intensity is determined mathematically. For collimated beam tests using a low-pressure lamp, the UV intensity measured by a radiometer, the UV absorbance of the water, the thickness of the water layer, the distribution of light across the water surface, and the reflection and refraction of light from the water surface all are considered in calculating the average intensity. The UV dose can be determined in a batch system by multiplying the calculated average intensity by the specific exposure time.

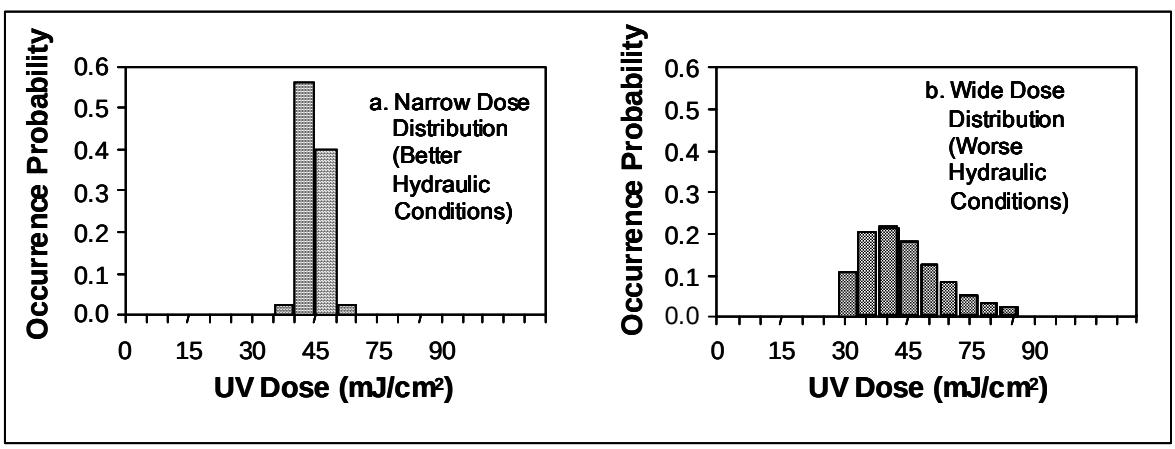
When using polychromatic light sources (e.g., medium-pressure lamps), UV dose calculations in batch, bench scale experiments also incorporate the same parameters as a low-pressure lamp collimated beam test. In addition, the intensity at each wavelength in the germicidal range and the germicidal effectiveness at the associated UV wavelengths are also considered because microorganisms absorb different amounts of UV light at different wavelengths. The UV dose-response measured with polychromatic lamps will match the UV

dose-response of monochromatic lamps when the UV dose delivered by the polychromatic source is properly calculated (Cabaj et al. 2001; section A.2.4.1).

Dose delivery in a continuous-flow UV reactor is subject to hydrodynamic irregularities and a variable UV intensity distribution and is a function of the UV absorbance of the water, the flowrate through the reactor, the UV output from the lamps, and the hydraulic characteristics within the reactor. As such, it is difficult to calculate directly UV dose within a UV reactor. If the reactor has plug flow with complete mixing perpendicular to that flow, all microorganisms leaving the reactor receive the same dose, and the reactor would be termed an "ideal" reactor. However, these ideal conditions do not generally do not exist in continuous-flow UV reactors. As such, microorganisms passing through a UV reactor are exposed to different doses. The difference in UV doses experienced by microorganisms in a flowing reactor is best characterized by a dose distribution.

A dose distribution is the probability distribution of UV doses that microorganisms receive in a flow-through UV reactor; typically shown as a histogram (Figure 2.7). Some microorganisms travel close to the UV lamps and experience a higher dose while others that travel close to the reactor walls may experience a lower dose. Some microorganisms move through the reactor quickly while others travel a more circuitous path. A narrow dose distribution (Figure 2.7a) indicates more ideal hydrodynamic conditions. A wider distribution (Figure 2.7b) indicates less efficient reactor performance and results in a greater degree of "overdosing" to ensure that the minimum desired dose is achieved for the microorganisms at the lower end of the dose distribution.

Figure 2.7 Hypothetical Dose Distributions for Two Reactors with Differing Hydraulics



There are currently no methods to measure directly the dose distribution in a continuous flow UV reactor, but mathematical models can help to characterize dose distribution. Therefore, the UV dose in a UV reactor is estimated as the reduction equivalent dose (RED). The RED is a calculated dose for a flow through UV reactor that is based on biodosimetry (i.e., measuring the level of inactivation of a challenge microorganism with a known UV dose-response). The RED is set equal to the UV dose in a collimated beam test that achieves the same level of inactivation

of the challenge microorganism as measured for the flow-through UV reactor during biodosimetry testing. Methods for collimated beam testing and biodosimetry are in Appendix E section 4.2, respectively.

2.3.4 Microbial Response (UV Dose-Response)

The response of microorganisms to UV light is calculated by determining the concentration of infectious microorganisms before and after exposure to a measured UV dose and applying Equation 2.2.

$$Log\ \ Inactivation = \log_{10} \frac{N_0}{N} \qquad \text{Equation 2.2}$$

Where

N_0 = Concentration of infectious microorganisms before exposure to UV light

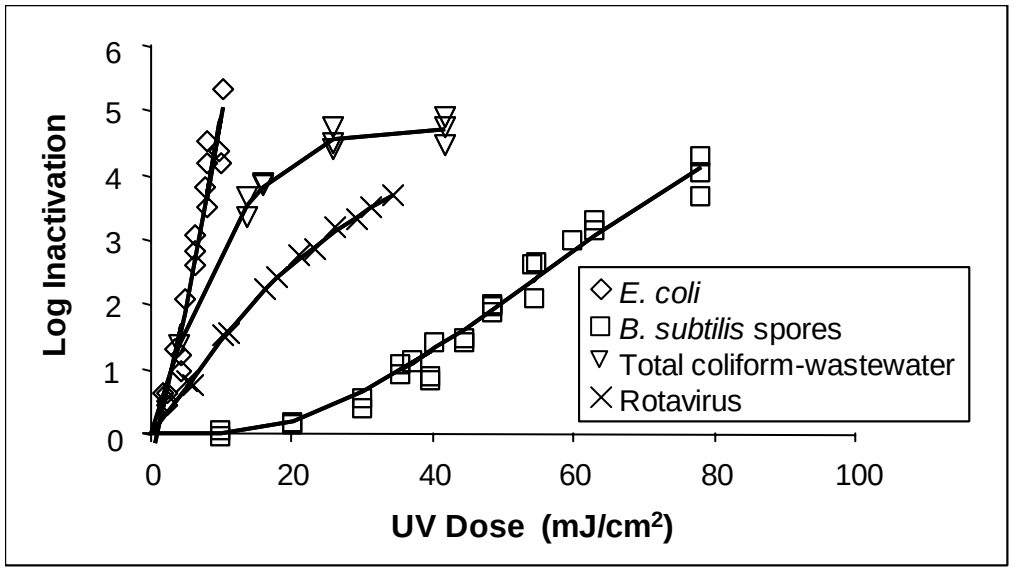
N = Concentration of infectious microorganisms after exposure to UV light

UV dose-response relationships can be expressed as either the proportion of microorganisms *inactivated* (log inactivation, results in a dose-response curve with a positive slope) or the proportion of microorganisms *remaining* (log survival, results in a dose-response curve with a negative slope) as a function of UV dose. The proportion of microorganisms remaining and the log inactivation are typically shown on a logarithmic (base 10) scale, while the UV dose is typically shown on a linear scale. This manual will present microbial response as log inactivation since the terminology is widely accepted in the industry. Therefore, all dose-response curves presented will have a positive slope.

Although several approaches may be used to measure microbial dose-response, the bench-scale collimated beam test has evolved as the customary method because it has carefully controlled conditions, allowing for accurate and repeatable determination of UV dose. Accurate determination of UV dose is beneficial for developing meaningful relationships between UV dose and microbial response.

Figure 2.8 presents examples of UV dose-response curves. In general, the UV dose-response of disperse microorganisms follows first order inactivation (Figure 2.8, *E. coli* curve; section A.2.5.1). However, some microorganisms are slower to respond, producing a shoulder at low UV doses followed by near-linear inactivation (Figure 2.8, *B. subtilis* curve; section A.2.5.2). UV dose-response is generally independent of how the germicidal UV light is produced (i.e., low-pressure or medium-pressure UV light), UV absorbance, temperature, and pH.

Figure 2.8 Shapes of UV Dose-Response Curves (adapted from Chang et al. 1985)



UV dose-response is affected by particle-association and clumping of microorganisms. Solids present in wastewater samples can cause a tailing or flattening of the dose-response curve at higher inactivation levels (Figure 2.8, total coliform curve; section A.2.5.3) because clumping or particle association shields a fraction of the microorganisms from UV light. In these wastewater experiments, the microorganisms are present in the treated water at very high concentrations so that any particle association with turbidity reflects the impact of upstream treatment processes.

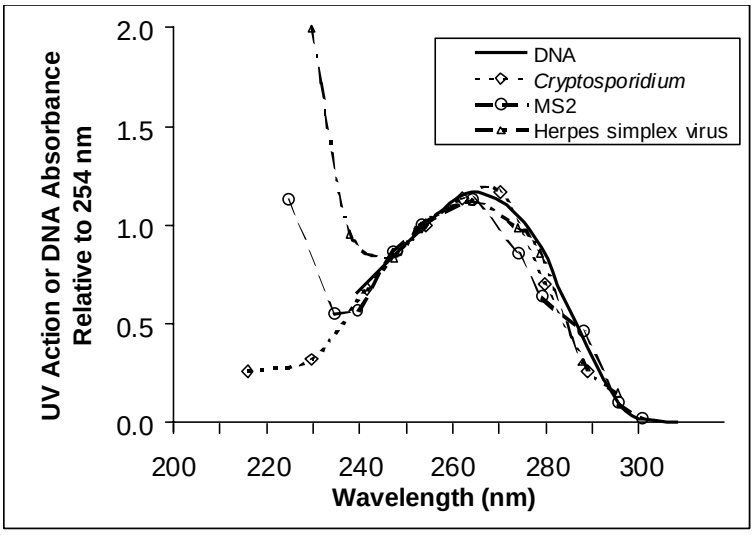
Research by Linden et al. (2002b) indicated that the UV dose-response of microorganisms added to filtered drinking waters is not altered by variation in turbidity that meets regulatory requirements (40 CFR 141.73). For unfiltered waters, Passantino and Malley (2001) found that source water turbidity up to 10 NTU does not impact the UV dose-response of separately added (seeded) microorganisms. In these experiments, however, microorganisms were added to waters containing various levels of treated or natural turbidity. Therefore, it was not possible to examine microorganisms associated directly with particles in their natural or treated states. Consequently, these drinking water studies can only suggest the impact of turbidity on dose-response as it relates to the impact of UV light scattering by particles, rather than particle-association or clumping of microorganisms.

2.3.5 Microbial Spectral Response

The action spectrum (also called UV action) of a microorganism is a measure of inactivation effectiveness as a function of wavelength. Figure 2.9 illustrates the UV action for three microbial species and also the UV absorbance of DNA as a function of wavelength. Because of the similarity between UV action and DNA absorbance, and because DNA absorbance is easier to measure than UV action, the DNA absorbance spectrum of a microorganism is often used as a surrogate for its UV action spectrum. The scale of the y-axis

represents the ratio of inactivation effectiveness at a given wavelength to the inactivation effectiveness at 254 nm. For most microorganisms, the UV action peaks at or near 260 nm, has a local minimum near 230 nm, and drops to zero near 300 nm. Although the sensitivity of the organism often increases below 230 nm, the strong absorption of UV light by components in natural water at these wavelengths offsets the increased organism sensitivity in this region. Nevertheless, an operating definition of the effective germicidal range for UV light in water includes wavelengths from 200 to 300 nm.

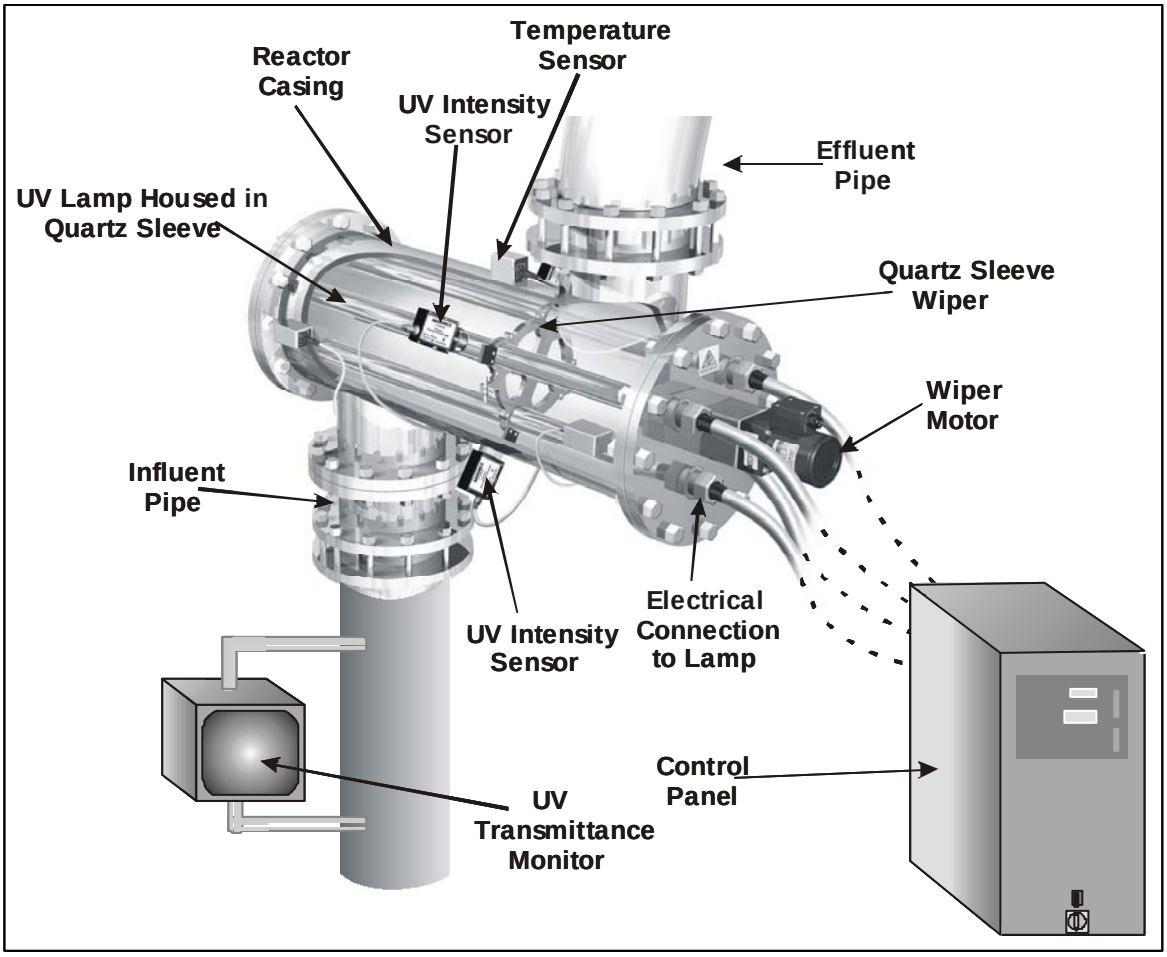
Figure 2.9 Comparison of Microbial UV Action and DNA UV Absorbance (adapted from Rauth 1965 and Linden et al. 2001)



2.4 UV Reactors

The goal in designing UV reactors for drinking water disinfection is to deliver efficiently the necessary dose to inactivate pathogenic microorganisms. An example UV reactor is shown in Figure 2.10. Commercial UV reactors consist of open or closed-channel vessels containing UV lamps, lamp sleeves, UV intensity sensors, lamp sleeve wipers, and temperature sensors. UV lamps are housed within the lamp sleeves, which protect and insulate the lamps. Some reactors include automatic cleaning mechanisms to keep the lamp sleeves free of deposits that may form due to contact with the water. UV intensity sensors, flow meters, and in some cases, UVT monitors are used to monitor dose delivery by the reactor. This section briefly describes UV reactor components. A more detailed discussion of these components is provided in section A.3.

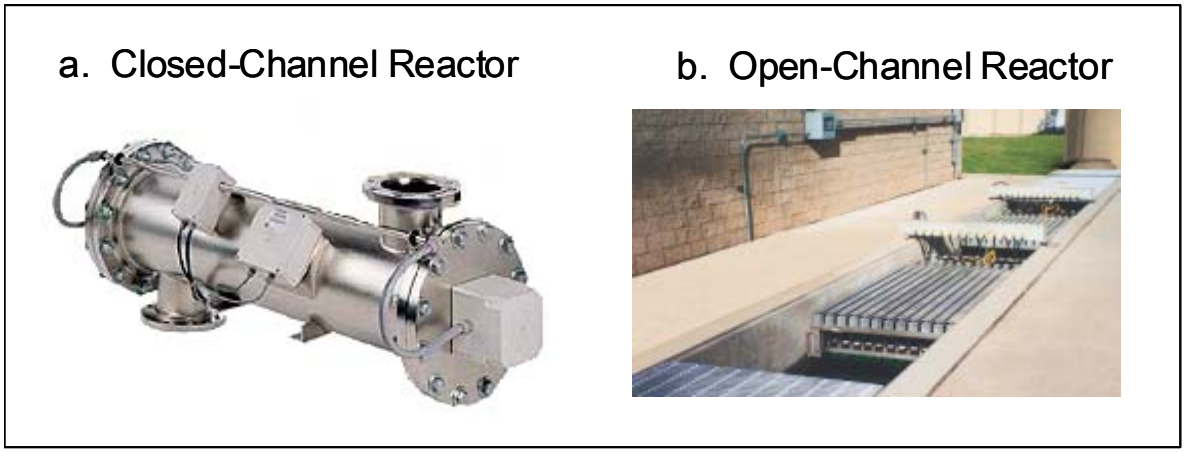
Figure 2.10 UV Disinfection System Schematic (courtesy of Severn Trent Services)



2.4.1 Reactor Configuration

UV reactors are typically classified as either open or closed channel. Water flows under pressure (i.e., no free surface) in closed channel reactors (Figure 2.11a). Drinking water UV applications have used only closed reactors to-date. Open channel reactors (Figure 2.11b) are open basins with channels containing racks of UV lamps. Open channel reactors are most commonly used in wastewater applications.

Figure 2.11 Example of Closed (a) and Open (b) Channel Reactors (courtesy of Trojan Technologies)



Reactors are designed to optimize dose delivery, and the reactor hydrodynamics play an important role in design. Lamp placement, inlet and outlet conditions, and baffles all affect mixing within a reactor. Improvements to the hydraulic behavior of a reactor are often obtained at the expense of headloss. Individual reactor designs employ various methods to optimize dose delivery (e.g., higher lamp output versus lower lamp output and improved hydrodynamics through increased headloss).

2.4.2 UV Lamps

UV light can be produced by the following variety of lamps:

- Low-pressure (LP) mercury vapor lamps
- Low-pressure high-output (LPHO) mercury vapor lamps
- Medium-pressure (MP) mercury vapor lamps
- Electrode-less mercury vapor lamps
- Metal halide lamps
- Xenon lamps (pulsed UV)
- Eximer lamps
- UV lasers

Full-scale drinking water applications generally use LP, LPHO, or MP lamps. As such, the subsequent discussions in this manual are limited to these UV lamp technologies. Table 2.1

lists characteristics associated with these lamps, and Table 2.2 lists operational advantages and disadvantages of the lamp types.

Table 2.1 Mercury Vapor Lamp Characteristics

Parameter	Low-pressure	Low-pressure high-output	Medium-pressure
Germicidal UV light	Monochromatic at 254 nm	Monochromatic at 254 nm	Polychromatic, including germicidal range (200 to 300 nm)
Mercury Vapor Pressure (torr)	Optimal at 0.007	0.76	300 – 30,000
Operating Temperature (°C)	Optimal at 40	130 – 200	600 – 900
Electrical Input (W/cm)	0.5	1.5 – 10	50 – 250
Germicidal UV Output (W/cm)	0.2	0.5 – 3.5	5 – 30
Electrical to Germicidal UV Conversion Efficiency (%)	35 – 38	30 – 40	10 – 20
Arc length (cm)	10 – 150	10 – 150	5 – 120
Relative Number of Lamps Needed for a Given Dose	High	Intermediate	Low
Lifetime (hrs)	8,000 – 10,000	8,000 – 12,000	4,000 – 8,000

Table 2.2 Mercury Vapor Lamp Comparison

	Low-pressure	Medium-pressure
Comparative Advantages	• Higher germicidal efficiency; nearly all output at 254 nm • Smaller power draw per lamp (less reduction in dose if lamp fails) • Longer lamp life	• Higher power output • Fewer lamps for a given application • Smaller reactors • Smaller footprint
Comparative Disadvantages	• More lamps needed for a given application • Larger footprint	• Higher operating temperature can accelerate fouling (section 2.5.1) • Shorter lamp life • Lower electrical to germicidal UV conversion efficiency

The light emitted by LP and LPHO lamps is essentially monochromatic at 253.7 nm (Figure 2.12a) and is near the maximum of the microbial action spectrum. MP lamps emit at a wide range of wavelengths across the action spectra (Figure 2.12b). Therefore, LPHO lamps convert power to germicidal light more efficiently. In either lamp type, power not converted to light is primarily lost as heat.

Figure 2.12 UV Output of LP (a) and MP (b) Mercury Vapor Lamps (Sharpless and Linden 2001)

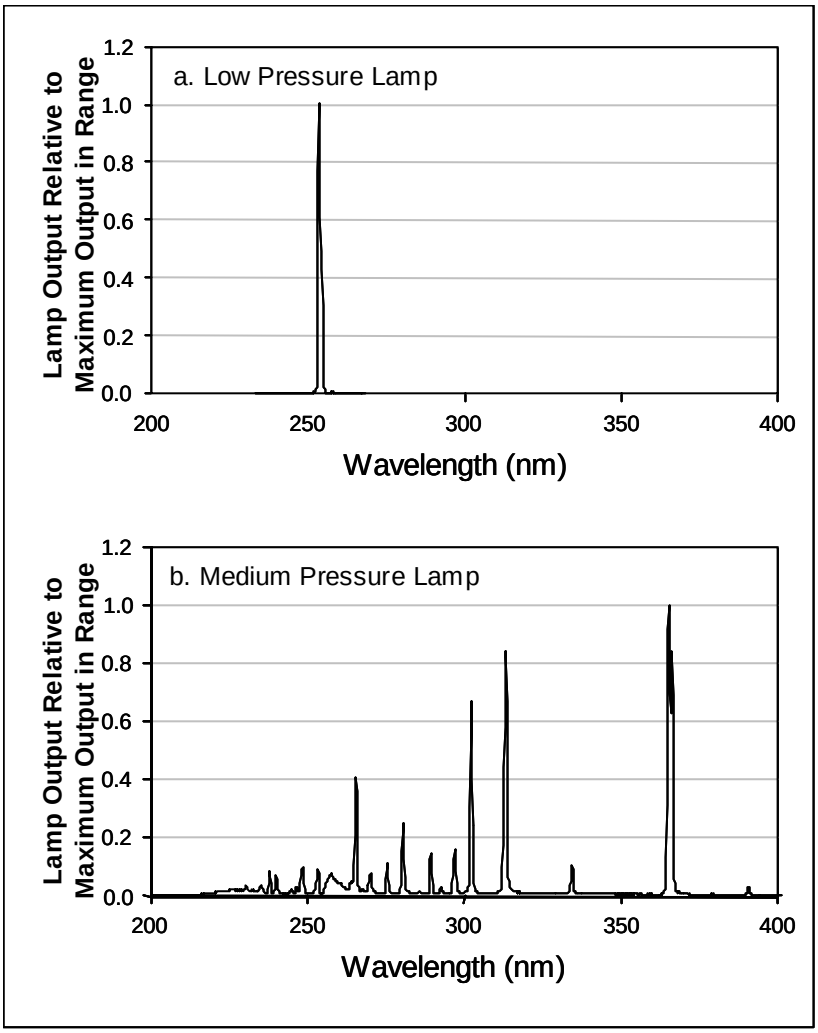
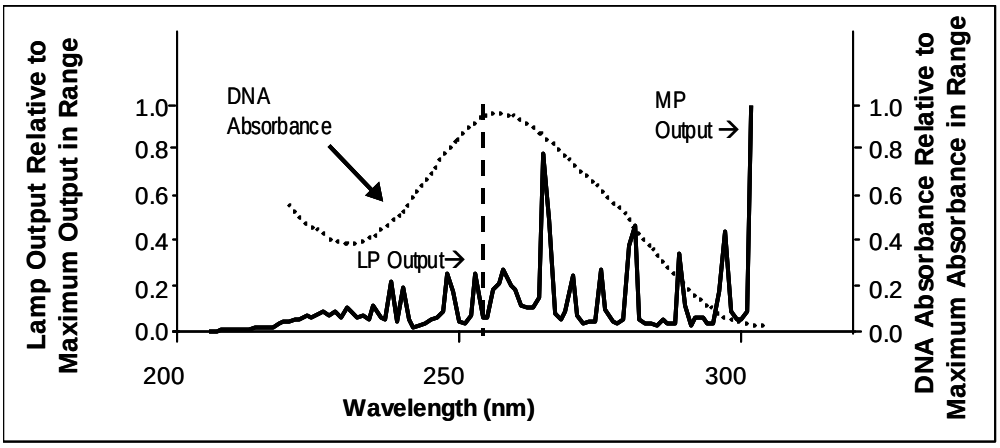


Figure 2.13 shows the output of LP and MP lamps superimposed with the DNA absorption spectrum. In Figure 2.13, the DNA absorbance is plotted relative to the maximum absorbance in the range (260 nm). The lamp outputs are also presented on a relative scale. However, in absolute terms, there is a significant difference in the intensity and power of LP and MP lamps (see Table 2.1 for more information on lamp operating characteristics).

Figure 2.13 UV Lamp Output and its Relation to the UV Absorbance of DNA (courtesy of Bolton Photosciences, Inc.)



UV lamps may be oriented parallel, perpendicular, or diagonal to flow or ground. Orienting MP lamps horizontally relative to the ground prevents differential heating of the lamps and reduces the potential for lamp breakage. Lamp breakage is discussed further in Appendix N.

UV lamps degrade as they age resulting in a reduction in output (section A.3.1.6). MP lamps may have a shift in spectral output as well. Lamp degradation will impact dose delivery over time.

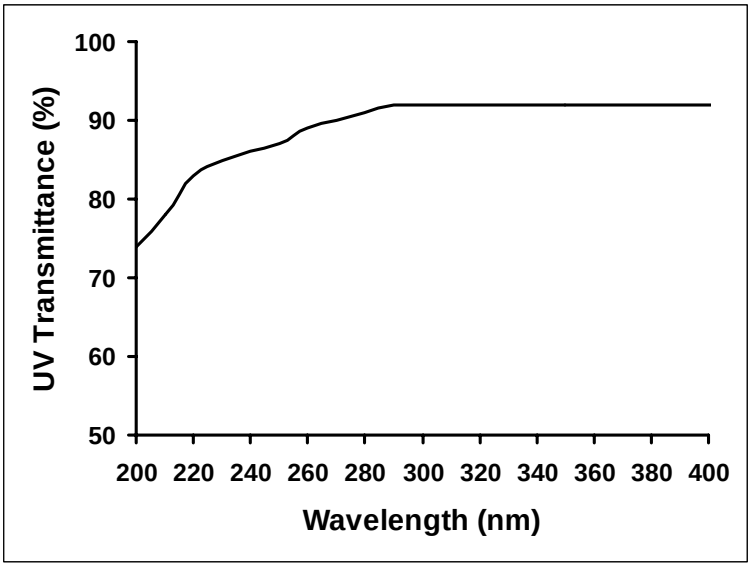
2.4.3 Lamp Power Supply And Ballasts

Ballasts supply the UV lamps with the appropriate power to energize and operate the UV lamps. Ballasts use inductance (coil or transformer), capacitance, and a starting circuit. Power supplies and ballasts are available in many different configurations and are tailored to a unique lamp type and application. UV reactors may use electronic ballasts, magnetic ballasts, or transformers. The various ballast types and their differences are detailed in section A.3.2.

2.4.4 Lamp Sleeves

UV lamps are housed within lamp sleeves to help keep the lamp at optimal operating temperature and to protect the lamp from breaking. Lamp sleeves are tubes of quartz (or vitreous silica). The sleeve length is sufficient to include the lamp and associated electrical connections. The sleeve diameter is typically 2.5 cm for LP lamps and 5 to 10 cm for MP lamps. The distance between the exterior of the lamp and interior of the lamp sleeve is approximately 1 cm. Sleeve walls are typically 2 to 3 mm thick and absorb some UV light (Figure 2.14). UV lamps are usually centered radially within lamp sleeves using spacers.

Figure 2.14 UV Transmittance of Quartz that is 1 mm Thick at a Zero Degree Incidence Angle (GE Quartz 2001)



Lamp sleeves can fracture and foul, and their transmittance will decrease as they age. Fractures can occur from internal stress and external mechanical forces such as wiper jams, water hammer, resonant vibration, and impact by objects. Microscopic fractures may also occur if lamp sleeves are not handled properly when removed for manual cleaning. If the sleeve fractures while in service, water can enter the sleeve, making the lamp vulnerable to breakage as a result of temperature differences between the lamp and the water. Lamp breakage is undesirable due to potential for mercury release. Appendix N discusses the potential effects of lamp breakage and possible response plans.

Fouling on the internal lamp sleeve surface arises from the deposition of material from components within the lamp or sleeve due to temperature and exposure to UV light. The UV reactor manufacturer can control internal lamp sleeve fouling through appropriate material selection. Fouling on external surfaces is caused by the reaction of compounds in the water with the lamp sleeve surface. Compounds that contribute to fouling are discussed in section 2.5.1. External fouling must be removed by cleaning. In addition, exposure of quartz contaminated with metal cations can cause solarization as lamp sleeves age. Both fouling and solarization can decrease the UV transmittance of the sleeve.

2.4.5 Cleaning Systems

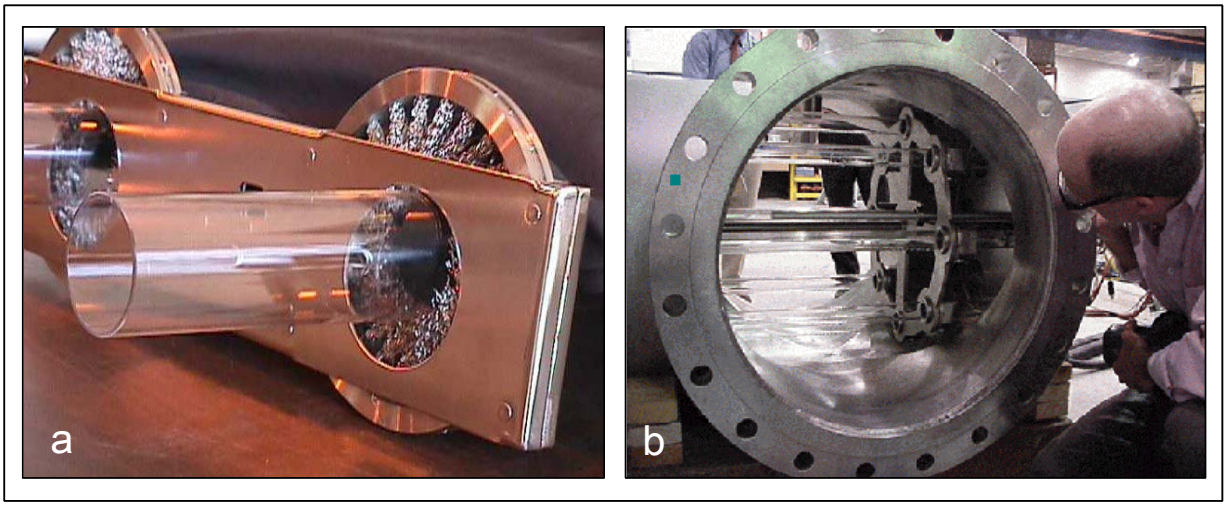
UV reactor manufacturers have developed different approaches for cleaning lamp sleeves, depending on the application. These approaches include both off-line chemical cleaning (OCC) and on-line mechanical cleaning (OMC) methods.

In OCC systems, the reactor is shut down, drained, and flushed with a cleaning solution. Solutions used to clean lamp sleeves include citric acid, phosphoric acid, or a food grade

proprietary solution provided by the UV reactor manufacturer. The reactor is rinsed and returned to operation after sufficient time to dissolve the substances fouling the sleeves is allowed. LPHO systems typically use OCC systems.

OMC systems are built-in UV reactor components that consist of wipers that are driven by either screws attached to electric motors or pneumatic pistons. There are two types of wipers used in OMC systems: mechanical wipers and physical-chemical wipers. Mechanical wipers may consist of stainless steel brush collars or Teflon® rings that move along the lamp sleeve (Figure 2.15a). Physical-chemical wipers have a collar filled with cleaning solution that moves along the lamp sleeve (Figure 2.15b). The wiper physically removes fouling on the lamp sleeve surface while the cleaning solution within the collar dissolves fouling materials. The use of mechanical and physical-chemical wipers does not necessitate that the UV reactor be drained. Therefore, the reactor can remain on-line while the lamp sleeves are cleaned. MP systems typically use OMC systems because the higher lamp temperatures can accelerate fouling under certain water qualities.

Figure 2.15 (a) Mechanical Wiper System (courtesy of Calgon Carbon Corporation), (b) Physical-Chemical Wiper System (courtesy of Trojan Technologies)

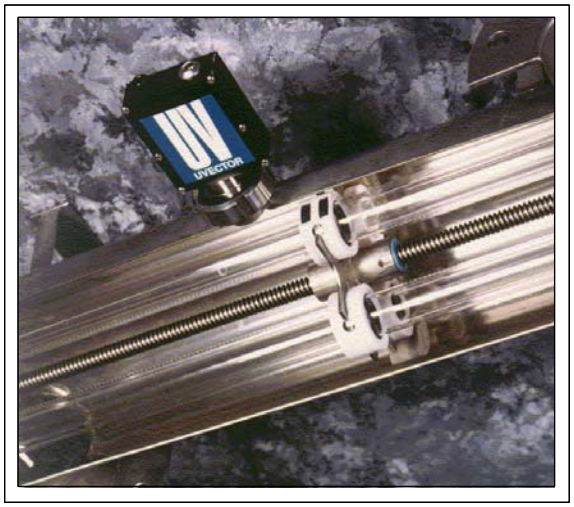


2.4.6 UV Intensity Sensors

UV intensity sensors are photosensitive detectors that measure the UV intensity at a point within the UV reactor (Figure 2.16). Sensors are used to indicate dose delivery by providing information related to UV intensity at different points in the reactor. The measurement responds to changes in lamp output due to lamp power setting, lamp aging, lamp sleeve aging, and lamp sleeve fouling. Depending on sensor position, UV intensity sensors may also respond to changes in UV absorbance of the water being treated (section A.3.8.2). UV intensity sensors are composed of optical components, a photodetector, an amplifier, a housing, and an electrical connector. The optical components may include monitoring windows, light pipes, diffusers, apertures, and filters. Monitoring windows and light pipes are designed to deliver light to the

photodetector. Diffusers and apertures are designed to reduce the amount of UV light reaching the photodetector, thereby reducing sensor degradation that is caused by UV energy. Optical filters are used to modify the spectral response such that the sensor only responds to germicidal wavelengths (i.e., 200 to 300 nm). At the time of publication, sensors are specific to each manufacturer and are subject to validation as described in sections 4.3.2.3 and C.4.7.

Figure 2.16 UV Intensity Sensor Viewing Lamps within a UV Reactor (courtesy of Severn Trent Services)



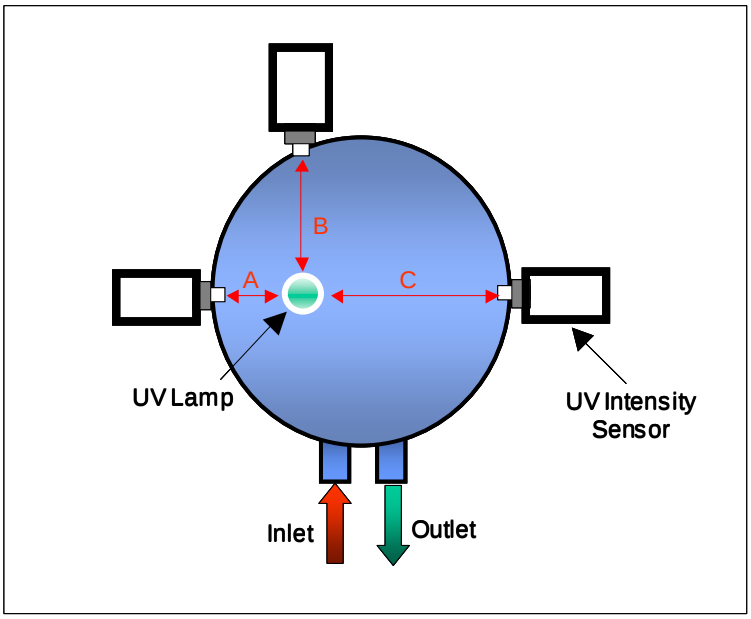
UV intensity sensors can be classified as wet or dry. Dry sensors monitor UV light through a monitoring window, whereas wet UV intensity sensors are in direct contact with the water flowing through the reactor. Monitoring windows and the wetted ends of wet sensors can foul over time and need cleaning similar to lamp sleeves.

2.4.7 UV Transmittance Monitors

As stated previously, UVT is an important parameter in determining the efficiency of UV disinfection. Therefore, monitoring UV transmittance (or UV absorbance to calculate UVT) is critical to ensure the success of a UV disinfection application. UVT can be determined either through grab samples with a laboratory instrument or on-line. Several commercial UV reactors use the measurement of UVT to help monitor and control the calculated UV dose in the reactor.

In general, commercial on-line UVT monitors calculate UVT by measuring the UV intensity at various distances from a lamp. One such monitor is schematically displayed in Figure 2.17. In this monitor, a stream of water passes through a cavity containing a LP lamp with three UV intensity sensors located at various distances from the lamp. The difference in sensor readings is used to calculate UVT.

Figure 2.17 UV Transmittance Monitor Design (courtesy of Severn Trent Services)



2.4.8 Temperature Sensors

Energy input per unit volume is relatively high for a UV reactor. The water flowing through a reactor efficiently absorbs the wasted heat and maintains operating temperatures within a desirable range. Nevertheless, temperatures can become elevated under the following circumstances:

- Water level in the reactor drops and lamps are exposed to air.
- Water stops flowing in the reactor.

UV reactors are equipped with temperature sensors that monitor the water temperature within the reactor. If the temperature is above the recommended operating temperature range, the reactor will shut off to minimize the potential for the lamps overheating.

2.4.9 Monitoring UV Disinfection Performance

The performance of an operating UV disinfection system must be monitored to demonstrate that adequate disinfection is being achieved (40 CFR 141, Subpart W, Appendix D). Because the concentration of pathogenic organisms cannot be measured continuously in the UV-treated water and the dose distribution cannot be measured directly in real time, various strategies have been developed to monitor dose delivery. Any dose monitoring method must be evaluated during reactor validation (as described in section 4.3.2.2), and the outputs measured during validation will be part of the monitoring requirements described in section 5.4.1 (40 CFR 141.729(d)).

Currently, there are three fundamental approaches to monitor UV disinfection performance in a UV reactor:

1. **UV Intensity Setpoint Approach.** In this approach, measurements made by the UV intensity sensor are used to control the UV reactor. The UV intensity sensor is located in a position that allows it to properly respond to both changes in UV intensity output of the lamps and also UVT of the water. The UV intensity sensor output and the flowrate are used to monitor dose delivery. The setpoint value for UV intensity over a range of flowrates is determined during validation.

2. **UV Intensity and UVT Setpoint Approach.** This approach is similar to the UV intensity sensor setpoint approach, except that the UV sensor is placed close to the lamp such that it only responds to changes in UV lamp output. UVT is monitored separately. For a specific flowrate, the UV intensity and UVT measurements are used to monitor dose delivery. The setpoints for UV intensity and UVT over a range of flowrates are determined during validation.

3. **Calculated UV Dose Approach.** In this approach, the UV intensity sensor is placed close to the lamp, which is similar to the UV intensity and UVT setpoint approach. Flowrate, UVT, and UV intensity are all monitored, and the outputs are used to calculate UV dose via a validated computational algorithm developed by the UV reactor manufacturer.

The strategy for dose monitoring depends on the manufacturer and may be proprietary. Dose monitoring recommendations are discussed in section 5.4.2.

2.5 Water Quality Impacts and Byproduct Formation

Constituents in the water subjected to treatment affect the performance of UV disinfection. In addition, all disinfectants can form byproducts, and the goal of the overall disinfection process is to maximize disinfection while minimizing byproduct formation. This section discusses water quality characteristics impacting UV disinfection performance and finishes with a discussion of byproducts formed during the UV disinfection process.

2.5.1 Water Quality Impacts

UVT, particle content, and constituents that foul lamp sleeves and other wetted components are the most significant water quality factors impacting UV disinfection effectiveness. In spite of these effects, the impact of water quality on dose delivery can be adequately addressed in virtually all drinking water applications if carefully considered during the design of the UV disinfection system, as discussed in section 3.1.3.1.

The most important water quality parameter affecting reactor performance is UVT. As UVT decreases, the intensity throughout the reactor decreases for a given lamp configuration. This results in a reduction in UV dose delivered to the microorganism and the measured UV

intensity for a given lamp output. Section 3.1.3.1 discusses how to incorporate the impact of UVT into UV disinfection system design.

Several chemicals used in water treatment processes can decrease the UVT of water (e.g., Fe^{+3} and ozone). However, some oxidants (including ozone) can increase the UVT (APHA et al. 1998) by degrading natural organic matter. Water treatment processes upstream of the UV reactors can be operated to control UVT, thereby optimizing the design and costs of the UV reactor (section A.4.1.3 and section 3.1.3.1).

Particle content can also impact UV disinfection performance. Particles may scatter light and reduce the UV intensity delivered to the microorganisms. Particles may also shield microorganisms from UV light, effectively reducing disinfection performance.

Compounds in the water can cause fouling in a UV reactor on the external surfaces of the lamp sleeves and other wetted components (e.g., monitoring windows of UV intensity sensors). Fouling on the lamp sleeves reduces the transmittance of UV light through the sleeve into the water, thereby reducing power efficiency. Fouling on the monitoring windows impacts UV intensity and dose monitoring. Hardness, alkalinity, temperature, iron concentration, and pH all influence the rate of fouling and, subsequently, the frequency of sleeve cleaning. The following compounds can cause fouling:

- Compounds whose solubility decreases as temperature increases will precipitate (e.g., $CaCO_3$, $CaSO_4$, $MgCO_3$, $MgSO_4$, $FePO_4$, $FeCO_3$, $Al_2(SO_4)_3$). These compounds will foul MP lamps faster than LP lamps due to differences in operating temperature.

- Compounds with low solubility will precipitate (e.g., $Fe(OH)_3$, $Al(OH)_3$).

- Particles will deposit on the lamp sleeve surface due to gravity settling and turbulence-induced collisions (Lin et al. 1999a).

Fouling rate kinetics have been reported as first order over time following a short induction period (Lin et al. 1999b). Depending on the water quality and UV lamp type, significant fouling may occur in hours or take up to several months. Although there is currently not sufficient information to predict fouling based on water quality, a facility can use the Langelier Saturation Index (LSI) or the Calcium Carbonate Precipitation Potential (CCPP) as a tool to determine if precipitation is likely to occur (section A.4.1.4). Data have been generated from pilot-scale testing on waters of low to moderate hardness and iron content (Mackey et al. 2001 and Mackey et al. 2003). At total and calcium hardness levels less than 140 mg/L and iron less than 0.1 mg/L, standard cleaning protocols and wiper frequencies (one sweep every 15 minutes to an hour) were sufficient to overcome the impact of sleeve fouling at all sites tested. At sites with high hardness or iron in the feed water, it may be advantageous to evaluate fouling rates as described in section J.5.1 on a site-specific or worst case basis via pilot-scale or demonstration-scale testing to identify how best to keep the lamp sleeves clean.

Table 2.3 is a summary of water quality data and the fouling observed for various pilot and full-scale UV reactors. All of the MP systems shown had mechanical cleaning (except at Boxalls Lane), and the LPHO systems used manual chemical cleaning. The fouling observed at individual sources is reported as shown in the following list:

- Not Significant – no significant drop in UV intensity (based on UV intensity sensor readings)
- Moderate – slight decrease in UV intensity and slight scale observed on sleeves
- Significant – large decrease in UV intensity and significant deposits observed on sleeves

Table 2.3 Water Quality Data and Fouling Observed for UV Disinfection Pilot and Demonstration Studies

Name of Plant	Boxalls Lane[1]	Atlanta[2]	Ulrich Water Treatment Plant[2]	Central Utah[2]	Neenah Water Utility[2]	Cudahy Water Utility[2]
Location	Hampshire, UK	Atlanta, GA	Austin, TX	Orem, UT	Neenah, WI	Cudahy, WI
Lamp Type	MP	MP/LPHO	MP/LPHO	MP/LPHO	MP/LPHO/ LP	MP/LPHO/ LP
A_{254} (cm^{-1})	NA	0.01-0.04	0.03-0.08	0.01-0.04	0.03-0.10	0.00-0.03
LSI	NA	NA	NA	0.5	0.7	-0.1
Iron (mg/L)	NA	<0.04	0.01	<0.02	0.02	0.01
Manganese (mg/L)	NA	<0.015	<0.001	<5.0[3]	0.003	0.012
Calcium Hardness (mg/L as $CaCO_3$)	NA	NA	40	162	54	80
Hardness (mg/L as $CaCO_3$)	325-370	21.5	101	180	87	138
Alkalinity (mg/L as $CaCO_3$)	260-280	13.7	60	159	52	125
pH	7.1-7.2	6.6	9.6	7.8	9	7.7
Fouling Observed	not significant	not significant[4] moderate[5]	not significant	moderate[6]	not significant	not significant

[1] Bourgine et al. 1995
[2] Mackey et al. 2001
[3] Detection Limit
[4] Cleaning wipers on (MP system)
[5] Cleaning wipers off (MP system)
[6] After 8 months of operation (LPHO system)
NA = Not available

None of the systems studied and listed in Table 2.3 exhibited "significant" fouling, and in all cases, the observed fouling was controllable by regular system maintenance and cleaning.

Lastly, algae may grow upstream or downstream of UV reactors. Visible light emitted from the lamps is transmitted through water at further distances than germicidal wavelengths.

Depending on the concentration of nutrients in the water and the amount of visible light transmitted beyond the reactor, algae growth may need to be controlled through periodic maintenance.

2.5.2 Byproducts from UV Disinfection

UV DBPs arise either directly through photochemical reactions or indirectly through reactions with products of photochemical reactions (section A.4.2). Photochemical reactions will only take place if a chemical species absorbs UV light, and the resulting excited state reacts to form a new species. The resulting concentration of new species will depend on the concentration of the reactants and the UV dose.

In drinking water, research has focused on the impact of UV light on the formation of halogenated DBPs after subsequent chlorination and the transformation of organic material to more degradable components. For ground water and filtered drinking water, UV disinfection at typical doses has been shown not to impact the formation of trihalomethanes or haloacetic acids, two categories of DBPs currently regulated by the United States Environmental Protection Agency (EPA) (Malley et al. 1995; Kashinkunti et al. 2003).

Several studies have shown low-level formation of non-regulated DBPs (e.g., aldehydes) as a result of applying UV light to wastewater and raw drinking water sources. However, a study performed with filtered drinking water indicates no significant change in aldehydes, carboxylic acids, or total organic halides (TOX) (Kashinkunti et al. 2003). The difference in results can be attributed to the difference in water quality, most notably the higher concentration of organic material in raw waters and wastewaters.

Finally, the conversion of nitrate to nitrite is possible with MP lamps that emit at low wavelengths (von Sonntag and Schuchman 1992). However, due to the low conversion rate (about 1 percent; Sharpless and Linden 2001), this is of minimal concern in drinking water applications.

3. Planning and Design Aspects for UV Installations

This chapter discusses the key planning and design features for UV installations. The planning section helps identify the parameters and constraints to be considered prior to design of the UV installation, and the design section presents factors that should be considered during detailed design.

The focus of Chapter 3 is UV disinfection implementation issues, not the determination of whether UV disinfection is the most appropriate technology. *Throughout Chapter 3, it is assumed, unless otherwise stated, that the water to be disinfected is filtered water meeting applicable regulatory requirements. Appendices G, H, and I provide additional information on unfiltered, ground water, and small systems, respectively*. The planning and detailed design for any UV installation is site-specific. Given the wide range of treatment scenarios that are possible, a document of this nature cannot address or anticipate all possible treatment conditions. The information presented here should be used within the context of sound engineering judgment as it can be applied on a case-by-case basis. In addition, this Guidance Manual was written with the understanding that UV technology will continue to expand and evolve.

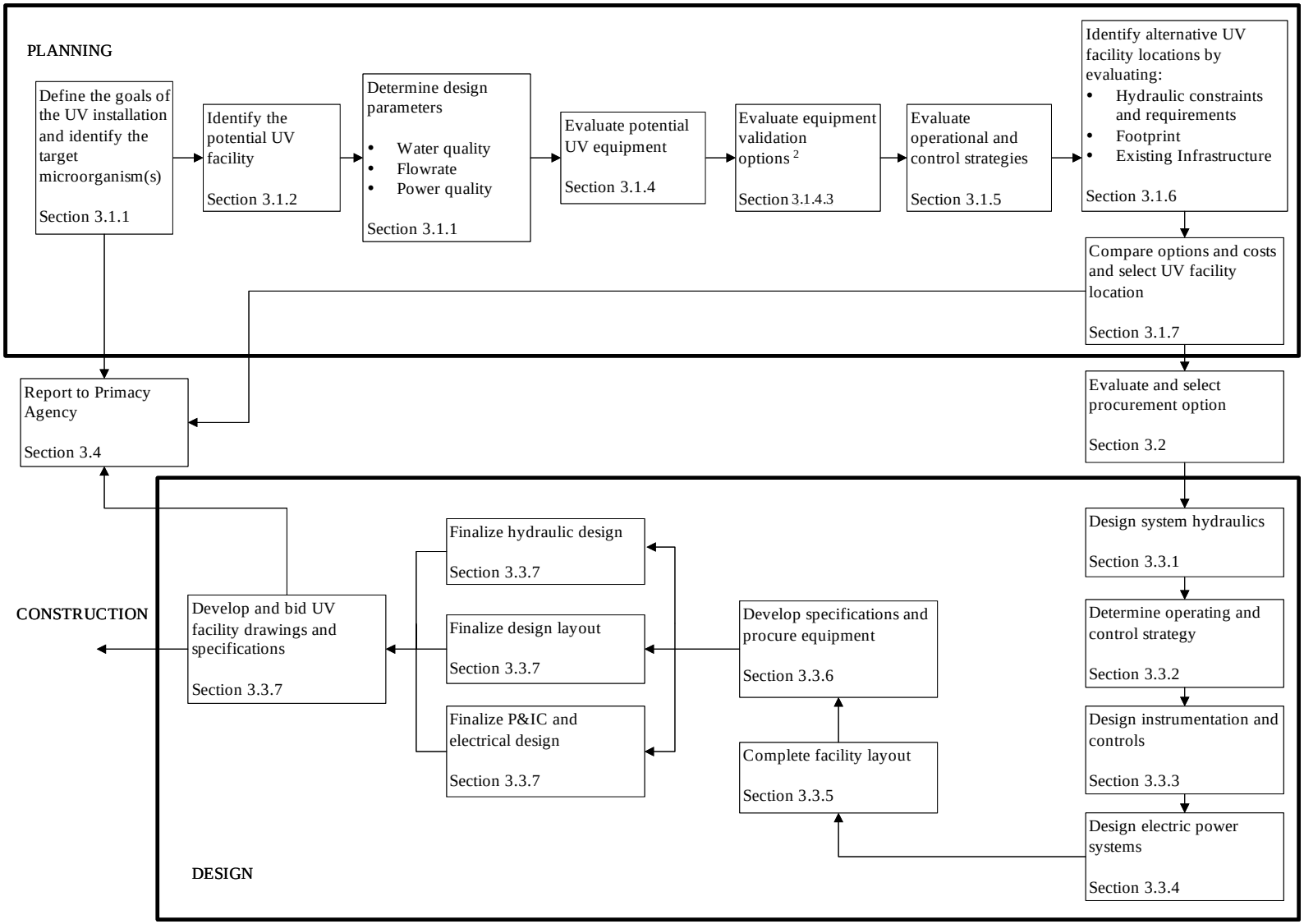
The organization of this chapter is presented below by the question that each section addresses.

- What are the goals of the UV installation? .....Section 3.1.1
- What are the potential installation locations? .....Section 3.1.2
- What design parameters need to be defined?.....Section 3.1.3
- How does the UV reactor selection affect design? .....Section 3.1.4
- What are the options for validation?.....Section 3.1.4.3
- How should potential installation locations be evaluated?.....Section 3.1.6
- What are the existing hydraulic conditions and UV installation hydraulic needs?.....Section 3.1.6.1
- What should be considered when estimating the process footprint of the UV installation?.....Section 3.1.6.2
- How can the installation options be evaluated?.....Section 3.1.7
- What are the options for UV reactor procurement?..... Section 3.2
- What are the options for addressing hydraulic constraints and what are the critical hydraulic system components?.....Section 3.3.1

- How does the control strategy influence the design of the process instrumentation and control for the UV installation? .....Section 3.3.2
- What are the elements in the process instrumentation and control system? .....Section 3.3.3
- What are the necessary electric power arrangements? .....Section 3.3.4
- What elements need to be considered for the UV installation layout?.....Section 3.3.5
- What information should the equipment specification include?.....Section 3.3.6
- What are the necessary drawings and specifications for the UV installation?.....Section 3.3.7
- What should be reported to the State and when?..... Section 3.4

The process of planning and designing a UV installation is presented as a flowchart in Figure 3.1. In the United States to date, the majority of the utilities undertaking the construction of UV installations have pre-purchased the UV reactors prior to design. Therefore, the design flowchart is based on the pre-purchase of the UV reactors and the use of a traditional design-bid-build approach for the project. Chapter 3 is generally organized to follow the flowchart. UV installations can be successfully constructed using any of the equipment procurement and contractor selection approaches currently used within the industry. It is the utility's and engineer's responsibility to select the most appropriate project approach. Whatever approach is utilized, the planning and design components discussed in Chapter 3 should be addressed even though the actual order of completion may vary.

Figure 3.1 Flowchart for Planning, Design, and Construction of UV Installations[1]



[1] Flowchart is based on pre-purchase of UV reactors and the traditional design-bid-build approach
[2] The timing of UV reactor validation testing depends on whether it has been validated off-site or if on-site validation is necessary.

3.1 UV Installations Planning

The planning process for a UV installation is similar to the process that would be employed for any retrofit, upgrade, or new construction project at a water treatment plant (WTP). In the planning phase, it is important to identify alternatives and define criteria needed to select the appropriate application and to facilitate detailed design. For a UV installation, this includes the following steps:

- Defining disinfection goals
- Identifying potential locations for UV disinfection
- Defining design parameters
- Evaluating potential UV reactors
- Evaluating control strategies
- Evaluating hydraulic factors and process footprint
- Preparing preliminary costs and selecting an installation option

This section provides planning guidance for each of these steps with a focus on specific elements that should be considered for UV disinfection.

3.1.1 Defining UV Disinfection Goals

A comprehensive disinfection strategy provides multiple barriers to reduce microbial risk while minimizing disinfection byproduct (DBP) formation. UV disinfection is a tool that can contribute to a comprehensive disinfection strategy by providing a cost-effective method of inactivating target pathogens that are more resistant to more traditional disinfection methods. The specific objectives of a given UV installation should be clearly defined during the planning stages. This can ensure that the design meets the utility's and the State's expectations based on the regulatory requirements, target microorganism(s), and the overall disinfection strategy. Chapter 1 presents the regulatory requirements that must be met for the overall water treatment process and specific requirements for UV disinfection.

The UV doses necessary for *Cryptosporidium* and *Giardia* inactivation are lower than that those needed to inactivate viruses. Accordingly, the capital costs for inactivating *Cryptosporidium* and *Giardia* should be lower. One study estimated capital costs for *Cryptosporidium* and *Giardia* inactivation by UV disinfection to be approximately 50 percent lower than the costs associated with the UV inactivation of viruses (Cotton et al. 2002). Therefore, the target microorganism and inactivation level should be determined early in the planning process.

Repair of UV light-induced damage is discussed in section 2.3.2. As discussed previously, repair has not been observed in *Cryptosporidium* and viruses, and *Giardia* only

exhibited repair when exposed to very low UV doses (0.5 mJ/cm^2). Therefore, repair of UV-induced damage of *Cryptosporidium*, *Giardia*, and viruses do not need to be considered in the UV installation design. However, bacteria have been shown to repair of UV damage. The residual disinfectant concentration (either chlorine or chloramines) in the distribution system will most likely prevent repair of UV damage in bacteria. Therefore, microbial repair of bacteria also does not affect UV installation design.

To a degree, UV disinfection can replace chemicals used to disinfect chlorine-resistant pathogens (e.g., *Cryptosporidium* and *Giardia*), thereby reducing DBP formation. However, UV disinfection is not as efficient at inactivating viruses as more traditional, chlorine-based disinfection processes. Because of its effectiveness at treating viruses and the need to maintain a disinfectant residual in the distribution system, some chlorine-based disinfectant (chlorine or chloramines) will be needed even if UV disinfection is implemented. Also, chemicals that serve as disinfectants may be added in the treatment process to oxidize other constituents present in the water (e.g., iron, manganese, or taste and odor causing compounds). Utilities that currently add a chemical disinfectant prior to the location of a future UV installation and plan to curtail the use of such chemicals, following implementation of UV disinfection should assess the effect that a reduction in pre-oxidant use may have on water quality at the point of UV application. Therefore, a utility considering a change in disinfection strategy should evaluate all water quality goals to ensure they are met and must prepare a disinfection benchmark as discussed in Chapter 1.

3.1.2 Identifying Potential Locations for UV Installations

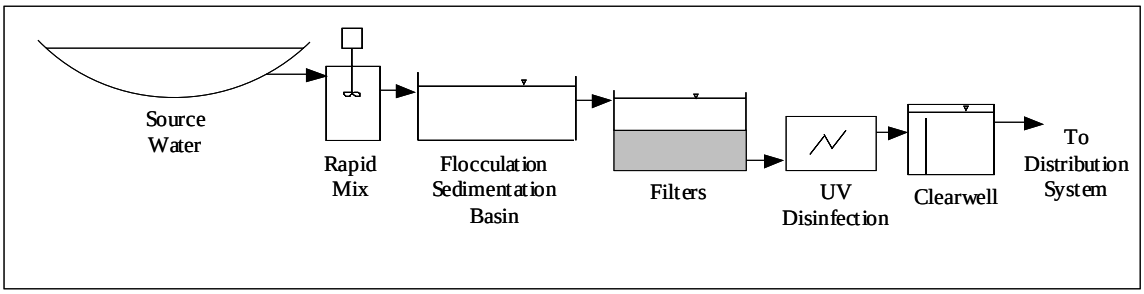
It is strongly recommended that the UV disinfection process be placed after filtration. Although UV disinfection can potentially be applied anywhere along the treatment train from the raw water intake to after high-service pumping, there are significant drawbacks to placing the UV installation upstream of filtration in conventional WTPs. Prior to filtration, UV absorbance at 254 nm (A_{254}) is higher (UV transmittance (UVT) is lower) due to higher concentrations of natural organic matter, turbidity, and particles. Coagulation can enmesh microorganisms in flocs and may block the UV light from reaching the microorganisms, which affects the UV dose-response of the microorganism. In addition, Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) UV dose requirements apply only to post-filter and unfiltered supplies that meet the criteria for filtration avoidance (40 CFR 141.729 (d)). Therefore, this section focuses on the post-filtration use of UV disinfection.

This section presents the general post-filtration locations that may be considered for the UV installation. For a location to be feasible, the UV installation hydraulic needs should be met (section 3.1.6.1) and the equipment must physically fit in the proposed location. Hydraulic profiles and preliminary drawings should be developed for each location under consideration to address these controlling criteria. Also, LT2ESWTR requires that all UV reactors be validated (40 CFR 141.729 (d)), and the validation protocol (Chapter 4) recommends specific piping configurations for both validation testing and UV installation. These recommendations for inlet and outlet conditions can affect the feasibility of the potential locations. Detail on the recommended inlet and outlet hydraulics for both validation and installation is given in section 3.1.4.3.

3.1.2.1 Combined Filter Effluent Installation (Upstream of Clearwell)

A combined filter effluent installation is defined here as the application of UV disinfection to the filter effluent after it has been combined (as opposed to individual filters) and prior to the clearwell as shown in Figure 3.2. This installation is typically in a separate building. Of the three options described, the combined filter installation is generally preferred when conditions permit.

Figure 3.2 Schematic for UV Installation Upstream of Clearwell



There are several advantages to this type of design and installation:

- The UV reactor operation is largely independent of the operation of individual filters, which provides flexibility for design and operation.
- If the entire UV installation failed, a WTP could still provide disinfection by adding a chemical disinfectant to the clearwell. (Note that backup chemical disinfection may not provide *Cryptosporidium* inactivation.)
- Surge and pressure issues that are concerns with UV reactors installed immediately downstream or upstream of high service pumps (HSPs) are usually not an issue for this installation location.
- Because the UV installation will typically be constructed in a new building for this installation location, there may be greater flexibility in maintaining the recommended inlet and outlet hydraulic conditions for the UV reactors (section 3.1.6.1).

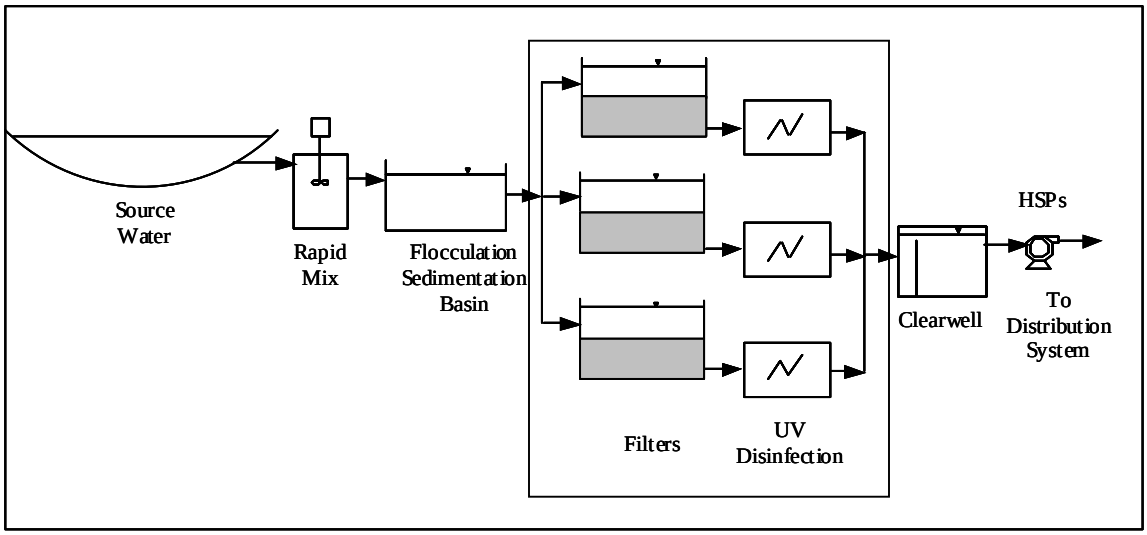
The primary disadvantages of this type of installation are that an additional building may be necessary and that piping and fittings may result in higher headloss than alternative configurations.

3.1.2.2 Individual Filter Effluent Piping Installation

Individual filter effluent piping installations are defined here as installations with UV reactors dedicated to each individual filter effluent pipe. The installation is typically within the existing filter gallery. Figure 3.3 schematically represents this type of installation. The main

advantage of this installation is that a new building would not be necessary, which may lower construction costs.

Figure 3.3 Schematic of Individual Filter Effluent Piping Installation in Filter Gallery



However, there are several disadvantages to this installation location. Many filter galleries do not have sufficient space within existing effluent piping to accommodate a UV reactor. The existing piping may also put constraints on how the UV reactor is validated because of the unique inlet and outlet conditions that may be present (section 3.1.6.1). In addition to accommodating the UV reactors, there needs to be sufficient space in the filter gallery or a nearby area for the control panels and electrical equipment. Access to existing equipment may be impaired by the UV reactor, and access to UV reactor components for maintenance may be more restricted than for a combined filter effluent installation. Also, the environmental conditions (e.g., moisture) in the filter gallery may not be appropriate for the installation of the UV reactors, associated control panels, and electrical equipment without improvements to the heating, ventilating, and air conditioning system for the area.

The in-line installation may also complicate treatment plant operations and limit operational flexibility as described below.

- In general, this option results in an increased number of UV reactors compared to a combined filter installation because the number of filters dictates the number of UV reactors. This may increase operation and maintenance costs in comparison to the combined filter effluent installation where the number of UV reactors is determined by the design flow, water quality constraints, UV reactor capacity, and redundancy needs.

- The increased headloss of the UV reactors may affect the operation of the filters and the clearwell.

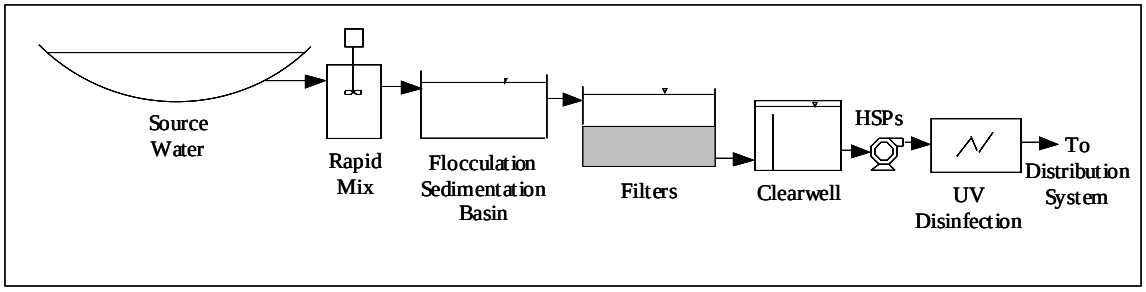
- With one UV reactor for each filter, the operation of each filter will be dependent on the reliable operation of each UV reactor and vice versa.

- The UV reactor operation during a filter backwash can complicate UV reactor operations. The lamp cooling need to addressed if it remains energized during a backwash because the lamps should not be energized in stagnant water or air. If a UV reactor is off during a backwash, the flow during the UV reactor warm-up (section 3.1.3.3) is off-specification, which may cause problems with exceeding off-specification requirements and recommendations (section 3.1.3).

3.1.2.3 UV Disinfection Downstream of the Clearwell

It may be possible for a WTP to build the UV installation after the clearwell either upstream or downstream of the high service pumps (Figure 3.4). In many WTPs, the HSPs take water directly from the clearwell, limiting space and the availability of suitable piping for installation of the UV installation upstream of the HSPs. Installation downstream of the HSPs may provide greater space and flexibility in locating the UV reactors. Either configuration may be advantageous if there is insufficient space or head to allow installation of the UV reactors between the filters and the clearwell; however, there are significant disadvantages to these options.

Figure 3.4 UV Disinfection Downstream of High Service Pumps



UV installations located downstream of the clearwell will experience greater fluctuations in flowrate since actual flowrates are more closely matched to system demand changes. This may increase the UV reactor size or more UV reactors to accommodate the flow fluctuations.

In post-HSP installations, the water will be at distribution system pressure. The UV reactor housing may need to be reinforced because of these high pressures, which would increase the cost of the UV reactors. In addition, these locations are more prone to water hammer because of their proximity to the HSPs and subsequent high pressures, which could lead to sleeve damage. If a lamp sleeve is damaged, the enclosed lamp may break, releasing mercury into the water. Hydropneumatic tanks or pressure relief valves may be necessary in this installation location to avoid water hammer. This issue is discussed in more detail in section 3.1.6.1 and section N.2.1.3.

A UV reactor located after the HSPs will reduce the discharge pressure to the distribution system, and a UV installation located between the clearwell and HSPs will reduce the suction head available for the pumps. As a result, discharge pressures and storage utilization could be impacted at these two locations.

In summary, UV installations downstream of the clearwell are not recommended because of the increased potential for adverse pressure conditions within the UV reactor and the increased reliability and size considerations. In general, these installations should only be considered if the combined filter effluent and in-line filter effluent locations are not feasible.

3.1.3 Defining Design Parameters

Water quality, lamp fouling/aging factor, flowrate, and power quality affect the sizing of the UV reactors and associated support facilities. These design parameters need to be determined to ensure compliance with LT2ESWTR requirements.

UV reactors are required to be validated by LT2ESWTR to demonstrate the UV installation achieves the required UV dose (40 CFR 141.729(d)). Validation testing establishes the conditions under which the UV reactors must be operated to ensure the required dose delivery (40 CFR 141.729(d)). Off-specification is defined as a UV reactor that is operating outside of its validated limits. (For example, the UV reactor is operating with a flowrate that is higher than the UV reactor was validated.)

To the extent practical, UV reactors should be designed with process monitoring and control components (e.g., alarms, shut-off valves) to prevent water from entering the distribution system when a UV reactor is operating outside of validated conditions. Unfiltered systems that use UV disinfection to meet the *Cryptosporidium* treatment requirement of the LT2ESWTR must demonstrate that at least 95 percent of the water delivered to the public during each month is treated by UV reactors operating within validated limits (40 CFR 141.721(c)(2)). Or in other words, the UV reactor cannot be off-specification for more than 5 percent of the water delivered to the public. The LT2ESWTR does not state an off-specification requirement for filtered systems; however, States may establish requirements for their filtered systems, including a limit for off-specification operation.

The UV reactors are off-specification when any of the following conditions occur:

- The flow, UV intensity, or lamp status is outside of the validated range.
- The UVT or UV intensity is outside of the validated range (if the UV intensity and UVT setpoint approach is used (section 3.1.5)).
- The calculated dose is outside of the validated range at a given flow (if the calculated dose approach is used (section 3.1.5)).
- All UV lamps in all UV reactors are off because of a power interruption or power quality problem, and water is flowing through the reactors.

It is important to determine the appropriate design values for water quality, lamp fouling/aging factor, flowrate, and power quality because of these LT2ESWTR requirements and recommendations. If the design parameters are not chosen conservatively enough, the UV reactors may be operating off-specification and be out of compliance. However, overly conservative design values may result in unnecessarily large UV reactors or more UV reactors than necessary.

3.1.3.1 Assessing Water Quality

As highlighted in Chapter 2, the following water quality parameters are the primary parameters that affect UV installation planning and design:

- Parameters that affect UV dose delivery
  - UV absorbance/transmittance from 200 - 300 nm (germicidal range)
  - Upstream chemical additives

- Parameters that typically determine sleeve and UV intensity sensor fouling
  - Calcium
  - Alkalinity
  - Hardness
  - Iron
  - pH
  - Lamp temperature

It should be reiterated that this manual is focused on post-filtration applications; therefore, it is assumed that turbidity is low (1 nephelometric turbidity units (NTU) or less) and results in insignificant particle effects on UV dose delivery (Linden et al. 2002b). It is also assumed that the water meets applicable maximum contaminant levels (MCLs) and secondary MCLs.

Water quality data should be collected from locations that are representative of the potential UV installation location. The duration of sampling, number of samples collected, and data analyses used to evaluate water quality for UV disinfection are similar to the approaches taken for other water treatment technologies. The data collection frequency should be a based on flow variability, the consistency of the source and treated water qualities, and the potential for obtaining cost and energy savings by refining the design criteria. The extent of water quality data collected should be left to the discretion of the utility and the designer based on experience and professional judgment. States may desire to provide input on data collection needs.

The four main considerations for assessing water quality are A_{254}, fouling potential, lamp fouling/ aging factor and upstream chemical impacts. Each of these is discussed in the following sections.

UV Absorbance

As discussed in Chapter 2, the A_{254}[1] of the water directly influences UV dose delivery. The A_{254} data should be evaluated to select a design A_{254} value. The design A_{254} along with the specified UV dose and flowrate will be used by the UV manufacturer to determine the appropriate UV reactor. In addition, UV manufacturers may use the A_{254} range at the WTP to determine the turndown (i.e., power modulation) needs of the UV reactors.

Overly conservative design A_{254} values (i.e., low UVT) can result in over-design and increased capital costs. Conversely, inappropriately low design A_{254} values can result in UV reactor operation outside the validated operating range and potential non-compliance. As with most designs, the larger the data set, the more refined the final design can be. A utility with very stable A_{254} might only need one or two months of data, while a utility that experiences seasonal changes would benefit from more frequent data collection during seasonal events and over a longer recording period.

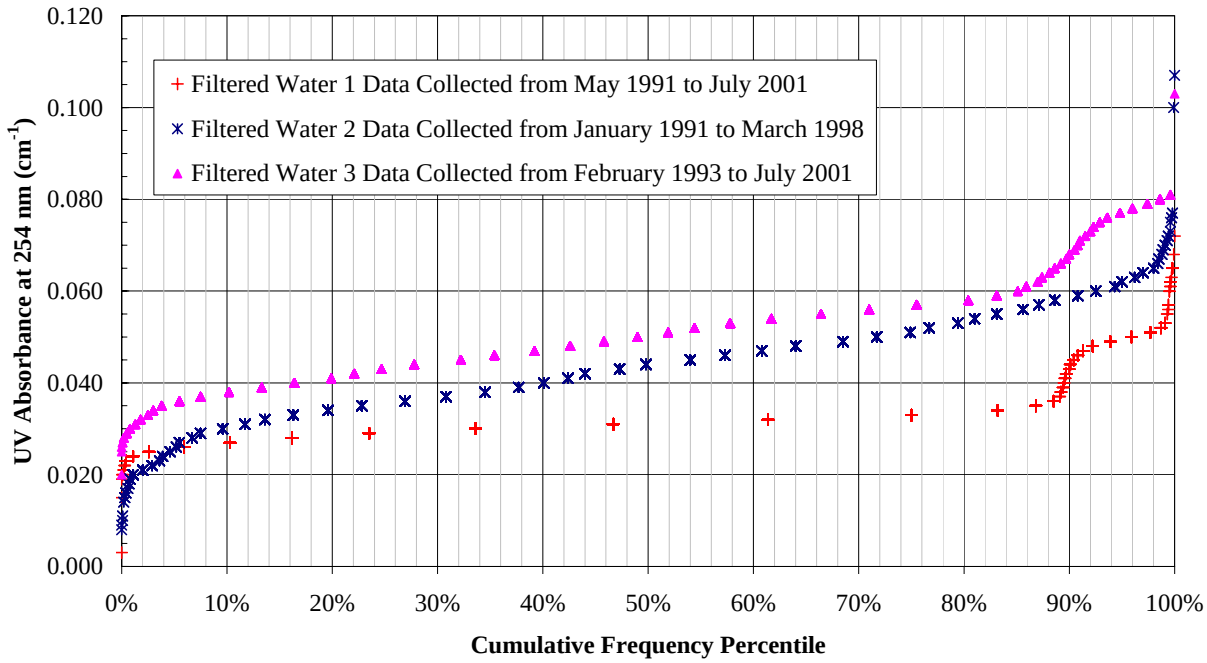
The A_{254} sampling plan should include collection of A_{254}[2] measurements in grab samples or continuously with an on-line A_{254} monitor. If A_{254} peaks occur regularly during the Spring and Fall, increased sampling frequency during these periods will better capture the magnitude and duration of the peaks. If different sources or combination of sources (i.e., blending) are used during the year, the A_{254} of the potential source water blends should be characterized to properly identify the appropriate water quality conditions. In addition, the maximum A_{254} may not correspond to the period of maximum water production. The relationship between seasonal production rates and A_{254} data should be considered when developing design criteria.

A cumulative frequency (CF) diagram of the A_{254} data may assist the utility in determining its design A_{254} value. Figure 3.5 presents a CF diagram for three filtered waters; the CF percentile (x-axis) shows the percentage of the dataset that is lower than a given value of A_{254} over the data collection period. For example, if the 90th percentile A_{254} is 0.043 cm^{-1}, then 90 percent were lower and only 10 percent of the measurements were higher than 0.043 cm^{-1} over the period of record.

[1] A_{254} in this section implies A_{254} measurement specifically at 254 nm unless otherwise noted

[2] A_{254} measurements for developing the design basis for UV disinfection systems should be performed on unfiltered samples, not with the 0.45 µm pre-filtered samples typically used to characterize NOM. However, if only measurements that have been filtered are available, they still provide valuable information. It should be noted that pre-filtered measurements are typically biased low (in terms of absorbance), but this bias is generally minimal.

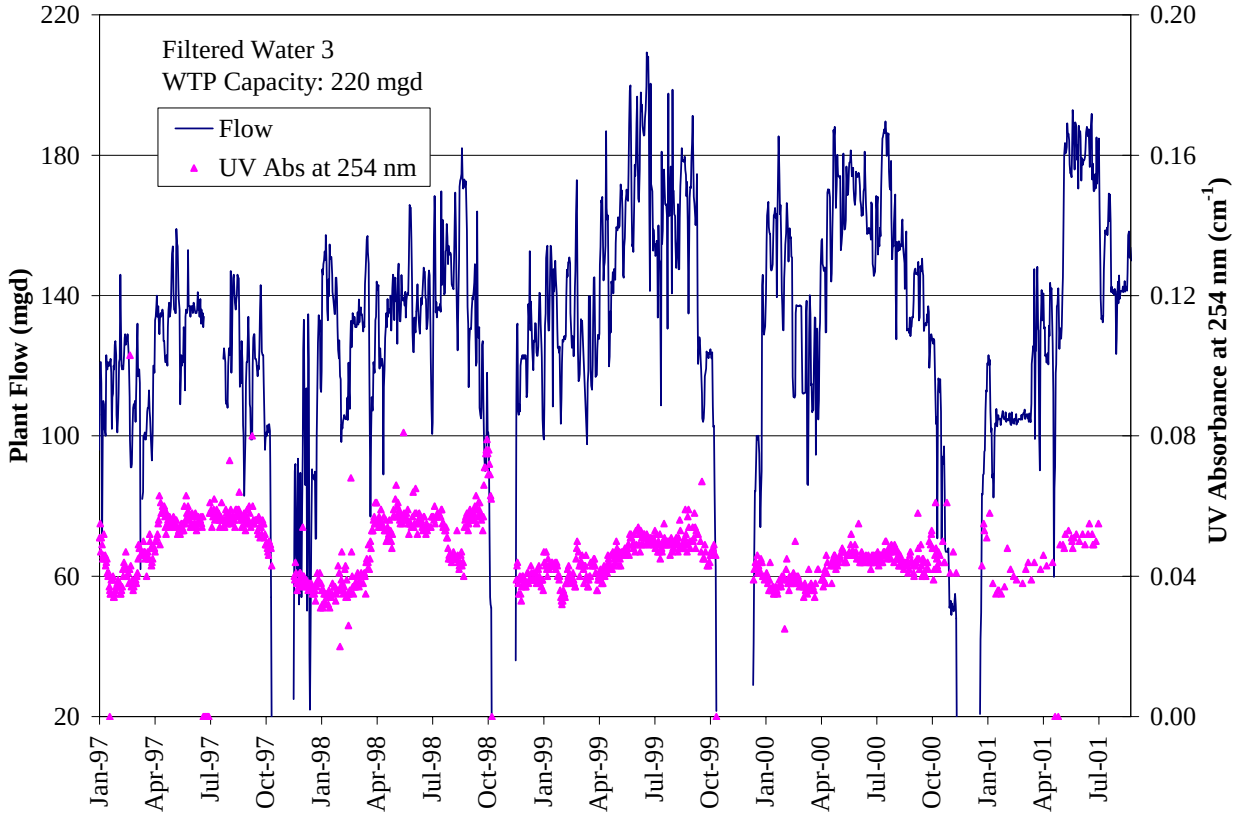
Figure 3.5 Example CF Diagram for Three Filtered Waters



In Figure 3.5, the A_{254} data for Filtered Waters 1, 2, and 3 display different characteristics. The A_{254} values for Filtered Water 1 are relatively constant between the 5th and 85th percentiles, indicating consistent water quality approximately 80 percent of the time. Values above the 85th percentile increase to a plateau, and then increase again above the 95th percentile. A_{254} data for Filtered Waters 2 and 3 exhibit greater variability by the gradually increasing slope between the 5th and 95th percentile. Selecting an appropriate design A_{254} value for these waters depends on an assessment of this variability as compared to the percentage of time that off-specification water could be delivered.

For example, a CF percentile of 95 percent would most likely meet the off-specification criteria for unfiltered systems. However, a 95 percent CF percentile may be overly conservative, depending on the flow observed at the planned UV installation. Therefore, plotting the A_{254} with the WTP flow can indicate if high A_{254} and high flow co-occur, which would be the worse case water quality condition. Figure 3.6 presents Filtered Water 3's flow and A_{254} variation and illustrates a seasonal variation in A_{254}. For this example WTP, the high A_{254} typically occurs during the high flow period; therefore, a more conservative design A_{254} of 0.077 cm^{-1} (84% UVT), which is a CF percentile of 95 percent, may be warranted for Filtered Water 3. However, a less conservative design A_{254} would be appropriate if the high A_{254} occurred during flows less than the design flow (e.g., average flow) because the UV reactors should have enough turndown (e.g., power modulation) to accommodate high A_{254} at lower flows than the design flow.

Figure 3.6 Example Flow and UV Absorbance (at 254 nm) Data



The design A_{254} (e.g., a CF percentile) also should be a function of the utility's preferred level of conservatism and the site-specific $A_{254}$and flow data. The UV reactor sizing and cost are not directly proportional to A_{254} but will increase for increased A_{254} design values. However, by evaluating the CF plot and collaborating with the UV manufacturer to assess the cost implications of using a lower A_{254} value, the utility and designer can select the most appropriate design A_{254} for the water quality and disinfection objectives of the project.

Typically, the UV manufacturers work in terms of UVT; therefore, the design A_{254} is typically converted to a design UVT[3]. Because UV manufacturers use UVT in their design and control of the UV reactors, the remainder of this chapter will use UVT as opposed to A_{254}.

The spectral absorbance of the water over a range of wavelengths (200 - 400 nm) should also be collected, especially if medium pressure (MP) reactors are being considered. MP lamps emit light at a range of wavelengths across the 200 nm to 300 nm range. The UV absorbance of water varies with wavelength, typically decreasing with increasing wavelength. As such, the attenuation of UV light in a UV reactor, the corresponding disinfection performance, and the UV intensity sensor response depend on the absorbance at each of the emitted wavelengths. Site-specific spectral absorbance can be used to model MP reactors and may be incorporated into UV dose monitoring and control systems by some UV manufacturers. Spectral absorbance may

[3] $UVT(\%) = 100 * 10^{-A_{254}}$

exhibit seasonal variation; therefore, spectral absorbance should be collected at different times during the year to assess this variation. Also, the spectral absorbance may be used to determine the appropriate UV-absorbing chemical for validation of the UV reactors that will be installed, which is discussed in section 4.3.3.2.

Fouling Potential

The rate of fouling and the corresponding frequency of sleeve cleaning depend on hardness, alkalinity, lamp temperature, pH, and certain inorganic constituents (e.g., iron and calcium). Fouling is typically caused by precipitation of compounds with low solubility or compounds where the solubility decreases as temperature increases (e.g., $CaCO_3$). If significant seasonal shifts in any of the parameters are expected, these trends should be captured in the monitoring period. Again, a CF diagram may assist in the selection of the appropriate design criteria.

While the specific rate of fouling and optimal cleaning protocol for any given application cannot currently be predicted, a proper cleaning protocol and sleeve-fouling factor can be adequately estimated for most water sources without pilot- or demonstration-scale testing and then adjusted during normal operation. Extensive data have been generated from pilot-scale testing on waters of low to moderate hardness and iron content (Mackey et al. 2001 and Mackey and Cushing 2003). At total and calcium hardness levels below 140 mg/L and low iron (less than 0.1 mg/L), standard cleaning protocols and wiper frequencies (one sweep every 15 minutes to an hour) were more than adequate to address the impact of sleeve fouling at the sites tested. At sites with hardness or iron that exceed these levels, it may be advantageous to evaluate fouling rates on a site-specific or worst case basis via pilot or demonstration testing (described in Appendix J) or during UV reactor start-up (section 5.1) to identify how best to address fouling.

Although fouling is not expected to be a significant problem for most utilities, the listed water quality parameters (page 3-10) should be monitored prior to designing the UV installation unless adequate water quality data are available. It is important to provide these data to the UV manufacturer to assist them in a qualitative assessment of the fouling potential for their UV reactors and to assist the designer in determining what cleaning system should be specified. In addition, the lamp fouling/aging factor will depend on the initial assessment of potential fouling, which is discussed in the next section.

Lamp Fouling/Aging Factor

Sleeve fouling, lamp aging, and UV intensity sensor window fouling (if applicable) affect long-term UV reactor performance. Accumulation of foulants on the lamp sleeve surface can reduce transmittance of the lamp energy to the water. The rate of fouling depends on the factors discussed in the previous section. In addition, lamp output decreases over time due to its physical aging. The rate at which lamp output will decrease is a function of the lamp physical characteristics, lamp hours in operation, number of on/off cycles, and power applied per lamp length. In MP reactors, UV lamp aging can also result in a change in the spectral output over time. Lamp aging is discussed in detail in section A.3.1.6.

A reduction in lamp output results in a reduction in UV dose. The effects of these parameters are typically incorporated into the UV reactor design by specifying a lamp

fouling/aging factor, which includes the effects of both sleeve fouling and lamp aging. The lamp fouling/aging factor will be site-specific and based on the assessment of fouling described previously and lamp aging information. The lamp aging characteristics can be obtained from the UV manufacturer and should be certified by an independent third party. The lamp fouling/aging factor is used by the manufacturer to assist in the selection of the appropriate UV reactor. For example, if a 0.5 lamp fouling/aging factor is specified, the UV manufacturer will choose a UV reactor the appropriate lamps (or number of lamps) where the specified UV dose can be achieved at half of the initial UV lamp output (after burn-in) with all the lamps energized at full power. The lamp fouling/aging factor typically ranges from 0.5 (NWRI 2000) to 0.9.

The lamp fouling/aging factor is typically specified with a corresponding guaranteed UV lamp life (e.g., 5000 hours). These items are typically specified together to ensure that the UV lamp replacement frequency does not occur more frequently than specified by the guaranteed lamp life given the specified lamp fouling/aging factor. The lamp fouling/aging factor can be estimated based on the designer's experience and UV manufacturer input. In addition, pilot and demonstration tests can be completed to estimate the lamp fouling/aging factor as described in Appendix J.

Selection of a lamp fouling/aging factor and a guaranteed lamp life value is a trade-off between maintenance costs (the frequency of lamp replacement or chemical cleans necessary) and capital costs (the size of the UV reactors). A lower lamp fouling/aging factor means the utility will have less frequent lamp replacements because the UV reactors are designed with higher powered lamps or more lamps to achieve the necessary UV output at the guaranteed lamp life. However, designing a UV reactor with higher powered lamps or more lamps will increase the size of the needed UV reactor. Thus, the use of a fouling/aging factor that is too conservative could result in the over-design of the UV reactors. Conversely, the use of a lamp fouling/aging factor that is not conservative enough may result in the underestimated reduction in the output of the lamp due to fouling/aging and potentially result in off-specification operation or more frequent lamp replacement.

Impacts of Upstream Treatment Processes

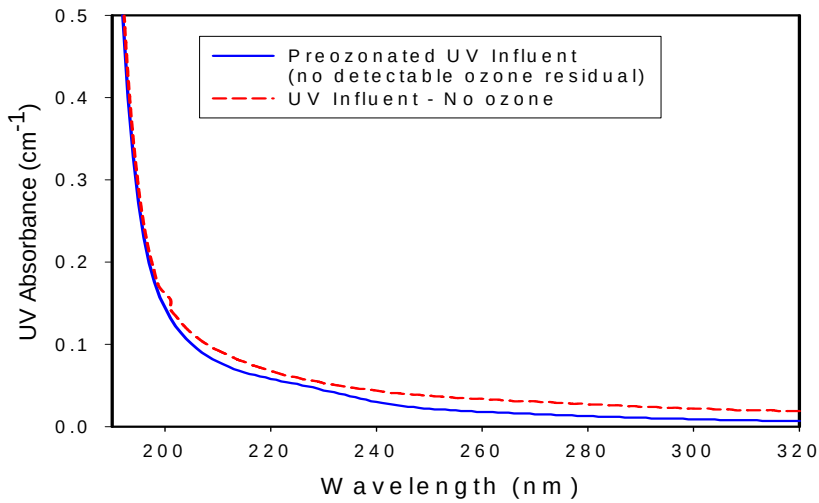
Unit processes upstream of UV reactors can have a significant impact on the UV reactor performance. The three potential ways that upstream processes may affect UV performance are (1) to increase UVT by increasing organics removal or oxidizing organics, (2) to decrease UVT because certain chemicals will absorb UV light, and (3) to affect the lamp sleeve fouling rate.

It is possible to increase filtered water UVT by increasing the coagulant dose; however, the results will be site-specific. In one study, the UVT was increased from 80% to 89% by increasing the alum dose from 15 to 45 mg/L (Cushing et al 2001). However, the UVT increase from an increased alum dose should be considered against the increased alum chemical costs and sludge production. UVT increases would also probably be observed if other iron coagulant and poly-aluminum chloride coagulant doses were increased.

Properly implemented, ozone disinfection prior to UV disinfection has the potential to increase the UVT from oxidation of organic matter. Conversely, ozone disinfection can decrease UVT if a residual ozone concentration is present in the UV reactors. If the ozone residual is adequately quenched, a net increase in the UVT will be observed (Malley 2002); an example of

this increase for an unfiltered water is shown in Figure 3.7. If a UVT increase is desired, then a combination of coagulant increase and ozone disinfection will likely give the greatest UVT increase (Cushing et al 2001).

Figure 3.7 Example Effect of Pre-ozonation on UV Absorbance if Ozone is Quenched Prior to UV Disinfection



Most common water treatment chemicals themselves will not significantly impact UVT. The following common water treatment chemicals do not significantly affect UVT at typical concentrations present in filtered water: Alum, aluminum, ammonia, ammonium, zinc, phosphate, calcium, hydroxide, and ferrous iron (Fe^{+3}) (Cushing et al 2001).

However, hypochlorite (ClO^-), ferric iron (Fe^{+2}), permanganate, and ozone were the only commonly used chemicals examined that might reduce UVT (Cushing et al 2001) as described below.

- Residual ClO^- has only a slight effect on UVT. For example, a ClO^- residual of 3.5 mg/L will cause the UVT to decrease from 91% to 90% (Cushing et al 2001). However, in most cases, a hypochlorite residual that high will not be flowing through the UV reactor.

- It is unlikely that ferric iron will be present in filtered waters because ferric iron is only present when there is low dissolved oxygen.

- Permanganate is a strong absorber of UV light; however, it is typically added in the raw water to oxidize taste and odor or iron and manganese. Therefore, when applied to raw water, there should not be a significant permanganate concentration in the filtered water.

- Ozone residual can be quenched, and then the UVT will not be decreased. Care should be taken when choosing the quenching agent because one popular choice, thiosulfate (often used in the form of calcium thiosulfate), is a strong absorber of UV light (section A.4.1.3, Table A.5) and will decrease the UVT. Sodium bisulfite, an alternative to calcium thiosulfate, will not significantly impact UVT.

The possible UVT variation from upstream processes should be assessed by collecting UVT data during various operating conditions (e.g., a range of alum doses) that are typically observed. Potential treatment process upsets should also be considered in the water quality analysis to determine the extent to which they impact the design UVT and cleaning regime.

Some unit processes that use metal-based coagulants may affect the rate of fouling; these effects will be site-specific. Mackey et al. (2001) found that iron levels less that 0.1 mg/L could be adequately cleaned by standard protocols as described previously. In addition, lime softening has been shown to reduce fouling potential (Mackey et al. 2001). Overall, the effect of upstream coagulant addition and residual metals should be considered in the fouling data monitoring described previously.

3.1.3.2 Determining Design Flowrate

Flowrate is a fundamental design parameter that, in combination with water quality, UV dose, and lamp fouling/aging factor determines the necessary size and number of UV reactors. The design criteria should identify the average, maximum, and minimum flowrates that the UV reactors will experience. Potential methods for determining the design flow for the three described retrofit locations are shown in Table 3.1. In addition, potential future changes in plant capacity should be considered when determining the UV installation design flow.

Table 3.1 Potential Method to Determine Design Flow

Retrofit Location	Design Flow Basis
Combined filter retrofit	Combined rated capacity of all duty filters[1]
Individual filter retrofit	Rated design flow for individual filter
Post-HSP	Rated capacity of the HSP station

[1]Flow does not include redundant filters

3.1.3.3 Assessing Electrical Power

The sensitivity of UV reactors to power fluctuations make electrical power supply a critical component of the UV installation planning and design. In addition, the electrical system design needs to ensure that the UV installation will meet the requirements or recommendation of operating within validated conditions (i.e., maximum allowed off-specification). Also, it is impossible to meet inactivation goals if the power quality causes the reactor to go down (i.e., no disinfection) for longer than the need to obtain the desired treatment level. For example, if a 2-log *Cryptosporidium* inactivation is desired, the UV reactors cannot be down while more than 1 percent of the flow passes through them.

UV lamps can potentially their lose arc if a voltage fluctuation, power quality anomaly, or a power interruption occurs. For example, voltage sags that vary from 10 to 15 percent from normal operating conditions for as low as 2 to 5 cycles (0.03 to 0.08 seconds) may cause UV lamps to lose their arc.

Low pressure (LP) lamps generally can return to full operating status within 15 seconds after power is restored. However, low-pressure high output (LPHO) and MP reactors that are more typically used in drinking water applications exhibit significant restart times if power is interrupted. The start-up and restart behavior for LPHO and MP lamps is summarized in Table 3.2.

Table 3.2 Start and Restart Times for LPHO and MP Lamps [1]

Lamp Type	Cold Start[2]	Warm Start[3]
LPHO	2 min warm-up + 4-5 min to full power total time: 6 – 7 minutes	2 min warm-up + 2-5 min to full power total time: 4 – 7 minutes
MP	No warm-up or cool down + 5 min to full power[4] total time: 5 minutes	5 min cool down + 5 min to full power[4] total time: 10 minutes

[1] Information shown in table is compiled from Calgon Carbon, Severn Trent, Trojan, and Wedeco.
[2] A cold start occurs when UV lamps are started when they have not been operating for a significant period of time.
[3] A warm start occurs when UV lamps are started after they have just lost their arc (*e.g.*, due to voltage sag).
[4] 60 percent intensity is obtained after 3 minutes.

The effects of temperature can increase or decrease the times listed in Table 3.2 and should be discussed with the UV manufacturer. Individual manufacturers report that colder water temperatures (below 50 degrees Fahrenheit, 10 degrees Centigrade) can result in slower startups for LPHO lamps than listed in Table 3.2. Conversely, MP manufacturers report shorter re-start times with colder temperatures because the cold water accelerates the condensation of mercury (i.e., cool down), which is necessary for re-striking the arc.

To minimize the potential for off-specification operation, utilities should evaluate the reliability and quality of their power supply. Local power suppliers can often provide power quality and reliability data and should be the first source of information on power quality. For those locations where power quality is unknown, a power quality assessment is recommended. An assessment may be as simple as reviewing operating records of power quality incidents (if available) and power interruptions or Supervisory Control and Data Acquisition (SCADA) information for the existing plant. More advanced assessments may include the installation of power quality monitors or the retention of an outside consultant to conduct a detailed power quality assessment. Generally, personnel with a working knowledge of electrical supply and installation will be able to review power supply data and determine if power quality problems exist. If a problem is identified, however, tracing it back to its source and determining an appropriate remedy is often best left to an expert that specializes in this area.

The most common sources of power quality problems are as follows:

- Faulty wiring and grounding
- Off-site accidents (e.g., transformer damaged by a car accident)
- Weather-related damage
- Animal-related damage
- Facility and equipment modifications
- Power transfer to emergency generator or alternate feeders

In specific locations that are subject to frequent power fluctuations or outages, the following options should be considered to minimize off-specification operation and ensure regulatory compliance:

1. Installation of a backup generator
2. Connection to a second, independent power source
3. Installation of power conditioning equipment or a battery-supported uninterruptible power supply (UPS)

These options will have different response and backup periods associated with them. For example, a backup generator cost-effectively provides backup power if an extended power interruption occurs; however, it will not ensure a continuous power supply to avoid UV reactor shutdown due to voltage sags. Connection to a second, independent power source may have the same issues as the backup generator, depending on the power quality associated with the second power source.

Power conditioning equipment will provide high quality power even if voltage sags or other power quality problems occur. However, power-conditioning equipment does not provide backup power for extended power outages. A battery-supported UPS provides continuous, high quality power (i.e., prevent voltage sags) and a specific amount of backup power for a longer outage. UPS systems can provide as much battery backup as specified; however, typically UPS systems for this purpose range between 2 and 15 minutes of battery backup.

The most suitable option will depend on the power quality of the utility, requirements limiting off-specification operation, and preferences of the utility and State. For example, an unfiltered system with poor power quality that experiences multiple voltage sags everyday and periodic interruptions lasting over 3 minutes may consider installing a UPS system with 5 minutes of backup batteries to ensure the 95 percent requirement of operating within validated ranges is met (40 CFR 141.721(c)(2)). However, a filtered system that experiences two or three voltage sags a month and no long-term power interruptions may not need to provide any additional power or power conditioning equipment.

Any equipment needed to address power quality problems affects both the cost and the feasibility of implementing UV disinfection. For example, the UV reactor cost and installation footprint has been estimated to increase by approximately 25 percent if a UPS system with 5 minutes of backup capacity is installed (Cotton et al. 2002). Other power conditioning options without backup power are less expensive and have lower footprint needs.

It is important that a utility have a complete WTP-wide assessment of its power quality when considering UV disinfection. Any actions involving the electrical system may also affect the WTP power quality and equipment performance. For example, the impact of the WTP's maintenance program for backup generators (e.g., routine startup and exercise) should be considered during the planning and design of the UV reactors to ensure that the program supports compliance goals and does not cause excessive UV reactor shutdown times. Other items that may affect power quality include future integration or upgrade of equipment (particularly equipment with a large power demand or variable frequency operation), testing of backup power supplies, deterioration of existing facility wiring (resulting in poorly grounded circuits), overload of electrical circuits, and any other activity that may affect the electrical supply or distribution within the facility.

3.1.4 Evaluating Potential UV Reactors

It is important to evaluate the available UV reactors in the planning process because each manufacturer's UV reactors are unique and proprietary. Process footprints and related installation needs (e.g., UV reactor to control panel distances) are different, depending on the UV manufacturer. This section provides a brief overview of different UV reactors, their impact on space requirements, and UV reactor validation issues. More detailed UV reactor information is presented in section 2.4. In addition, UV manufacturers should be contacted directly to gain a better understanding of the UV reactors available and what UV reactors are applicable to the utility's installation locations given the design criteria developed in section 3.1.3.

3.1.4.1 UV Reactors

There are different types of UV reactors for disinfecting drinking water with unique characteristics, such as lamps, lamp configuration in the reactor, cleaning systems, ballasts, and control systems (section 2.4.). This section briefly highlights the differences in UV reactors that affect design of the UV installation.

UV reactors can generally be characterized based on lamp type with LPHO and MP lamps being the most applicable to WTPs. One of the fundamental differences between LPHO and MP reactors is the lamp intensity output, which influences the UV reactor configuration and size, lamp life, number of lamps, electrical needs, and ballasts. Each has its inherent advantages and disadvantages. While a competitive procurement can be made among these two reactor types when the construction contract is bid, the overall layout and supporting facilities will be different for each.

The UV reactor footprint depends on the UV reactor configuration and UV lamp type. There are several different UV reactor configurations. Typically, LPHO reactors are in-line (i.e.,

configured like a pipe). However, MP reactors can be in-line, S-shaped, or U-shaped, depending on the UV manufacturer and the site constraints of the specific installation location. Typically, LPHO reactors have a larger footprint than MP reactors because more UV lamps are needed to deliver the same UV dose. MP reactor footprints will also vary, depending on lamp orientation (e.g., parallel versus perpendicular to flow). When evaluating locations for installation, the largest UV reactor footprint of those being considered should be used to estimate the UV installation footprint.

Lamp life also varies between LPHO and MP reactors. Most manufacturers provide warrantees of 8,000 to 12,000 hours for LPHO lamps. Guaranteed life for MP lamps range from 4,000 to 8,000 hours. Although the lamp life for LPHO is greater than that for MP reactors, due to the need for a greater number of lamps, the actual number of lamps that are replaced during a given period may be less for a MP reactor. It is important to consider the labor associated with lamp replacement, as well as the actual unit cost of the replacement lamps, when estimating the operating and maintenance costs of the two technologies. In addition, while LPHO reactors typically have more lamps, the actual power input is less than that for similarly sized MP reactors because MP lamps are less efficient in converting the power input to germicidal wavelengths for disinfection. This may result in a higher input power and an increase in the overall power consumption for MP reactors compared to LPHO reactors.

The lamp sleeve cleaning systems can also be different between LPHO and MP reactors. LPHO reactors may have off-line chemical cleaning (OCC) systems instead of on-line mechanical cleaning (OMC) because of the larger number of lamps. With OCC systems, the UV reactors must be taken off line to be cleaned. OMC and OCC systems are described in section 2.4.5. This may result in higher maintenance costs for LPHO reactors, depending on the extent to which cleaning is necessary.

Finally, the type of ballast used will affect the UV installation layout. Ballasts regulate the power supply at the appropriate level needed for energizing and driving the UV lamps. UV reactors may use electronic ballasts, electromagnetic ballasts, or transformers. Transformers are typically more stable than electronic or electromagnetic ballasts and allow a greater separation distance between the UV reactor and control panel. However, most transformers allow only step adjustment of lamp intensity. Compared to transformers, ballasts have the capability to provide almost continuous intensity adjustment but may increase lamp aging and spectral shift and have lower allowable separation distances between the UV reactor and control panel. It is important to discuss the implications of these various components with the UV manufacturers to determine their effect on the UV installation layout and design. Specific items that should be discussed include ballast cooling needs, allowable separation distances, and intensity adjustment capabilities.

The differences described above imply that UV reactor evaluation should not be based solely on capital costs. Operation and maintenance costs, including energy usage and labor, will be important in an overall life cycle cost comparison. This is discussed in greater detail in section 3.1.7.

3.1.4.2 UV Reactor Control Strategies

There are currently three different control strategies for UV reactors, which affect how UV reactors are validated and operated. The three general control strategies relate to three methods for monitoring dose-delivery and are summarized in Table 3.3. The first strategy utilizes one or more UV intensity sensors located at a distance from the lamps that yields an intensity signal that is proportional to UV dose (UV intensity setpoint approach), and the intensity sensor measurement and flowrate are used to monitor dose delivery. The second and third methods utilize UV intensity sensors that are positioned close to the lamps (so that there is minimal absorbance by the water) and separate monitors for UVT. The second approach incorporates a validated setpoint value for UVT, in addition to setpoints for UV intensity and flowrate, to ensure a given dose (UV intensity and UVT setpoint approach). In the third approach, the UV dose is calculated based on these measurements of flowrate, UV intensity, and UVT via a validated computational algorithm developed by the manufacturer (calculated dose approach).

Table 3.3 UV Reactor Control Strategies

Control Strategy	Dose Delivery Monitoring and Control Basis
UV Intensity Setpoint	UV intensity sensor measurement
UVT and UV Intensity Setpoint	UV intensity sensor and UVT measurement
Calculated Dose	The calculated UV dose[1]

[1] The UV reactor calculates a UV dose, using the UV intensity sensor measurement, the UVT of the water, and the flowrate.

In the planning phase, these control strategies need to be evaluated by the designer and utility to determine if a particular control strategy is preferable based on the ease of integration into their existing operation and control system. The impacts of the control strategy on the instrumentation and controls are discussed in section 3.3.2, and the specific validation recommendations for each control strategy are presented in section C.4.9.

3.1.4.3 Equipment Validation Issues

The LT2ESWTR requires that UV reactors be validated (40 CFR 141.729(d)). A utility's approach to UV reactor validation will affect the UV installation design. The issues to consider are the hydraulic parameters for validation and whether equipment will be validated on-site or off-site.

This section describes how these issues affect the design and installation footprint estimation. Chapter 4 provides an overview of validation, and Appendix C details UV reactor validation guidelines in detail.

Validation Hydraulics

The inlet and outlet hydraulics of the UV reactor can significantly affect dose delivery; therefore, the following validation and corresponding installation strategies are recommended in the validation protocol (section C.3.1.5) and are presented in Table 3.4.

Table 3.4 Summary of Recommended Hydraulic Configurations for Validation and Installation

Option	Validation	UV Installation
1	The inlet and outlet configuration is the same as the installation for 10 diameters upstream and 5 diameters downstream of the UV reactor.	Inlet and outlet configuration is the same as when the UV reactor was validated for 10 diameters upstream and 5 diameters downstream of the UV reactor.
2	The UV reactor is validated with a 90-degree bend directly upstream of the UV reactor. The UV reactor is defined to include a specific amount of straight pipe upstream or downstream of the UV reactor as specified by the UV manufacturer.	The UV reactor should be installed with a minimum of 5 pipe diameters of straight piping between the UV reactor and any upstream hydraulic configuration.[1]
3	The velocity at the validation facility is measured at evenly spaced points through a given cross section of the flow upstream and downstream of the UV reactor.	The velocity at the installation is measured at evenly spaced points through a given cross section of the flow upstream and downstream and is within 20 percent of the theoretical velocity determined during validation.

[1] This approach is not acceptable if the upstream fitting is an expansion or if the upstream valve will be used for flow control. A valve that will be exclusively used for open/close service (e.g., isolation) is acceptable.

Option 1 is most applicable when unique piping configurations are needed or if the inlet and outlet conditions validated in Option 1 cannot be achieved because of site constraints. For example, Option 1 may be the only validation option for an individual filter effluent location, which probably does not have 5 diameters of straight pipe before the UV reactors (Option 2) because of existing site constraints.

The validation and installation of a particular UV reactor should meet one of these options. Option 2 provides more general applicability for validation and installation of UV reactors. For example, the inlet and outlet piping configuration for installations in a new building could be designed based on how the procured UV reactor was validated. Option 3 also provides flexibility but may have the practical limitation of measuring the velocity through a cross section at the installation.

Off-site Versus On-site Validation

Manufacturers will likely validate UV reactors over a wide range of flowrates and water quality (e.g., UVT) conditions at off-site testing facilities. The inlet and outlet hydraulic conditions during validation will probably be selected so the UV reactors can be installed in most WTPs. Off-site validation has several advantages, including simplicity, cost, and the ability to design around a UV reactor with known performance characteristics and inlet and outlet hydraulics. However, the LT2ESWTR requires that the site-specific installation and operating

conditions must fall within the range of conditions used when the installed UV reactor was validated off-site (40 CFR 141.729(d)). If the validation conditions do not encompass the utility's design criteria or inlet and outlet piping configurations, the utility may request that the UV manufacturer re-validate the unit off-site under specific testing conditions that closely match those of the proposed installation. Alternatively, on-site validation can be performed.

The advantage of on-site validation are that the UV reactors can be validated under the exact piping hydraulic conditions at which it will operate, and the UVT will more accurately represent the UV installation even if a UV-absorbing chemical is added. In addition, the equipment necessary for on-site validation will also provide the flexibility for future testing to optimize the UV reactor performance under specific hydraulic and water quality conditions even if they are not completed for the initial validation. However, a disadvantage of on-site validation is that the UV installation is designed and constructed without prior validation of the performance of the UV reactors. This may lead to the UV installation failing to meet performance requirements, and it may be difficult to increase UV disinfection efficiency after the UV reactors are already installed. In addition, on-site validation is limited to the highest UVT available at the time of testing. Consequently, UV reactor performance characteristics cannot be determined at higher UVT, and the UV reactors may need to be operated at conditions other than optimal, resulting in higher power use and faster lamp and ballast replacement frequencies. Other disadvantages include the logistics and cost of the testing. For example, one unit must be isolated from the system to allow validation testing to occur, and a permit may be needed to discharge the non-pathogenic challenge microorganism.

If on-site validation is desired, then the UV installation design should be adapted to enable testing. The UV reactor design would need to incorporate feed and sample ports, static mixers, space for tanks near the UV installation (for the addition of the challenge microorganism and UV absorbing chemical), and adequate facilities for laboratory testing, and discharge of the treated water.

3.1.5 Evaluating Operational Strategies

The operational strategy is defined in this manual as the method in which the utility chooses to operate the UV reactors given the UV reactor's control strategy and validation data. It is important for the utility to understand the control strategies unique to various UV reactors (section 3.1.4.2) and select equipment consistent with their operating philosophy and energy efficiency objectives. The control strategy is defined as the method that the UV reactor uses to monitor and control the UV lamp power based on flow and UVT to deliver the specified UV dose. For each UV reactor, the operating conditions must be defined based on validation testing results (40 CFR 141, Subpart W, Appendix D), and the validation data will vary with different control strategies. The validation data can be utilized in different ways that facilitate a simple or complex operating strategy; three potential approaches are described in Table 3.5. Detailed examples of how to determine the operational parameters for these operational strategies are described in section 5.5.

Table 3.5 Potential Operational Strategies

Operational Strategy	Description	Advantages	Disadvantages
Single Operation Setpoint	One setpoint is used for all flows and UVT values that were validated	Simplest operational strategy	Not as energy efficient because the UV reactor is over-dosing at low flows
Variable Setpoint Operation	A setpoint would be used for a given flowrate and UVT range using a lookup table	Increased energy efficiency over the single setpoint approach	More complex operation compared to single setpoint approach and may necessitate more advanced controls for the UV reactor
Setpoint Interpolation	The setpoints are calculated as a function of flowrate, typically automatically using the UV reactor controls[1]	The most energy efficient operation and may reduce operational hours needed if operated automatically	Potentially more validation data is needed (which may increase validation costs) and necessitates advanced reactor controls

[1] Only an option for UV intensity setpoint and calculated dose setpoint approach because the UV intensity and UVT setpoint approach is controlled as function of flowrate and UVT (as opposed to only flowrate)

3.1.6 Evaluating Hydraulics and Process Footprint

The potential locations for UV disinfection identified in section 3.1.2 can be evaluated based on an understanding of the candidate UV reactors, the hydraulics, and the estimated process footprint. This section discusses the principle criteria that affect the feasibility of a UV installation location – (1) hydraulic needs and limitations and (2) space availability and site constraints.

3.1.6.1 Hydraulic Considerations

When selecting the appropriate location for UV reactors, the hydraulic needs should be addressed. Headloss through a UV installation is dependent on the specific UV reactor and flowrate and generally varies from 0.5 to 3 feet. Characteristic headloss data should be obtained from the UV manufacturer(s) for all candidate UV reactors. In addition to the headloss associated with the UV reactor itself, the headloss associated with piping, valves, flow meters, and flow distribution devices should be considered when assessing the feasibility and location of the installation. The overall headloss of a UV installation is typically between 1 and 8 feet.

If the headloss through the UV installation is greater than the available head, modifications to the plant design and/or operation may be necessary. Some potential modifications, alone or in combination, that may be considered to address hydraulic limitations are listed below followed by details about each:

- Eliminating existing hydraulic inefficiencies within the facility to improve head conditions (e.g., replace undersized or deteriorated piping and valves)
- Modifying the operation of the clearwell to accommodate the UV installation
- Modifying the operation of the filters to accommodate the UV installation

- Installing booster pumps
- Modifying the UV reactor design (through the UV manufacturer) to reduce headloss. If the UV reactor design is modified, it must be validated in its modified condition to ensure it meets performance requirements

Eliminating Existing Hydraulic Inefficiencies

Replacing undersized piping and valves with larger diameter piping and valves may increase the available head for the proposed UV installation. Older piping can also produce excessive headloss if the inner pipe surface is pitted or scaled or if the original pipe material has a high coefficient of friction. Slip-lining the interior of existing pipe with a lower coefficient of friction pipe material (e.g., high density polyethylene) is one method of reducing friction losses. Re-lining the existing pipe interior with a smooth coating will also reduce headloss.

Modifying Clearwell Operation

A utility may increase head available to a UV installation by lowering the surface water level of the clearwell. However, this strategy decreases the storage volume available to meet peak demands. In addition, a lower clearwell level will reduce the contact time available in the clearwell for chemical disinfectants and may affect pump discharge head. It is important to evaluate any potential reduction in disinfection credit if contact time in the clearwell is used for calculating CT. The UV installation, though, may reduce the *Giardia* CT requirements sufficiently to offset the reduction in contact time .

Modifying Filter Operation

A treatment facility may alter the operation of its filters to increase the head available for the UV installation. However, this may reduce filter run times, unit filter run volumes, and result in more frequent backwashing. If conditions upstream of the filters are such that additional freeboard and hydraulic head are available, a second option is to increase the water surface elevation over the filters to help minimize the reduction in head available for filtration.

Installing Booster Pumps

When modifications to the existing facility or operations will not provide adequate head for the UV reactors, booster pumps can be installed. Booster pumping provides additional flexibility in the location of the UV reactors. The installation of booster pumps will increase facility operation and maintenance cost and space requirements. The reliability of the pumps should also be considered in the evaluation because the pumps become a critical operating component. Additional detail on booster pump design is provided in section 3.3.1.6.

Modifying UV reactors

Modifying a UV reactor to reduce headloss (e.g., removing baffles) can affect disinfection performance and should only be considered in careful collaboration with the UV manufacturer. Any resulting gains in system head must be weighed against diminished disinfection efficiency, which could result in more UV reactors being needed to accommodate

the flow and provide the necessary UV dose. Any modified UV reactors will also need to be validated in its modified condition.

Other Options to Address Hydraulic Constraints

If none of the above options are feasible, the utility could consider installing the UV reactors upstream or downstream of the HSPs. If a location adjacent to the HSPs is selected, the potential for damage from pressure surges is increased and a surge analysis should be completed. Most lamp sleeves are designed to withstand continuous positive pressures of at least 120 pounds per square inch gauge (psig) (Roberts 2000; Aquafine 2001; Dinkloh 2001). However, lamp sleeves are vulnerable to negative gauge pressure transients associated with water hammer. The tolerance level of the sleeve depends on the quality of the quartz and the thickness and length of the sleeve. However, pressures of negative 1.5 psig have been shown to negatively affect sleeve integrity (Dinkloh 2001). Hydropneumatic tanks, surge relief valves, air release valves, or air vacuum valves on pumps or at different locations along the pipeline can be used to help control surge conditions.

3.1.6.2 Process Footprint

The process footprint should be estimated in the planning phase to determine potential UV installation locations. One critical component needed to estimate the UV installation footprint is the number, capacity, and configuration of the UV reactors. The number of UV reactors depends on the redundancy chosen. UV reactor redundancy should be determined early in the planning process and should use sound engineering approaches similar to those used for other major equipment (e.g., capacity to provide full treatment with the largest unit out-of-service). The specific level of redundancy should be determined by the utility based on operating history and process requirements and should take into account the site constraints. For example, one UV reactor dedicated to each filter may have different redundancy needs than UV installations treating combined filter effluent. Any excess capacity that may be available within the UV reactors (e.g., incorporation of additional lamps or change in lamp power) should also be considered.

The number of UV reactors necessary is also affected by the acceptable power turndown of the UV reactors and the LT2ESWTR requirement that the UV reactors must operate within their validated flow range (40 CFR 141.729(d)). Some UV reactors will operate at low power efficiency at reduced flowrates, and more UV reactors with a lower capacity may increase energy efficiency, depending on water quality and flowrates. For the potential combinations of number and capacity of UV reactors, the available turndown should be determined for each configuration with respect to the anticipated flow range and power modulation capabilities of the UV reactors.

The overall UV reactor and piping configuration will be affected by site constraints. For example, a vertical orientation of the UV reactors may be necessary to reduce building footprint because of little land availability. Ultimately, the selected configuration should balance the capital cost of the equipment, which may be lower for designs incorporating high capacity reactors, with the improved operating efficiency and flexibility that may be achieved using a larger number of lower capacity reactors.

The following items should be considered when estimating the UV installation footprint in the planning phase:

- The number, capacity, and configuration of UV reactors (including redundancy and connection piping)
- The configuration of the connection piping and the inlet/outlet piping necessary before and after each UV reactor, based on validated hydraulic conditions and UV manufacturer recommendations
- Booster pumps (if necessary)
- The space needed for electrical equipment including control panels, transformers, ballasts, backup generator(s), and possible UPS systems
- The maximum allowable separation distance between the UV reactors and electrical controls since distance limitations may apply
- Access for maintenance and replacement, room for storage of spare parts, and chemicals (if needed), and lifting capability for heavy equipment
- Provisions for on-site validation (if applicable)

Once the UV installation footprint is estimated, the feasible site locations may be determined based on the available land and buildings to accommodate the installation footprint. UV installation layout is discussed in more detail in section 3.3.5.

3.1.7 Preparing Preliminary Costs and Selecting the UV Installation Option

The amount of analysis necessary to determine the appropriate application point for a UV installation is site-specific. Some options will clearly be infeasible while others may necessitate a more detailed comparison of the installation options. Once feasible alternatives are identified, the development of life cycle costs can be useful in selecting among alternatives.

Preliminary life-cycle cost estimates should include both capital cost and operation and maintenance cost elements. Capital cost elements includes the cost of the UV reactors, pumping (if necessary), electrical and instrumentation provisions, and site work; contractor overhead and profit; piloting and validation costs; engineering, legal, and administrative costs. Depending on the detail of the cost estimates being developed, the existing infrastructure may need to be evaluated to develop the cost estimate. These issues are discussed in detail in section 3.3.5.

The average conditions for flowrate and UVT are typically the most representative for determining annual operating costs, as opposed to the maximum design flowrate and minimum UVT. Nevertheless, the specific operating limitations of the equipment and the electrical cost rate structure for the installation should be considered. If a utility's electricity charge includes both a usage and a demand component, the demand charge may need to be estimated based on the worst-case operating conditions to accurately represent the cost to the utility. Similarly, it

may be important to correlate the anticipated energy demand for the UV reactors to the actual rate structure for the facility if power costs vary based on the time of day and the flowrate and UVT fluctuate significantly.

Selection of the best option may not be based solely on capital and operation and maintenance costs. The final selection criteria should also consider the following factors:

- Cost-effectiveness and ability to meet the utility disinfection and design objectives.
- Ease of installation (where applicable).
- Operational flexibility and reliability.
- Specific maintenance needs.
- Flexibility for future treatment expansion (if applicable)

3.2 Equipment Procurement Options

The same equipment procurement options that are used to acquire traditional equipment (e.g., pumps) within the water industry can also be used for UV reactors. Owner pre-purchase; base bid, under which the design is based on a single UV manufacturer but is open to alternatives at the discretion of the owner; and contractor selection, in which operating or performance criteria are established and final equipment selection is left to the discretion of the contractor are the most common methods of procurement for traditional design-bid-build projects. Because the use of UV reactors in drinking water treatment plant applications has been limited in the United States, many of the projects to date have pre-purchased the UV reactors. Pre-purchase allows the designer to work more closely with the UV manufacturer during design, reducing the potential for errors that could occur with an evolving technology. However, pre-purchasing may necessitate that a more detailed assessment be completed during the planning stage of the project to ensure that the appropriate equipment is selected and that a second set of contract documents be prepared. Further, this may result in the owner assuming increased responsibility for equipment delivery and performance when compared to base bid or contractor selection. If owner pre-purchase is selected, these factors need to be carefully considered and addressed by the designer during development of the equipment procurement document.

The advantages and disadvantages of the procurement methods with respect to designing and constructing a UV installation are described in Table 3.6. It should be noted that funding sources or municipalities might have specific bidding and procurement requirements. These requirements are site-specific and should be reviewed prior to establishing a project approach to ensure all requirements are met.

Table 3.6 Potential UV Reactor Procurement Options

Procurement Method	Advantages	Disadvantages
Owner Pre-Purchase	• Single design around selected equipment. • Actual UV reactor pricing is better defined earlier in project. • Owner receives equipment warranty directly from UV manufacturer. • May result in shorter project schedule if equipment fabrication time occurs during design and bidding phases of the UV installation.	• Option may necessitate the preparation of two sets of documents; an equipment procurement document and contract documents for the construction of the overall UV installation. • Option may not be possible under some procurement codes. • Except where procurement is assigned, installation contractor is not single point of responsibility for equipment. • Equipment disputes need to be dealt with by owner.
Base Bid	• Single design around selected UV reactors. • Contractor handles all pricing and coordination with UV manufacturer.	• Low incentive for contractor to bid alternates to selected UV manufacturer. • It is difficult to prevent supplier "packaging" of UV reactors. • UV reactor disputes are problematic because contractor was directed to use equipment.
Contractor Selection	• Fits most procurement codes. • UV reactor disputes are the responsibility of the contractor.	• Contractor is likely to select UV reactors with lowest capital cost rather than lowest life-cycle cost. • Multiple UV installation designs may be necessary, increasing engineering effort and cost.

As discussed previously, Chapter 3 is organized in the same manner as the flow chart shown in Figure 3.1, utilizing equipment pre-purchase and a design-bid-build approach for project implementation. It should be noted that successful implementation of UV installations can be accomplished using any of the equipment procurement and contractor selection approaches currently available.

3.3 UV Installation Design Elements

Additional design concepts are expanded and refined in this section, particularly with regard to hydraulic issues, control strategy, instrumentation, and electrical power. The section concludes with considerations for the layout of UV installations.

3.3.1 UV Installation Hydraulics

Following the selection of an installation option during the planning phase, a more detailed evaluation of system hydraulics should be conducted, including flow control, distribution, and measurement. It is important that design of the inlet and outlet conditions be coordinated with the validation process to ensure that the proposed configuration can be cost-

effectively validated and will provide hydraulic conditions that result in dose delivery equal to or better than that provided during validation testing.

3.3.1.1 Inlet and Outlet Piping Configuration

Optimal hydraulic conditions vary based on the UV reactor design and lamp configuration, but turbulent flow with a reasonably uniform velocity profile is generally preferred. Turbulent flow conditions can be achieved at very low flowrates when compared to the actual capacity of a given pipe cross section.

The recommended inlet and outlet conditions for validation and the installation are summarized in section 3.1.4.3 and described in detail in section C.3.1.5. These recommendations should be considered when designing the inlet and outlet conditions for the UV reactors. The designer should contact the UV manufacturer to determine how the procured UV reactors were validated and what the inlet and outlet piping constraints are for the UV installation. If on-site validation is planned, the inlet and outlet hydraulics should be designed as recommended by the UV manufacturer and as the site-specific constraints permit.

3.3.1.2 Flow Distribution, Control, and Measurement

Regulations specify flowrate, UV intensity, and lamp status as the minimum operating conditions a utility must routinely monitor (40 CFR 141, Subpart W, Appendix D). Accordingly, proper flow distribution and measurement are essential for compliance monitoring of the UV reactors. Confirmation of compliance will be dependent on understanding the flow through each UV reactor, regardless of the dose monitoring or control strategy used by the utility. Moreover, UV reactors are validated within specific flow ranges and have associated operating characteristics that demonstrate dose delivery as a function of flow. Therefore, the flowrate through the UV reactor must be known to ensure that proper dose delivery is achieved.

This section discusses different methods for ensuring proper flow distribution and measurement through UV reactors. In some instances, flow can be determined through flow splitting and proper hydraulic design without an individual flow measurement device for each UV reactor. Nevertheless, the need for individual flow measurement for each UV reactor is at the discretion of the State. Utilities implementing UV disinfection are encouraged to discuss flow measurement requirements with their State during the planning and preliminary design phases.

<u>Flow Distribution and Control</u>

Two approaches for flow measurement and control have generally been used. The first involves the installation of a dedicated flow meter and flow control valve for each UV reactor. The second involves the use of passive flow distribution, with confirmation of equal flow split by monitoring pressure differential across identical pipe segments (or the UV reactor) or with flow meters. For identical reactors, the differential pressure across each parallel UV reactor train should be the same if equal flow distribution is occurring and valves are in the same operating position. The use of dedicated flow meters and modulating downstream valves to control flow

through the UV reactors provides the greatest hydraulic control in applications with widely varying flowrates.

Assuming multiple, parallel UV reactors of the same capacity, the UV reactors should be sized and configured to provide approximately equal headloss through each treatment train (i.e., portion of distribution and recombination channel or manifold, lateral piping, and UV reactor with associated valves and flow measurement). This is particularly important if passive flow distribution is used. Because flowrates may deviate from equal distribution, the maximum design flowrate for each reactor should account for any potential distribution imbalance. Equation 3.1 can be used to determine the appropriate upper design flowrate for each UV reactor:

$$Q_{reactor} = \frac{Q_{total} * (1+E)}{N} \qquad \text{Equation 3.1}$$

where

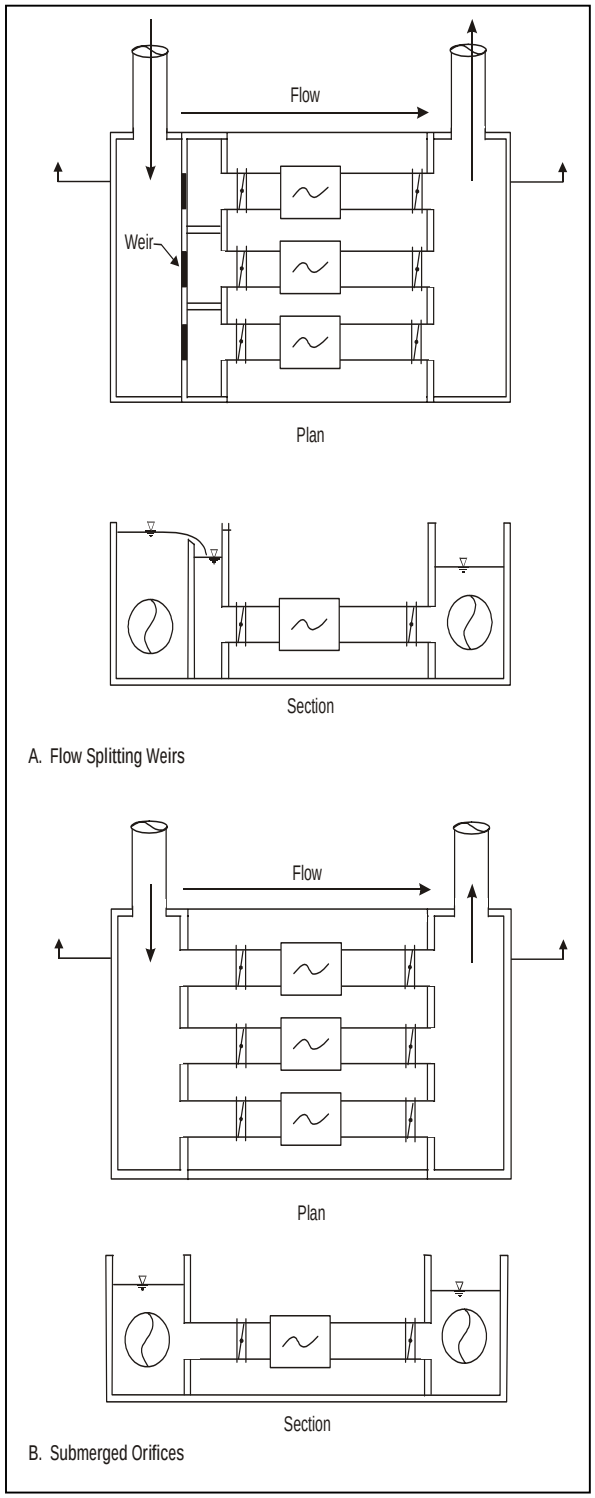
$Q_{reactor}$ = UV reactor design flow
Q_{total} = Plant maximum design flow
E = Calculated maximum flow distribution error (percent as a decimal)
N = Number of on-line UV reactors

The maximum flow distribution error (E) should be determined through hydraulic calculations or hydraulic modeling of the UV installation. For example, ideally two identical, parallel reactors would have a 50/50 flow split. If the actual flow split between the reactors is calculated or modeled to be 60/40 percent, then a 20 percent (E=0.20) maximum flow distribution error (E=(60-50)/50=0.2) would be used in the above equation to estimate the proper design flow for the reactor.

The reactor flow should be estimated over the range of anticipated operating reactors (i.e., number of operating reactors). In general, with passive distribution, as the number of UV reactors increases and flowrate decreases, the potential for flow distribution imbalance is magnified. Effective passive distribution relies on the headloss through each treatment lateral being significantly greater than the headloss through the common influent manifold or chamber. Under the conditions of reduced flow and an increased number of operating reactors, the relative amount of headloss through each lateral becomes less significant when compared to the headloss through the manifold, resulting in less controlled distribution.

For utilities that use distribution and recombination channels (as opposed to influent and effluent manifolds), designers typically have two basic choices to achieve passive flow distribution (Figure 3.8): a series of individual weirs set at the same elevation or a series of orifices submerged into the individual UV reactor laterals.

Figure 3.8 Open-Channel Flow Distribution Options



Flow Measurement

Depending on the design and control strategy of the UV reactor, a number of options are available for flow measurement. As discussed previously, flow measurement devices installed specifically for the UV reactors may not be needed in all applications. It should be noted that some level of inaccuracy or drift is likely to occur with all flow meters. This potential error should be accounted for during design and validation.

If a single UV reactor is installed, the plant's raw water metering station can be used to determine a reasonably accurate flow through the reactor. The use of raw water flow metering data, however, may not account for backwash and residuals flow losses, which would create flow measurement inaccuracies for UV reactors installed downstream of the filters or clearwell. For applications where the UV reactor is dedicated to a rate-of-flow control filter, flow information from the filters may be used to determine the flowrate through the UV reactors.

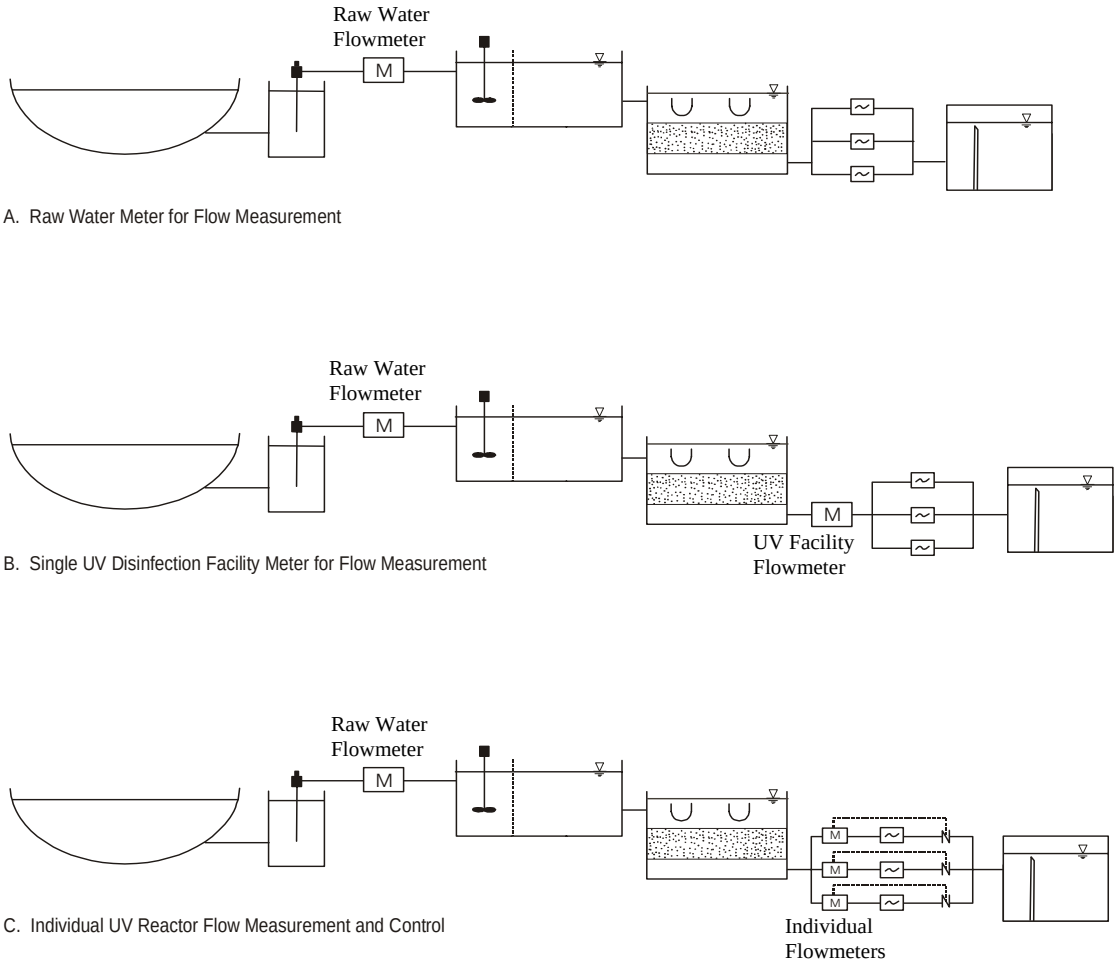
If equal flow distribution between multiple UV reactors can be achieved passively under all hydraulic conditions, a single, common flow meter (new or existing) may be used to measure flow. The total flow can then be divided by the number of operating UV reactors to determine the flow through each UV reactor. If this approach is selected, some method of confirming the equal flow split should also be incorporated (e.g., differential pressure measurement).

A single flow meter for the entire UV installation or individual meters (with or without rate-of-flow control) should be considered to provide increased flow measurement accuracy. Magnetic flow meters or other meter types, such as doppler, that do not protrude into the flow path have the least effect on the velocity profile, which minimizes the potential effect on reactor inlet or outlet hydraulics. The desired means of flow measurement for the UV reactors should be selected based on the level of flow measurement accuracy needed to accomplish the operating and control strategy for the installation and satisfy validation criteria, as well as an understanding of the variability in the plant flowrate. Several options are listed in Table 3.7 and are illustrated in Figure 3.9.

Table 3.7 Comparison of Techniques for UV Installation Flow Measurement

Flow Measurement Method	Description	Flow Control Method	Advantages	Disadvantages
A. Raw or Filtered Water Flow Measurement (Figure 3.8A)	Use plant flow information upstream of UV reactors.	Passive flow control such as a weir or orifice.	• New flow meters not needed • Minimizes UV installation capital cost • Simplifies control strategy	• Introduces potential errors in measured flow versus actual UV reactor flow • Relies on adequate flow distribution between UV reactors • Relies on a single meter • May need oversized UV reactors to provide adequate dose delivery at all times
B. Single Flow Meter for Flow Measurement to Entire UV Installation (Figure 3.8B)	Measure total UV reactor flow.	Passive flow control such as a weir or orifice.	• Measures flows accurately • Only one new flow meter needed	• Relies on adequate flow distribution between UV reactors • Relies on a single meter • May need oversized UV reactors to provide adequate dose delivery at all times
C. Individual UV Reactor Flow Measurement (Figure 3.8C without flow control valve)	Measure flow for each UV reactor.	Passive flow control such as a weir or orifice.	• Measures UV reactor flows accurately • Does not have one meter as a single point of failure • Equal flow distribution is not necessary for dose control	• Relies on adequate flow distribution • Increases capital cost • Increases UV installation complexity • Increases installation footprint to achieve necessary meter hydraulics • Increases reactor headloss
D. Individual UV Reactor Flow Measurement and Control (Figure 3.8C)	Measure and control flow for each UV reactor.	Individual flow control (valve) for each UV reactor.	• Does not introduce potential errors in measured flow • Does not rely on adequate flow distribution • Does not rely on a single meter	• Increases capital cost • Increases UV installation complexity • Increases installation footprint due to hydraulics of UV reactor, meter, and valves • Increases reactor headloss

Figure 3.9 Flow Measurement and Control Options



3.3.1.3 Level Control

The UV reactors must be flowing full at all times during operation. Therefore, the reactors should be placed below the hydraulic grade line elevation. There are two basic options commonly used to maintain the level in the reactors. One option is with a fixed downstream weir; in many WTPs, a fixed weir is already located in a clearwell and can be used for this purpose. If not, another option is to install a weir immediately downstream of the UV reactor or at another location that ensures full pipe flow through the UV reactors. A final option is to use flow control valves to monitor and maintain the downstream hydraulic grade line.

3.3.1.4 Air Relief and Pressure Control Valves

UV reactors should be kept free of air to prevent lamp overheating. The formation of negative pressures or surge effects within the UV reactors should also be prevented to avoid damage to the lamp sleeve and UV lamps. The use of air release valves, air/vacuum valves, or combination air valves may be appropriate to prevent air pockets and negative pressure

conditions. The locations of the valves will be dictated by the specific configuration of the installation and should be determined during design.

3.3.1.5 Flow Control and Isolation Valves

Each UV reactor should have the capability of being isolated and taken out of service. This will necessitate a valve, gate, or other isolation device upstream and downstream of the UV reactor. Valves are generally preferred, since they provide a tighter seal. Utilities that use passive flow distribution will rely on the valves primarily for isolation and sequencing of UV reactor operation (as opposed to flow control). Valves downstream of the UV reactor should be equipped with an actuator to automatically open or close on a critical alarm occurrence and to enable start-up sequencing.

If the isolation valves are used for flow control, either the upstream or the downstream valve can be used. However, it is generally recommended that the valve downstream of the UV reactor be used to minimize disturbance of the flow entering the UV reactor, particularly if the separation distance between the upstream valve and the UV reactor is relatively small. The flow characteristic curve of the valve and the operating speed of the actuator should be matched to the flow control needs of the UV reactors. During design, the valve configuration should be discussed with the UV manufacturer to ensure that UV reactor performance will not be adversely affected by the location or operation of the valves. It is important to coordinate the location of the valves with the validation conditions for the reactor, as discussed in section C.3.1.1.

Valve seats and other in-pipe seals and fittings within the straight pipe lengths adjacent to the UV reactors should be constructed of materials that are resistant to UV light to avoid degradation. If in-place rehabilitation of existing piping is used to improve system hydraulics, the materials used to slip-line or reline the piping adjacent to the proposed UV reactors should also be resistant to degradation from exposure to UV light. Organic materials and plastics that have not incorporated UV-resistant additives are typically most susceptible to UV degradation.

3.3.1.6 Intermediate Booster Pumps

A detailed evaluation and design of a booster pumping system is recommended if it is determined during the planning phase that head constraints necessitate the installation of a pumping system. Pumps common in water treatment plants (i.e., vertical turbine, end-suction centrifugal, and split-case centrifugal pumps) tend to have higher discharge pressures than intermediate pumping applications and are generally not appropriate for this application. Mixed flow or axial flow pumps with high-flow and low-head operating characteristics are typically more appropriate. However, additional headloss may need to be added to the system, based on the capabilities of the pump. Smaller diameter piping, backpressure valves, or control valves can be used to increase the system head to more closely match the pump discharge curve.

Pumps may be installed before or after the UV reactors, allowing more flexibility in the UV installation's design elevations and the location of the UV reactors. Regardless of pump location, some form of wetwell should be provided upstream of the pump station. Existing clearwells, recombination channels, or dedicated pump wetwells may be used. Direct connection

clearwells, recombination channels, or dedicated pump wetwells may be used. Direct connection to filter effluent piping may adversely affect upstream process performance and should be avoided. Booster pump operation may be controlled by the water level within the upstream wetwell. The use of variable frequency drives (VFDs) to moderate flow peaks is recommended. This is especially important if the pump station is upstream of the UV reactors. By minimizing hydraulic peaks, the UV reactors can be sized to more closely match the flow through the WTP.

If pumps are located adjacent to the UV reactors, the impact of surge conditions should be evaluated. Of particular concern is the potential for surge if the pumps are operating and power is lost. Pump start-up procedures should be carefully selected with possible inclusion of pump control valves. Control of individual UV reactor isolation valves should be coordinated with pump starts and stops and with pump control valves where appropriate. Likewise, the warm-up time associated with the start-up of the UV reactors must be taken into account with the sequencing of the pump operation.

3.3.2 Operational Strategy Determination

Once the UV reactors are procured, a utility should determine the preferred operational strategy given the UV reactor's control strategy and available validation data. The different operational strategies are described in section 3.1.5, and an example of how to interpret the validation data to develop an operational strategy is described in section 5.5.

The power needs for UV reactors can be moderately high, and an inefficient UV installation can result in unnecessarily high operating costs. When considering what operational strategy to use for a particular installation, the operational complexity should be compared to the potential for energy savings. It should be noted, however, that intensity adjustment does not correlate directly to the amount of energy that is saved. Lamp output efficiency may decrease as the lamp intensity is reduced, resulting in a reduced energy savings. Lamp output efficiency as a factor of intensity should be discussed with the UV manufacturer and considered when determining the potential cost savings associated with dose pacing. An operational strategy consistent with the procured UV reactor should be selected to facilitate the instrumentation and control design.

3.3.3 Instrumentation and Control

After the hydraulic needs of the UV reactors have been addressed and a dose control strategy has been selected, the instrumentation and controls necessary to satisfy both can be identified. The level of instrumentation and control that is needed will depend on the flow control, flow distribution, and flow measurement approach that is selected, as well as the dose control strategy that is employed. Passive flow distribution with an intensity setpoint dose control strategy is a relatively simple operation and demands limited instrumentation and control. Operating flexibility and the ability to optimize UV reactor energy efficiency, however, are reduced. The use of dedicated flow meters and flow control valves, in combination with on-line transmittance monitors and dose pacing, demands a higher level of instrumentation and control. However, this approach provides significant operating flexibility and the ability to optimize

The specific instrumentation and control elements included with the UV reactors may not be known until a final UV reactor selection is made. Most of the equipment manufacturers, however, share common instrumentation and control attributes and alarm conditions in the designs of their UV reactors. To enable a procurement document to be prepared, a control strategy should be established. To the extent practicable, the designer should identify the elements of the control system that are preprogrammed into the UV reactor control panel and those that will be addressed through the installation of supplemental controls and equipment. At a minimum, the LT2ESWTR requires that UV lamp intensity, flowrate, and lamp status be monitored (40 CFR 141.729(d)). The final instrumentation and control design can be modified as needed after equipment is selected.

3.3.3.1 UV Reactor Start-up

Regardless of the UV reactors that are selected, the start-up cycle will likely be the same. For a UV reactor that is starting cold (i.e., previously off as opposed to shutdown for a very short period due to power interruption), a typical control sequence will open the isolation valves, ignite the lamps, and bring the lamps to full power. During the typical control sequence, the water being treated will be off-specification until the lamps reach full operating power, which can take up to 10 minutes. However, the amount of off-specification water can be reduced by providing a low flow of cooling water that can be discharged to waste. Alternatively, if a LP or LPHO reactor is procured, the downstream valve may remain closed as the UV lamps are warming up. However, the designer should consult the LP or LPHO manufacturer to ensure this strategy is feasible. It is recommended that the utility discuss these practices with the State to confirm their acceptance.

3.3.3.2 UV Reactor Automation

Depending on the size and complexity of the UV reactor, its operation can range from manual to fully automatic. Manual operation includes manual initiation of lamp start-up and shut down, and appropriate valve actuation. Different levels and types of automation can be added to the manual sequence. A first level of automation includes the sequencing of lamp start-up and valve actuation to bring individual UV reactors on-line after manual initiation. Further levels of automation could include starting up UV reactors, activating rows of lamps, or making lamp intensity adjustments based on lamp condition, water quality, and/or flowrate.

Automatic UV reactor shutdown under critical alarm conditions (e.g., high temperature, lamp or sleeve failure, loss of flow) is important for all operating approaches, including manual operation. The shutdown cycle will be site-specific. However, to the extent practicable, the downstream flow control or isolation valve should be closed whenever the UV reactor is shut down to minimize the distribution of water that has not been disinfected by the UV installation.

3.3.3.3 UV Intensity and Calculated Dose (If Applicable)

Signals from UV intensity sensors should be displayed locally or on the UV reactor control panel. Because the output from the UV intensity sensor is integral to the determination

of adequate dose delivery, the UV intensity sensor output should be monitored continuously. If the calculated dose control strategy is used, the calculated dose should be displayed locally and be monitored continuously.

3.3.3.4 UV Transmittance

An on-line UVT monitor or bench-top spectrophotometer may be used to monitor UVT, depending on the control strategy (section 3.1.4.2). An on-line UVT monitor is typically used for the UV intensity and UVT setpoint approach and the calculated UV dose setpoint approach. However, for utilities that have water with a stable UVT, periodic grab samples may be adequate. Results from a bench-top spectrophotometer can be manually input into a SCADA system or other control system. Output from an on-line UVT monitor can be input directly into a control loop for most UV reactors, a SCADA system, or both.

If the UV intensity setpoint approach is used, UVT does not need to be monitored because the UVT is accounted for in the UV intensity measurement. However, it may be advantageous to monitor UVT with an on-line UVT monitor or bench-top unit to assist with troubleshooting UV reactor performance issues.

The specific size and operating characteristics of the UVT monitor will vary dependent on the UV manufacturer. If an on-line UVT monitor is included in the design, it is important to provide adequate space and access to an electrical supply for installation of the monitor and to include appropriate sample taps and drains in the design for the withdrawal and discharge of sample water. The sample line should be equipped with a valve to isolate the unit. If insufficient pressure is available in the system, then a sample pump should be installed.

3.3.3.5 Flow Measurement

Flowrate is one of the operating conditions a utility must routinely monitor (40 CFR 141, Subpart W, Appendix D). To maintain regulatory compliance, the flowrate through a UV reactor must be known to ensure that flow is within the validated range. Section 3.3.1.2 discusses flow measurement and control options. If flow meters are installed, the flow signal should be displayed locally or be input directly into a control loop for the UV reactor, a SCADA system, or both.

3.3.3.6 Lamp Age

Each lamp or an integral bank of lamps should be monitored for operating time. Lamp replacement should be based on the dose delivery and the age of the lamp. Initially, the number of lamp hours used to trigger lamp replacement can be estimated based on UV manufacturer recommendation and validation data. Later, the actual frequency of replacement should be correlated to the operating performance of the UV installation. Frequent restarting of the lamps may reduce their useful life.

3.3.3.7 Lamp and Reactor Status

Lamp status is one of the operating conditions a utility must routinely monitor (40 CFR 141, Subpart W, Appendix D). In addition to the status of individual lamps, whether the reactor is on-line or off-line should also be monitored and indicated locally and remotely. Power and valve status are two methods that utilities can consider to perform such monitoring.

3.3.3.8 Alarms and Control Systems Interlocks

Many UV reactor signals and alarms are specific to the UV installation and the level of automation employed. Alarms may be designated as minor, major, or critical, depending on the severity of the condition being indicated. The same alarm condition may represent a different level of severity dependent on the conditions under which the UV reactor was validated, the type of UV reactor, the control strategy, and the disinfection objectives of the utility. For example, if a UV reactor was validated with one lamp out of service, a single lamp failure alarm may be a minor alarm. Had the reactor been validated with all lamps in operation, then a single lamp failure may be a major alarm. At a minimum, alarm conditions should be displayed locally. The use of an audible alarm may be beneficial. If UV reactors will frequently be unstaffed, provisions should also be included in the design to allow remote monitoring.

A minor alarm generally indicates that a UV reactor needs maintenance but that the UV reactor is not operating out of compliance. For example, a minor alarm would occur when the end-of-lamp-life is reached, indicating the possible need for lamp replacement. A major alarm indicates that the UV reactor needs immediate maintenance (e.g., the UV intensity sensor value has dropped below the validated setpoint) and that the unit may be operating off-specification. Based on the utility's disinfection objectives, this condition may also be handled as a critical alarm. A critical alarm typically shuts the unit down until the cause of the alarm condition is remedied. An example of a more typical critical alarm is the UV reactor temperature exceeding a pre-determined maximum value, resulting in automatic shutdown to prevent overheating and equipment damage.

The designer should work with the UV manufacturer to determine what elements of the control system are integral to the UV reactor and what will be addressed through the installation of supplemental controls and equipment. For installations with multiple UV reactors, a common, master control panel may be necessary to enable sequencing of the UV reactors and to allow the UV reactor operations to be optimized. Table 3.8 summarizes typical UV reactor monitoring and alarms; additional detail is provided in section 5.4. Many of the alarms shown will be integral to the UV reactor control panel.

Table 3.8 Typical Alarm Conditions for UV Reactors

Alarm/Sensor	Purpose/Descriptions
Lamp Age	• Minor alarm occurs when run-time for lamp indicates end of defined operational lamp life.
Calibrate UV Intensity Sensor	• Minor alarm occurs when UV intensity sensor needs calibration based on operating time.
Differential Pressure Out of Range (When Differential Pressure is Used for Flow Split Confirmation)	• Necessary only if a single master flow meter is used. • Minor alarm occurs if pressure drop across parallel, identical UV reactors indicates unequal flow split. • Major alarm occurs if differential pressure across a given UV reactor indicates flow outside of the validated range.
Low UV Dose	• Major alarm occurs when dose condition falls below required dose. • Triggered by signals gathered by control system and compared to validated UV reactor dose requirements.
Low UV Intensity	• Major alarm occurs when intensity falls below design conditions.
Low UV Transmittance	• Major alarm occurs when UVT falls below design conditions.
High/Low Flow	• Major alarm occurs when flowrate falls outside of validated range. • Based on measurement from dedicated flow meters or calculated based on total flowrate divided by number of units operating.
Lamp/Ballast Failure	• Major alarm occurs when a single lamp/ballast failure is identified. • Critical alarm occurs when multiple lamp/ballast failures are identified.
Low Liquid Level	• Critical alarm occurs when liquid level within the UV reactor drops and potential for overheating increases.
High Temperature	• Critical alarm occurs when the temperature within the UV reactor or ballast exceeds a setpoint.
Mechanical Wiper Function Failure	• Needed only if a mechanical wiper system is used. • Critical alarm occurs if wiper function fails.

Note: Alarm conditions and relative severity shown above may vary dependent on specific conditions under which the UV reactor is validated, the type of UV reactor, the control strategy, and the disinfection objectives of the utility.

3.3.4 Electrical Power Configuration

The electrical power configuration that is used should take into account the findings of the power quality assessment conducted during the planning phase described in section 3.1.3.3, the power requirements of the selected equipment, and the disinfection objectives and control strategy of the utility. Issues that should be addressed include harmonic distortion and off-specification operation due to power quality problems (fluctuation in line voltage).

3.3.4.1 Power Requirements

The proper supply voltage and total load requirements must be coordinated with the UV manufacturer, considering the available power supply. In addition, the power needs for each of the UV reactor components may differ. For example, the UV reactors may require a 3-phase, 480-volt service while the on-line UVT monitor may need a single phase, 110-volt service. The method of handling the power feed must be carefully coordinated to ensure all electrical equipment and services are included and to clearly establish the responsible party for each element of the electrical supply (e.g., primary service, transformer, secondary service). Excluding high service pumping, the electrical load from UV reactors will typically be one of the larger loads at the WTP.

Due to the varying nature of UV reactor loads, current and voltage harmonic distortion can be induced. Such disturbances can result in electrical system problems, including overheating of some power supply components and effects on other critical systems such as VFDs, program logic controllers (PLCs), and computers. Proper selection of the UV reactors, including a thorough analysis of the potential for the equipment to induce harmonic distortion, should minimize the potential for harmonic distortion. Another method for controlling harmonics is to use a transformer with Delta Wye connections to isolate the UV reactors from the remainder of the WTP power system. The delta-connected primary feed could be designed and sized to trap and moderate any induced harmonics. The Wye-connected secondary should be solidly grounded so that the ballasts are powered from a grounded source in accordance with electrical code requirements. If a separate transformer for the UV reactors is impractical, harmonic filters could be added to the UV reactor power supply to control distortion. Regardless of the method used to address harmonic issues, electrical acceptance testing during start-up should include a harmonic analysis to verify that the UV reactor harmonics are not affecting other electrical components at the WTP.

3.3.4.2 Backup Power Supply

The continuous operation of the UV reactors is highly dependent on its power supply. This dependence, when combined with the sensitivity of the UV reactors to power fluctuations, increases the importance of a high quality, dependable power supply. The utility should work with the State to establish specific power reliability objectives for the UV installation, as power reliability may directly affect the utility's ability to meet the State's allowable off-specification requirements. As discussed in section 3.1.3.3, minor power transients can lead to lamp outages. If the power reliability objectives, and, consequently, the disinfection objectives, cannot be met solely by relying on the commercial power supply, then the use of a backup power supply (i.e., backup generator, separate commercial service, and/or battery-supported UPS) may be necessary. If an existing backup power supply is in place, the load capacity of this supply should be assessed to determine if it is able to accept the additional load associated with the UV reactors. Additionally, the time needed to transfer from the primary power supply to a backup power supply and the potential effect of the transfer time on compliance with the State's allowable off-specification operation should be determined.

An alternate backup power supply may be needed if a backup power supply is not in-place or the available load capacity is insufficient to handle the new load associated with the UV

reactor equipment. The type of backup power supply that is needed will depend on the frequency and duration of the power interruptions and the potential for those interruptions to result in off-specification operation of the UV reactors. If power quality issues are infrequent and of short duration (on the order of seconds or minutes), it is possible that a backup power supply may be unnecessary, or a simple backup power supply may be sufficient. If the frequency of power outages increases or the duration of the outages increases, the need for a more extensive backup power supply becomes more significant.

If a backup power supply is necessary, but continuous power is not needed, the use of a traditional diesel or natural gas-fired backup generator set, a standby UPS, or a rotary UPS may be adequate. Should a continuous power supply be needed to meet reliability objectives, the use of a line-interactive UPS will be necessary. The line-interactive UPS provides a continuous power supply, but is generally less efficient, has a lower starting current, and costs more than a similarly sized standby UPS. Typically, a line-interactive UPS would be installed in conjunction with a backup generator to provide a cost-effective backup power supply for longer duration power interruptions or for frequent, shorter duration power interruptions. Although unlikely to be a requirement for compliance monitoring, it may be beneficial to include a data logger that records instances of UPS operation as part of the UPS system design.

The elements that should be considered when assessing the need for a backup power supply for a UV reactor are somewhat unique when compared to those associated with more typical WTP equipment. However, once it is determined that a backup power supply is necessary, the design for a UV reactor is very similar to that for any other equipment or treatment process. Factors that should be considered during design include isolation, in-rush current, purchase and installation cost, maintenance requirements, voltage regulation, electrical surge protection, attenuation of harmonic current, run-time, transformer continuity, and the ability to operate with other power supply equipment. In most circumstances, a UPS should not be used without a backup generator because of the battery reserve necessary to power a UV installation for longer durations. To minimize capital cost, the battery reserve time should be sufficient to allow the power supply to switch to the backup generator.

3.3.4.3 Ground Fault Interrupt and Electrical Lockout

Ground fault interrupt (GFI) is an important safety feature for any electrical system in contact with water, including UV reactors. All UV reactor suppliers should provide GFI circuits for their lamps, which should be included in the specifications that are developed for equipment procurement. For a GFI to function properly, the transformer in the UV reactor ballast must not be isolated from the ground. If the UV reactor ballast isolates the output from the ground, ground faults will not be properly detected, and safety can be compromised.

Provisions enabling the UV reactors to be isolated and locked out for maintenance, both hydraulically and electrically, should be included in the design. Control of all lockout systems should remain local; however, when appropriate, the status of local lockouts could be monitored remotely. In all cases, the design must comply with electrical code and policy requirements for equipment lockout.

3.3.5 UV Installation Layouts

Once the previous design elements (i.e., section 3.3.1 through section 3.3.4) have been evaluated, an installation layout can be prepared as part of the equipment procurement document. The layout should take into account the findings of all previous work. Because the design process is iterative and many elements of the layout are dependent on the specific UV reactors that are used and the validation scenario that is proposed, the layout may change after the UV reactors are selected and any additional space constraints are identified.

3.3.5.1 Site Layout

Site layout for a UV installation is generally similar to the layout of any treatment process. When locating the UV installation, access for construction, operation, and maintenance should be addressed. The availability of adequate existing infrastructure (e.g., power, drains, lifting devices) is also important. In general, when compared to other treatment processes at a WTP, the UV installation has a relatively small footprint.

3.3.5.2 UV Installation Layout

In large part, the piping layout will be dictated by the validated hydraulic conditions because the inlet and outlet conditions for the installed UV reactors should be equal to or better than the hydraulic conditions used during validation. Additional details on the relationship between the validated inlet and outlet configuration and the actual installed configuration are given in section C.3.1.5. Nevertheless, the designer can prepare a reasonable UV installation layout based on the type of technology (i.e., LPHO versus MP), the number of UV reactors that is needed, and the manner in which flow is controlled and measured. This layout can then be used in the selection and procurement of the UV reactors.

Most UV reactors available for drinking water applications are of a closed-chamber type. Filtered water is conveyed via pipes or covered channels to a series of UV reactors for primary disinfection. As such, laying out UV installation typically involves designing the method by which water is divided between UV reactors (channel or piping), and routing the sections of pipe between inlet and discharge headers in which the UV reactors are inserted via flanged connections (although other types of connections may be used). The number and configuration of the UV reactors will vary depending on lamp type/reactor design, reactor size, flow range to be treated, control strategy, and degree of redundancy.

Although most components of UV reactors are fairly compact, it is important not to underestimate the necessary space for the building that will house the UV installation. In addition to those items identified in section 3.1.6.2, the following factors should be considered in the layout for the UV installation:

- The length of straight-run piping before and after each flow meter to achieve the proper hydraulic conditions for accurate and repeatable flow measurement (if applicable)

- Field instrumentation
- Isolation valves and flow control devices
- Control and power panels, and code-required clear space
- Potential space for power monitors and UPS systems
- Drain provisions for the process area and to permit UV reactor draining
- Provisions for future expansion of UV disinfection capacity

Components of the UV reactors are typically located inside a building for protection from the weather and to provide a clean, convenient area for maintenance. The UV reactors themselves, associated electrical components and controls, and electrical support equipment such as a UPS should be enclosed. There are installations, however, where UV reactors and control panels are uncovered. Prior to implementing an uncovered installation, it is recommended that the State and UV manufacturer be consulted. Any exposed equipment and control panels should be rated for the anticipated environment and appropriate site security should be in-place to restrict public access.

The power and control panels associated with UV reactors should be located so that there is adequate space for panel doors to be opened without interference, and to allow unhindered access to the UV reactors with panel doors open. In selecting the location of the power and control panels, UV manufacturer cable length limitations should not be exceeded. The maximum allowable cable length is UV manufacturer-specific and may be less than 30 feet. If harmonic feedback is a concern, extra room should be provided for power conditioning equipment.

When allotting space for maintenance activities, adequate space to remove the lamps and the lamp wiper assembly should be provided. In some cases, access may be needed on both sides of the UV reactor. In addition, provisions should be included to collect and convey water that is discharged during maintenance activities.

Certain UV reactors need maintenance involving an OCC procedure in which a UV reactor is taken off-line, isolated, drained, filled with a cleaning solution, cleaned, flushed, and returned to service. The OCC equipment is typically self-contained and the cleaning chemical is recirculated. Where applicable, sufficient space around the UV reactors should be maintained to provide access for the OCC procedure. In addition, the OCC solution often has specific handling requirements. Appropriate drains, storage, and health and safety equipment (e.g., emergency eyewash station) should be provided as recommended by the chemical manufacturer.

Sample taps are recommended upstream and downstream of each UV reactor within the lateral pipe. The sample taps may be used for the collection of water quality samples or may be used during validation testing if on-site validation is necessary. If on-site validation will be conducted, the number and location of sample and feed ports should be coordinated with the UV manufacturer or third party validation service to comply with the recommendations of the selected validation protocol. Additional detail on the locations of sample taps and other

validation-related appurtenances, as well as the methods used to validate a reactor are provided in section C.3.1.4.

Drain valves or plugs should be located on each lateral between the two isolation valves. In many cases, the UV manufacturer may have already incorporated a drain into the UV reactor design. Drain valves should also be provided at one or more low points in the UV installation to enable the UV reactor to be fully drained for future maintenance activities.

3.3.6 Elements of UV Reactor Specifications

Table 3.9 summarizes the elements that should be considered in developing equipment specifications for the UV reactors. The information included in Table 3.9 is not exhaustive and should be modified to meet the specific needs of the utility.

Table 3.9 Recommended Content for UV Reactor Specifications

Specification Item	Purpose/Description
Flowrate	Maximum, minimum, and average flowrates should be clearly identified. The minimum and maximum flowrates must be within the range of validation flowrates. The minimum flowrate is important to avoid overheating with MP reactors.
UV Dose	The required reduction equivalent dose as well as the validation technique that will be used to measure the dose should be established. Additional detail is provided in Chapter 4.
Water Quality and Environment	The following water quality criteria should be included: - Influent temperature - Turbidity - UV Transmittance at 254 nm - Spectral absorbance 200-300 nm (MP reactors only) - Total Hardness - pH - Iron For some parameters, a design range may be most appropriate.
UV Intensity Sensors	It is recommended that at least one UV intensity sensor be specified per UV reactor. The number of reference sensors that should be determined based on the time and labor associated with checking and maintaining the duty sensors.
Redundancy	If a combined filter effluent UV reactors are used, it is recommended that at least one completely redundant UV reactor be specified as a standby. For other configurations, the designer should determine the appropriate redundancy based on the State's requirements and the utility's disinfection objectives.
Hydraulics	The following hydraulic information should be specified: - Maximum system pressure at the UV reactor - Maximum allowable headloss through the UV reactor - Special surge conditions that may be experienced - Hydraulic constraints based on site-specific conditions and validated conditions (e.g., upstream and downstream straight pipe lengths)
Size/Location Constraints	Any size constraints or restrictions on the location of the UV reactor or control panels (e.g., space constraints with in-line installation).
Validation	The specifications should establish the validation protocol that will be followed, provide the conditions under which the validation will be conducted (e.g., water quality, flow range, hydraulic conditions, UVT), and require the submittal of a validation report (40 CFR 141.730).
Control Strategy and Operating Sequence	The specification should provide a narrative description of the operating sequence and control strategy for the UV reactors.
Lamp Sleeves	At a minimum, the following items should be specified: - Lamp sleeves should be annealed to remove internal stress. - UV manufacturer should perform QA / QC checks of a fraction of each lot using a polarized light or other approved method. - UV manufacturer should submit documentation on the integrity of their sleeve, monitoring practices, and rationale for using a given internal QA / QC frequency. - UV manufacturer should submit calculations showing the maximum allowable pressure for the lamp sleeves and the maximum bending stress experienced by the lamp sleeves under the maximum specified flow conditions.

Table 3.9 Recommended Content for UV Reactor Specifications (continued)

Specification Item	Purpose/Description
Safeguards	At a minimum, the following UV reactor alarms should be specified: - Lamp or ballast failure - Low UV intensity or low UV dose (dependent on control strategy used) - High temperature - Low or high flow - Wiper failure (as applicable) - Other alarms discussed in section 3.3.3.8, as appropriate
Control Systems	At a minimum the following signals and indications should be specified: - UV reactor status - UV intensity - Individual lamp status - Lamp cleaning cycle and history - Accumulated runtime for individual lamps - Influent flowrate At a minimum the following UV reactor controls (as applicable) should be specified: - UV dose setpoints, lamp intensity setpoints, or UVT setpoints (dependent on control strategy used) - UV reactor on/off control - UV reactor manual/auto control - UV reactor local/remote control - Manual lamp power level control - Manual lamp cleaning cycle control - Automatic lamp cleaning cycle setpoint control
Performance Guarantee	The performance guarantee should specify that the equipment provided under the UV reactor specification should meet the performance requirements stated in the specification for an identified period. The following specific performance criteria may be included: - Allowable headloss at each of the design flowrates. - Estimated power consumption under the design operating conditions. - Disinfection capacity of each reactor under the design water quality conditions.
Warranties	A physical equipment guarantee and UV lamp guarantee should be specified. The specific requirements of these guarantees will be at the discretion of the utility and engineer.

3.3.6.1 Information Provided by Manufacturer in UV Reactor Bid

It is important that UV manufacturers provide adequate information when bidding to enable the designer to conduct a proper, timely review of the proposed equipment. Suggested information to be obtained from the UV manufacturer is presented in Table 3.10.

Table 3.10 Recommended Information to be Provided by UV Manufacturer/Vendor

Item	Purpose
Design Parameters	Demonstration of an understanding of the design parameters for the UV reactors. All UV reactor design parameters from the contract documents should be repeated in the proposed UV reactor submittal information.
Summary of Design	A summary of the equipment proposed (number of UV reactors, lamp type) and specify equipment redundancies.
Reactor Technical Specifications	Ability of proposed UV reactors to meet technical specifications and an explanation of any exceptions taken.
UV Manufacturer's Experience	Information on project experience, including previous installations and references.
UV Intensity Sensor	Information on the UV intensity sensor(s) including acceptance angle, external dimensions, working range in mW/cm^2, spectral response, measurement uncertainty, environmental requirements, linearity and temperature stability. Data and calculations should be provided showing how the total measurement uncertainty of the sensor is derived from the individual sensor properties. (See sections 4.3.2.3 and C.4.7)
Validation Data	UV reactor validation data as described in Appendix C of these Guidelines. If on-site validation is proposed, validation data for the UV reactors from other, similar installations should be included to provide a baseline comparison to the proposed operating conditions.
Upstream and Downstream Hydraulic Requirements	A statement of the length of straight pipe and hydraulic conditions necessary upstream and downstream from the UV reactor to ensure the desired flow profile is maintained and the design conditions are met.
Power Requirements	The power needs of each UV reactor and which elements, including electrical cable and wiring, are included as part of their equipment.
Cleaning Strategy	The strategy that will be employed for cleaning the UV lamps in the UV reactor.
Control Strategy	The proposed UV reactor control strategy, including manual and automatic control schemes and a listing of inputs, outputs, and the types of signals that are available for remote monitoring and control.
Reactor Data	The materials of construction, dimensions of the UV reactors and ancillary equipment, a listing of spare parts, and a sample operations and maintenance manual.
Safeguards	The safeguards built into the UV reactor and accompanying equipment, such as high temperature protection, wiper failure alarms, and lamp failure alarms.
Warranties	A statement of the proposed UV reactor guarantees, including the physical equipment, the UV lamp, and the system performance guarantee. Any exceptions should be indicated and explained.

Warranties

The UV reactor specification should include suitable written guarantees regarding physical equipment, UV lamps, and performance.

It is recommended that the UV lamp guarantee specify that each lamp is warranted to provide the lamp output necessary to meet the required reduction equivalent dose (RED) under

the design conditions for a minimum number of operating hours, which will vary depending on lamp type. To limit the UV manufacturer's liability and to potentially reduce the contingency costs included in their equipment bid prices, the guarantee could be prorated after a specified number of operating hours. It is important that the appropriate lamp fouling/aging factor be included in the design conditions as discussed in section 3.1.3.1. If these specifications are not met, significant operation and maintenance costs may occur because lamps may need to be replaced frequently for the UV reactors to operate within the validated range. The combination of lamp fouling/aging factor and the guaranteed lamp life will make the UV manufacturer responsible if the UV lamps do not meet these specifications. The guaranteed lamp life will depend on the available technology at the time of the UV installation design and will likely change as lamp technology improves.

3.3.7 Final UV Installation Design

After the equipment procurement document is developed and competitively bid, and all bids have been carefully reviewed, the UV reactors can be selected. Once the UV reactors are selected, the designer can work with the selected UV manufacturer to develop the final disinfection installation design based on the specific needs and design of the selected equipment. The hydraulic design, instrumentation and control design, electrical design, and installation layout should be modified to address the specific needs of the selected equipment and to ensure that the control strategy can be implemented within the constraints established during the validation testing.

Particular emphasis should be given to the integration of the overall control strategy with the alarms, signals, and interlocks that are integral to the UV reactor design. For designs with multiple UV reactors, a master control panel may be necessary to enable the sequenced operation of the individual UV reactors and to optimize the efficiency of the UV installation. It is critical that the final design be coordinated with the validation testing to ensure that validation criteria are sufficient to implement the proposed control strategy and to ensure that the UV reactors will meet the utility's disinfection objectives under the anticipated operating conditions.

3.3.7.1 Design Drawings

The drawings may include the following content:

- Existing conditions
- Site work
- Structural work
- Architectural work
- Mechanical work (heating, ventilation, and air conditioning)

- Electrical work
- Instrumentation work

3.3.7.2 Specifications

The content of the specifications will vary dependent on the complexity and size of the UV installation and the selected method of project delivery. However, it is likely that portions of nearly all of the 16-Division Construction Specifications Institute (CSI) MasterFormat may be necessary. For those UV installations that pre-purchase the UV reactors, the equipment procurement document should be included as an appendix to the specifications to facilitate contractor review and installation of the equipment.

3.4 Reporting To The State

Interaction with the State throughout the planning and design phases, as well as during development of the reactor validation protocol, is recommended to ensure that the objectives of both the utility and the State are met.

Given the relatively limited past use of UV disinfection in drinking water treatment and the unique technical characteristics of this technology, State agencies may not have developed approval requirements specifically for UV disinfection. This section provides guidance on the information that may be included in submittals to the State. Utilities are urged to consult with their State early in their UV disinfection planning process to understand what approvals and documentation will be required for the use of UV disinfection.

3.4.1 Planning

The State may require that a pre-design report be submitted that summarizes the decision logic used to identify, evaluate, and select UV disinfection. Appendix K is an example pre-design report, including installation alternatives and analysis. The following items may be addressed in the pre-design report:

- Disinfection objectives (target organism and inactivation)
- Overall disinfection strategy
- Summary of reasons for incorporating UV disinfection
- Description of the overall process train
- Description of the proposed UV reactors
- Water quality data

- UV reactor reliability targets (i.e., off-specification limits)
- UV reactor validation

3.4.2 Equipment Procurement

If the utility pre-purchases the equipment, a separate procurement document would be prepared. The equipment procurement document should be consistent with the pre-design report and should include technical specifications and a preliminary layout of the UV installation. Details on the recommended content of the specifications are given in section 3.3.7. While the State may not require submittal of the equipment procurement document prior to equipment purchase, it is recommended that acceptance of a pre-design report be received from the State prior to proceeding with equipment purchase. The State should also be notified of any deviations from the pre-design report.

3.4.3 Drawings and Specifications

The UV installation drawings and specifications should be submitted to the State for approval. Under the equipment pre-purchase option, the drawings and specifications should address the installation of the UV reactors and related equipment as well as other necessary facility modifications. The specific items that would be included in this submittal are discussed in section 3.3.7. If an alternative approach is used (e.g., design-build or design-build-operate) the level of detail included in the design documents will differ.

3.4.4 Validation Report/Start-up Confirmation

States may request that a validation report or other preliminary testing results be submitted. As discussed in section 3.1.4.3, validation may occur off-site or on-site. If the UV reactors are validated at an off-site location, the validation report should be available from the UV manufacturer and should be a required submittal from the UV manufacturer as part of either the equipment procurement documents or the UV installation specifications. If on-site validation is used, a validation protocol should be developed and accepted by the State prior to implementation. Following completion of the on-site validation, a validation report should be prepared and submitted to the State. Recommended validation protocols are provided in Appendix C.

In addition, some States may request that the utility provide as-built documentation (i.e., start-up confirmation) certifying construction was completed in accordance with the approved drawings and specifications. Start-up confirmation may be most important where alternative project delivery approaches are used and the State does not have the benefit of reviewing 100 percent design drawings and specifications prior to construction.

4. Overview of Validation Testing

The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) requires the use of validated UV reactors for receiving *Cryptosporidium*, *Giardia*, or virus inactivation credit (40 CFR 141.729(d)). The purpose of validating a UV reactor is to provide confidence that the UV reactor can provide the level of inactivation required for a given application. The rule specifies only basic components of a validation process (presented in section 4.1). Using those requirements as a framework, this guidance manual describes recommended procedures and data analysis for one possible approach to validating a UV reactor. Other approaches or modifications to this approach may be used at the discretion of the State.

The validation protocol provided in this manual has two tiers, specifying two different methods for addressing uncertainty with a safety factor to determine the log inactivation credit. These tiers differ in level of complexity. Tier 1 is simplified while Tier 2 is more complex, potentially allowing for a less conservative safety factor based on detailed knowledge and testing of equipment performance. Appendix C provides all the necessary procedures and descriptions to complete a validation for both Tier 1 and Tier 2 methods. This chapter provides a brief overview of the validation process, describing all the basic steps of the testing procedures and interpretation of results, with references to Appendix C for more detailed descriptions. For those conducting a validation test of a given reactor, it is important to understand the background and detailed procedures described in Appendix C.

4.1 LT2ESWTR UV Disinfection Requirements

This section reviews the LT2ESWTR requirements related to UV reactor validation specified under 40 CFR 141.729(d) and 40 CFR141, Subpart W, Appendix D.

Validation testing must determine a set of operating conditions that can be monitored by a utility to ensure that the UV dose required for a given pathogen inactivation credit is delivered; and the utility must then monitor to demonstrate it is operating within the range of conditions under which the reactor was validated.

Validation operating conditions must include, at a minimum, the following:

- UV intensity (as measured by a UV intensity sensor)
- Flowrate
- Lamp status

Many design and equipment factors affect the UV dose delivered by the reactor. The validated operating conditions must account for the following factors:

- Lamp aging
- Lamp sleeve fouling

- UV transmittance (UVT) of the water
- Inlet and outlet piping or channel configurations of the UV reactor
- Dose distributions arising from the velocity profiles through the reactor
- Failure of UV lamps or other critical system components
- Measurement uncertainty of on-line sensors

Unless the State approves an alternative approach, validation testing must involve the following:

- Full-scale testing of a UV reactor that conforms uniformly to the reactors used by the utility.
- Inactivation of a test microorganism whose dose-response characteristics have been quantified with a low-pressure (LP) mercury vapor lamp.

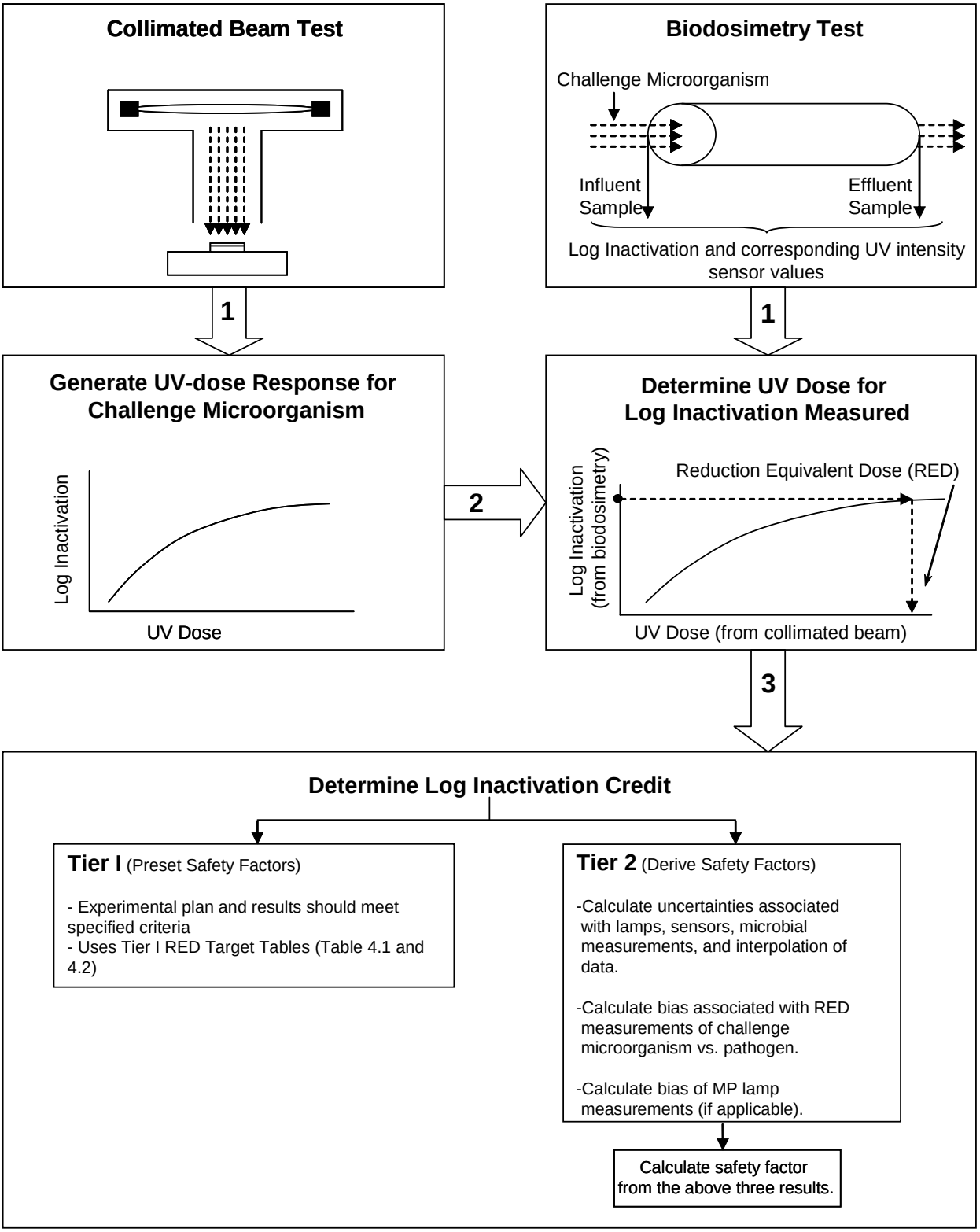
4.2 Overview of Validation Process

The validation process determines the log inactivation achieved for a specific pathogen and relates it to the operating conditions at the time of the testing (e.g., UV transmittance at 254 nm, or UVT, flowrate). Figure 4.1 shows the key steps of a validation process, with the differentiation of Tier 1 and Tier 2 approaches.

The experimental portion of the validation process is referred to as "biodosimetry." It consists of a UV reactor test that measures log inactivation of a surrogate (challenge) microorganism under various flowrate, UVT, and lamp power combinations. Log inactivation is then benchmarked to the corresponding operational conditions and UV intensity sensor values. Since the true UV doses delivered to the challenge microorganisms cannot be measured directly by the UV reactor, a separate test must be conducted to relate the inactivation measured in the field to a UV dose value. Current practice in the UV industry uses a collimated beam to generate a UV dose-response curve for a given challenge microorganism (log inactivation versus UV dose). The log inactivation from the biodosimetry test is then related to a UV dose from the UV dose-response curve. This dose is termed the reduction equivalent dose (RED).

Hydraulic effects, UV reactor equipment, and error in on-line UV intensity sensors all create uncertainty in translating an RED measured during a validation test to a given level of pathogen inactivation during routine operation. To account for this uncertainty, a safety factor should be applied to the required UV dose values for pathogen inactivation credit. The required UV dose value multiplied by the appropriate safety factor is the RED that should be demonstrated during a validation test for a given level of pathogen inactivation credit. Tier 1 and Tier 2 approaches provide methods for incorporating the safety factor to determine the log inactivation credit.

Figure 4.1 Steps of a Validation Process



4.2.1 Relating the Experimental RED to Log Inactivation Credit

Chapter 1 presents the UV dose needed to achieve various inactivation credits for *Cryptosporidium*, *Giardia*, and viruses. These dose requirements were derived from batch (collimated beam) dose-response data and account for the uncertainty and statistical variability in the dose-response of the pathogen.

There is significant, additional uncertainty associated with applying these batch data to full-scale, continuous flow testing results. This additional uncertainty associated with UV reactor validation and on-line dose monitoring should also be considered when determining the log inactivation credit from UV reactor validation. To account for this uncertainty, the RED measured during validation should be greater than the dose requirement multiplied by a safety factor. The safety factor incorporates random uncertainty and corrections for expected variation, and is defined according to Equation 4.1:

$$SF = B_{RED} \times B_{Poly} \times (1 + e) \qquad \text{Equation 4.1}$$

where

B_{RED} = RED bias

B_{Poly} = Polychromatic bias

e = Expanded uncertainty expressed as a fraction

The RED bias is a correction that accounts for the difference between the expected dose delivered to the target pathogen and the actual dose measured using a challenge microorganism during biodosimetry. That is, the RED measured for two microorganisms is not identical if the dose-response behavior of the two microorganisms is different. The magnitude of the difference will depend on the dose distribution of the UV reactor and the unique inactivation kinetics of the challenge microorganism and target pathogen. If the challenge microorganism is more resistant to UV light than the target pathogen, the RED measured during validation will be greater than the expected dose delivered to the pathogen. If the challenge microorganism is as sensitive or more sensitive to UV light than the target pathogen, the RED bias has a value of one. Appendix F describes this concept in more detail.

The polychromatic bias is a correction for the spectral differences in the lamp output, lamp sleeve UV transmittance, water UVT, and action spectrum between validation and operation of a UV reactor. This bias only applies to polychromatic lamps.

The expanded uncertainty, *e*, accounts for the uncertainty in the measurements taken during validation and associated with the equipment (e.g., UV intensity sensors) used to monitor dose delivery.

Appendix F discusses in greater detail the basis for the uncertainty and bias terms of the safety factor. Later sections of this chapter and Appendix C describe the application of the safety factor.

4.2.1.1 Tier 1 and Tier 2 Approaches for Establishing Inactivation Credit

As stated previously, the Tier 1 and Tier 2 approaches differ in the complexity of the method used to determine the log inactivation credit based on the RED measured during biodosimetry. The Tier 1 approach provides RED target values to be met during validation that correspond to the log inactivation credit (presented in Tables 4.1 and 4.2). These RED values incorporate pre-determined safety factors based on characteristics of the UV reactor and validation testing (section 4.6 provides further details). In the Tier 2 approach, the user calculates the safety factor using detailed knowledge of the equipment and testing conditions and then applies it to the required dose. This allows the user to optimize their experimental methods which may reduce the safety factor.

4.2.2 Location and Application of Validation Testing

Validation testing may be conducted either on-site, being the location where the UV reactor will be installed and operating, or off-site. Off-site validation may be conducted at either a manufacturer's facility or at a centralized facility dedicated to validating a variety of UV equipment.

Reactors may be validated for a specific WTP or may validate under a wide array of conditions for a variety of treatment applications. In addition to a range of operating conditions (e.g., flowrate, UVT), the reactors may also be validated for a wide range of target doses, thereby allowing reactor operation to be tailored to achieve different levels of pathogen inactivation credit at different WTPs. The test conditions and target doses can allow interpolation of the validation data to conditions of flowrate, UVT, and lamp output specific for application to various WTP applications. Section C.4.9.3 describes interpolation of validation results as a function of those variables.

Utilities installing a pre-validated UV reactor should ensure that validation conditions are appropriate for their plant operations and the quality of testing is acceptable to their State. At a minimum, the following hydraulic and operating test conditions impact the application of pre-validated UV reactors:

- UV reactor inlet and outlet configurations
- Flowrate
- UVT

Validating on-site at the WTP is not trivial and should be regarded as a relatively complex experimental procedure. Utilities conducting on-site validation should consider the following issues (section C.3.1 provides further details):

- Obtaining water with a sufficiently high UVT to allow validation over the entire UVT range expected at the WTP

- Adequate facilities to culture the challenge microorganism to the necessary levels to demonstrate the desired inactivation
- Adequate facilities and chemicals to adjust UVT to the range expected during full-scale operation
- Providing sufficient mixing of additives prior to entering the UV reactor and mixing of the challenge microorganisms after the reactor
- Obtaining permits for the disposal of water used for validation
- Verification of the behavior of UV intensity sensors used during validation (sections C.3.2 and C.4.7)
- Testing with inlet and outlet conditions representative of those conditions used at the WTP (issue for off-site validation)

UV reactors previously validated under existing protocols may receive inactivation credit if the validation used the appropriate challenge microorganism(s) and test conditions met the needs of the operating conditions at the WTP. Both the Austrian Standard ONORM M 5873-1 and German Guideline DVGW W294 require an RED of 40 mJ/cm^2, using a microorganism more representative of *Cryptosporidium* (*B. subtilis*) than that used to develop Tier 1 criteria (MS2 phage). Based on criteria in this document, UV reactors validated with those protocols should be granted 3 log *Cryptosporidium* and *Giardia* inactivation credit. Validation by NWRI/AwwaRF Guidelines and NSF Standard 55 should be evaluated on a case-by-case basis as indicated in Appendix C.

4.2.3 Third-Party Oversight

Third-party oversight is recommended to ensure that validation testing and data analyses are conducted in a technically-sound manner and without bias. The validation testing should be overseen by a registered professional engineer, independent of the UV manufacturer, with experience in testing and evaluating UV reactors. Furthermore, expert opinion should be sought from additional parties in areas of UV validation where the engineer has limited experience. These areas can include, but are not limited to, lamp physics, optics, hydraulics, microbiology, and electronics.

4.3 Considerations for Validation Testing

This section highlights the key factors that should be considered in the early planning stages of UV reactor validation.

4.3.1 Inlet and Outlet Hydraulics

The inlet and outlet configurations of the validation location should produce conditions that result in equal or worse dose delivery than those that will be obtained at the WTP. Sections 3.1.4.3 and C.3.1.5 provide recommended approaches to ensure such hydraulic conditions.

Computation fluid dynamics (CFD)-based dose modeling can also be used in conjunction with any approach to conservatively address reactor hydraulics during testing. However, due to uncertainty in the CFD predictions, the predicted dose delivery during validation should be at least 20 percent greater than the dose delivery predictions at the WTP.

4.3.2 UV Equipment

This section discusses the following UV equipment related issues: documentation, monitoring control strategies, UV intensity sensors, and lamp aging effects.

4.3.2.1 UV Reactor Documentation

In the weeks prior to testing, the UV manufacturer should provide documentation identifying and describing the UV reactor to the testing organization (or to third-party oversight if the manufacturer is conducting the testing with their facilities). This documentation should include all reactor and component information relating to dose delivery and monitoring, such as technical descriptions of all internal components, lamp and sleeve specifications, UV intensity sensor and sensor port information. See section C.2.2 for a complete list and discussion of the documentation requirements.

4.3.2.2 Control Strategies

The UV reactor's control strategy for monitoring dose delivery affects the selection of test conditions (i.e., flowrate, UV intensity, and UVT). At present, three strategies are commonly used for monitoring UV dose delivery. Sections C.4.9.4.1 to C.4.9.4.3 describe these strategies in detail and recommend validation conditions for each. (Sections 3.1.5 and 5.5 also describe these strategies with relation to design and operation, respectively).

- <u>UV intensity setpoint</u> – relies on UV intensity measurements (i.e., UV intensity sensors) and flowrate to confirm dose delivery. The system is in compliance when the measured intensity value is greater than the setpoint at that flowrate.

- <u>UV intensity/UVT setpoint</u> – relies on the UVT as well as the UV intensity and flowrate to determine dose delivery. The system is in compliance when both the UV intensity and UVT are greater than the preset setpoint values.

- <u>Calculated dose</u> – relies on calculated dose delivery from UV intensity, UVT (in some cases), lamp power and flowrate using an algorithm provided by the UV reactor manufacturer. Typically, this method is tested over a range of

combinations of flow, UVT, and lamp power to determine the UV dose and validate the algorithm.

4.3.2.3 UV Intensity Sensor

Monitoring of the UV dose is achieved through the use of on-line UV intensity sensors. The properties of both on-line and reference sensors should be measured by an independent laboratory that is equipped to confirm sensor calibration and measure the sensor's angular and spectral response, linearity over the working range, and temperature response. The Tier 1 approach specifies criteria for sensor placement in the UV reactor, sensor spectral response, and measurement uncertainty.

4.3.2.4 Lamp Aging

Prior to the initiation of validation testing, all lamps should undergo 100 hours of burn-in. This practice improves the stability of lamp output. Additional testing may also be performed, if requested, in order to assess the effects of lamp age on dose delivery. With time, medium-pressure (MP) UV lamps can undergo non-uniform aging that causes spectral shifts in output. These changes can have an impact on the dose delivery registered by the monitoring systems. Manufacturers should test dose delivery of new and aged lamps to determine if the aged lamps reduce disinfection performance. If so, validation should be conducted using both new and aged lamps. (Section C.4.8 describes a procedure for testing new versus aged lamps.)

4.3.3 Additives Used in Validation Testing

4.3.3.1 Challenge Microorganism

UV reactor validations should be performed with a microorganism with the following characteristics: inactivation kinetics closely resembling those of the target pathogen and the ability to be cultured in a reproducible manner to high concentrations. Currently, research has not identified such a microorganism that is ideal for *Cryptosporidium*. Challenge microorganisms typically used include MS2 phage and *Bacillus subtilis*, both of which are significantly more resistant to UV than *Cryptosporidium*.

The RED bias, an important component of the safety factor, is due to the differences in inactivation kinetics between the challenge microorganism and the target pathogen. Under the Tier 1, the RED bias is based on MS2 phage as the challenge organism. If a challenge microorganism is identified in the future that exhibits a dose-response similar to the target pathogen (e.g., *Cryptosporidium)*, the RED bias could be decreased.

4.3.3.2 UV-Absorbing Compound

During validation, the UVT can be lowered through the addition of a UV-absorbing compound to simulate the range of UVT that may be encountered for a given UV application. For the validation of MP UV systems, the absorbing compound should have a UV absorbance spectrum similar to the water being treated in the full-scale application. However, obtaining an exact replica is usually not possible. Coffee and lignin sulfonate are commonly used UV absorbing compounds; however, sodium thiosulfate and fluorescein have also been used with some success.

The polychromatic bias, a component of the safety factor for only MP reactors, is determined as a function of the UV-absorbing compound. The Tier 1 approach specifies criteria for minimum UVT for MP reactors using UV-absorbing compounds and applies a correction factor based on validation testing performed to-date with various UV absorbing compounds.

4.4 Validation Testing

Validation provides an assessment of UV reactor dose delivery and monitoring under specific conditions of **flowrate**, **UVT**, and **lamp output**. This section briefly discusses the steps involved in conducting a validation test and provides references to more detailed procedures in Appendices C and D.

4.4.1 Microorganism Preparation

Challenge microorganisms should be prepared in accordance with peer-reviewed methods. All information regarding the source of the host, media descriptions, and preparation steps should be documented. It is expected that the microorganism stock will be prepared by laboratory personnel familiar with methodologies designed to prevent microbial stock contamination. The use of these same techniques in the field during validation is critical and any personnel participating in the validation should be familiar with them to avoid sample contamination.

Preparation methods for the two most common challenge microorganisms, MS2 phage and *B. subtilis* spores, are provided in Appendix D. Note, the same batch of challenge organisms should be used for both collimated beam and biodosimetry testing, as described below.

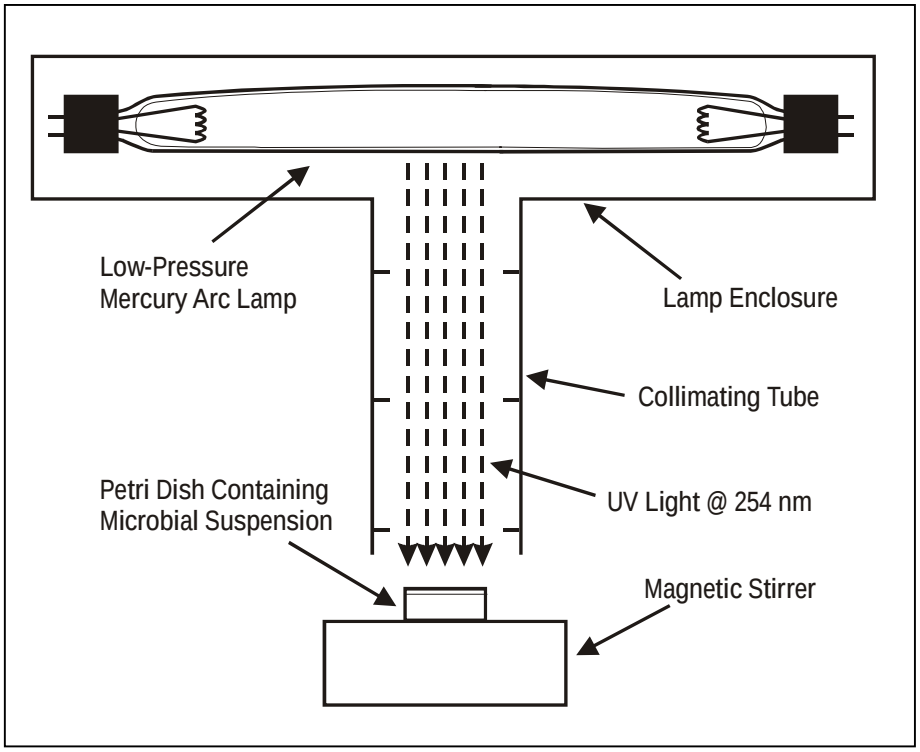
4.4.2 Collimated Beam Testing

The collimated beam data are used to develop the dose-response curve for the challenge microorganism. A collimated beam apparatus typically consists of an enclosed low-pressure UV lamp and a tube with a non-reflective inner surface (see Figure 4.2). A sample of the challenge microorganism (preferably taken from the influent to the biodosimetry test stand) is placed in a petri dish and exposed to the UV light for a predetermined amount of time. The UV dose is

calculated using the intensity of the incident UV light, UV absorbance of the water, and exposure time. Appendix E provides a complete description of collimated beam testing.

At least two water quality conditions should be tested–one with the highest UVT (no absorbing chemical added) and a second with the lowest UVT used in the biodosimetry test. UV doses should be selected to target microorganism inactivations of approximately 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 log.

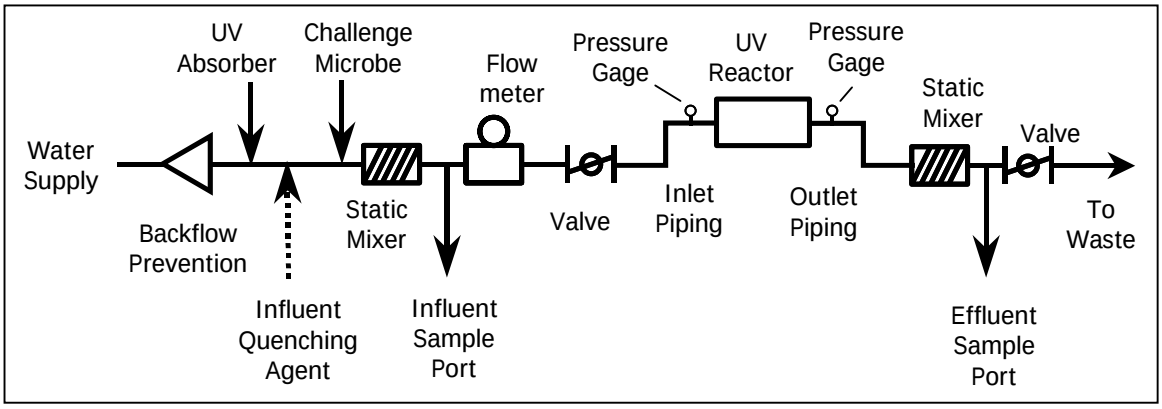
Figure 4.2 Collimated Beam Test Apparatus



4.4.3 Biodosimetry of Full-Scale Reactors

The biodosimetry test is used to determine the inactivation of the challenge microorganism by the UV reactor under continuous-flow test conditions. Figure 4.3 provides a schematic of the components used in a typical biodosimetry test. Section C.3.1 describes the key features.

Figure 4.3 Biodosimetry Test Components



The following facilities are typically required in biodosimetry testing:

- Injection of the challenge microorganism and UV absorbing compound
- Mixing of the added compounds upstream and downstream of the reactor before sampling
- Flow measurement
- Pressure measurement upstream and downstream of the reactor
- Sample collection before and after the UV reactor

Proper facilities should be provided, along with appropriate permits, to discharge the treated water. The testing should be conducted after steady-state conditions are achieved for the desired matrix of experimental conditions evaluating variations in challenge organism concentration, flowrate UVT, and lamp power/output. Samples collected from the influent and effluent sample ports are used to determine the inactivation achieved for the specific reactor condition being tested. Operational parameters, such as UV intensity, flowrate, UVT, and lamp power, are measured during the test.

A detailed description of sampling requirements is provided in Appendix C.

4.5 Data Analysis

Results from the collimated beam testing, biodosimetry testing, and uncertainties associated with equipment and data are used to determine the log inactivation credit achieved by the UV reactor. Data analysis consists of four steps:

1. Developing a UV dose-response curve for the challenge microorganism from the collimated beam test

2. Calculating log inactivation from the biodosimetry test

3. Determining the RED(s) from the results of steps 1 and 2

4. Applying safety factors to determine log inactivation credit (Tier 1 or Tier 2 approach)

The following sections describe these steps. References to the appropriate sections in Appendix C are provided for further details and examples.

4.5.1 Developing Challenge Microorganism Dose-Response Curve

Dose-response curves should initially be generated separately for each collimated beam test condition (a minimum of two conditions—lowest and highest UVT—is recommended). The curves should predict similar dose-response relationships, as indicated by statistical analyses. If statistically similar, the data can be combined and one curve generated for the entire dataset. If the curves are statistically different, the cause of the difference should be determined, and the test should either be redone or the different dose-response curves should be used for the different test conditions. Differences in UV dose-response could occur if the dose-response were determined with different batches of the challenge microorganism or if coagulation or other water quality interferences impacted the dose-response.

The following sub-sections describe how to calculate the log inactivation from collimated beam test data and generate a dose-response curve. Section C.4.9.7.2 discusses the statistical analysis for comparing curves and combining data.

4.5.1.1 Calculate Dose-Response Data From Collimated Beam Testing

The log inactivation for each dose delivered by the collimated beam should be calculated using Equation 4.2:

$$Log\ \ Inactivation = \log\left(\frac{N_0}{N}\right) \qquad \text{Equation 4.2}$$

where

N = Challenge microorganism concentration in an aliquot of sample

N_0 = Average concentration of the challenge microorganism in the zero dose aliquots

4.5.1.2 Fitting Dose-Response Data to a Curve

The following steps describe how to develop a dose-response curve:

1) Plot log inactivation achieved as a function of UV dose in the collimated beam test

2) Use regression analysis to derive an equation that best fits the data

   - For first-order kinetics, a linear equation should fit best:

     $$Dose = A \times Log\ Inactivation + B$$

   - For dose-responses showing tailing effects, a quadratic equation should fit best:

     $$Dose = C \times Log\ Inactivation + D \times (Log\ Inactivation)^2$$

   - For dose-response showing shoulder effects, other polynomial equations should be used.

3) Evaluate fit of equation

   - Equation coefficients should be significant at a 95 percent confidence level (section C.4.9.7.1 provides an example that uses p-statistics to evaluate the coefficients).

   - Confidence intervals for the fit should be determined at an 80 percent confidence level. (The Tier 1 approach specifies criteria the confidence intervals must meet and the Tier 2 approach includes an uncertainty term for the confidence intervals in the safety factor calculation.)

   - The differences between the predicted dose and measured dose at a given log inactivation should be randomly distributed around zero and not dependent on dose. In other words, the data points should be randomly distributed above and below the curve (section C.4.9.7.1 provides an example of this evaluation).

4.5.2 Determining Log Inactivation from Biodosimetry Testing

At each test condition—flowrate, UVT, and lamp output—the arithmetic mean and standard deviation of the log influent and effluent challenge microorganism concentrations should be calculated. From the mean concentrations, log inactivation should calculated using the following equation:

$$Log\ Inactivation = \log(N_I) - \log(N_E) \qquad \text{Equation 4.3}$$

where
$\log(N_I)$ = Mean challenge microorganism log concentration of the reactor influent samples
$\log(N_E)$ = Mean challenge microorganism log concentration of the reactor effluent samples

The standard deviation is used in the safety factor calculation for Tier 2, while Tier 1 specifies a limit for the standard deviation.

4.5.3 Determining the RED

This section describes how to calculate RED values for all test conditions and select the appropriate RED for subsequent log inactivation credit determination.

4.5.3.1 Calculating the RED Values

The RED is calculated by inputting the biodosimetry log inactivation values for each test condition into the equation describing the UV dose-response curve of the challenge microorganism.

Example. For 0.5 MGD flow, 80 percent UVT, and lamp output of 70 percent, the inactivation calculated from Equation 4.3 was 4.0 log. The UV dose-response equation was best fit with the equation:

$$Dose = 15.5 \times Log\ Inactivation - 6.0$$

Inputting 4.0 log into the above equation results in an RED of 56 mJ/cm^2. This calculation should be repeated for each test condition (i.e., flowrate, UVT, and lamp output combination).

4.5.3.2 Selecting the Appropriate RED for Log Inactivation Credit Determination

Since the biodosimetry test is conducted at various flowrates, UVT, and lamp output combinations, the validation results will have more than one RED value for each setpoint. Choosing the appropriate RED to determine log inactivation credit depends first on the monitoring approach used to indicate dose delivery. The following three approaches are considered in this text:

- UV intensity setpoint approach - the UV reactor should be rated at the lowest inactivation observed for each set point condition tested.

- UV intensity and UVT setpoint approach - the UV reactor should be rated at the inactivation observed with UV reactor operation under setpoint conditions.

- Calculated dose approach - the UV reactor should be rated at the lowest inactivation observed for each calculated dose setpoint evaluated.

Section C.4.9.4 recommends validation conditions for each of the above approaches. Section C.5 provides examples of interpreting validation results for the different approaches.

4.5.3.3 Interpolating RED as a Function of Test Conditions

The RED measured during validation testing can be interpolated as a function of inverse flowrate, UVT, or UV intensity by fitting an equation to the data being interpolated (e.g., RED as a function of inverse flowrate). The equation should not be used for extrapolation (i.e., projecting RED outside the range of tested conditions). The following provides guidelines for interpolation:

- The equation should pass through the origin (0,0) if the RED is interpolated as a function of measured intensity or inverse flowrate

- The equation coefficients should be significant at a 95 percent confidence level

- The differences between the values measured and predicted by the equation should be randomly distributed around zero

- An 80 percent confidence interval should be used to determine the uncertainty of the equation used to interpolate the RED values. For Tier 1, the uncertainty of the interpolation should be 10 percent or less at an 80 percent confidence level. For Tier 2 it should be included as an uncertainty term in the safety factor calculation as described in section C.4.10.2.3.

4.5.4 Determining Inactivation Credit

As discussed in the introduction to this chapter, there are two approaches described for determining log inactivation.

- Tier 1 - pre-determined safety factor.

- Tier 2 - calculated safety factor from the following dose delivery monitoring and validation bias and uncertainties:

  - RED bias
  - Polychromatic bias (for MP reactors)
  - Measured RED
  - Interpolation of RED as a function of flowrate, UVT, or UV intensity
  - Sensors used during validation (UV intensity, UVT)
  - On-line and reference sensors used at WTP (UV intensity, UVT)
  - Lamp output quantification

The remainder of this chapter describes how to determine the log inactivation credit achieved using the Tier 1 approach and the criteria that should be met in order to use this approach. Appendix C contains a detailed description of the basis the Tier 2 approach.

Tier 1 Log Inactivation Credit

Tables 4.1 and 4.2 present the RED target values for UV reactors using LP/LPHO and MP lamps, respectively. The values in these tables are derived by multiplying the required dose values by the Tier 1 safety factors (see Appendix C for details). The values in Table 4.2 (MP) are higher than in Table 4.1 (LP/LPHO) because they include the polychromatic bias, which is not a factor in monochromatic (LP/LPHO) reactors.

For a given pathogen and level of log inactivation credit, the RED measured during validation should be greater than or equal to the corresponding RED target listed in the table. Note, validation testing with multiple setpoints may result in different log inactivation credits for the different setpoints.

Example. Using an LP reactor and meeting the Tier 1 validation criteria (see section 4.6), the lowest RED measured for the challenge microorganism during validation was 29 mJ/cm^2. Consequently, the log inactivation credits achieved are 2.5 for *Cryptosporidium* and 2.5 for *Giarida*. No inactivation credit is achieved for viruses.

Table 4.1 Tier 1 RED Targets for UV Reactors with LP or LPHO Lamps

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

Table 4.2 Tier 1 RED Targets for UV Reactors with MP Lamps

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

4.6 Tier 1 Criteria

The safety factors derived for the Tier 1 approach are based on assumed uncertainties and corrections for given experimental methods. For these assumptions to be practical, and thus the use of Tier 1 numbers appropriate, the validation conditions should meet the criteria specified in this section. Note, the equipment criteria should be provided by the UV manufacturer and reviewed by a third-party for verification.

4.6.1 UV Intensity Sensors

- UV reactors with MP lamps should be equipped with one sensor per lamp. UV reactors with LP or LPHO lamps should be equipped with at least one sensor per bank of lamps.

- UV intensity sensors should view a point along the length of the lamp that is between the electrode (lamp end) and within 25 percent of the arc length away from the electrode.

- UV intensity sensors should have a spectral response that peaks between 250 and 280 nm. When mounted on the UV reactor and viewing the lamps through water, the measurement of UV light greater than 300 nm made by the sensor should be less than 10 percent of the total measurement made by the sensor. Conformance to these criteria can be demonstrated using UV intensity field modeling. Figure 4.4 presents examples of two sensors where both have the appropriate peaks, but one has too much UV light in the >300 nm range.

- The UV intensity sensors used during validation and the duty and reference sensors used during operation of the UV reactor at the WTP should provide National Institute of Standards and Technology (NIST)-traceable measurements with an uncertainty of ± 15 percent or less at an 80 percent confidence level.

- During operation of the UV reactor at the WTP, measurements made by the duty UV intensity sensor should be checked using a reference UV intensity sensor. If the duty sensor reads higher than the reference sensor (i.e., overestimating dose delivery), or substantially lower, it should be recalibrated. For a recommended control standard, the duty sensor should not read less than the reference by the following amount:

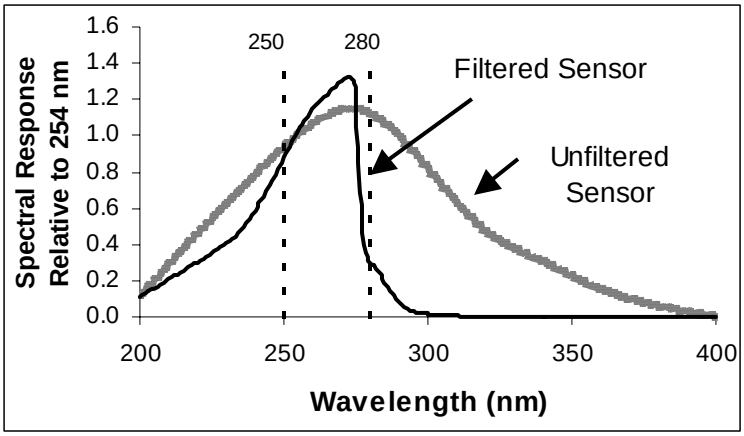
$$\left(\frac{I_{Duty}}{I_{Ref}} - 1\right) \times 100 \leq \left(\sigma_{Ref}^2 + \sigma_{Duty}^2\right)^{1/2} \qquad \text{Equation 4.4}$$

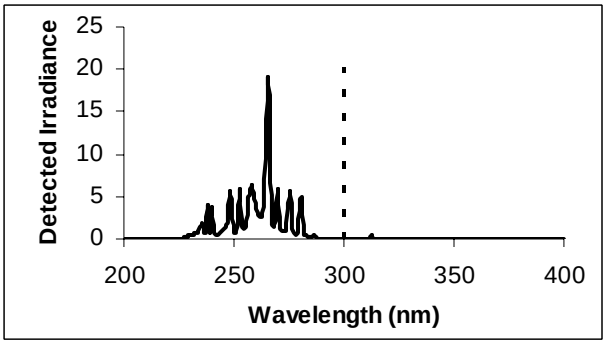
where

I_{Ref}	=	Intensity measured by the reference sensor
I_{Duty}	=	Intensity measured by the duty sensor
σ_{Ref}	=	Measurement uncertainty of the reference sensor (%)
σ_{Duty}	=	Measurement uncertainty of the duty sensor (%)

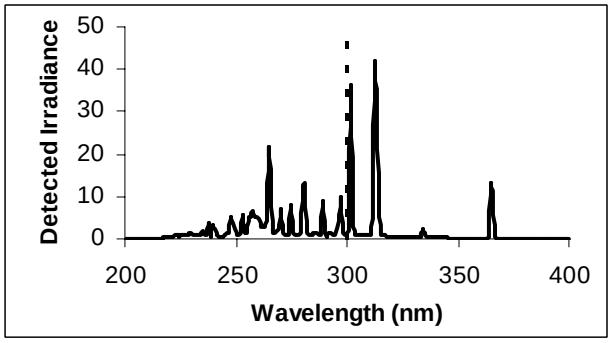
- If the dose-monitoring strategy uses an on-line UVT monitor, the UV absorbance at 254 nm (A_{254}) calculated from the measured UVT should have an uncertainty of ±10 percent or less at an 80 percent confidence level.

Figure 4.4 Examples of UV Intensity Sensor Spectral Response Ranges

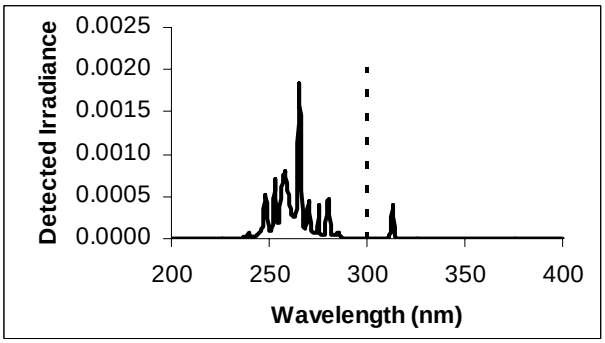




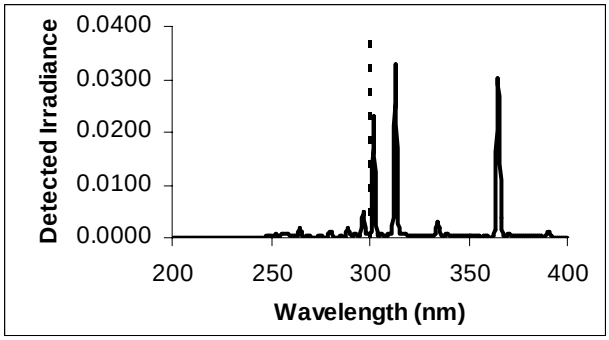
Filtered Sensor. Detected UV light with a 0 cm sensor-to-lamp water layer. Detected UV > 300 nm is 0.7% of total UV light detected.



Unfiltered Sensor. Detected UV light with a 0 cm sensor-to-lamp water layer. Detected UV > 300 nm is 41% of total UV light detected.



Filtered Sensor. Detected UV light with a 20 cm sensor-to-lamp water layer. Detected UV > 300 nm is 5% of total UV light detected.



Unfiltered Sensor. Detected UV light with a 20 cm sensor-to-lamp water layer. Detected UV > 300 nm is 85% of total UV light detected.

4.6.2 UV Lamp Output

- The standard deviation of the UV output of LP or LPHO lamps should be 15 percent or less of the mean output. The standard deviation should be determined using either life test or field test data on aged lamps.

4.6.3 Flow Measurements

- The flow measurements made during validation and during operation of the UV reactor at the WTP should have an uncertainty of ± 5 percent or less at an 80 percent confidence level.

4.6.4 Collimated Beam Apparatus

- The calculated dose delivered by the collimated beam apparatus should have a measurement uncertainty of ± 15 percent or less at an 80 percent confidence level.

4.6.5 Challenge Microorganism Dose-Response

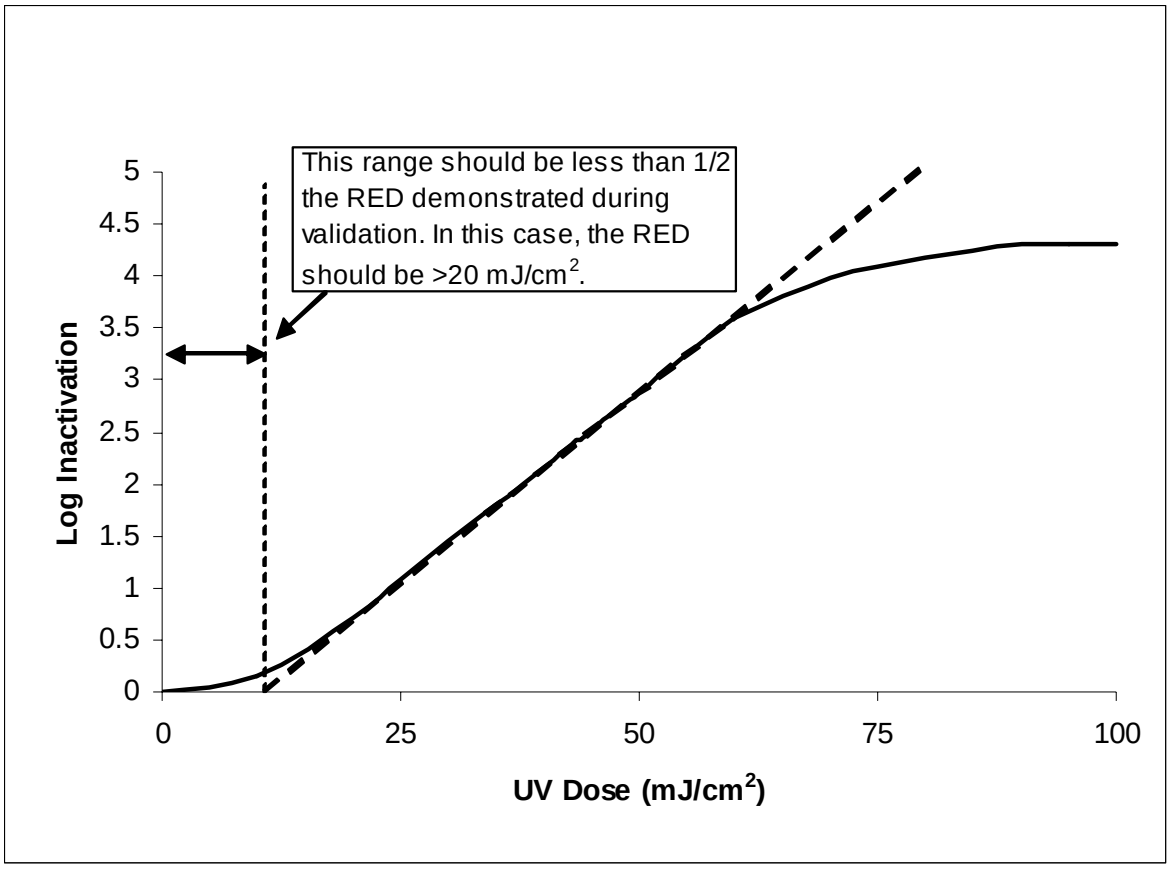
- Over the range of doses within one log unit of the log inactivation demonstrated during validation, the UV sensitivity of the challenge microorganism should be less than or equal to 25 mJ/cm^2 per log inactivation (the dose-response of a resistant strain of MS2). For example, if the challenge microorganism log inactivation measured by the UV reactor ranges between 1.5 and 3.5 log, the dose-response of the challenge microorganism should be less than or equal to 25 mJ/cm^2 per log inactivation between 0.5 and 4.5 log inactivation.

- If the dose-response of the challenge microorganism has a shoulder, that shoulder should not occur over a dose range greater than 50 percent of the RED demonstrated during validation. The shoulder is defined by extrapolating the exponential reduction region of the dose-response curve to the dose-axis (see Figure 4.5).

- If the dose-response demonstrates tailing, the tailing should not occur until one log reduction greater than the log reduction demonstrated during validation.

- A plot of dose versus log inactivation for the collimated beam test should have an 80 percent confidence interval of 10 percent or less at the log inactivation demonstrated by the UV reactor.

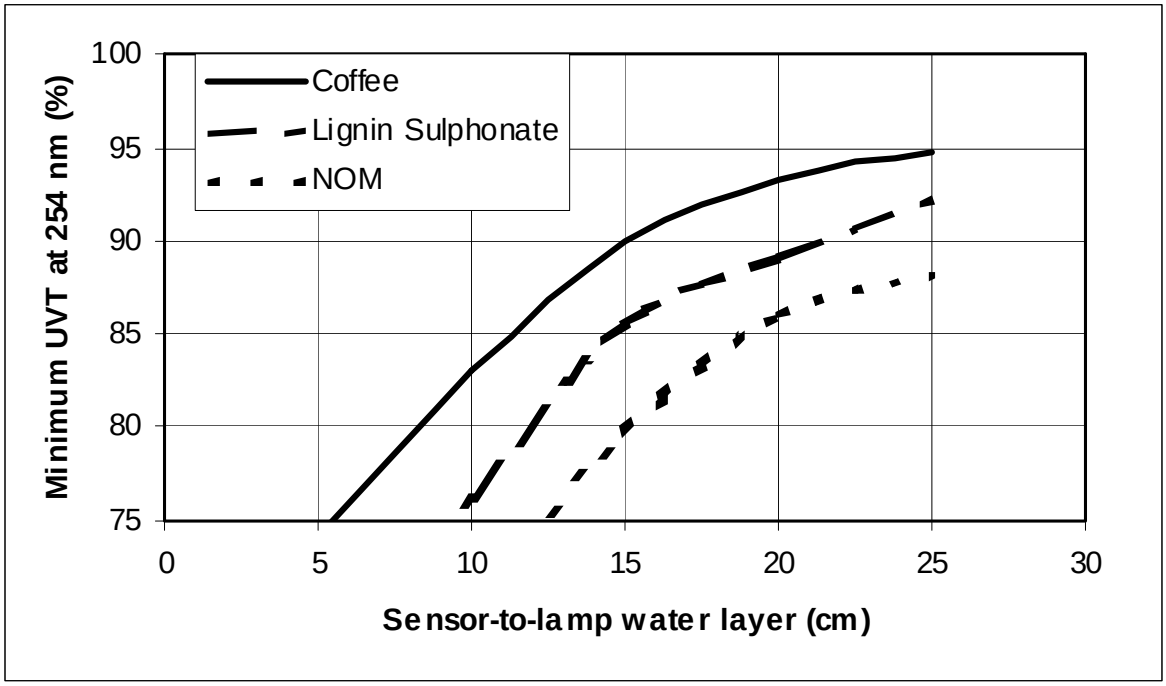
Figure 4.5 Dose-Response With a Shoulder



4.6.6 Medium Pressure Lamps

- During validation, the UVT of the water at 254 nm should be greater than the values specified in Figure 4.6 for a given sensor-to-lamp water layer and UV-absorbing chemical. The sensor-to-lamp water layer is defined as the distance traveled through water by UV light passing from the lamp to the sensor. The values in Figure 4.6 were taken from Figure C.7 of Appendix C for a polychromatic bias of 1.2.

Figure 4.6 Criteria for the Minimum UVT of MP Reactors under Tier 1



4.6.7 Biodosimetry Sampling

- Five influent and five effluent samples should be collected for each test condition and evaluated as described in section C.4.9.5.
- The standard deviation of the challenge microorganism concentration measured with the influent and effluent samples should be less than or equal to 0.20 log units.

5. Start-Up and Operation of UV Installations

This chapter describes the start-up activities and routine operational issues associated with a UV disinfection facility. The start-up discussion focuses on the functional and performance testing that should be conducted during the start-up process. The remainder of the chapter describes the requirements and recommendations for operation, maintenance, monitoring, and reporting for UV installations. The organization of this chapter is presented below by the key question each section addresses.

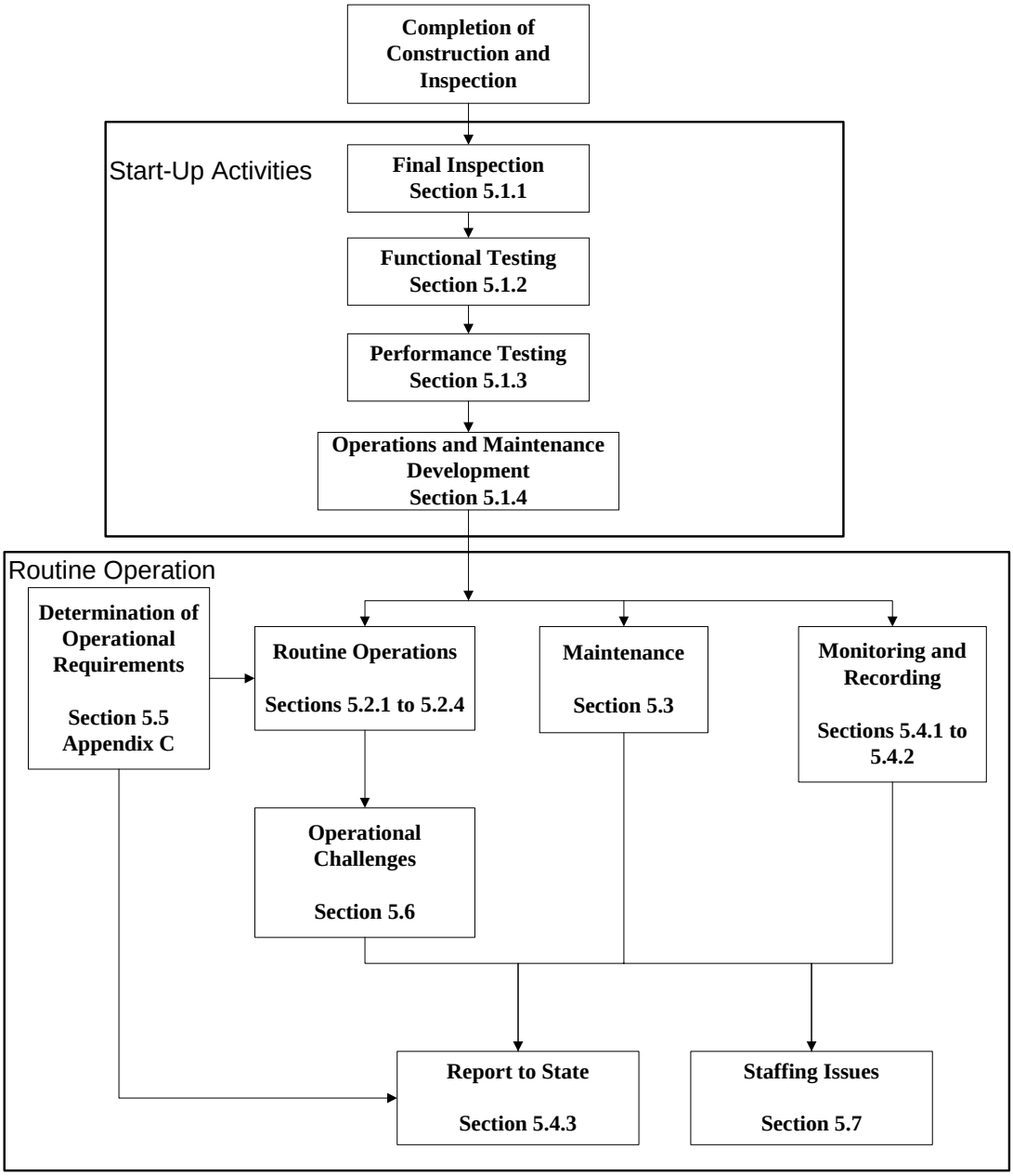
- What is included in final UV installation inspection? .....Section 5.1.1
- What testing should be completed during start-up?..... Sections 5.1.2 and 5.1.3
- What items should be included in the operations and maintenance manual?.....Section 5.1.4
- What are the operational requirements and recommended tasks? ..... Sections 5.2.1 and 5.2.2
- What are the routine start-up and shutdown procedures? .....Section 5.2.3
- What maintenance tasks are recommended? .....Section 5.3.1
- What spare parts are recommended to be kept on hand?.....Section 5.3.3
- What monitoring is required for regulatory compliance?.....Section 5.4.1
- What additional monitoring is recommended? .....Section 5.4.2
- What should be reported to the State? .....Section 5.4.3
- How do you determine the operational requirements from validation testing? ..... Section 5.5
- What should be done if there is: ..... Section 5.6
  - Low UV intensity?
  - High UV absorbance?
  - Rapid flow increase/high flow?
  - Unreliable UV intensity sensor readings?
  - Power loss?
- What staffing issues are associated with operation, maintenance, and monitoring of UV installations? ..... Section 5.7

Given the wide range of UV installations and UV reactors available, this document cannot address or anticipate all scenarios. The guidelines provided in this manual are a compilation of industry experience and manufacturers' recommendations. Therefore, they may

differ from those provided by specific manufacturers for their equipment. In these situations, the manufacturer's standards should be followed.

The general process to be followed for the start-up and routine operation of a UV installation is shown in Figure 5.1. A detailed description of each activity is given in the remainder of this chapter.

Figure 5.1 Start-up and Operation Flowchart



5.1 Start-up of UV Installation

For the purposes of this manual, the start-up of the UV installation is considered as the transition from the construction phase to the operation phase. Start-up activities include final inspection of the UV reactors and ancillary equipment, functional testing, performance testing, operations and maintenance (O&M) manual development. Functional testing confirms the mechanical, instrumentation and controls, and hydraulic conditions of the UV installation to ensure they meet the requirements of the contract documents. It also verifies that the operational conditions are consistent with the validated conditions. Performance testing verifies that the UV reactors are operating in accordance with the contract documents. In addition, an O&M manual should be developed during UV installation start-up.

A start-up plan should be developed in collaboration with the UV installation designer, plant operations staff, and the UV manufacturer. The designer will be most familiar with the layout of the reactors, piping, and how to integrate the UV installation with the other treatment processes. The operations staff will be able to identify potential impacts on routine plant operations. The manufacturer will be most familiar with operation of the UV reactors. The start-up plan should include a pre-start checklist, a procedure for checking equipment installation and calibration (functional testing), a procedure for verifying system operation, and a procedure for checking alarm settings and system controls (performance testing).

5.1.1 Final Inspection

As the first step in the start-up process, a detailed inspection of the UV installation should be completed. The inspection should include a visual assessment to ensure that all components meet the technical specifications and that the UV installation was completed in accordance with the construction documents. The configuration of the piping and UV reactors should meet the constraints established during validation testing (see section 4.3.1). If on-site validation will be performed, the availability of the necessary features (e.g., feed and sample ports, mixing systems, drains) should be confirmed. In addition, leak testing should be performed, and then all UV installation components and associated valves and piping should be thoroughly cleaned and disinfected (State requirements may apply).

5.1.2 Functional Testing

Functional testing consists of a series of short duration tests that assess the ability of each component of the system to function in accordance with the specifications detailed in the contract documents. Some of the evaluations are conducted by monitoring performance during normal operations. However, the majority of functional testing is completed through simulations of specific operating conditions and monitoring the UV reactor operation and response. Functional testing entails flooding and energizing the UV reactors to confirm the operation of the following items:

- UV lamps and UV intensity sensors
- Operating sequence and control logic for the reactor

- Ancillary equipment, including UV transmittance (UVT) monitors, flowmeters, and control valves

- Electrical system components, including ballasts, uninterruptible or standby power supplies, and the ballast cooling system

It is strongly recommended that the UV manufacturer inspect the UV installation prior to energizing the UV reactors and be present when the UV reactors are first energized. Manufacturers may require the presence of one of their representatives during these activities as a condition of their equipment warranty.

5.1.2.1 Verification of Mechanical Operation

UV reactors may incorporate mechanical elements such as valves and on-line mechanical cleaning (OMC). During functional testing, the satisfactory operation of these mechanical components should be confirmed. The procedures used to confirm valve operation for a UV installation are not different from those for other applications that use valves for isolation or flow control and, therefore, are not described here. The OMC system, if provided, should be checked for proper operation. Specifically, the following items should be verified:

- Smooth movement of the wiper with no jamming or binding of the wiper on the sleeve

- Extension of wiper stroke to the full length of the sleeve with no impact at the end of travel that could damage or break the sleeve

- Proper operation of the wiper drive mechanism and motor with no slipping or binding

5.1.2.2 Verification of Monitoring Equipment

The monitoring equipment is important for UV reactor operation, and its proper operation should be verified during functional testing.

Flowmeter

Accurate measurement of the flow is essential to ensure that the UV reactors are operating within the validated conditions. Not all utilities will install dedicated flowmeters. For those facilities that rely on flow measurement using an existing, common flowmeter (e.g., raw water flowmeter), the functionality of the flowmeter should be verified in conjunction with its intended use with the UV installation. Specifically, the accuracy and operating range of the flowmeter should be verified and the availability of the necessary output signals from the meter should be confirmed. If pressure gauges are used to monitor the flow split between UV reactors, the calibration and installation of the pressure gauges should be verified as well.

The uncertainty associated with the existing flowmeter should be determined to ensure that the appropriate validation constraints were used. It is recommended that the original

certification of calibration be reviewed in conjunction with the equipment specifications to establish the measurement uncertainty for the existing flowmeter. There are three methods to verify the flowmeter operation: flow verificators, a time-discharge test, and a clamp-on flowmeter. The flow verificators assess the physical condition of the installed equipment relative to its condition at the time of factory calibration to confirm that the original uncertainty can be maintained. For example, verification of a magnetic flowmeter would consist of an insulation test of the entire flowmeter system and cable; testing of the sensor magnetic properties; testing of signal converter gain, linearity and zero point; testing of digital output; and testing of analog output. A time-discharge test compares the flowrate measured by the flowmeter against the value calculated by measuring the volume of water discharged over a predetermined amount of time (using a bucket, clearwell, or tank of known volume). A temporary or clamp-on flowmeter can be used to assess the accuracy of the existing flowmeter. It is important to consider the uncertainty of the reference flowmeter when using this approach.

If a new flowmeter is used to measure the flow through the reactor, the flowmeter manufacturer should provide a certification of calibration at the time of equipment delivery. It is also recommended that the manufacturer inspect the UV installation and confirm that it was completed in accordance with their recommendations to ensure the certified accuracy of the flowmeter is achieved. The flowmeter measurement uncertainty should be equal to or better than that used during validation.

On-line UVT Monitor

An on-line UVT monitor may be included as part of the UV reactor, especially if a UV intensity and UVT setpoint or calculated dose control strategy (section 3.1.4.2) is used. The on-line UVT monitor should be calibrated and its operation verified. Calibration can be completed using a buffer solution of known UVT and may be operation may be verified by collecting and analyzing grab samples, using a bench top spectrophotometer.

5.1.2.3 Verification of Instrumentation and Control Systems

The amount of testing needed for the instrumentation and control systems is proportional to the complexity of the control strategy that is used. Testing should include verification of monitoring equipment (including calibration of all instruments), tuning of control loops, checking operation functions, and verifying all final control actions. As described below, the UV reactors should be run through a series of simulations that represent the possible operating scenarios in order to confirm that the appropriate UV reactor response occurs. Typically, the packaged UV reactor control panel contains all of the components to control and operate the UV reactor. The panel should provide the operating status, diagnostic information, and operator interface capability. It should also include lamp status indicators and programmable logic controllers (PLC) and may include ballasts, and lamp starters. The PLCs are typically used to control the operation of a UV reactor based on certain input signals. A manufacturer representative should be present during the simulations to assist in troubleshooting and addressing any issues that may result from the packaged UV reactor controls.

Simulations should be used to confirm the operation of the UV reactors and the operation of all ancillary equipment and instrumentation, including valves, flowmeters, and UVT monitors.

As applicable, specific operating conditions that should be simulated include the following conditions:

- Cold start of the UV reactors
- Cool down and restart of the UV reactors
- Sequencing of the UV reactors in multiple reactor installations
- Adjustment of lamp intensity in response to varying water quality or flowrate
- Shutdown of the UV reactors
- Operation of the UV reactors during line power failure (when backup or uninterruptible power supplies (UPS) are available)
- Manual override, safety interlocks, and report generation

During these simulations, the utility should record the amount of off-specification time and discharge volume (i.e., operation outside of validated conditions) associated with each action. This is necessary to assess the potential effect of the conditions associated with these actions on the utility's ability to meet its disinfection goals and comply with the State-established limitations for off-specification operation. In addition to simulating possible operating conditions, each of the alarm conditions and monitoring functions incorporated in the design should be verified. Possible monitoring functions and alarm conditions are discussed in section 3.3.3.8 and may include the following conditions:

- Low UV dose and UV intensity
- Low UVT
- Low and high flowrate
- Lamp age
- Lamp or ballast failure
- Low liquid level in the UV reactor
- High temperature
- OMC system failure

5.1.2.4 Verification of Flow Distribution and Headloss

If each reactor is not equipped with a dedicated flowmeter, then it will be necessary to verify the flow split between reactors over the entire operating flow range. This flow split and the total plant flow should be used to estimate the flow through each UV reactor and confirm

operation is within the validated conditions. Clamp-on type flowmeters or differential pressure readings across each parallel reactor are alternatives for field verification of the flow split.

The allowable difference in flow among reactors (flow split differential) is established during validation and should be accounted for in the validation protocol safety factor (section 4.2.1 and section F.5). If the actual flow split differential is greater than assumed in validation, then steps should be taken to improve the flow split. The Tier 1 recommendations for validation of UV reactors (section 4.6) necessitates a flow split differential of 10 percent or less. If this is not observed during functional testing, then a Tier 2 analysis for validation safety factor needs to be completed for the UV reactor. Appendix C provides details about the Tier 1 and 2 analysis and Appendix F provides details about the development of the safety factor.

The headloss should be measured for each reactor and compared to the headloss specified in the contract documents (if applicable). Pressure transducers or pressure gauges can be used to measure the headloss.

5.1.3 Performance Testing

Performance testing is intended to assess the operating performance of the UV reactor as a whole, as well as the individual performance of its components. While functional testing is primarily completed through simulations of specific operating conditions, performance testing is generally accomplished through extensive monitoring of reactor performance during the early stages of continuous operation. It is important to note that performance testing is not intended to validate disinfection performance, which is completed during validation testing (as described in Chapter 4). However, performance testing can be used to confirm that the actual operating conditions are within the constraints established during validation testing. Performance testing focuses on the accuracy, reliability, and repeatability of UV reactor operation, whereas validation is used to measure the effectiveness of the UV reactor at delivering the UV doses required for target pathogen inactivation credit.

When UV lamps are first energized, they go through a stabilizing period called “burn-in.” For some UV lamp designs, the initial lamp output may significantly exceed the design value. During burn-in, the lamp output may rapidly decrease to a value more consistent with the design. Following burn-in, lamp output becomes relatively stable until the end of lamp life is approached. Typically, new UV lamps will not have undergone burn-in prior to installation. Because performance testing should compare actual operating conditions to validated conditions, it is important that the lamps be in the same condition as they were during validation testing. Therefore, UV lamps should be burned-in prior to performance testing, which typically takes 100 hours of continuous operation. The actual required burn-in time should be discussed with the manufacturer and confirmed through documented operating experience at other UV installations.

The duration of performance testing and the extent of monitoring will be project-specific and should be established by the utility and designer based on the objectives of the performance testing. Performance testing may range in duration from as little as 48 hours of uninterrupted operation to greater than four months of demonstrative operation. Similarly, the scope of the testing may range from an increased monitoring frequency to confirm performance to an

extensive testing protocol to fully optimize reactor performance and establish long-term operating procedures. During performance testing, treated water may be sent to the distribution system if upstream treatment has not changed and meets existing regulations. However this should be confirmed with the State.

Performance testing may include the following items:

- Operation of each UV reactor in automatic mode and demonstration that actual operating conditions are within the constraints established during validation testing
- Demonstration of UV reactor start-up and switchover sequences that result from water quality and/or flowrate changes
- Observation of operation, including periods of off-specification operation, due to power quality problems, and other alarm conditions
- Measurement of electrical service voltage, current, and power consumption with different flow and water quality combinations to optimize energy use within the constraints established during validation
- Assessment of the effectiveness of the cleaning system by inspecting sleeve clarity and condition at regular intervals throughout the test period
- Confirmation that the programmed cleaning frequency correlates with the actual frequency of cleaning
- Verification of UV intensity sensor operation
- Confirmation of duty sensor accuracy using reference sensors (see section 5.3.2.2)
- Observation of ballast temperature and cooling system performance
- Verification of the accuracy and repeatability of the on-line UVT monitor through the collection of grab samples and analysis using a bench-top spectrophotometer (if applicable)
- Confirmation of backup generator and/or UPS power transfer to the UV reactor. This may necessitate simulation of line power failure to trigger the backup power supply. It is recommended that the backup power supply be tested for a minimum of two separate one-hour periods.

The performance testing should be tailored to the specific UV installation. An example monitoring program for a 4-week performance test is shown in Table 5.1.

Table 5.1 Example Monitoring During a Four Week Performance Test

Frequency	Task	Notes
Continuous	Confirm the operating setpoint(s)	Monitor reactor operation to confirm compliance with the setpoint(s) established during validation.
	Develop energy efficient operation	Monitor the power consumption. Test the automatic operation and power consumption under the flow and water quality variations to determine if energy efficiency improvements can be made within the validation constraints.
Weekly	Check the on-line UVT monitor calibration	Check the on-line UVT monitor against a bench-top spectrophotometer to determine if the on-line unit is in calibration.
	Check UV intensity sensor calibration	Check the duty sensor against a reference sensor, using the recommended protocol (section 5.3.2.2) to determine whether the duty sensor is in calibration.
Twice during testing period	Switch to standby reactor	Monitor the time it takes to switch to a standby reactor to determine if there will be off-specification operation during switchover.
	Switch to standby power or UPS	Monitor the time it takes to switch to the standby power supply to determine if there will be off-specification operation because of power transfer.
After 4 weeks, 100 OMC cycles or one Off-line chemical clean (OCC)	Inspect lamp sleeves for fouling	Remove a sleeve from the reactor and inspect as recommended in section 5.3.2.3.

Any off-specification time and flow should be recorded during all performance tests, and these results should be evaluated to ensure that off-specification requirements are met. During performance testing, any component that is not operating properly should be corrected and retested to ensure satisfactory operation. This may necessitate manufacturer involvement, especially if specifications in the contract documents were not met. Following performance testing, ongoing monitoring and recording of reactor operation should continue at a reduced frequency as discussed in section 5.4 and as required by the State.

5.1.4 Operations and Maintenance Manual

The O&M manual should be site-specific and based on as-built drawings, manufacturer's shop drawings, operating procedures, recommended maintenance tasks, and results from the performance testing. If possible, the O&M manual should be developed prior to routine operations. At a minimum, O&M manuals should include the following items:

- Federal and State regulatory requirements and guidelines
- Overall treatment objectives
- Role of the UV installation in the overall disinfection strategy
- Relationship to adjoining unit processes
- UV reactor design criteria
- UV reactor validation criteria
- General description of UV installation
- Controls and monitoring
- Standard operating procedures
- Start-up procedures
- Shutdown procedures (manual and automatic)
- Safety issues
- Emergency procedures and contingency plan
- Alarm response plans
- Preventative maintenance needs and procedures
- Equipment calibration needs and procedures
- Troubleshooting guide
- Equipment component summary
- Spare parts inventory
- Contact information for equipment manufacturers and technical services

5.2 Operation of UV Installations

The operation of UV installations will vary based on the UV manufacturer, the UV reactor configuration, and the dose control strategy. This section discusses the required and recommended operational and routine start-up and shutdown procedures that are common to all UV reactors. The operational tasks presented in this section are general in nature, and the specific operational procedures for the installed UV reactors should be developed with assistance from the manufacturer and UV installation designer. Examples of how to determine the operational requirements are presented in section 5.5.

5.2.1 Operational Requirements

To receive inactivation credit, the UV reactors are required to operate within the validated limits (40 CFR 141, Subpart W, Appendix D). When a UV reactor is operating outside of these limits, the UV reactor is operating off-specification as described previously. Unfiltered systems that use UV disinfection to meet the *Cryptosporidium* treatment requirement of the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) must demonstrate that at least 95 percent of the water delivered to the public during each month is treated by UV reactors operating within validated limits (40 CFR 141.721(c)(2)). In other words, the UV reactors cannot operate off-specification for more than 5 percent of the water delivered to the public.

The LT2ESWTR does not establish an off-specification requirement for filtered systems; however, States may adopt a 5 percent off-specification or more stringent requirement. Although the specific criteria limiting off-specification water are defined by the State, the United States Environmental Protection Agency (EPA) recommends that the UV reactors be operated to minimize off-specification water. The UV reactors must operate under the validated conditions that are determined based on validation testing (section 5.5) (40 CFR 141, Subpart W, Appendix D). The specific monitoring requirements associated with off-specification are described in section 5.4.

5.2.2 Recommended Operational Tasks

UV reactors typically use automatic control systems and do not need significant operational attention. This section outlines the general operational tasks that are recommended (Table 5.2). Site-specific operational tasks should be determined by the manufacturer, UV installation designer, and facility operators, and should be described in the O&M manual (section 5.1.4). Recommended maintenance tasks are discussed in section 5.3.1.

Table 5.2 Recommended Operational Tasks for the UV Reactor

Frequency	Recommended Tasks
Daily	• Perform overall visual inspection of the all UV reactors. • Ensure system control is on automatic mode (if applicable). • Check control panel display for status of system components and alarm status and history. • Ensure all on-line analyzers, flowmeters, and data recording equipment are operating normally. • Review 24-hour monitoring data to ensure that the reactor has been operating within validated limits during that period.
Weekly	• Initiate manual operation of wipers (if provided) to ensure proper operation.
Monthly	• Check lamp run time values. Consider changing lamps if operating hours exceed design life or UV intensity is low.
Semi-annually	• Check ballast cooling fans for unusual noise. • Check operation of automatic and manual valves.

5.2.3 Start-up and Shutdown of UV Reactors

UV reactors may be turned on and off regularly in response to varying flowrate and water quality. This section describes the routine start-up procedures, shutdown procedures, and winterization of the UV reactors. The routine start-up and shutdown procedures shown are not all inclusive. Utilities should modify these procedures based on the specific manufacturer's recommendations and operating requirements for their system.

5.2.3.1 Routine Start-up

The following start-up procedure serves as an example procedure. The UV reactors should be operating within validated conditions once the start-up sequence is complete.

1. Follow site-specific procedures for removal of lockouts and tag-outs of the power supply and control panel.

2. Ensure all lamp and ground connections are properly made. Verify that all incoming power conductors, including ground conductors are properly terminated.

3. Ensure that the lamp ends and all other reactor ports are covered and/or sealed to eliminate the potential for operator exposure to UV light.

4. Ensure the breakers are turned on, and all electrical cabinets and equipment are clear and closed.

5. Initiate the UV reactors' start-up sequence.

6. Initiate water flow (if it is not automatically done in UV reactor controls) to the reactor and gradually increase the flow until the minimum flow required for lamp cooling is reached. The water exiting the reactor is not disinfected and is considered off-specification.

7. Verify that all air is purged from reactors (i.e., reactor completely full). Check the top of the reactor for heat buildup, which indicates an air pocket.

8. Check the UV reactor control panel to ensure that all of the lamps are on and all of the monitoring parameters are being displayed.

9. Check and resolve any system alarms being displayed.

10. Ensure all of the on-line analyzers (UV intensity sensors and UVT monitors, if applicable) and flowmeters are operating as intended.

11. After lamp warm-up period, increase flow to the minimum validated flow (if flow is not automatically adjusted with UV reactor control sequence).

12. Verify correct flow split between parallel UV reactors using flowmeters and/or differential pressure gauges.

13. Verify that the UV reactor is operating within validated limits.

5.2.3.2 Routine Shutdown

UV reactors will need to be shut down periodically for maintenance or to accommodate water quality or flow changes. The main steps involved in shutting reactors down are as follows:

1. Throttle the effluent valve (if not part of the control sequence) to reduce flow through the reactor to the minimum required for cooling. If complete closure of the effluent valve can be accomplished without overheating the lamps, it is recommended.

2. De-energize the reactors.

3. Close effluent valve if not completed in Step 1. The water exiting the de-energizing reactor is considered off-specification.

4. If maintenance is being performed, the following steps should be followed. If the UV reactor is to be placed on standby, the following steps are not necessary.

5. Follow lock out and tag-out procedures for the facility.

6. Drain the reactor if necessary for the specific maintenance task.

7. Inspect and repair or replace any necessary equipment.

After an extended shutdown period (greater than 30 days), the operator should perform a cleaning and then inspect the lamp sleeves for fouling. Additional cleaning may be necessary prior to start-up.

5.2.3.3 Winterization

In most drinking water applications, the UV reactors will probably be located within a building. However, in some instances, the reactors may be located in unheated concrete vaults. When it is necessary to shut down a UV reactor for an extended period of time and freeze damage is possible, the UV reactors should be winterized in accordance with the manufacturer's recommendations.

5.3 Maintenance of UV Reactors

There are no specific regulatory requirements for maintenance of a UV reactor. However, the UV reactors need to be maintained to ensure that disinfection requirements are met. Poor maintenance may cause the UV reactors to be operating off-specification. As part of

the maintenance tasks, UV reactor components will need to be replaced; therefore, an inventory of spare parts is necessary. These tasks are described in this section.

5.3.1 Summary of Recommended Maintenance Tasks

Table 5.3 summarizes the recommended maintenance tasks and refers to the general guidelines for those tasks that are discussed in section 5.3.2. Before any maintenance is performed, the main electrical supply to the UV reactors should be disconnected, lockout and tag-out protocol should be followed, and the operator should wait at least 5 minutes (or as recommended by the manufacturer) for the lamps to cool down and energy to dissipate.

Table 5.3. Recommended Maintenance Tasks

Frequency	Task *General Guideline Section Reference*	Action
Weekly	Check on-line UVT monitor calibration *section 5.3.2.5*	Calibrate UVT monitor when manufacturer's guaranteed measurement uncertainty is exceeded.
Monthly	Check reactor housing, sleeves, and wiper seals for leaks	Replace housing, sleeve, or wiper seals if damaged or leaking.
Monthly	UV intensity sensor calibration check protocol *section 5.3.2.2*	Check the sensor calibration at the lamp power utilized during routine operating conditions (e.g., the majority of operation). A sensor is out of calibration when it fails the criteria shown in *section 5.3.2.2*
When UV intensity sensor fails calibration check	Replace duty sensor with calibrated backup sensor *section 5.3.2.2*	• Check the reference sensor with second reference sensor or two other duty sensors to ensure the first reference sensor is calibrated. • If reference sensor is properly calibrated, replace the duty sensor with calibrated sensor, and send the duty sensor that failed calibration to the manufacturer. • Check the replaced sensor one hour later.
Monthly (OCC) Semi-annually (OMC)	Check cleaning efficiency *section 5.3.2.4*	• Record UV intensity sensor reading. • Extract one sleeve per reactor (or bank of lamps for low pressure high output (LPHO) reactors) for inspection. • Check remaining sleeves if fouling is observed on the first sleeve. • Manually clean sleeve(s) if fouling is seen on the sleeves. • Record UV intensity sensor reading and compare to original reading after cleaning. • Replace sleeve if UV intensity is not restored to validated level.
Semi-annually (OMC)	Check cleaning fluid reservoir (if provided) *section 5.3.2.4*	Replenish solution if the reservoir level is low. Drain and replace solution if the solution is discolored.
Annually	Calibrate reference sensor *section 5.3.2.2*	Send the reference sensor to the manufacturer for calibration.
Annually	Test-trip GFI *section 5.3.2.8*	Maintain ground fault interrupt (GFI) breakers in accordance with the manufacturer's recommendations.

Table 5.3. Recommended Maintenance Tasks (continued)

Frequency	Task *General Guideline Section Reference*	Action
Manufacturer's recommended frequency	Check flowmeter calibration *section 5.3.2.6*	Calibrate flowmeter when manufacturer's guaranteed measurement uncertainty is exceeded.
Lamp/ manufacturer specific	Replace lamp *section 5.3.2.1*	Replace lamps when any one of the following conditions occur: • Initiation of low UV intensity alarm (UV intensity equal to or less than set point value) after verifying that this condition is caused by low lamp output. • Initiation of lamp failure alarm.
When lamps are replaced	Properly dispose of lamps *section 5.3.2.1*	Send spent lamps to a mercury recycling facility or back to the manufacturer.
Sleeve/ Manufacturer specific	Replace sleeve *section 5.3.2.3*	Replace sleeve every 3 to 5 years or when damage, cracks, or excessive fouling significantly decreases UV intensity of an otherwise acceptable lamp to the minimum validated intensity level. The replacement frequency should be adjusted based on operational experience.
Pressure gauge manufacturer specific	Check operation of the pressure gauges that are used to confirm flow split (if applicable) *section 5.3.2.6*	Replace the pressure gauge if deemed faulty by manufacturer's evaluation procedure.
Manufacturer specific	Clean UVT monitor	Clean according to manufacturer's recommended procedure.
Manufacturer specific	Inspect OMC drive mechanism	Inspect and maintain OMC drive routinely as recommended by the manufacturer.
Manufacturer specific	Inspect ballast cooling fan	Check the ballast cooling fans for dust buildup and damage. Replace if necessary.

5.3.2 General Guidelines for UV Reactor Maintenance

This section describes general guidelines for UV reactor components that relate to maintenance tasks. Specific operations, maintenance, and monitoring tasks are described individually in later sections. These latter sections also refer back to this section as a reminder of the general recommendations.

5.3.2.1 UV Lamp Characteristics

UV lamp output decreases over time, and UV lamps will need to be replaced periodically to maintain sufficient UV intensity (i.e., the validated UV intensity setpoint). Replacement lamps should be identical to those used during reactor validation with respect to arc length, lamp envelope material and dimensions, amount of mercury, and spectral output. If the lamps supplied are not equal to the lamps used during validation, the UV reactor is not operating as validated and is considered off-specification.

If the mercury content or power rating changes, the different lamp should be assessed by comparing UV intensity sensor readings, after burn-in, to the lamps that were validated to determine if the new lamps are equal to the validated lamps. If the sensor reading is equal to or greater than that of the validated lamps after burn-in, the different lamps are acceptable and comparable to the validated lamps. However, if a utility replaces the lamps with higher power lamps to receive higher log inactivation credit, validation testing should be performed to confirm performance. Lamp manufacturers should also provide documentation of lamp output decay characteristics, guaranteed life, and lamp burn-in period. This information will help the utility determine the lamp replacement frequency. It should be noted that different lamps might have different aging characteristics, which may affect operations and maintenance costs.

The frequency of UV lamp replacement can be based on a utility-determined schedule, lamp operating hours, or the UV intensity reduction as measured by the UV intensity sensor (after sleeve and sensor window cleaning); lamp replacement recommendations are discussed in section 5.3.2.1. During replacement, the lamps and sleeves should be handled in accordance with manufacturer recommendations, using clean cotton, powder-free latex, or vinyl gloves because fingerprints can cause damage to the lamps or sleeves during operation.

Lamp manufacturers are required to determine whether their products exhibit the toxicity characteristic for mercury and whether their lamp is regulated as a universal hazardous waste under Subtitle C of Resource Conservation and Recovery Act (RCRA) [40 CFR Part 260, 261, 264 and 273]. Currently, most UV lamps exceed these toxicity characteristics and require regulated disposal. As such, these lamps should be sent to a mercury recycling facility where the mercury is recovered and lamp components are recycled. Some UV reactors and lamp manufacturers will accept spent or broken lamps for recycling or proper disposal (Dinkloh 2001; Lienberger 2002; Gump 2002). Utilities should contact their lamp manufacturer to determine if they accept spent lamps or should contact their State for a list of local mercury recycling facilities.

5.3.2.2 UV Intensity Sensors

Well performing UV intensity sensors are necessary to assess whether the validated UV intensity is being achieved. Sensor calibration, rotation, and placement affect operation. This section describes these effects and provides recommendations to minimize them.

There are two types of sensors used for UV reactor operation: duty and reference sensors. Duty sensors are on-line sensors and continuously monitor UV intensity, while the reference sensors are off-line sensors used to assess the duty sensor performance. Therefore, the reference sensor specifications should exactly match those of the duty sensors, so that a valid comparison can be completed. Both duty and reference sensors are described in this section.

Duty UV Intensity Sensor Calibration

Prior to installation, manufacturers calibrate the UV intensity sensors. However, over time the sensor may drift out of calibration. Because these sensors are vital to assessing the UV disinfection performance, the calibration of each sensor should be checked at least monthly

against the reference sensor. To assess the calibration, the following sensor calibration check protocol should be followed:

1. Measure the UV intensity with the duty sensor, and record the measurement result.

2. Replace the duty sensor with the reference sensor in the same location (i.e., port) as the duty sensor used in Step 1.

3. Measure the UV intensity with the reference sensor and record the measurement result.

4. Determine if Equation 5.1 holds true for the two UV intensity sensor readings:

$$\left(\frac{I_{Duty}}{I_{Ref}} - 1\right) * 100 \leq \left(\sigma_{Ref}^2 + \sigma_{Duty}^2\right)^{1/2} \qquad \text{Equation 5.1}$$

where

I_{Ref}	=	Intensity measured with the reference sensor (mW/cm^2)
I_{Duty}	=	Intensity measured with the on-line sensor (mW/cm^2)
σ_{Duty}	=	Measurement uncertainty of the on-line UV intensity sensor (%) as provided by the UV manufacturer in the validation report
$\sigma_{Reference}$	=	Measurement uncertainty of the reference UV intensity sensor (%) as provided by the UV manufacturer in the validation report

5. Replace the duty sensor with another calibrated duty sensor if the relationship Equation 5.1 does not hold true.

The calibration of the UV intensity sensor is sensitive to the power level of the UV lamps (Swaim et al. 2002). To most effectively compare the duty sensor to the reference sensor, the power level should be set at the level typically used during routine operation (e.g., the majority of operation).

UV Intensity Sensor Rotation

Some UV intensity sensors are sensitive to their rotational alignment within the sensor port and will have different readings at different rotations. This may be due to the UV intensity sensor configuration (e.g., acceptance angle). Section A.3.5 discusses UV intensity sensors configurations in more detail. The sensors should be rotated until the lowest UV intensity reading is obtained for routine monitoring purposes. Alternatively, UV reactors may be designed so the UV intensity sensors are keyed in the same rotational position at all times. This may not be an issue for all UV intensity sensors.

Measuring Lamp Output Variability

UV lamp output differs for each lamp, depending on lamp age and lot. As discussed in section 2.4.6, a sensor measures the UV intensity at its location in the UV reactor and cannot assess lamp output variability unless there is one sensor per lamp. Many low pressure (LP) or LPHO reactors have one sensor to monitor a bank of lamps, and some MP reactors use one UV

intensity sensor to monitor more than one lamp in the reactor. The effect of variable lamp output is accounted for in the validation protocol safety factor as discussed in section F.3. For routine operation, the oldest lamp should be placed in the position closest to the UV intensity sensor if one sensor monitors multiple lamps.

Reference UV Intensity Sensor

The reference sensor should be calibrated at least once per year at a qualified facility (e.g., manufacturer) to ensure that it is calibrated properly for the regular duty sensor calibration checks. The reference sensor should not be exposed to UV light for longer than it takes to perform the reference sensor measurement. When not in use, the reference sensor should be stored under conditions that will maintain its integrity and accuracy as recommended by the manufacturer. If the reference sensor is found to be out of calibration, the calibration interval should be shortened. One indicator that the reference sensor itself may be out of calibration is if it shows that all on-line sensors are out of calibration. Some utilities may choose to have multiple reference sensors to help determine if one reference sensor is out of calibration, as a replacement reference sensor, or to allow multiple duty sensors to be checked simultaneously.

5.3.2.3 Lamp Sleeves

Lamp sleeves degrade over time due to solarization (section 2.4.4) and internal sleeve fouling, resulting in cloudiness and a loss of UV transmittance. Abrasion of the sleeve surface during handling or mechanical cleaning may also be a contributing factor to the loss of UV transmittance. Sleeve transmittance loss is reflected in the UV intensity sensor reading and, therefore, does not need to be monitored. However, a low UV intensity sensor reading may be from sleeve transmittance loss and should be considered when troubleshooting the cause of this problem (as discussed in section 5.6.1). Sleeves will need to be replaced in the case of UV transmittance loss or other damage.

Sleeves should be replaced every 3 to 5 years or when damage, cracks or excessive fouling diminishes UV intensity to the minimum validated intensity level, whichever occurs first. This replacement frequency should be increased or decreased based on operational experience. Replacement sleeves should be identical to the sleeves used during validation, meet the design and UV manufacturer's material and construction specifications, and be certified as described in section F.6.3. The sleeves should be handled in accordance with manufacturer recommendations, using clean cotton, powder-free latex, or vinyl gloves because fingerprints can cause damage to the sleeves during operation. When the sleeves are replaced, the manufacturer's procedure should be closely followed because the lamp sleeve can crack and break from over-tightening of the compression nuts that hold it in place.

5.3.2.4 Fouling

As discussed in Chapters 2 and 3, the lamp sleeves and UV intensity sensors/windows may foul over time, depending on the water quality, lamp type, and cleaning regime. This section describes possible cleaning techniques and provides some specific recommendations for addressing fouling issues.

Sleeve and UV Intensity Sensor Surface/Window Fouling

There are two types of sleeve cleaning techniques as discussed in section 2.4.5. The first type is an OMC system, which typically utilizes an automatic mechanical wiper (e.g., O-ring, brush) to wipe the surface of the sleeve at a prescribed frequency. Some OMC systems have O-rings with cleaning fluid enclosed in them to enhance cleaning. The second type is an OCC, which is also a called flush and rinse system. OCC systems are off-line, manual systems that pump cleaning solution (typically an acid) into the reactor and circulate the solution for a period of time. Helsinki Water uses an OCC system; a description of their cleaning regime is discussed in Appendix O. Also, OCC systems clean the sensor wetted surface/window; however, OMC systems may not, depending on the UV reactor.

The frequency of cleaning is site-specific. An appropriate sleeve cleaning frequency (manual or automatic) can be determined based on the rate of fouling during the start-up period, which can be assessed by monitoring the UV intensity sensor measurement. For routine operation, the cleaning frequency should be increased or decreased based on the amount of fouling left on the sleeves after the cleaning cycle and the loss of UV intensity prior to cleaning.

Sleeves should initially be inspected for fouling every six months if OMC is employed and every month if OCC is used. This frequency should be adjusted after 2 years of operating data are available. A decrease in UV intensity may indicate sleeve fouling, and sleeves should be inspected if fouling is the suspected cause of the UV intensity drop. In addition, the sensor windows (if applicable) should be inspected for fouling and supplemental cleaning should be conducted if necessary, according to the manufacturers recommendation.

For sleeve inspection, one sleeve per reactor (or bank of lamps for LP or LPHO reactors) should be inspected. The sleeves should be handled in the same manner as described for UV lamps. If damage or fouling is observed, the remaining sleeves should be inspected. External fouling can be difficult to identify. Sleeve discoloration is more easily seen by laying the sleeve on a clean, white, lint-free cloth along side of a new sleeve. If streaks are observed, this may indicate that the OMC wiper material may be worn or damaged or not aligned properly; therefore, the wiper should also be inspected. If fouling is observed, the cleaning frequency should be increased, and supplemental manual cleaning should be conducted as necessary.

If manual cleaning (i.e., beyond routine OCC or OMC cleaning) of lamp sleeves is necessary, this should be done according to manufacturer recommendations and procedures. Abrasive cleaners or pads that might scratch the lamp sleeve should not be used. In addition, the inside of the sleeve should be dry prior to re-installation because water or cleaning solutions could cause a coating to form during operation. One method of drying the sleeve is to use isopropyl alcohol and a lint-free cloth; however, there should not be any alcohol left inside the sleeve after this procedure. As noted earlier, when the sleeves are re-installed after inspection, the manufacturer's procedure should be closely followed to avoid over-tightening of the compression nuts.

If OMC cleaning is used, the OMC wipers should be checked for deformation or degradation at the same time the sleeves are checked. If the OMC cleaning uses a cleaning solution, the cleaning solution reservoir should be checked every six months to determine

whether more solution should be added. In addition the solution should be replaced if it is discolored or if the OMC system is not effectively cleaning the sleeve.

Fouling During Periods of Standby

When the UV reactors are out-of-service and full of water, the sleeves may become fouled (Toivanen 2000). The rate of fouling is site-specific and depends on the influent water quality. UV reactors equipped with OMC should continue to clean the sleeves even though the UV reactor is off-line. This should prevent fouling of the sleeves. For UV reactors that do not include OMC, the utility should consider draining the UV reactor if it is off-line for more than one week. However, this period could be shorter or longer, depending on the water quality. After an extended shutdown period of greater than 30 days, the operator should perform a cleaning (OCC or OMC) and then inspect the lamp sleeves for fouling. Additional cleaning may be necessary prior to start-up after extended periods of standby.

5.3.2.5 On-line UVT Monitor Calibration

On-line UVT measurements should be compared to those obtained using a bench-top spectrophotometer every week. The grab samples that are used to check calibration should be collected from a location close to the on-line UVT monitor sampling point. The frequency may be decreased or increased based on the performance demonstrated over a one-year period. For example, the frequency could be reduced to once per month if the UVT monitor was consistently within the calibration specification for over a month during the first year of monitoring.

5.3.2.6 Flowmeter Calibration

The flowmeter calibration should be checked at the frequency recommended by the manufacturer. Techniques for verifying calibration are discussed in section 5.1.2.2.

Some UV installations will not have dedicated flowmeters and may use a combination of an upstream flowmeter and differential pressure gauges to verify flow split as described in section 3.3.1.2. If differential pressure is used to verify the flow split, the calibration of the main flowmeter should be checked at the manufacturer's recommended frequency and the accuracy of the pressure gauges should be periodically verified using a reference gauge or redundant gauge to confirm measurement consistency between the gauges.

5.3.2.7 UV Reactor Temperature

UV lamps operate at high temperatures (as discussed in section 2.4.2) and need water flow to maintain them at their optimal temperature and to prevent overheating. Another concern related to overheating is the formation of air pockets in the UV reactor. Air pockets can cause the UV reactor temperature to increase and may alter the flow pattern in the UV reactor. UV lamps can break if their threshold temperature is exceeded, which is discussed in more detail in section N.2.1.2.

The water temperature should be monitored. If the water temperature exceeds manufacturer recommendations, the UV reactor should be shut down. Water level monitoring or reactor temperature monitoring are typically included in the packaged control systems for the UV reactor. The water level monitoring should detect any air pockets in the UV reactor. During start-up and whenever necessary, air should be bled from the UV reactors. The UV reactor surface can become hot during operation if air pockets or stagnant water are present in the UV reactor. As a result, nothing unrelated to reactor equipment should be in external contact with the reactor while in service.

5.3.2.8 Electrical Concerns

UV reactors operate at high voltages. Before any maintenance on the UV reactor is performed, the main electrical supply to the UV reactors should be disconnected and the operator should wait at least 5 minutes for the lamps to cool down and energy to dissipate. Lockout, tag-out procedures and all applicable codes should be followed. The UV reactors should not be operated if any of the control panel doors are open, and water should not be sprayed around the electrical equipment.

Typically, power to the UV reactors are provided via a distribution transformer, a circuit breaker, a disconnect switch at the UV reactor, and related wires and conduits. If maintenance is necessary on the control panel, the main electrical supply should be disconnected. The power to the lamps is typically delivered through individual GFI circuit breakers and ballasts. Maintenance of the GFI breakers is important because they are safety devices that protect the operators when they are working around the powered equipment. The GFI breakers should be test-tripped at least once per year and should be maintained in accordance with the manufacturer’s recommendations. Ballast output should be monitored through the UV reactor's control panel. Irregularities or instabilities in ballast output may indicate a problem with the electrical feed or the ballast itself.

The ballasts, typically connected between the GFI breakers and the lamps, are electrical components that regulate the line power to match the input requirement of the lamps. Three types of ballasts are typically used with UV reactors for converting power: electronic ballasts, electromagnetic ballasts, and transformers. Electromagnetic ballasts and transformers are very similar in that both contain a specially wound coil of wire that is used to control the current to the lamp. Typically inductors or capacitors are used to allow step adjustment of the lamp output. Electronic ballasts, sometimes referred to as solid-state ballasts, contain semiconductors and other electronic components that allow the ballast to behave like a switching power supply. Electronic ballast technology allows nearly continuous adjustment of lamp output.

Power regulation, particularly with electromagnetic ballasts and transformers, will result in significant heat build-up within the ballast enclosure. If the excess heat is not dissipated, it can damage the ballast electronics and cause failure. A cooling system is normally provided with LPHO and medium pressure (MP) reactors to maintain the ballast temperature below the maximum specified limit. LP reactors typically do not need ballast cooling. The ballast cooling system should be inspected and maintained as recommended by the manufacturer.

Power use depends on the specific UV reactor and how it adjusts to changes in water quality and flow. Power use should be monitored as operational adjustments are made for changes in flow, UV intensity, UVT, lamp aging and output, and other factors. This information can be used to determine the most energy efficient operating strategies. For example, some UV reactors can both increase lamp output and energize additional lamps to respond to a low UV intensity reading. The power use under these two strategies can be compared to determine which is more energy efficient.

5.3.3 Spare Parts

The actual life of a component is a function of many variables, including operating conditions, maintenance practices, the quality of the materials of construction, and fabrication practices. As a consequence, it is impossible to predict the actual life of a component. To overcome the operational impacts of this uncertainty, an adequate inventory of critical spare parts should be maintained to ensure reliable and consistent performance of the UV reactors and minimize the delivery of off-specification water.

All UV components have a design life and a guaranteed life. The design life represents the expected duration of operation. The guaranteed life incorporates the risk, assumed by the manufacturer, to account for the uncertainties associated with the quality of materials used, production, and operating conditions. Generally, guarantees are conditional in nature and are valid under certain operating conditions. For example, guaranteed lamp life is normally linked to the lamp power setting or the number of on/off cycles per 24-hour period. If equipment failure occurs during the warranty period and if all of the warranty conditions are satisfied, the manufacturer will typically replace the component and charge the owner a prorated fee for the use of the replaced component.

Table 5.4 provides typical design and guaranteed lives for major UV reactor components. These represent current industry trends and are likely to change as more operation and maintenance information becomes available and technological advances occur. Manufacturers should be contacted directly for details specific to their equipment.

Table 5.4. Design and Guaranteed Lives of Major UV Components (Based on Manufacturers' Input)

Component	Design Life[1]	Guaranteed Life [2]
Low pressure lamps (LP and LPHO)	12,000 hours	8,000 - 12,000 hours
MP lamps	10,000 hours	4,000 - 8,000 hours
Sleeve	8 to 10 years	1 to 3 years
UV Intensity Sensor	3 to 10 years	1 year
UVT monitor	3 to 5 years	1 year
Cleaning systems	3 to 5 years	1 to 3 years
Ballasts	10 to 15 years	1 to 3 years

[1] Expected duration of operation
[2] Accounts for variability of material quality, production, and operating conditions.

The following is a suggested minimum inventory of spare parts, expressed as a percentage of the installed number. A full list of spare parts will vary depending on the specific equipment installed and should be coordinated with the UV manufacturer. The number of spare parts needed depends on the guaranteed life of the specific equipment. For example, a higher percentage of MP lamps may be necessary compared to LP lamps because the guaranteed lamp life is less for MP lamps, and therefore they need to be replaced more frequently.

- UV lamps- 10 percent with a minimum of two lamps
- Sleeves- 5 percent with a minimum of one sleeve
- O-ring Seals- 5 percent with a minimum of two seals
- OMC wipers- 5 percent with a minimum of two wipers
- OMC wiper drive mechanisms- 2 percent with a minimum of one drive
- Ballasts- 5 percent with a minimum of one unit
- Ballast cooling fan- 1 unit
- Duty UV intensity sensor- minimum of 2 units (adjust number based on operating experience)
- Reference UV intensity sensor- 2 units
- On-line UVT monitor- 1 unit (if used for control strategy)

5.4 Monitoring, Recording, and Reporting of UV Installation Operation

Operation of the UV reactors should be monitored to ensure the reactors are operating within validated limits, to diagnose operating problems, to determine when maintenance is necessary, and to maintain safe operation. This section discusses the required and recommended monitoring, recording, and reporting activities for UV installations.

5.4.1 Monitoring and Recording Frequency for Compliance Parameters

Utilities must monitor each reactor to determine whether it is operating within validated conditions. They also must determine the percentage of flow that was treated within validated limits (40 CFR 141, Subpart W, Appendix D). The flow is off-specification when a reactor is operating outside of validated limits. The monitoring parameters depend on the control strategy used and the validation results. Table 5.5 presents the monitoring parameters for each control strategy, the criteria for when off-specification occurs, and examples of off-specification operating conditions.

Table 5.5 Off-Specification Operations for Each Control Strategy

Control Strategy	Parameters Monitored	Off-Specification	Examples
UV intensity setpoint	UV intensity, flowrate, lamp status	Anytime these values are outside of the validated limits for these parameters	1) UV intensity below setpoint 2) Flowrate outside validated limits 3) UV lamp failure 4) UV intensity sensor failure
UVT and UV intensity setpoints	UV intensity, flowrate, UVT, lamp status	Anytime these values are outside of the validated limits for these parameters	1) UV intensity below setpoint 2) Flowrate outside validated limits 3) UV lamp failure 4) UV intensity sensor failure 5) UVT below setpoint
Calculated dose	Calculated dose, flowrate, UVT, lamp status	Anytime the calculated dose is below the validated setpoint (if validation certifies that the calculated dose can be used to control the UV reactor – see section F.2)[1]	1) Calculated dose below setpoint 2) Flowrate outside validated limits 3) UV lamp failure 4) UV intensity sensor failure 5) UVT below setpoint

[1] If validation deems that the calculated dose control is not acceptable, the UV reactor should use the UVT and UV intensity setpoint control strategy.

It is recommended that the required monitoring parameters be continuously monitored for each UV reactor and that these values be recorded at least once every four hours. These four-hour records should be used to determine the percentage of flow that is off-specification. Very small systems (e.g., systems serving less than 500 people) that are unable to record reactor status every 4 hours (e.g., manual recording is practiced) can consider a reduced recording frequency; however, the frequency should not be less than once per day and should be approved by the State. The monitoring guidelines are summarized in Table 5.6.

Table 5.6 Monitoring Parameters and Recording Frequency

Parameter ***General Guideline Section Reference (if applicable)***	**Recommended Recording Frequency**	**Notes**
UV intensity	Every 4 hours	The UV intensity must be above the validated setpoint
UVT[1]	Every 4 hours	The UVT must be above the validated setpoint. If not required to be monitored, this information will assist in determining if low UV intensity readings are because of low UVT
Calculated dose[1]	Every 4 hours	The calculated dose must be above the validated setpoint
Lamp status	Every 4 hours	The lamps should be energized if water is flowing through the UV reactor
Calibration of UV intensity sensors *section 5.3.2.2*	Monthly	The UV intensity sensor calibration must be checked, using sensor calibration check protocol

[1] Only required if necessary for the control strategy (Table 5.11)

5.4.2 Monitoring and Recording for Other Operational Parameters

In order to minimize operational problems, facilitate regulatory compliance, and evaluate UV reactor performance, it is recommended that additional parameters, beyond those needed for regulatory compliance, be monitored. Table 5.7 presents these additional parameters recommended for monitoring and the recommended recording frequency. These recommended parameters and their monitoring frequency should be adjusted based on site-specific operating experience. For example, if sleeve fouling is a maintenance issue and supplemental reactor cleaning is frequent (e.g., monthly), then the fouling parameters should be monitored on a daily basis as opposed to weekly as shown in the table below.

Table 5.7 Recommended Monitoring Parameters and Recording Frequency

Parameter *General Guideline Section Reference (if applicable)*	Monitoring Frequency	Recording Frequency	Notes
Power draw *section 5.3.2.8*	Continuous	Every 4 hours	This information can be used to determine the most energy efficient operation strategies
Water Temperature *section 5.3.2.7*	Continuous	Daily	Monitor to ensure the high temperature limit is not exceeded (usually part of packaged UV control system)
UV lamp on/off cycles *section 5.3.2.1*	Continuous	Weekly (Total cycles in a week)	Monitor to assess status of the UV lamps since the of on/off cycles can help assess lamp aging
Turbidity	Daily	Weekly	Monitor if chemicals (e.g., lime) are added post-filtration or prior to UV disinfection (monitoring may not be necessary for many UV reactors)
pH, iron, calcium, alkalinity, hardness *section 5.3.2.4*	Weekly (reduce if fouling is not prevalent)	Weekly	Monitor to help assess fouling issues if necessary
UVT monitor calibration *section 5.3.2.5*	Weekly (reduce if appropriate based on operational experience)	Weekly	Information can assist in planning scheduled maintenance and O&M budget
Age of the following equipment: • Lamp • Ballast • Sleeve • UV intensity sensor	Monthly	Monthly	Information can assist in planning scheduled maintenance and O&M budget
Calibration of flowmeter *section 5.3.2.6*	Monthly	Monthly	Information can assist in planning scheduled maintenance and O&M budget

All data related to UV reactor operation should be gathered, compiled, and stored for easy retrieval. The recorded data should be stored for at least two years. Appendix M provides example logs for many of the parameters listed in Table 5.13.

5.4.3 Reporting to the State

Monthly reports must be prepared and submitted to the State. The report must include the percentage of off-specification flow, which should be based on at least 4-hour records for each reactor. The State may have additional reporting requirements. In addition, the percentage of the UV intensity sensors that were checked for calibration must be reported monthly; all sensors should be checked every month. An example monthly monitoring form is shown in the Appendix M. The State should be contacted to determine the specific content of the monthly reports and to coordinate with other reporting requirements.

5.5 Determination of Validated Operational Parameters

For each UV reactor, the operating conditions associated with a given level of inactivation credit must be defined based on validation testing results (40 CFR 141, Subpart W, Appendix D). The validation testing and resultant data that are used to determine these operating conditions will vary with different control strategies. A detailed discussion of the three common control strategies is presented in section 3.3.2. A brief description of each of the control strategies is shown in Table 5.8.

Table 5.8 UV Reactor Control Strategies

Control Strategy	Dose Delivery Monitoring and Control Based On
UV Intensity Setpoint	UV intensity sensor measurement
UV Intensity and UVT setpoints	UV intensity sensor and UVT measurement
Calculated Dose	The calculated UV dose[1]

[1] The UV reactor calculates a UV dose using the UV intensity sensor measurement, the UVT of the water, and the flowrate.

This section provides example operational requirements based on the validation examples described in section C.5 of the validation protocol. Each example describes how the operating requirements are determined based on the control and operation strategy used and the validation results.

Example 1. UV Intensity Setpoint Control - Single Operational Setpoint for all Conditions (Section C.5.1)

The simplest operational strategy uses one single UV intensity setpoint for all flows. In this example, a LPHO reactor that uses the UV intensity setpoint control strategy was validated at flows between 100 and 500 gallons per minute (gpm) and a UVT range of 84 to 98 percent. This reactor passed the criteria for 2-log inactivation of *Cryptosporidium* with an intensity sensor setpoint of 5 mW/cm^2. The validation testing verified that the UV intensity setpoint control strategy is appropriate for this reactor

Based on this validation, this reactor must operate at a minimum UV intensity sensor setpoint of 5.0 mW/cm^2 and a flow range between 100 and 500 gpm to claim 2 log *Cryptosporidium* credit. The UV intensity setpoint approach accounts for the UVT in the UV intensity measurement. Therefore, the intensity setpoint of 5.0 mW/cm^2 can be used for any UVT. Although this is a simple and straightforward operating strategy, single setpoint operation will not be as energy efficient as using a variable setpoint approach, which is described in Example 2.

Example 2. UV Intensity Setpoint Control - Variable Setpoint Operation for Different Flow Conditions (Section C.5.2)

The variable UV intensity setpoint approach has a different UV intensity setpoint at different flowrates. This operation promotes more energy efficient operation compared to the

single setpoint approach because the UV intensity setpoint can be decreased at lower flows. For this example, a LPHO reactor that uses the UV intensity setpoint control strategy was validated under the conditions shown in Table 5.9 and passed the criteria for 3-log inactivation of *Cryptosporidium* at each condition.

Table 5.9 Example Validation Data for Variable Setpoint Operation

Flow (mgd)	UVT (%)	UV Intensity (mW/cm^2)
0.90	70	6.1
1.2	75	7.5
1.7	83	10
2.4	92	14

The UV intensity measurements recorded during validation verified that the UV intensity setpoint approach is appropriate for this reactor. Because of the data collected, this UV reactor can be operated at a different setpoint for each flow range. These intensity setpoints could be used in three ways.

1. A single setpoint as described in Example 1. For example, a setpoint of 14 mW/cm^2 could be used at between 0.90 and 2.4 mgd with any UVT.

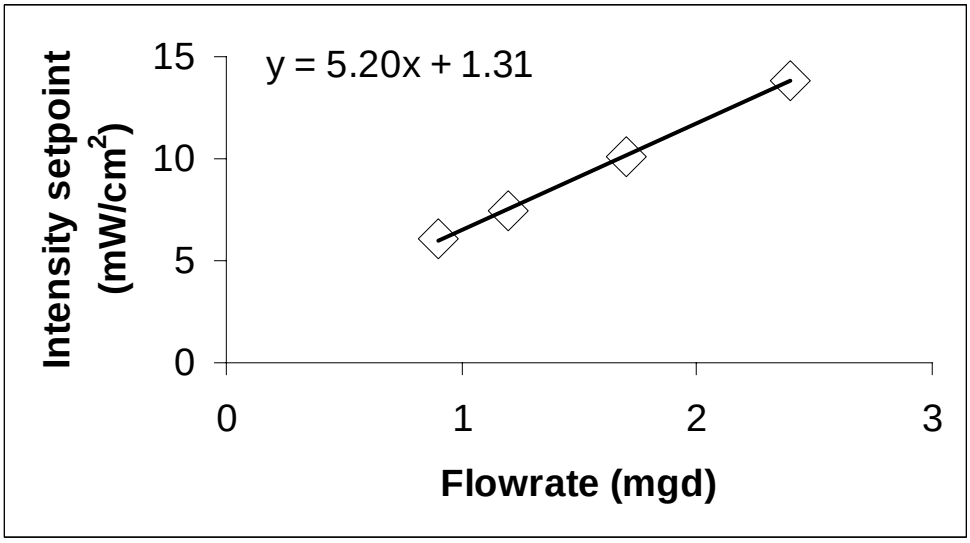
2. Each intensity setpoint could be used over a given flow range as shown in Table 5.10. The higher UV intensity measurement from each flow range should be used as the UV intensity setpoint to be conservative.

Table 5.10 UV Intensity Setpoint for Different Flow Ranges

Minimum Flow (mgd)	Maximum Flow (mgd)	UV Intensity (mW/cm^2)
0.90	1.2	7.5
1.2	1.7	10
1.7	2.4	14

3. The intensity setpoints could be interpolated as a function of flowrate. Figure 5.2 presents an equation based on interpolation. For example, for a flowrate of 2 mgd, interpolation indicates that a setpoint of 12 mW/cm^2 is needed to achieve 3-log inactivation.

Figure 5.2 Example 2 – Interpolation of Validation Data to Determine UV Intensity Setpoints



Example 3. UV Intensity Setpoint Control - Variable Setpoint Operation for Different Flow Conditions and Inactivation Goals (Section C.5.3)

For this example, a UV manufacturer has completed a matrix of tests at different flowrates, UVT, and lamp power to develop a relationship between UV intensity readings, log inactivation credit, and flow. Table 5.11 shows the results of the validation tests.

Table 5.11 Example Validation Data for Variable Setpoint Operation

Flow (mgd)	UV Intensity (mW/cm^2)	*Cryptosporidium* Log Credit
5	5.1	3.0
5	3.3	2.5
5	1.8	1.0
10	9.1	3.0
10	5.6	2.5
10	2.6	1.0
20	15	3.0
20	11	2.0
20	5.6	1.0

The UV intensity measurements recorded during validation verified that the UV intensity setpoint approach is valid for this reactor. In contrast to Example 2, this reactor was validated for three different levels of *Cryptosporidium* inactivation credit. For a utility that only is required to achieve a 2.0-log inactivation, using this reactor would reduce energy costs compared to a reactor that had only been validated for 3.0-log *Cryptosporidium* inactivation.

These intensity setpoints could be used in three ways to achieve 2.0-log *Cryptosporidium* inactivation credit with this reactor,

1. A single setpoint as described in Example 1. For example, a setpoint of 11 mW/cm^2 could be used at or between 5 and 20 mgd with any UVT.

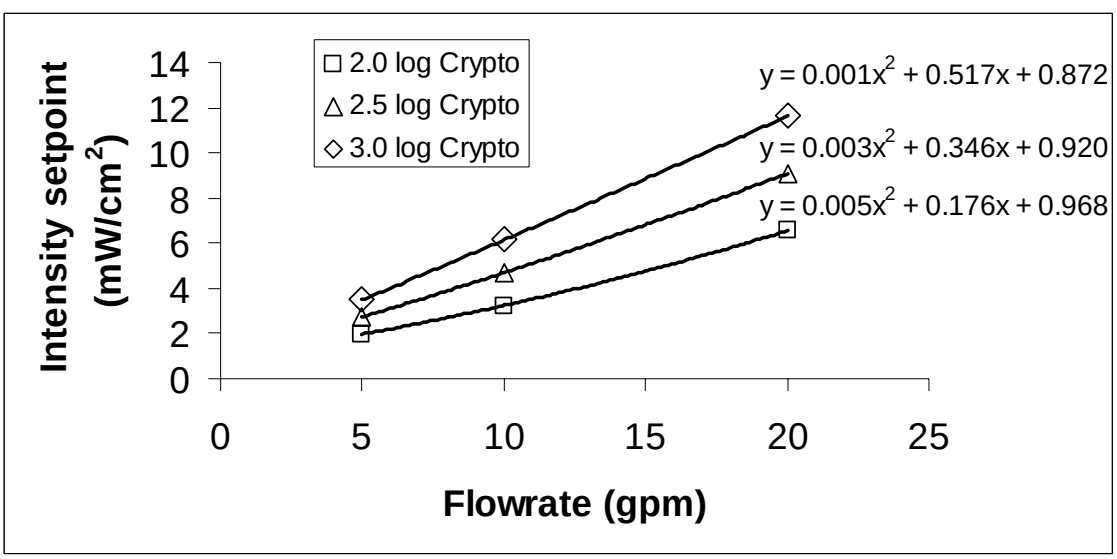
2. Each intensity setpoint could be used over a given flow range as shown in Table 5.12. The higher UV intensity measurement from each flow range should be used as the UV intensity setpoint to be conservative.

Table 5.12 UV Intensity Setpoint for Different Flow Ranges

Minimum Flow (mgd)	Maximum Flow (mgd)	UV Intensity (mW/cm^2)
5	10	5.6
10	20	11

3. The intensity setpoints could be interpolated as a function of flowrate. Figure 5.3 presents an equation based on interpolation for three different levels of *Cryptosporidium* inactivation. For example, for a flowrate of 12 mgd, interpolation indicates that a setpoint of 3.8 mW/cm^2 is needed to achieve 2-log inactivation.

Figure 5.3 Example 3 – Interpolation of Validation Data to Determine UV Intensity Setpoints at Different Flows and *Cryptosporidium* Inactivation



Example 4. UV Intensity and UVT Setpoint Control Strategy - Single Operational Setpoint for all Conditions (Section C.5.4)

This example uses single operational setpoint as the operating strategy, which is the same as example 1. However, this example uses both a UV intensity *and* a UVT setpoint to control the reactor operation. In this example, a MP reactor that uses the UV intensity and UVT setpoint control strategy was validated at flows between 0.1 and 0.5 mgd and a UVT range of 75 to 98 percent. This reactor passed the criteria for 3-log *Cryptosporidium* inactivation credit with a UV intensity sensor setpoint of 41 mW/cm^2 and a UVT setpoint of 85 percent.

Therefore, to claim 3-log *Cryptosporidium*, this reactor must operate under the following conditions:

- Maintain minimum UV intensity sensor setpoint of 41.0 mW/cm^2.
- Operate within a flow range of 0.1 mgd and 0.5 mgd.
- Operate within a UVT range of 85 to 98 percent.

Example 5. Calculated Dose Setpoint Control - Variable Setpoint Operation for Different Flow Conditions and Inactivation Goals (Section C.5.5)

The calculated dose control strategy uses UVT, UV intensity, and flow measurements to estimate a UV dose. For this example, a UV manufacturer has completed a matrix of tests at different flowrates, UVT, and lamp power to develop a relationship between calculated dose, log inactivation, and flow. A MP reactor that uses the calculated dose control strategy was validated at flows between 10 to 40 mgd and a UVT range of 75 to 98 percent. Table 5.13 shows the results of the validation tests.

Table 5.13 Dose Setpoints for Various Log Inactivation of *Cryptosporidium*

Cryptosporidium Log Inactivation	Calculated Dose Setpoint (mJ/cm^2)	UVT Range (%)
1.0	14	75 - 98
1.5	18	75 - 98
2.0	23	75 - 98
2.5	28	75 - 98
3.0	30	79 - 98

The validation tests as described in section C.5.5 verified that the calculated dose approach is valid for this reactor and that the calculated dose setpoints could be used for the ranges of flows tested (10 – 40 mgd). In addition, this reactor can be utilized by utilities that need different levels of *Cryptosporidium* inactivation credit. For a utility that only is required to achieve a 2.0 log inactivation credit, using this reactor would reduce energy costs compared to a reactor that had only been validated for 3-log *Cryptosporidium* inactivation credit. Therefore, this reactor could be operated at any flow between 10 and 40 mgd, the UVT range specified in

Table 5.8, and at the specified calculated dose in Table 5.13 to achieve a specific level of *Cryptosporidium* inactivation credit. For example, a reactor must operate at a minimum calculated dose of 28 mJ/cm^2 and a flow range between 10 and 40 mgd and UVT between 75 and 98 percent to achieve 2.5-log *Cryptosporidium* inactivation credit.

5.6 Operational Challenges

An excursion from validated limits can be caused by low UV intensity, low UVT, high or low flowrate, poor UV intensity sensor performance, power quality problems, or a combination of these conditions. These conditions will need to be resolved quickly to ensure regulatory compliance because they can result in prolonged off-specification operation. This section discusses some of the potential operational challenges and suggested corrective measures.

5.6.1 Low UV Intensity or Low Calculated UV Dose

Although the UV intensity and calculated dose control strategies are different, approaches for addressing either a low UV intensity or low calculated dose are typically the same. This is because the UV intensity setpoint control strategy uses UV intensity as an indicator for UV dose; therefore, the causes of a low UV intensity in a UV intensity control strategy and a low calculated dose in a calculated dose control strategy are similar.

The output of the UV lamps, UV transmittance of the sleeves, status of the UV intensity sensor, and fouling of both lamp sleeves and sensor windows affect UV intensity sensor readings. In the UV intensity setpoint control strategy, UV intensity sensors are placed far enough from the UV lamp to be affected by UVT. In the UV intensity and UVT setpoint or calculated dose setpoint control strategy, the UV intensity sensors are close to the lamps and should not be affected by UVT changes.

If one or more UV intensity sensors reads below the required setpoint, the cause could be low UV lamp output. If the UV lamp life is greater than the design life, the lamp should be replaced. If the UV intensity is still low, sensor accuracy should be determined by replacing the duty sensor with the reference sensor. If the duty and reference sensor agree within the required uncertainty (from validation), the cause of the low intensity reading may be due to UV intensity sensor surface or sensor window fouling or sleeve UV transmittance loss. Potential corrective measures include cleaning of fouled surfaces and replacement of defective sleeves.

Figure 5.4 presents a decision tree for evaluating low UV intensity problems. If the above strategies cannot be implemented or are not successful in reducing the low UV intensity, the UV manufacturer or UV installation designer should be contacted to investigate the problem further. The utility should activate any backup disinfection or consider shutting down the water treatment plant (WTP) until the UV intensity is within the validated limits. Anytime that the UV intensity is lower than the validated limit, it should be recorded as off-specification even if this does not occur at precisely the time (e.g., 4-hour interval) when the 4-hour recording is completed.

Figure 5.4 Low UV Intensity or Low Calculated UV Dose Decision Chart

5.6.2 Low UV Transmittance

This evaluation of low UVT assumes either that the low intensity evaluation has been completed and the cause of the low UV intensity was low UVT or that the operational staff has observed low UVT. Some UV reactors may increase lamp output or number of lamps in service to accommodate a decrease in UVT. If the system does not sufficiently compensate, or if the UV reactor cannot adjust lamp output, the UV intensity may go below the validated limits. The steps for evaluating low UVT are described below.

The first step is to evaluate the UVT monitor function. If UVT is monitored using an on-line instrument, the utility should verify the low reading with a bench-top spectrophotometer. If the second measurement differs significantly from the on-line instrument response, appropriate repair and calibration of the on-line instrument is necessary.

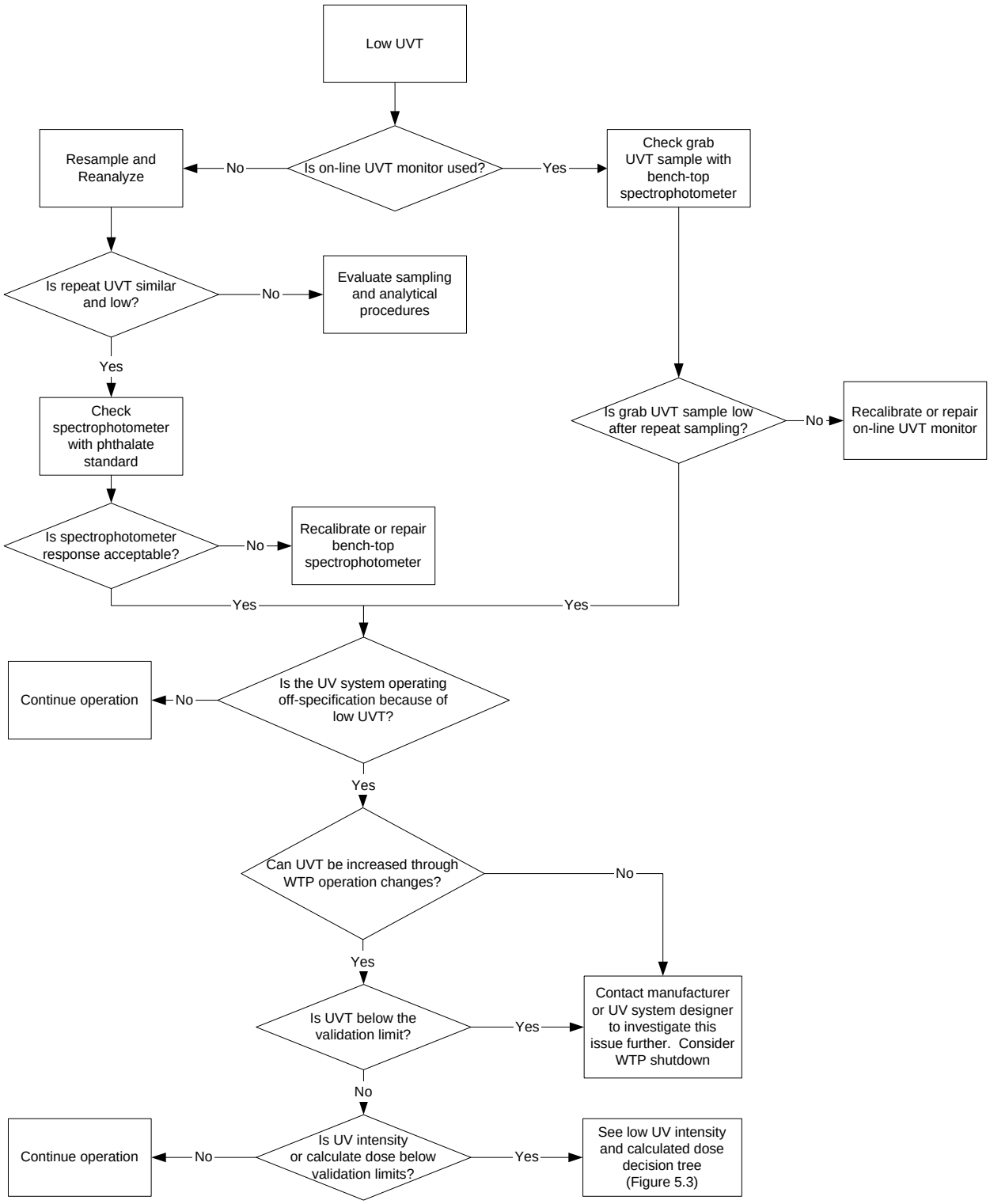
If UVT is determined using grab samples, a duplicate sample should be obtained and analyzed. If the UVT of the duplicate sample remains low, the spectrophotometer response should be checked using a phthalate standard (EPA ICR UV254 method or Standard Method 5910). If the spectrophotometer response is determined to be inaccurate, the spectrophotometer monitor should be calibrated or repaired.

If the low UVT is determined to be real and not due to a faulty instruments, it should be compared to the validated UVT set point. If UVT is below the validated UVT set point, the following operational changes should be considered:

- Vary source water blending ratio (if available) to increase UVT.
- Evaluate whether the coagulation process has been optimized for natural organic matter (NOM) removal and whether the coagulant dose should be increased. Poor coagulation caused by coagulant under-dosing can lead to increased NOM concentration and an associated decrease in UVT.
- Increase oxidant dose prior to the UV installation if possible. However, this strategy may increase disinfection byproduct (DBP) formation, which must also be evaluated if this option is used.
- Investigate potential upstream chemical interferences that may be from a process failure or upset. For example, if the ozone quenching system failed, the UVT would decrease.

If the above strategies cannot be implemented or are not successful in reducing the low UVT, the UV manufacturer or UV installation designer should be contacted to investigate the problem further. The utility may consider shutting down the WTP or activating any backup disinfection capacity until the UVT is within the validated limits. A decision tree that summarizes the approach for troubleshooting low UVT is shown on Figure 5.5. Anytime the UVT is lower than the validated limit, it should be recorded as off-specification even if it does not occur at precisely the time (e.g., 4-hour interval) that recording is completed.

Figure 5.5 High UV Absorbance Decision Chart



5.6.3 Rapid Flow Increase or High Flow

It may be possible to compensate for increased flow (depending on validation data) by completing one or more of the following actions:

- Increasing the output of the UV lamps
- Using additional lamps or banks of lamps
- Using additional UV reactors

The success of these strategies depends on the magnitude of the flowrate increase and the type and configuration of the UV reactors. These changes should occur automatically for reactors that are controlled using PLCs.

If the measured flowrate is higher than the validated limits and cannot be reduced, the flowmeter and/or differential pressure meter (if used) should be evaluated to determine if it is functioning properly. Instrument error can be assessed by comparing signals from individual flowmeters or differential pressure devices to anticipated values based on facility flowrate and historic operating data. Alternatively, a calibrated clamp-on type flowmeter may be used to verify flowrates. If the flowmeter is not operating properly, it should be repaired or replaced. If flow monitoring devices appear to be functioning properly, valve position or blockage may be the cause of unequal flow distribution and should be evaluated.

If the flow is below the validated limits, one UV reactor should be taken off-line, which will transfer that flow to the other energized reactors. This change in operation should result in the UV reactors being within the validated flow range. Anytime the flow is lower or higher than the validated limit, it should be recorded as off-specification even if it does not occur at precisely the time (e.g., 4-hour interval) that the recording is completed.

5.6.4 Unreliable UV Intensity Sensor Readings

Consistent UV intensity sensor readings are important to ensure that the UV reactors are operating within the validated limits. Unreliable UV intensity sensor readings can be described by one or more of the following behaviors:

- Calibration checks outside of uncertainty specified in the validation testing
- Random fluctuations of greater than 25 percent
- Biased readings (UV intensity sensor reading is offset from the reference sensor readings by a certain value)

Unreliable UV intensity sensor readings can be due to UV intensity sensor malfunction, condensation in the sensor or between the sensor and sensor window, lamp malfunction, poor grounding, degradation of sensor electronics, or electronic short circuits.

The UV intensity sensor and lamp electrical cables should be secured, and a reference or standby sensor should be compared to the duty sensor reading. If the duty sensor is found to be defective or out of calibration, it should be sent to the manufacturer for repair, and the standby sensor used in its place.

5.6.5 Power Quality Problems

UV lamps can potentially lose their arc if a voltage sag, power quality anomaly, or a power interruption occurs. Voltage sags as little as 10 to 15 percent from the nominal voltage for as few as 2 to 5 cycles can cause a UV lamp to lose its arc. LP lamps generally can return to full operating status within 15 seconds after power is restored. LPHO and MP lamps will need to be re-struck, which generally requires between 4 and 10 minutes to get to full lamp power, to restart. LPHO and MP lamps are affected differently from power losses as discussed in more detail in section 3.1.3.3.

The corrective actions for short-term power failures (e.g., voltage sag) are different for LPHO and MP reactors. LPHO lamps need to warm-up before the arc can be struck, and MP lamps need to be cooled before the arc can be struck. Standby MP reactors (i.e., not in operation when voltage sag occurred) should be energized instead of "warm" reactors because they will take less time to restore operation to within validated limits because the UV lamps do not have to cool down before re-striking. However, installations using LPHO reactors should energize their "warm" reactors (i.e., the reactors on-line when the voltage sag occurred) instead of standby LPHO reactors because the UV lamp warm-up time will be less compared to a cold LPHO reactor.

For long-term power failure (e.g., > 5 minutes) without a UPS system, the UV reactors should be powered by the backup generator until power is restored. When power is restored, the shift from the backup generator will likely cause the UV lamps to lose their arc again.

Given the restrictions on operation outside of validated limits (section 1.3.1.3), the utility should stop water flow through the UV reactors when the lamps are not operating. Also, utilities should consider installing a UPS if power quality problems are frequent because a standby generator alone may not adequately alleviate frequent, off-specification flows due to power quality problems. A UPS system delivers consistent, continuous power even when power problems occur.

5.7 Staffing Issues

In order to provide consistent and reliable operation of UV reactors, the utility needs to have appropriate staffing, training, and safety measures in place. This section discusses these issues.

5.7.1 Staffing Levels

During start-up operation, a UV reactor will need more operator attention to assist with functional and performance testing and to establish site-specific O&M procedures (described in section 5.1.4). However, a typical UV installation needs little operator attention during normal operation, depending on the level of automation. Generally, UV installations use PLCs to monitor operating parameters, control the UV reactor, and generate alarms. Increased automation (e.g., remote monitoring capability) may be incorporated to further reduce operator requirements. Table 5.14 describes how various site-specific factors affect staffing needs for a UV installation.

Table 5.14 Factors Impacting Staffing Needs

Factor	Impact on Staffing
Type of UV reactor	LP and LPHO reactors may need more maintenance compared to a MP reactor because they have more lamps and usually employ OCC cleaning. However, MP lamps will probably need to be replaced more often than LP lamps.
Instrumentation and control strategy	More automated control strategies will result in lower staffing levels due to enhanced remote operation and monitoring capability.
Water quality	Sleeve fouling and cleaning frequency is affected by water quality and the design of the UV reactor. These in turn impact the staffing needs for manual cleaning for OCC systems and for maintaining the OMC system.

5.7.2 Training

Training is necessary for all personnel who are associated with the UV installation, including operators, maintenance workers, instrumentation technicians, electricians, laboratory staff, custodial staff, engineers, and administrators. The training program should incorporate any State requirements and should emphasize both normal and emergency operating procedures, safety issues, process control and alarm conditions, validated operation, and response to deviations.

The UV manufacturer and UV installation designer should provide training on the UV reactors, UV installation design, and operation and maintenance activities. It is recommended that training include both classroom instruction and field training. In addition, actively involving the operating staff during start-up will provide another opportunity to reinforce classroom instructions. Continued training should be provided when new employees are hired or when a process or control alteration is made.

5.7.3 Safety Issues

The Office of Safety and Health Administration (OSHA) issues regulations and guidance to support operator safety in the workplace. There may also be specific safety requirements imposed by the State. In addition to the standards and procedures established for WTP operations, the following safety issues pertain specifically to UV reactors:

- UV light exposure
- Electrical safety
- Burns from hot lamps or equipment
- Abrasions or cuts from broken lamps
- Potential exposure to mercury from broken lamps - Over-exposure to UV light can cause eye injury and skin damage.

Threshold Limit Values (TLVs) are issued biannually by the American Conference of Governmental Industrial Hygienists (ACGIH). The TLVs for UV radiation apply to occupational exposure to UV incident on the skin or eye. The recommended TLVs depend on the lamp wavelengths emitted and the irradiance (mW/cm^2); the utility can determine the appropriate TLV for their UV reactors, using the *TLVs for Chemical Substances and Physical Agents and Biological Exposure Indices* (ACGIH 2002). These values are not enforceable standards but should be considered when establishing operational procedures. To limit or prevent operator exposure to the UV light, UV reactors should have interlocks that deactivate the lamps when reactors are accessed. Viewing ports, if provided, should be fitted with UV filtering windows, or operators should wear a UV resistant face shield when looking at lamps or the reaction chamber. In addition, warning signs should be placed to minimize the danger of exposure.

To reduce the risk of electrical shock, the main electrical supply to the UV reactors should be disconnected and the operator should wait at least 5 minutes for the lamps to cool down and energy to dissipate before any maintenance is performed. All safety and operation precautions required by the National Electric Code (NEC), OSHA, local electric codes, and the UV manufacturer should be followed and include the following precautions:

- Proper grounding
- Lockout, tag-out procedures
- Use of proper electrical insulators
- Installation of safety cut-off switches

The ballasts and the reactor chamber can also become hot during operation. The temperature of these components should be assessed prior to contact.

Broken lamps pose two potential safety hazards. The lamps and sleeves are constructed of quartz tubing, which can fracture and cause serious cuts or injury. In addition, broken lamps may release mercury. Operators should be trained in proper mercury cleanup and disposal procedures to prevent mercury inhalation or absorption through the skin. Appendix N discusses potential mercury cleanup procedures.

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Appendix A. Fundamentals of UV Disinfection

This appendix supplements Chapter 2, Overview of UV Disinfection, with an additional level of detail. The purpose of this appendix is to provide technical information regarding the physical mechanisms of UV light generation, biological reactions causing disinfection, and UV reactor equipment. The organization of this appendix is presented below, including the key questions addressed by each section.

- How is UV light generated?.....Section A.1.1
- What happens to UV light as it propagates through water?.....Section A.1.2
- How does UV light inactivate microorganisms? .....Section A.2.2
- Can microorganisms undergo repair and become infectious after inactivation by UV light?.....Section A.2.3
- How is UV dose determined in a bench-scale (batch) system?.....Section A.2.4.1
- How does UV dose vary in a UV reactor?.....Section A.2.4.2
- How do microbial dose-response curves differ?.....Section A.2.5
- What factors influence microbial dose-response? .....Section A.2.6
- Do all microorganisms have the same sensitivity to UV light? .....Section A.2.7
- What are the components of a UV installation? .....Section A.3
- How do low pressure, low-pressure high-output, and medium pressure lamps differ?..... Section A.3.1.2-A.3.1.4
- What happens to UV lamps as they age?.....Section A.3.1.6
- How are UV lamps powered?.....Section A.3.2
- What is the function of the lamp sleeve?.....Section A.3.3
- How are lamp sleeves cleaned and why is it necessary to clean them? .....Section A.3.4
- How is UV light monitored in a reactor?.....Section A.3.5
- How are the components of a UV reactor arranged?.....Section A.3.8

- How do the utility and the State know the UV reactor is delivering the required UV dose? ..... Section A.3.9
- What are the impacts of water quality on UV disinfection? ..... Section A.4.1
- Do any disinfection byproducts form as a result of UV disinfection? ..... Section A.4.2

A.1 UV Light Generation and Propagation Through Liquid Media

Using UV light to disinfect drinking water involves generating UV light with the desired germicidal properties and subsequently delivering that light to the target pathogens. This section describes fundamental concepts related to the generation and transmission of UV light.

A.1.1 UV Light Generation

Atoms and ions emit light when they change from a higher to a lower energy state. An atom and most ions consist of electrons orbiting a nucleus of protons and neutrons. The electrons in each orbital occupy a unique energy state, where the electrons closest to the nucleus have a lower energy and the electrons further away have a higher energy. When an electron makes a transition from a higher energy state to a lower energy state, a discrete amount of energy is released as photons of light at a particular wavelength (λ) according to Equation A.1.

$$E_2 - E_1 = \frac{hc}{\lambda} \qquad \text{Equation A.1}$$

where

E_1	=	Lower energy state (J)
E_2	=	Higher energy state (J)
h	=	Planck's Constant (6.626×10^{-34} J•s)
c	=	Speed of light (2.997×10^{8} m/s)
λ	=	Wavelength (m)

Energy levels of a given atom or ion are unique and depend on the number of electrons, protons, and neutrons within that atom or ion and their interaction with external force fields. As such, each element emits a unique spectrum of light. If the difference between energy levels is appropriate, the light emitted is in the UV range.

A transition from a lower to a higher energy state requires an energy input. This energy may be derived from the collision of the atom with a photon of light of wavelength λ or by collision with other atoms, ions, or electrons. Energy transferred to the atom may result in an increase in the atom's kinetic energy, the transfer of an electron to a higher energy level, or the removal of an electron from the atom. Removal of an electron from the atom is termed ionization and results in a positively charged cation and a negatively charged free electron. The energy required to remove an electron from an atom is termed the ionization energy.

Recombination of a free electron and a cation may result in the emission of light. Since the free electron and cation may have a range of kinetic energies, the wavelength of emitted light will vary. The wavelength range will be bound by the ionization energy of the atom, and there will be a peak within the rage that depends on the temperature of the electrons and cations. The following sections discuss the relationship between atomic energy states and the generation of UV light through gas and mercury discharges.

A.1.1.1 Gas Discharges

A gas discharge is a mixture of non-excited atoms, excited atoms, cations, and free electrons formed when a sufficiently high voltage is applied across a volume of gas. The wavelength of light emitted from the gas discharge depends on the elemental composition of the gas discharge and the excitation, ionization, and kinetic energy of those elements.

The formation of the gas discharge within a UV lamp involves several stages. When a voltage is first applied, free electrons and ions present in the gas are accelerated by the electric field formed between two electrodes. Initially, the concentration of free electrons and ions arises from natural radioactivity and is very low. With sufficient voltage, the electrons are accelerated to high kinetic energies. Collisions of the free electrons with atoms result in a transfer of energy to the atoms. If the energy transferred is sufficient, the atoms are ionized. This ionization provides a rapid increase in the number of free electrons and cations, a corresponding increase in lamp current, and a drop in the voltage across the lamp.

Cations colliding with an electrode cause electrons to be emitted. If sufficient electrons are emitted, a self-sustaining discharge termed a glow discharge occurs. Initially, only a small fraction of each electrode emits electrons. With an increase in current, this area increases until the entire electrode is in use. To increase the current beyond that point, the voltage is increased to provide more kinetic energy to the cations. High energy cations that collide with the electrode increase the electrode's temperature. At sufficiently high temperatures, the electrode begins to thermally emit electrons, and a further increase in current reduces the voltage requirement. At this point, the electrode discharge is termed an arc discharge.

The start voltage, which is the voltage required to start the gas discharge, is typically higher than the ionization potential of the gas unless a means is used to introduce electrons. Preheating the electrode or producing a strong local field using a third electrode located close to one of the electrodes can be used to introduce electrons and aid in starting the gas discharge.

A gas discharge has a negative impedance that is intrinsically unstable unless a ballast is placed in series to provide a positive impedance to the power supply. With a direct current (DC) supply powering the gas discharge, the ballast is a resistor. With an alternating current (AC) supply, the ballast is either an inductor, capacitor, or some combination of those components. Inductors and capacitors are preferred over resistors because they do not consume power. More detail on ballasts is presented in section A.3.2.

The frequency of the AC supply impacts the performance of the gas discharge. If the frequency of the AC supply is low (<< 1 kHz), electron-cation recombination extinguishes the discharge every half cycle of the lamp voltage. Re-ignition during the next half cycle is

facilitated by electron emission from the still warm electrodes. If the frequency of the AC supply is greater than 1 kHz, the free electrons and cations do not have sufficient time to recombine and the discharge does not extinguish.

A.1.1.2 Mercury Discharges

Mercury in a gas discharge is used to generate the UV light produced in most commercial UV lamps. Mercury is an advantageous element for UV disinfection due to the following factors:

- Electron transitions within mercury provide electromagnetic energy in the germicidal wavelength range.
- Mercury at low vapor pressure and near room temperature produces light at wavelength 253.7 nm from electrical energy with high efficiency. This wavelength is near optimal for UV disinfection (section A.2.2).
- Mercury at high vapor pressures produces high intensity polychromatic UV light with reasonably high efficiency.
- Mercury has a low ionization energy; therefore, free electrons and cations required for the formation of a gas discharge are easily created using a relatively low start voltage.
- Mercury reacts minimally with the lamp envelope and electrode materials.

The wavelength and magnitude of light output from a mercury discharge depend on the concentration of mercury atoms, which is directly related to the mercury pressure. At low pressures of 0.001 to 0.01 torr (2×10^{-5} to 2×10^{-4} psi), the concentration of mercury is low, and the distance electrons travel between collisions is relatively long. Electrons achieve higher kinetic energies with the longer travel distance. Collisions between those free electrons and mercury atoms excite mercury to the first energy state above the lowest or ground state. Transition of electrons back to ground state results in the emission of electromagnetic energy at 253.7 and 185 nm. UV lamps with this type of mercury discharge are commonly referred to as low pressure (LP) lamps.

At higher mercury pressures (100 to 10,000 torr; 2 to 20 psi), a much greater collision frequency occurs between free electrons and mercury. This increases the energy state of the mercury atoms and cations to near that of the electrons and increases the temperature of the gas discharge to near 6,000 °C. When the atoms return to lower energy states, electromagnetic energy at several wavelengths in the UV light and visible light regions is produced. Recombination of free electrons and mercury cations produces a small continuum of UV light between 200 and 245 nm. UV lamps with this type of discharge are called medium pressure (MP) lamps.

A.1.2 UV Light Propagation

This section details the effects that the UV reactor and the water being treated have on the propagation of UV light. As UV light propagates, it interacts with the materials it encounters through absorption, reflection, refraction, and scattering.

A.1.2.1 Absorption

Absorption is the transformation of light to other forms of energy as it passes through a substance. UV absorbance is the water quality parameter that measures the extent to which the intensity of UV light is reduced as it passes through water. The impact of absorption on the intensity light as it travels through a substance is calculated as follows:

$$\frac{I_2}{I_1} = 10^{-\sum \varepsilon_i c_i d} = 10^{-a_{10} d} = 10^{-A_{254}} = e^{-\alpha_e d} \qquad \text{Equation A.2}$$

where

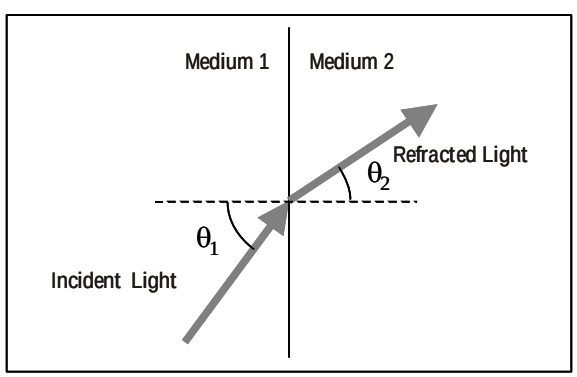
I_1	=	Light intensity incident on a cell (mW/cm^2)
I_2	=	Light intensity passing through a distance, d, in the cell containing a solution with various absorbing components (mW/cm^2)
d	=	Distance traveled by light through the cell (cm)
ε_i	=	Molar absorption coefficient of component i (L/mol/cm)
c_i	=	Concentration of component i (mol/L)
a_{10}	=	Decadic (base 10) absorption coefficient, (cm^{-1})
A_{254}	=	Decadic (base 10) absorbance (unitless)
α_e	=	Naperian (base e) absorption coefficient (cm^{-1})

When UV light is absorbed, it is no longer available to disinfect microorganisms.

A.1.2.2 Refraction

Refraction (Figure A.1) is the change in the direction of light propagation as it passes from one medium to another.

Figure A.1 Refraction of Light



Refraction is governed by Snell's Law, which is shown in Equation A.3:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{Equation A.3}$$

where

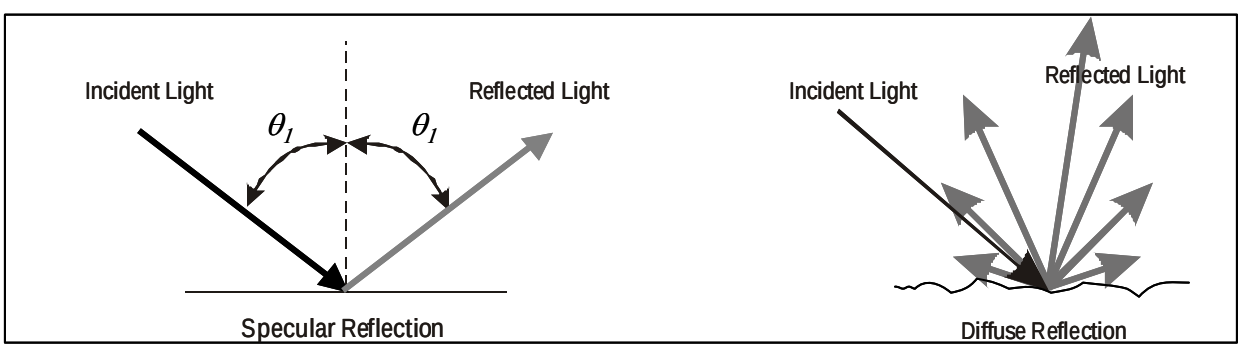
n_1	=	Index of refraction of the first media
n_2	=	Index of refraction of the second media
θ_1	=	Incident angle on the interface
θ_2	=	Exit angle from the interface

In UV reactors, refraction occurs when light passes from the lamp through an air gap, through the lamp sleeve, and into the water. Although refracted light is still available for disinfection, refraction changes the angle that the light strikes target pathogens.

A.1.2.3 Reflection

Reflection is the change in the direction of light propagation when it is deflected by the interface between two media (Figure A.2). Reflection may be classified as specular or diffuse. Specular reflection occurs at smooth polished surfaces where the roughness of the surface is smaller than the wavelength of light. Reflection from specular surfaces follows the Law of Reflection, which states that the angle of incidence is equal to the angle of reflection. Diffuse reflection occurs at rough surfaces. Light is scattered in all directions with little dependence on the incident angle. The intensity of diffuse reflected light is proportional to the cosine of the reflectance angle. Reflected light is still available for disinfection.

Figure A.2 Specular and Diffuse Reflection of Light



In a UV reactor, reflection will take place at UV-transmitting interfaces like an air-quartz interface and at also interfaces that do not transmit UV light like the reactor wall. The intensity of reflected light from a UV-transmitting interface is governed by Fresnel's Law, which is shown in Equation A.4.

$$R = \frac{1}{2}\left[\left(\frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2}\right)^2 + \left(\frac{n_2 \cos\theta_1 - n_1 \cos\theta_2}{n_1 \cos\theta_2 + n_2 \cos\theta_1}\right)^2\right] \qquad \text{Equation A.4}$$

where

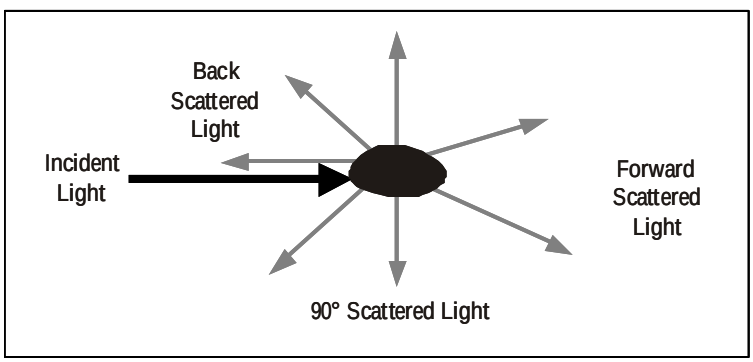
R	=	the ratio of reflected intensity to incident intensity
n_1	=	Index of refraction of the first media
n_2	=	Index of refraction of the second media
θ_1	=	Incident angle onto the interface
θ_2	=	Reflected angle from the interface

The intensity of reflected light from a non-transmitting interface depends on the material, incident angle, wavelength of light, and nature of the surface. Currently, most UV reactors are constructed of stainless steel, which reflects 24 percent of UV light at 254 nm at a zero degree incident angle (Jagger 1967). This indicates that 76 percent of the light energy reaching the reactor wall is lost. In the future, UV reactors may be developed using materials that reflect more light, which may improve efficiency.

A.1.2.4 Scattering

Scattering of light is the change in direction of light propagation caused by interaction with a particle (Figure A.3). Scattered light is still capable of disinfecting microorganisms.

Figure A.3 Scattering of Light



Rayleigh scattering is the scattering of light by particles that are smaller than the wavelength of the light. With Rayleigh scattering, light is scattered uniformly in all directions at an intensity inversely proportional to the wavelength of light to the fourth power ($1/\lambda^4$). As such, scattering is more evident at shorter wavelengths. For example, the intensity of scattered light at 200 nm is five times greater than at 300 nm because $1/(200^4)$ is over five times greater than $1/(300^4)$. Particles in water that cause Rayleigh scattering of UV light at 254 nm include small viruses and large molecules (25 to 300 nm). With larger particles, the scattering observed is non-uniform, and more light is scattered in the forward direction. The larger particles also cause backscattering, which is nearly independent of the wavelength of light.

A.1.2.5 UV Absorbance and UV Transmittance

UV absorbance (A_{254}) is a commonly used water quality parameter that characterizes the decrease in the amount of incident light as it passes through a water sample over a specified distance or pathlength. If the measurement is made according to a modified version of Standard Method 5910B (APHA et al. 1998) where the water sample is not filtered or pH adjusted, the modified measurement accounts for scattering and some absorption from particles in the water sample that may interfere with UV disinfection. Although the Standard Method identifies this measurement as UV absorption, this manual will refer to it as UV absorbance since the latter term is widely used in the water treatment industry.

The term UV transmittance (UVT) has also been used extensively in the literature when describing the behavior of UV light. UVT is the percentage of light passing through a water sample over a specified distance and is related to UV absorbance by Equation A.5:

$$\% \ UVT = 100 * 10^{-A_{254}} \qquad \text{Equation A.5}$$

where

UVT = UV Transmittance at specified wavelength (e.g., 254 nm) and pathlength (e.g., 1 cm)

A_{254} = UV Absorbance at specified wavelength, based on 1 cm pathlength (unitless; UV absorption as measured by Standard Method 5910B)

Since UV light scattered from particles is capable of disinfecting microorganisms, it should be considered when assessing UVT. Much of the scattered light is in the forward direction and is a significant portion of the transmitted UV light. Typically, conventional spectrophotometers use narrow beams of light and small detectors that will not measure the forward scattered light and therefore underestimate the effective UVT of the water sample (Jagger et al.1975; Linden and Darby 1998). However, spectrophotometers can be equipped with integrating spheres (Linden and Darby 1998) or detectors capable of measuring forward scattered light (Jagger et al. 1975) in order to provide a proper assessment of the UVT of water samples with significant scattering.

A.1.2.6 Estimating UV Light Intensity Within a UV Reactor

The distribution of light intensity about a UV lamp is influenced by the shape of the lamp and the absorption, refraction, scattering, and reflection of light. Complex models factoring all of these effects can be used to determine the intensity profile about a lamp, and simplified models can be used to approximate those profiles. These models are useful tools for understanding the impact of UV absorbance, UV reactor properties, and UV reactor dimensions on UV dose delivery and measurements of UV intensity.

If the distance from the lamp is greater than the radius of the arc discharge, the lamp can be treated as a line source to estimate the intensity. For LP lamps, since the arc discharge fills the entire lamp, the radius is the same as the lamp radius. For MP lamps, the arc discharge is much smaller than the radius of the lamp. There are two approaches commonly used for modeling a line source: the radial model and the point source summation model. If the distance

from the lamp is smaller than the radius of the gas discharge, more complex modeling tools must be used.

The **radial model** provides a two-dimensional representation of a three-dimensional intensity profile. The model assumes light is emitted perpendicular from the line source in the radial direction as per Equation A.6:

$$I(r) = \frac{P_L}{2\pi r} e^{-\alpha_e r} \qquad \text{Equation A.6}$$

where

P_L	=	UV power emitted per unit arc length of the line source (mW/cm)
r	=	Radial distance from the line source (cm)
α_e	=	Naperian (base e) absorption coefficient of the media (cm^{-1})
I(r)	=	UV intensity (mW/cm^2) at a distance r from the line source

The **Point Source Summation model** (Jacob and Dranoff 1970) treats the lamp as a series of point sources radiating uniformly in all directions. The UV intensity at a point within the reactor is the sum contribution from each of these points as per Equation A.7.

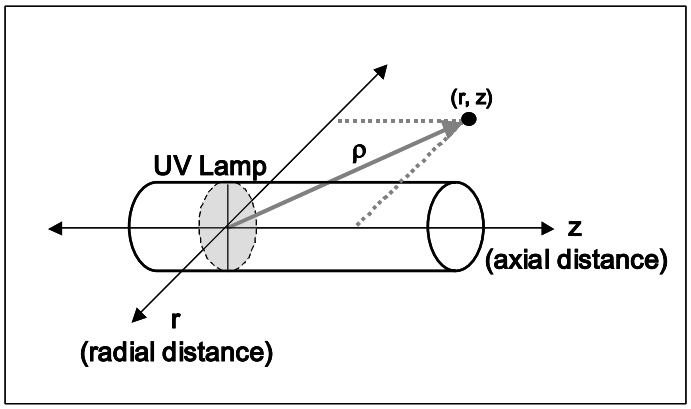
$$I(r,z) = \sum \frac{P_p}{4\pi \rho_i^{\,2}} e^{-\alpha_e \rho_i} \qquad \text{Equation A.7}$$

where

P_p	=	UV power emitted by each point source (mW)
i	=	Number of point sources used to simulate the lamp
ρ_i	=	Distance from the ith point source (cm)
α_e	=	Naperian (base e) absorption coefficient of the media (cm^{-1})
r	=	Radial distance from the lamp (cm)
z	=	Axial distance along the lamp (cm)
I(r,z)	=	UV intensity (mW/cm^2) at a coordinate position (r,z)

The radial and axial distance from the lamp are shown in Figure A.4.

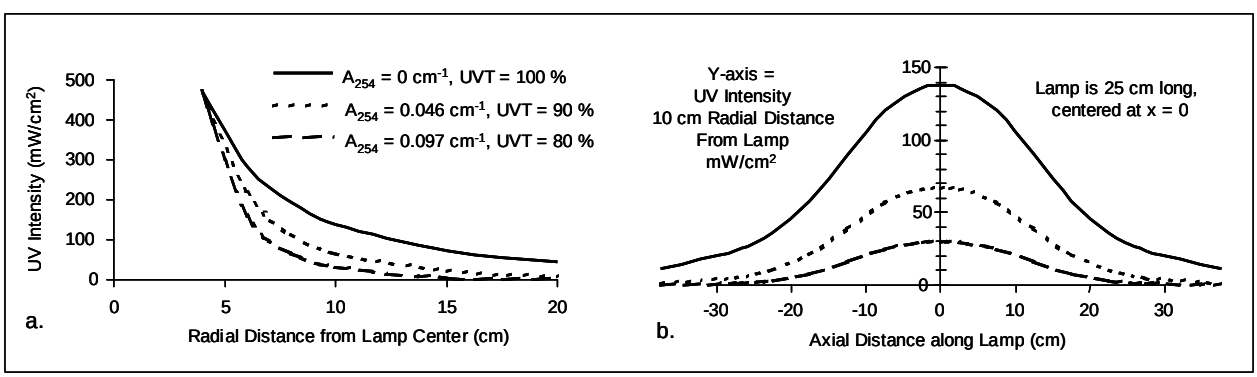
Figure A.4 Radial and Axial Distance from a UV Lamp



Note: The point where z = 0 is arbitrary. It can be at the lamp ends or anywhere along the lamp length.

For a 25 cm long UV lamp housed in a lamp sleeve (radius = 4 cm) and immersed in water, Figure A.5 presents the intensity profile predicted using Point Source Summation as a function of radial and axial distance and the water UV absorbance. For a given radial distance, the model predicts a greater UV intensity at an axial position corresponding to the center of the lamp than at an axial distance corresponding to the lamp ends. The model also demonstrates that UV intensity will decrease with increased distance from the lamp even in water that does not absorb UV light (i.e., $A_{254} = 0$) due to the divergence of UV light from the source. Last, the model predictions show that the water UV absorbance has a profound impact on the UV intensity profile about a UV source.

Figure A.5 UV Intensity Profile of a 25 cm Medium-Pressure Mercury Arc Lamp as a Function of (a) Radial and (b) Axial Position for Waters with Different UV Absorbance



More advanced models of the intensity profile about a lamp account for the impacts of refraction and reflection from reactor components as the light propagates from the discharge

(Bolton 2000), the three-dimensional nature of the gas discharge (Irazoqui et al. 1973), and the direction of light emission (Phillips 1983).

A.2 Microbial Response to UV Light

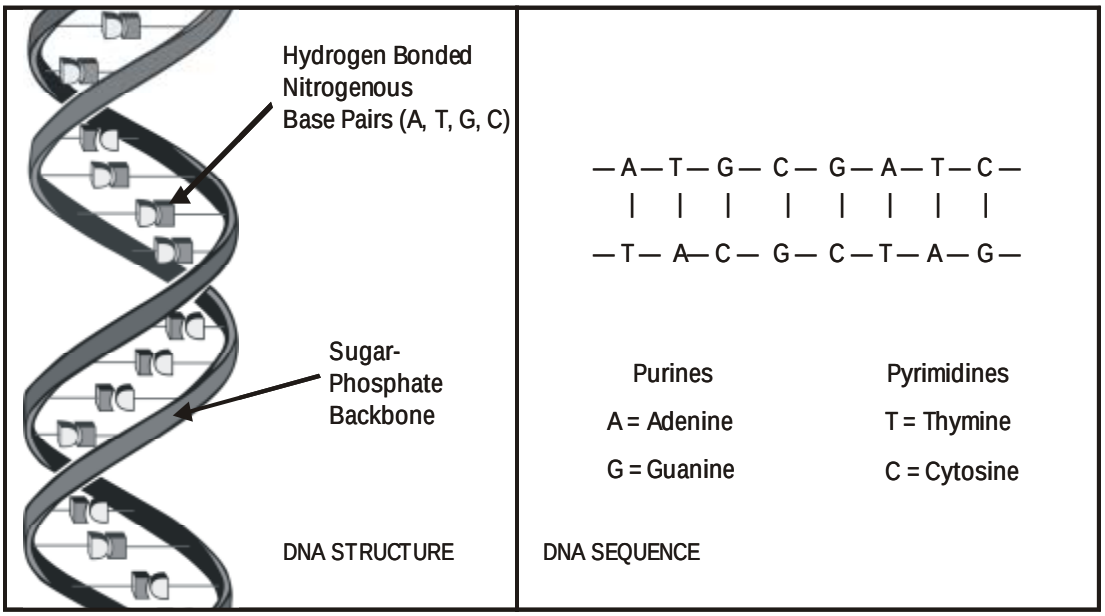
Disinfection by UV light differs from chemical disinfectants such as chlorine and ozone. Chemical disinfectants inactivate microorganisms by destroying or damaging cellular structures, thereby interfering with metabolism, biosynthesis, and growth (Snowball and Hornsey 1988). In UV disinfection, microorganisms are inactivated by inducing damage to their nucleic acid such that they can no longer reproduce. This section discusses nucleic acid structure, the damage that causes microbial inactivation, the ability of microorganisms to repair the damage, methods for determining microbial inactivation, and factors that affect inactivation.

A.2.1 DNA/RNA Structure

Nucleic acid is a fundamental building block of life and is responsible for reproduction and defining the nature of life. The nucleic acid is either deoxyribonucleic acid (DNA) or ribonucleic acid (RNA). The nucleic acid within the nucleus of most cells, including bacteria and protozoa, is composed of double stranded DNA. DNA contains the information necessary for the synthesis of ribosomal, transfer, and messenger RNA, which are responsible for synthesizing enzymes that drive metabolic processes within the cell. The genetic material of viruses may either be DNA or RNA and can be single or double stranded.

DNA and RNA are long polymers comprised of combinations of four nucleotides. In DNA, the nucleotides are purines (adenine and guanine) and pyrimidines (thymine and cytosine). In RNA, the nucleotides are the same except that uracil replaces thymine. Each nucleotide can be broken down into two parts – a sugar-phosphate backbone and a nitrogenous base (Figure A.6). If the nucleic acid is double-stranded, nucleotides on one strand will compliment those on the other strand. Adenine pairs with thymine in DNA (or uracil in RNA) while guanine pairs with cytosine. Hydrogen bonds form between each pair (Figure A.6).

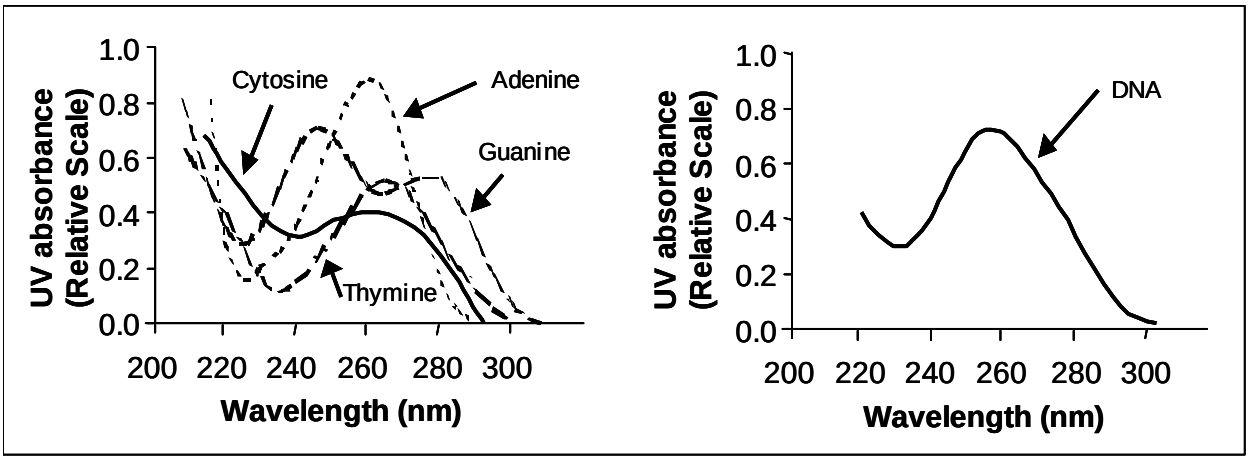
Figure A.6 Structure of DNA and Nucleotide Sequences Within DNA



A.2.2 Mechanism of Inactivation by UV Light

UV light inactivates microorganisms by damaging DNA or RNA, thereby interfering with replication of the microorganism. Only light that is absorbed by a system can induce a chemical reaction (First Law of Photochemistry). As shown in Figure A.7, nucleotides absorb UV light in from 200 to 300 nm, which enables the photobiological effects that lead to nucleic acid damage. The UV absorption of nucleic acid is a combination of the absorbance of the nucleotides and has an absorption peak near 260 nm and a local minimum near 230 nm.

Figure A.7 UV Absorbance of Nucleotides and Nucleic Acid at pH 7 (adapted from Jagger 1967)



While both purines and pyrimidines strongly absorb UV light, the rate of UV-induced damage is greater with pyrimidines (Jagger 1967). Absorbed UV light induces six types of damage within the pyrimidines of nucleic acid (Setlow 1967; Snowball and Hornsey 1988; Pfeifer 1997), with varying levels of effectiveness dependent on UV dose:

- **Single and double strand breaks** are only significant with UV doses several orders of magnitude higher than those practical for UV disinfection.

- **DNA-DNA cross-links** are covalent bonds between two different strands of DNA, and they are also only significant with UV doses orders of magnitude higher than those practical for UV disinfection.

- **Protein-DNA cross-links** are covalent bonds between a protein and a DNA strand, and they may be important for the disinfection of certain microorganisms such as *Micrococcus radiodurans*.

- **Pyrimidine hydrates** do not contribute to UV disinfection.

- **Pyrimidine (6–4) pyrimidine photoproducts** are a major class of UV damage.

- **Pyrimidine dimers** are covalent bonds between two pyrimidines on the same DNA strand, and they are the most common damage resulting from UV disinfection.

While it is possible for thymine-thymine, cyctosine-cytosine, and thymine-cytosine dimers to form within DNA, thymine-thymine dimers are the most common. However, since thymine is not present in RNA, uracil-uracil and cytosine-cytosine dimers are formed. Microorganisms with DNA rich in the thymine tend to be more sensitive to UV disinfection (Adler 1966).

Dimers cause faults in the transcription of information from DNA to RNA, which in turn results in disruption of cell metabolism. However, damage to nucleic acid does not prevent the cell from undergoing metabolism and other cell functions. As discussed in the next section, enzyme mechanisms within the cell are capable of repairing some of the damage to the nucleic acid. To directly damage the internal structure of the cell, UV doses much higher than those required for inactivation are necessary (Brandt and Giese 1956).

A.2.3 Repair Mechanisms

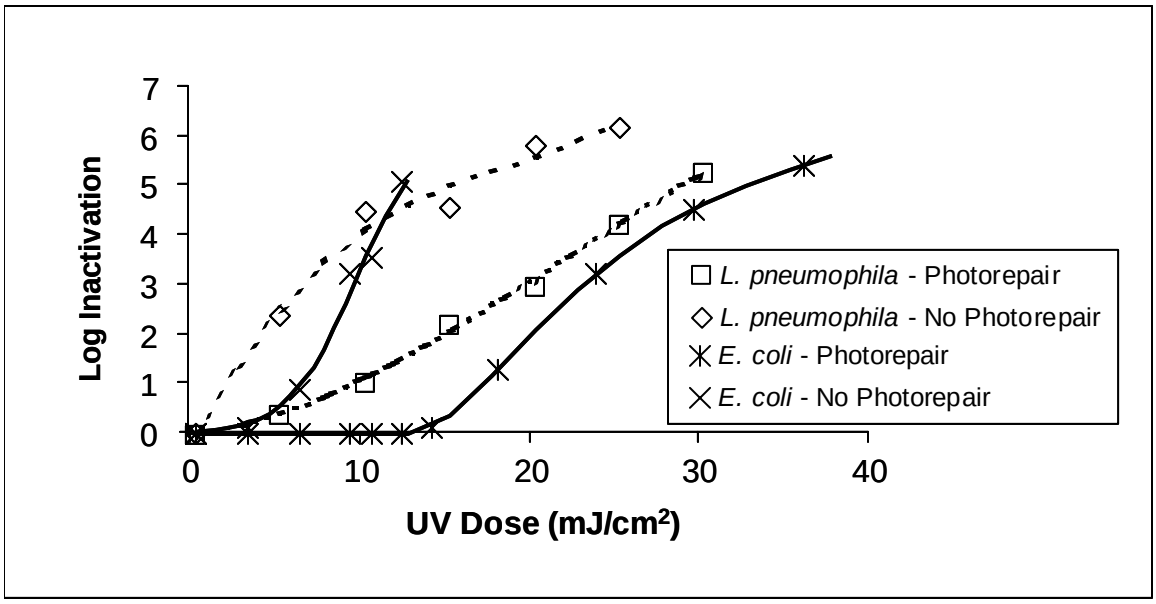
Because microorganisms that have been exposed to UV light still retain metabolic functions, some are able to repair the damage done by UV light and regain infectivity. Repair of UV light-induced DNA damage includes photoreactivation and dark repair (Knudson 1985). At the doses typically used in UV disinfection, microbial repair can be controlled and accounted for as discussed in section 3.1.1.

A.2.3.1 Photoreactivation

Photreactivation or photorepair is the cleaving of pyrimidine dimers by the enzyme DNA photolyase (Setlow 1967). The repair mechanism is termed photorepair because exposure of the enzyme to light between 310 and 490 nm is needed to activate the enzyme and provide it with the energy necessary to split the paired dimers.

Figure A.8 shows the difference in UV dose necessary to achieve a certain log inactivation with and without considering photoreactivation for two organisms. Photorepair varies with different microorganism types, different species, and different strains of a given species. The extent of photorepair depends on many factors, including type of microorganism, degree of inactivation, time between exposure to UV light and photoreactivating light, and the nutrient state of the microorganism.

Figure A.8 Repair of *L. Pneumophila* and *E. Coli* (adapted from Knudson 1985)



Photoreactivation increased the UV dose necessary to achieve 3-log inactivation of seven *Legionella* species between 1.1 and 6.3 fold (Knudson 1985). Photoreactivation also increased the dose necessary for 4-log inactivation of twelve species of bacteria by 1.2 to 3.5 fold (Hoyer 1998). However, Shin et al. (2001) did not observe photorepair with *Cryptosporidium parvum*.

Although viral DNA does not have the necessary enzymes for repair, the photorepair of viral DNA can occur using the enzymes of their host cells. Lytle (1971) reported that the photorepair of Herpes simplex virus by mammalian cells varies significantly, depending on the host cell. RNA viruses lack the ability to photorepair in a host cell (Rauth 1965).

Kelner (1950) reported that the ratio of UV dose necessary to achieve a certain log inactivation with and without considering photorepair is independent of the degree of inactivation. However, more recent research by Lindenauer and Darby (1994) reported that the

effect of photorepair of coliform bacteria in wastewater becomes less pronounced as UV dose increases. Knudsen (1985) also found a slight reduction in the ability of *Legionella* in wastewater to repair after higher inactivation levels.

The time between UV light exposure and exposure to photoreactivating light has a significant effect on the ability to photoreactivate. Dulbecco (1950) reported that the ability of T2 phage to repair using *E. coli* as a host organism decreases as the time between exposure to UV light and photoreactivating light increases. Kelner (1950) reported that *E. coli* at 37 °C in a nutrient broth lost the ability to photorepair after 140 minutes in the dark after exposure to UV light (the same time the survivors took to attempt cell division). In the same study, cells kept at colder temperatures maintained their ability to photorepair for several hours longer.

The rate of photorepair is constant with time until it reaches saturation, where saturation is defined as the maximum amount of repair possible by the microorganism given its repair ability and the extent of damage. Kashimada et al. (1996) reported photorepair saturation of *E. coli* occurs after 2 hours of exposure under fluorescent lighting. With exposure to sunlight, however, they reported photorepair saturation after 15 minutes followed by inactivation that was attributed to the UV component of sunlight. The rate of repair increases with temperature (Kelner 1950) but is nearly independent of the reactivating light intensity (Setlow 1967), suggesting photorepair is rate limited by the enzyme concentration within the microorganism.

The nutrient state of the microorganism also impacts the ability to photorepair. Giese et al. (1954) reported that a starved strain of paramecium, *Colpidium colpoda*, needed more reactivating light to reach saturation than organisms with sufficient nutrients.

A.2.3.2 Dark Repair

Dark repair is when repair processes do not need reactivating light. The term is somewhat misleading because dark repair can occur in the presence of light and therefore does not need dark conditions. The forms of dark repair include excision repair, recombinational repair, and inducible error prone repair. Excision repair, the most common form of dark repair, is an enzyme-mediated process involving four steps:

1. Repair endonnuclease enzyme recognizes the DNA damage and cleaves the DNA strand.

2. Exonuclease enzyme excises the damaged section.

3. DNA polymerase rebuilds the removed section using the complementary strand as a template.

4. Polynucleotide ligase rejoins the severed strand.

One study (Knudsen 1985) examined two different strains of *E. coli*: one that has the enzymes necessary for repair (B/R strain) and one that lacks the necessary repair enzymes ($recA^-$ uvr^- strain). The difference in UV dose needed for 1-log inactivation of the strain capable of repair was over two orders of magnitude higher than the dose needed for 1-log inactivation of the

repair deficient strain, indicating that dark repair impacts the UV dose-response of microorganisms.

Based on the difference in UV sensitivity of repair proficient and deficient bacteria, Jagger (1967) discovered that roughly 99 percent of repair that occurs is dark repair. However, the rate at which dark repair occurs is unknown. It is possible that microorganisms have dark repaired prior to the microbial assay, and dark repair is not detected. Therefore, the effects of dark repair can be difficult to measure. Unlike bacteria, viruses do not have the enzymes necessary for dark repair. However, virus can repair in the host cell using the host cells' enzymes (Rauth 1965).

A.2.4 UV Dose and Dose Distribution

UV dose is a measurement of the amount of the energy per unit area that is incident on a surface. UV dose is the product of the average intensity acting on a microorganism from all directions and the exposure time. Units commonly used for UV dose are J/m^2, mJ/cm^2, and mWs/cm^2 ($10\ J/m^2 = 1\ mJ/cm^2 = 1\ mWs/cm^2$) with mJ/cm^2 being the most common units in North America and J/m^2 being the most common in Europe. This section discusses how UV dose is calculated in bench-scale, batch systems and also how the UV dose distribution is determined in continuous flow pilot- or full-scale UV reactors.

A.2.4.1 Calculation of UV Dose in Bench-Scale, Batch Systems

The most carefully controlled method of determining UV dose is in a batch system with a bench-scale collimated beam apparatus. Appendix E presents procedures for collimated beam testing. The factors impacting UV dose calculation in collimated beam tests are described in this section.

The general definition of UV dose is the product of UV intensity multiplied by the exposure time.

$$UV\ Dose = I \cdot t \qquad \text{Equation A.8}$$

where

I = UV intensity (mW/cm^2)

t = Exposure time (s)

If intensity is not constant with respect to time, the integral of the intensity output over the exposure time should be used in place of intensity as in Equation A.9.

$$UV\ Dose = \int_0^t I \cdot dt \qquad \text{Equation A.9}$$

where

variables are defined as in Equation A.8.

Due to several conditions present in collimated beam testing, the intensity measured by the radiometer does not accurately represent the intensity of light that reaches the target organisms. To get an accurate calculation of the UV dose delivered to the microorganisms, the following factors are considered as shown in Equation A.10 (Bolton and Linden 2003): absorbance/transmittance of the water, thickness of the water layer, distribution of light across the surface of the suspension, and reflection and refraction of light from the water.

$$UV\ Dose_{254} = I_{avg} \cdot t = \frac{I_0 P_f (1-R)(1-10^{-a_{10}d})}{-a_{10} d \ \ln 10} \cdot t \qquad \text{Equation A.10}$$

where

I_{avg}	=	Average intensity within the suspension (mW/cm^2)
t	=	Exposure time (s)
I_0	=	Intensity measured at the suspension's surface (mW/cm^2)
R	=	Fraction of light reflected at the suspension's surface (from Fresnel's Law)
a_{10}	=	Decadic (base 10) absorption coefficient of the suspension, A_{254} (cm^{-1})
d	=	Thickness of water layer (cm)
P_f	=	Petri factor, ratio of measured intensity at the center of the exposure dish to average intensity across the surface area of the exposure dish (unitless)

Because microorganisms respond differently to different wavelengths of light, if a polychromatic light source (e.g., MP lamp) is used, it is also critical to incorporate the light intensity and the inactivation effectiveness of each wavelength in the germicidal range when determining UV dose. For microorganisms that exhibit inactivation kinetics that are independent of wavelength, the equivalent dose at 254 nm from a polychromatic source is calculated as follows (Meulemans 1986):

$$D_{254} = \sum_{\lambda=200}^{300} I(\lambda) G(\lambda) \cdot t \qquad \text{Equation A.11}$$

where

D_{254}	=	UV dose equivalent at 254 nm
λ	=	Wavelength of light (nm)
$I(\lambda)$	=	Intensity at wavelength λ over 1 nm increments
$G(\lambda)$	=	Relative action spectrum of the microorganism defined as k_λ/k_{254}
k_λ	=	First order inactivation constant at wavelength λ
k_{254}	=	First order inactivation constant at 254 nm wavelength
t	=	Exposure time (s)

However, if the microorganism does not exhibit the same inactivation kinetics at each wavelength, the dose-response curve may be characterized by a shoulder (section A.2.5.2), and the dose equivalent at 254 nm is calculated using Equation A.12 (Cabaj et al. 2001):

$$\frac{N}{N_0} = 1-(1-e^{-k_{254}D_{254}})^{d_{254}} = \sum_{\lambda=200}^{300} 1-(1-e^{-k_\lambda D_\lambda})^{d_\lambda} \qquad \text{Equation A.12}$$

where

D_λ = Dose delivered at wavelength λ

k_λ = First order inactivation constant at wavelength λ

d_λ = Intercept of the exponential region with the y-axis at wavelength λ

A.2.4.2 Dose Distribution in Continuous Flow UV Reactors

Determining the UV dose in a continuous flow pilot- or full-scale UV reactor is complicated by hydrodynamics (particle paths) and variations in UV intensity throughout the reactor.

In an ideal reactor that has plug-flow conditions and complete mixing perpendicular to the flow, all microorganisms entering the reactor will receive the same UV dose, which is calculated according to Equation A.13.

$$UV\ Dose = I_{avg} t_r = I_{avg} \frac{V}{Q} \qquad \text{Equation A.13}$$

where

I_{avg} = Volume-averaged UV intensity within the reactor (mW/cm^2)

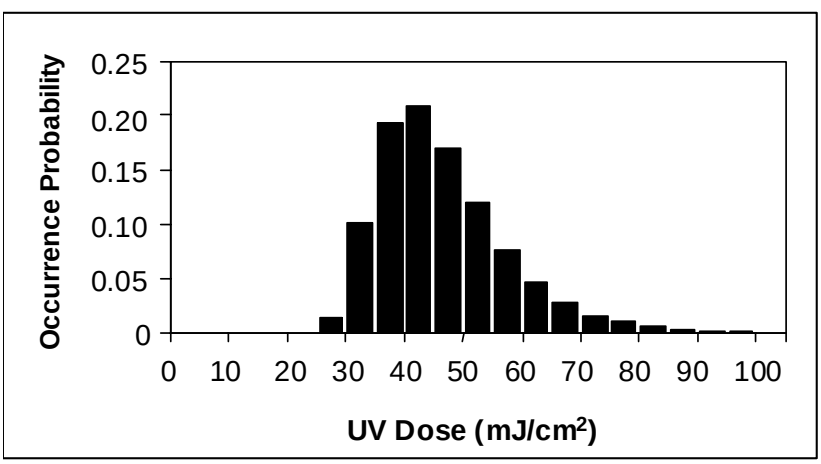
t_r = Theoretical residence time of the reactor (s)

V = Volume of water within the reactor (gal)

Q = Flowrate through the reactor (gal/s)

Equation A.13 calculates the maximum UV dose possible in an ideal reactor. However in practice, microorganisms take different paths through a reactor and thus do not all receive the maximum dose. Instead, the UV dose delivered to the organisms is best described using a dose distribution (Figure A.9). A dose distribution is a curve or histogram that indicates the probability of a microorganism receiving a certain dose as it travels through the UV reactor.

Figure A.9. Hypothetical Dose Distribution Delivered by a UV Reactor



The width of the dose distribution is an indication of the hydraulic conditions in the reactor. The more narrow the distribution, the better the hydraulic conditions approximate plug-flow with complete mixing. However, a narrow dose distribution does not always imply efficient dose delivery. An annular reactor with a thin water layer between the lamp sleeve and the reactor wall will deliver a narrow dose distribution. However, if the reactor wall absorbs UV light, energy losses at the wall will be excessive and the reactor will not efficiently utilize the UV output of the lamp. The most cost effective design of a UV reactor will have a dose distribution that reflects a compromise between inefficiency due to energy losses at the reactor wall and by adjacent lamps as well as inefficiency due to hydrodynamics.

The dose distribution of a UV reactor cannot be measured in a practical manner with current technology. However, by predicting particle trajectories through the intensity field of a UV reactor using computational fluid dynamics (CFD), dose distributions can be calculated (Wright and Lawryshyn 2000).

Inactivation achieved by a reactor with a modeled dose distribution can be calculated by summing the inactivation achieved by each dose in the dose distribution according to Equation A.14.

$$\frac{N}{N_0} = \sum_i p(D_i) f(D_i) \qquad \text{Equation A.14}$$

where

$p_i(D_i)$ = Probability of dose D_i occurring

$f(D_i)$ = Mathematical function describing microorganism inactivation as a function of dose

Using the inactivation kinetics of the microorganism, the inactivation is related to a single dose value termed the reduction equivalent dose (RED) by Equation A.15.

$$\frac{N}{N_0} = \sum_i p(D_i) f(D_i) = f(RED) \qquad \text{Equation A.15}$$

where

N = Concentration of organisms after exposure to UV light

N_0 = Concentration of organisms before exposure to UV light

$p(D_i)$ = Probability of D_i occurring

$f(D_i)$ = Mathematical function describing inactivation as a function of dose

D_i = UV Dose

RED = Reduction equivalent dose

If microorganism inactivation can be described using first order kinetics (section A.2.5.1), inactivation is related to RED by Equation A.16.

$$\frac{N}{N_0} = \sum_i p(D_i) e^{-kD_i} = e^{-k\,RED} \qquad \text{Equation A.16}$$

where
variables are defined as in Equation A.15 and
k = First order inactivation coefficient

By re-arranging Equation A.16, the reduction equivalent dose is calculated according to Equation A.17.

$$RED = \frac{1}{k} \ln\left[\sum_i p(D_i) e^{-kD_i}\right] \qquad \text{Equation A.17}$$

where
variables are defined as in Equation A.15 and A.16

Because UV reactors do not exhibit ideal dose delivery, the RED of a reactor delivering a dose distribution depends on the UV sensitivity of the microorganisms used to calculate RED. The RED determined when using a challenge microorganism that is more resistant to UV disinfection will be higher compared to when using a less resistant microorganism. In contrast, the RED of an ideal reactor has the same value for all microorganisms. Also, the RED of a reactor delivering a dose distribution will vary in a non-linear fashion with the lamp power and a flowrate while the ideal reactor model predicts a proportional relationship. Lastly, the dependence of RED on UV absorbance of the water will be more pronounced with a reactor delivering a dose distribution than an ideal reactor. The RED will decrease with increased UV absorbance at a greater rate with the reactor with a dose distribution than is predicted by ideal models.

The inactivation of a microorganism and the associated RED are measured using biodosimetry (described in section 4.2).

A.2.5 Dose-Response Relationships

UV dose-response relationships can be expressed as either the proportion of microorganisms *inactivated* (log inactivation, results in dose-response curves with positive slope) or the proportion of microorganisms *remaining* (log survival; results in dose-response curves with negative slope) as a function of UV dose. The proportion of microorganisms remaining and the log inactivation are typically shown on a logarithmic (base 10) scale, while the UV dose is typically shown on a linear scale. This manual will present microbial response as log inactivation since the terminology is widely accepted in the industry. Therefore, all dose-response curves presented will have a positive slope. The log inactivation of the microorganisms is determined by measuring the concentration of replicating microorganisms after exposure to a measured UV dose and is calculated according to Equation A.18.

$$Log\ \ Inactivation = \log_{10} \frac{N_0}{N}$$ Equation A.18

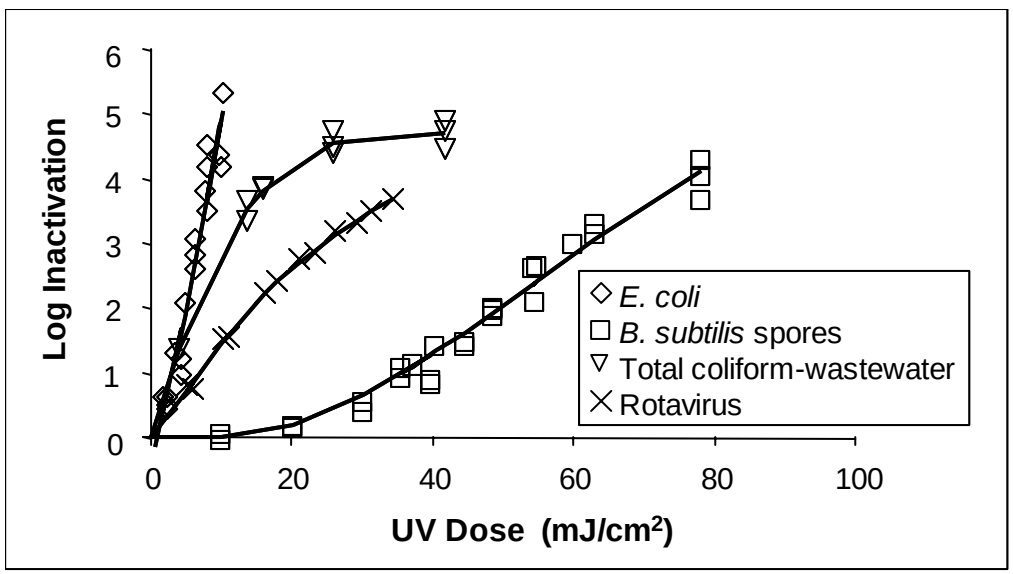
where

N_0 = Concentration of viable microorganisms before exposure to UV light

N = Concentration of viable microorganisms after exposure to UV light

Many UV dose-response curves for disperse microorganisms follow first order inactivation, but in some cases, the dose-response curves take other shapes such as shoulders or tailing. A shoulder is characterized by a period of very little inactivation at lower doses followed by linear or exponential inactivation. A dose-response curve that exhibits tailing is characterized by a decrease in the inactivation rate after a certain degree of inactivation has been observed. Figure A.10 shows various shapes of dose-response curves. Note that the terms "shoulder" and "tailing" refer to the shape the curves take when the y-axis of the dose-response curve is presented as log survival with negative slopes, which is the inverse of log inactivation.

Figure A.10. UV Dose-Response Curves (adapted from Chang et al. 1985)



A.2.5.1 First Order Response

The *E. coli* data shown in Figure A.10 exhibit first order dose-response behavior. The equation for first order inactivation is shown in Equation A.19:

$$\frac{N}{N_0} = e^{-kD} = 10^{-D/D_{10}}$$ Equation A.19

where

N_0	=	Concentration of viable microorganisms before UV exposure
N	=	Concentration of viable microorganisms after UV exposure
k	=	First order inactivation coefficient of the microorganisms (cm^2/mJ)
D	=	UV dose delivered to the microorganisms (mJ/cm^2)
D_{10}	=	UV dose needed to inactivate microorganisms by one log (i.e., 90 percent inactivation) (mJ/cm^2)

In first-order response, only one photon of light is needed to inactivate a microorganism.

A.2.5.2 Shoulders

The *B. subtilis* data shown in Figure A.10 exhibit a shoulder followed by first order dose-response behavior. The shoulder is attributed to a delayed response of a microorganism when exposed to UV light. Unlike first order inactivation, more than one photon of light is needed to inactivate a microorganism. Although the number of photons can not be measured directly, it can be related to first order response through curve fits of empirical equations. Equation A.20 (Cabaj et al. 2001) is one of the many equations derived from empirical curve fits that can be used to model inactivation curves with shoulders.

$$N/N_0 = 1 - \left(1 - e^{-kD}\right)^d$$ Equation A.20

where

N_0	=	Concentration of viable microorganisms before UV exposure
N	=	Concentration of viable microorganisms after UV exposure
k	=	First order inactivation coefficient of the microorganisms (cm^2/mJ)
D	=	UV dose delivered to the microorganisms (mJ/cm^2)
d	=	Intercept of the exponential region of the dose-response with the y-axis

Morton and Haynes (1969) reported a decrease in the shoulder with nutrient-depleted *E. coli* and proposed that the shoulder was associated with dark repair. Photoreactivation significantly increased the shoulder observed with *E. coli* (Hoyer 1998) and *Legionella* (Knudson 1985).

Note that the equation presented is only one of the many equations derived from empirical curve fits. There are many methods to model UV dose-response data not presented here that may better describe specific UV dose-response data (Severin et al. 1984).

A.2.5.3 Tailing

If the irradiated microorganisms are a mixture of disperse microorganisms and clumped or particle-associated microorganisms, the UV dose-response will demonstrate tailing, or a flattening of the curve at higher UV doses (Parker and Darby 1995). With wastewaters, tailing begins after 2 to 3 log of disperse microorganism inactivation, with diminishing inactivation occurring beyond that level despite increasing UV dose (Figure A.10, Total coliforms). Dose-response with tailing can be modeled using Equation A.21.

$$N = N_0 e^{-kD} + N_p e^{-k_p D} \qquad \text{Equation A.21}$$

where

N	=	Concentration of viable microorganisms after UV exposure
N_0	=	Concentration of disperse microorganisms before UV exposure
k	=	First order inactivation coefficient of the microorganisms (cm^2/mJ)
D	=	UV dose delivered to the microorganisms (mJ/cm^2)
N_p	=	Concentration of particles containing the microorganisms
k_p	=	Pseudo first order inactivation constant of particle-associated microorganisms (cm^2/mJ)

A.2.6 Factors Impacting Microbial Response

Several factors impact the response of microorganisms to UV light. This section discusses these factors, including UV intensity, UV absorbance, temperature, pH, particles, and UV wavelength.

A.2.6.1 UV Intensity

Oliver and Cosgrove (1975) reported that UV dose-response of microorganisms follows the Law of Reciprocity over an intensity range of 1 to 200 mW/cm^2. For example, the inactivation effectiveness observed with UV intensity of 1 mW/cm^2 and an exposure time of 200 seconds is equivalent to the inactivation observed with an exposure time of 1 second and UV intensity of 200 mW/cm^2 as well as all intensity-time combinations between 1 and 200.

Exceptions to this reciprocal relationship between time and intensity occur at very low and high intensities (Setlow 1967). With low UV intensities and long exposure times, repair may compete with inactivation. Sommer et al. (1998) found less inactivation of *E. coli* at a given dose with low intensities ranging from 0.002 to 0.2 mW/cm^2. However, inactivation of *B. subtilis* spores, MS2 bacteriophage (MS2), ϕx174 phage, and B40-8 phage at a given dose was the same regardless of UV intensity. At UV intensities on the order of 10^{10} to 10^{11} mW/cm^2 (several orders of magnitude higher than the intensity from lamps used for UV disinfection), Gurzadyan et al. (1981) reported an increase in single strand breaks and a reduction in dimerization in the nucleic acid of ϕx174 phage.

A.2.6.2 UV Absorbance

Because the calculation of dose delivered to a microbial suspension (Equation A.10, section A.2.4.1) accounts for UV absorbance in bench-scale batch experiments, measured UV dose-response curves like those presented in Figure A.10 are independent of the suspension's UV absorbance. However, as the UV absorbance of the suspension increases, the UV intensity incident on the sample may need to increase in order to deliver a given dose. In bench-scale, batch experiments, there are several ways to keep the UV dose constant such as increasing exposure time or decreasing the depth of the solution, thereby decreasing the pathlength.

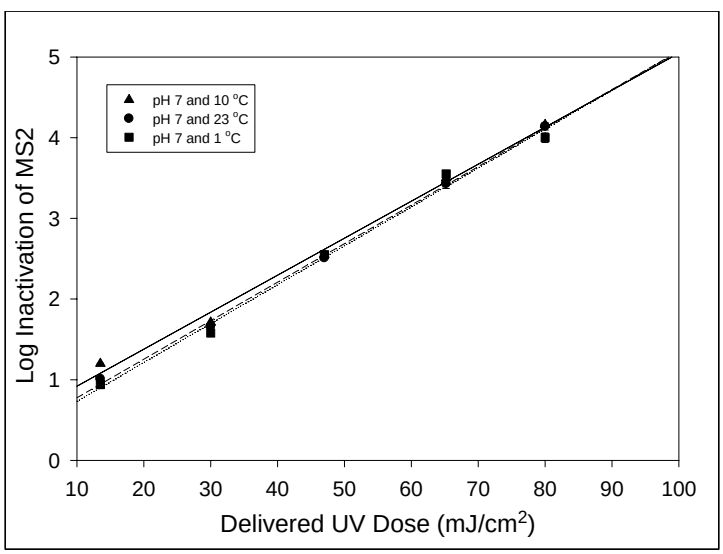
A.2.6.3 Temperature

Temperature affects the configuration of nucleic acid and the activity of repair enzymes; however, existing research shows temperature effects on UV dose-response are minimal and depend on the microorganism. Severin et al. (1983) found the UV dose needed for a given log reduction of *E. coli*, *Candida parapsilosis*, and f2 phage increases slightly as temperature decreased (Table A.1). Malley (2000) reported the dose-response of MS2 is independent of temperature from 1 to 23°C (Figure A.11).

Table A.1 Impact of Temperature on UV Disinfection

Microorganism	UV dose (mJ/cm^2) needed to achieve 2 log inactivation at a temperature of		
	5 °C	20 °C	35 °C
E. coli	11.8	11.2	10.7
C. parapsilosis	30.9	28.8	28.0
f2 phage	72.5	65.6	60.7

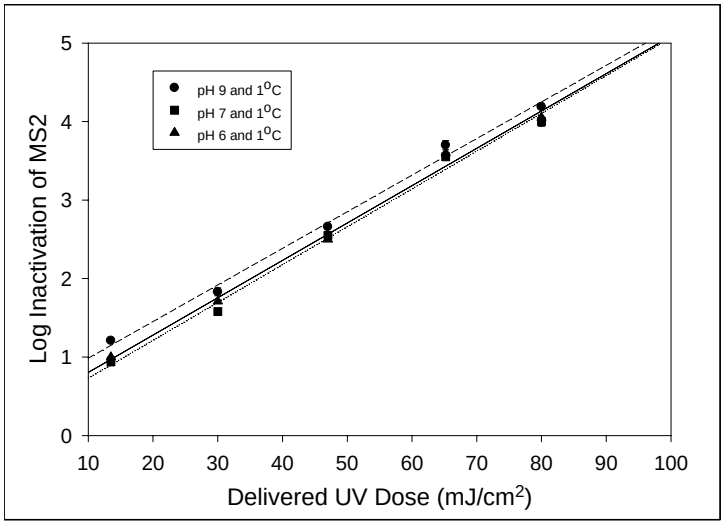
Figure A.11 Impact of Temperature on MS2 UV Dose-Response (Malley 2000)



A.2.6.4 pH

UV dose-response is usually independent of the pH of the water. The UV absorbance of nucleic acid and repair enzyme activity vary with pH (Jagger 1967). However, the pH within a cell is buffered to a relatively constant value, independent of water pH. For example, Malley (2000) reported the dose-response of MS2 is independent of the suspension pH from pH 6 to 9 (Figure A.12).

Figure A.12 Impact of pH on MS2 UV Dose-Response (Malley 2000)



A.2.6.5 Particle Association

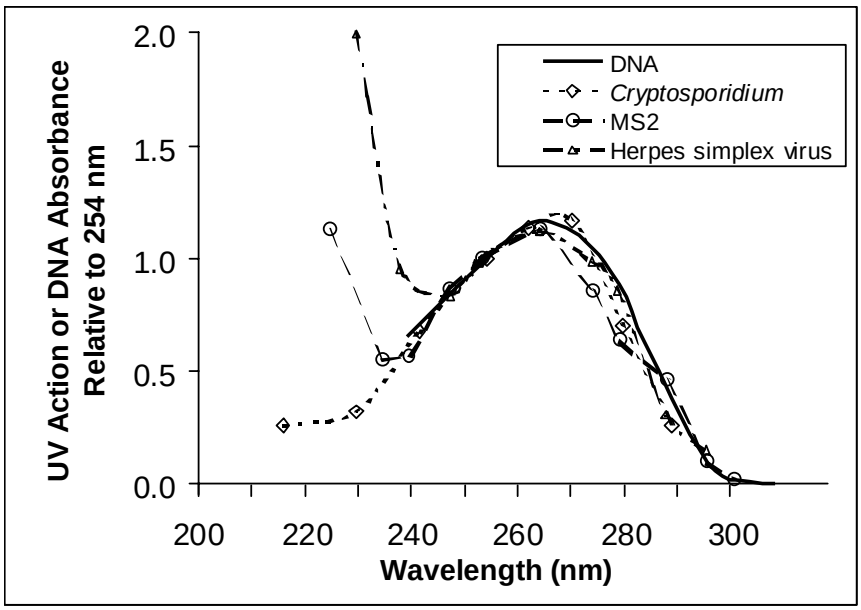
To date, research examining the effects of naturally occurring particles and microorganisms is limited to wastewater studies. Due to the limited concentration of microorganisms in drinking water sources, methods of directly examining the impact of particles do not currently exist. However, the phenomena observed in wastewater studies may also apply to particle association occurring in drinking water. The effects of individual particles (such as those that cause turbidity) on UV disinfection are discussed in section A.4.1.2.

Results from research with wastewaters have indicated that clumping or particle association will shield microorganisms from UV light. The UVT at 260 nm through 10 microns of cell tissue is roughly 10 percent (Jagger 1967), suggesting that clumps of organisms would offer protection. The water content of cells and intracellular material and the porous nature of flocculated particles will influence the penetration of light into waterborne particles. Qualls et al. (1983) reported that filtration of secondary effluent through an 8 micron filter removes the particles responsible for the tailing in the dose-response of coliforms. With 8 micron filtration, coliform inactivation at 12 mJ/cm^2 increased from 3 log to over 4.5 log inactivation. Loge et al. (1999) reported the UV absorbance of wastewater solids varied from 0.33 to 56.9 μm^{-1} (3,300 to 569,000 cm^{-1}) with the high absorbance associated with activated sludge plant using iron to remove phosphorus. Petri et al. (2000) reported coagulation of MS2 by iron in ground water increased the UV dose needed to inactivate MS2 by a factor of 2.5 to 3.5.

A.2.6.6 Wavelength

Microbial dose-response varies with the wavelength of UV light. The action spectrum (also called UV action) of a microorganism is a measure of inactivation as a function of the wavelength for a given UV dose. The dependence of UV action on wavelength is similar to the dependence of the UV absorbance of DNA on wavelength (Figure A.13). UV action peaks near 260 nm, has a local minimum near 230 nm, and drops to zero near 300 nm. While it is generally believed that microorganisms are most sensitive near 260 nm, there are exceptions. For example, the UV sensitivities of tobacco mosaic virus (Hollaender and Duggar 1936), reovirus (Rauth 1965), and Herpes simplex virus (Powell 1959) are greater below 230 nm. Although the UV action increases below 230 nm for most microorganisms, the UV absorbance of natural waters at these wavelengths make this region impractical for UV disinfection of microorganisms in water. Because of the similarity between UV action and DNA absorbance, and because DNA absorbance is easier to measure than UV action, the DNA absorbance spectrum of a microorganism is often used as a surrogate for its UV action spectrum.

Figure A.13 Comparison of Microbial Action to DNA UV Absorbance (adapted from Rauth 1965 and Linden et al. 2001)



A plot of the first order inactivation coefficient as a function of wavelength can be used to show the action spectrum if the dose-response follows first order inactivation. Plots of two kinetic terms as a function of wavelength are necessary to plot the action spectrum if the dose-response has a shoulder (Cabaj et al. 2001) as discussed in section A.2.5.2. Plots of UV action spectra are often presented relative to some wavelength, typically 254 nm.

A.2.7 UV Dose-Response of Differing Microorganisms

The UV dose-responses of microorganisms have been tabulated in a number of review articles and are summarized in this section.

Data presented in Tables A.2 and A.3 show that the UV sensitivity of microorganisms varies with different species. Of the pathogens of interest in drinking water, viruses are most resistant to UV disinfection followed by bacteria, and *Cryptosporidium* oocysts and *Giardia* cysts. The most UV resistant viruses of concern in drinking water are adenovirus Type 40 and 41. Appendix B provides dose-response data for *Giardia* cysts, *Cryptosporidium* oocysts, and viruses, and Chapter 1 (Table 1.4) contains the regulatory UV dose requirements for inactivating these pathogens.

Table A.2 provides average dose reported without photoreactivation for incremental log inactivation of various pathogenic bacteria, virus, and protozoa of concern in drinking water. Table A.3 provides similar information for various non-pathogenic indicator bacteria, spore forming bacteria, and bacteriophage. All data in Tables A.2 and A.3 are for microorganisms suspended in water and irradiated using a collimated beam apparatus with UV light at 254 nm.

Spore-forming and gram-positive bacteria are more resistant to UV light than gram negative bacteria (Jagger 1967). With microorganisms larger than 1 micron, the absorption of UV light by the cytoplasm can be significant, depending on the wavelength, and therefore can affect UV sensitivity.

Rauth (1965) found that the UV sensitivity of virus and bacteriophage varies over two orders of magnitude from the most sensitive to the most resistant. The same study showed viruses with single-stranded nucleic acid are ten times more sensitive than viruses with double-stranded nucleic acid.

Table A.2 UV Sensitivity of Pathogenic Microorganisms in Water[1]

Microorganism	Type	UV Dose (mJ/cm^2) inactivation indicated				Reference
		1-log	2-log	3-log	4-log	
Aeromonas hydrophila	Bacteria	1.1	2.6	3.9	5	Wilson et al. 1992
Campylobacter jejuni	Bacteria	1.6	3.4	4	4.6	Wilson et al. 1992
Escherichia coli O157:H7	Bacteria	1.5	2.8	4.1	5.6	Wilson et al. 1992
Legionella pneumophila	Bacteria	3.1	5	6.9	9.4	Wilson et al. 1992
Salmonella anatum	Bacteria	7.5	12	15		Tosa and Hirata 1998
Salmonella enteritidis	Bacteria	5	7	9	10	Tosa and Hirata 1998
Salmonella typhi	Bacteria	1.8	4.8	6.4	8.2	Wilson et al. 1992
Salmonella typhimurium	Bacteria	2	3.5	5	9	Tosa and Hirata 1998
Shigella dysenteriae	Bacteria	0.5	1.2	2	3	Wilson et al. 1992
Shigella sonnei	Bacteria	3.2	4.9	6.5	8.2	Chang et al. 1985
Staphylococcus aureus	Bacteria	3.9	5.4	6.5	10.4	Chang et al. 1985
Vibrio cholerae	Bacteria	0.8	1.4	2.2	2.9	Wilson et al. 1992
Yersinia enterocolitica	Bacteria	1.7	2.8	3.7	4.6	Wilson et al. 1992
Adenovirus Type 40 [2]	Virus	30	59	90	120	Meng and Gerba 1996
Adenovirus Type 41 [2]	Virus	22	50	80		Meng and Gerba 1996
Coxsackievirus B5	Virus	6.9	14	21		Battigelli et al. 1993
Hepatitis A HM175	Virus	5.1	14	22	30	Wilson et al. 1992
Hepatitis A	Virus	5.5	9.8	15	21	Wiedenmann et al. 1993
Hepatitis A HM175	Virus	4.1	8.2	12	16	Battigelli et al. 1993
Poliovirus Type 1	Virus	4.0	8.7	14	21	Meng and Gerba 1996
Poliovirus Type 1	Virus	6	14	23	30	Harris et al. 1987
Poliovirus Type 1	Virus	5.6	11	16	22	Chang et al. 1985
Poliovirus Type 1	Virus	5.7	11	18	13	Wilson et al. 1992
Rotavirus SA11	Virus	7.6	15	23		Battigelli et al. 1993
Rotavirus SA11	Virus	7.1	15	25		Chang et al. 1985
Rotavirus SA11	Virus	9.1	19	26	36	Wilson et al. 1992
Cryptosporidium parvum [2]	Protozoa	< 2	< 3	< 5		Shin et al. 2001
Cryptosporidium parvum [2]	Protozoa		< 3	< 6		Clancy et al. 2000
Giardia lamblia [2]	Protozoa	<1			<2	Linden et al. 2002a
Giardia lamblia [2]	Protozoa	<1	< 3	< 6		Mofidi et al. 2002

[1] Adapted from Wright and Sakamoto 1999
[2] Additional data for adenovirus, *Cryptosporidium,* and *Giardia* are in Appendix B.

Table A.3 UV Sensitivity of Non-Pathogenic Bacteria, Bacteriophage, and Spore-Forming Bacteria in Water[1]

Microorganism	Type	UV Dose (mJ/cm^2) inactivation indicated				Reference
		1-log	2-log	3-log	4-log	
Escherichia coli	Bacteria	2.5	3	3.5	5	Harris et al. 1987
Escherichia coli	Bacteria	3	4.8	6.7	8.4	Chang et al. 1985
Escherichia coli	Bacteria	4.0	5.3	6.4	7.3	Sommer et al. 1998
Escherichia coli	Bacteria	4.4	6.2	7.3	8.1	Wilson et al. 1992
Streptococcus faecalis	Bacteria	6.6	8.8	9.9	11	Chang et al. 1985
Streptococcus faecalis	Bacteria	5.5	6.5	8	9	Harris et al. 1987
MS-2	Phage	4	16	38	68	Wiedenmann et al. 1993
MS-2	Phage	16	34	52	71	Wilson et al. 1992
MS-2	Phage	12	30			Tree et al. 1997
MS-2	Phage	21	36			Sommer et al. 1998
MS-2	Phage	17	34			Rauth 1965
MS-2	Phage	14	29	45	62	Meng and Gerba 1996
MS-2	Phage	19	40	61		Oppenheimer et al. 1993
ϕX174	Phage	2.2	5.3	7.3	10	Sommer et al. 1998
ϕX174	Phage	2.1	4.2	6.4	8.5	Battigelli et al. 1993
ϕX174	Phage	4	8	12		Oppenheimer et al. 1993
PRD-1	Phage	9.9	17	24	30	Meng and Gerba 1996
B-40	Phage	12	18	23	28	Sommer et al. 1998
Bacillus subtilis spores	Spores	36	49	61	78	Chang et al. 1985
Bacillus subtilis spores	Spores	29	40	51		Sommer et al. 1998

[1] Adapted from Wright and Sakamoto 1999.

A.3 UV Reactors

This section discusses UV reactor components, UV reactor configurations, and how reactor performance is monitored. The following UV reactor components are discussed:

- Mercury lamps
- Ballasts and power supplies
- Lamp sleeves
- Cleaning systems
- UV intensity sensors
- UV transmittance monitors
- Temperature sensors

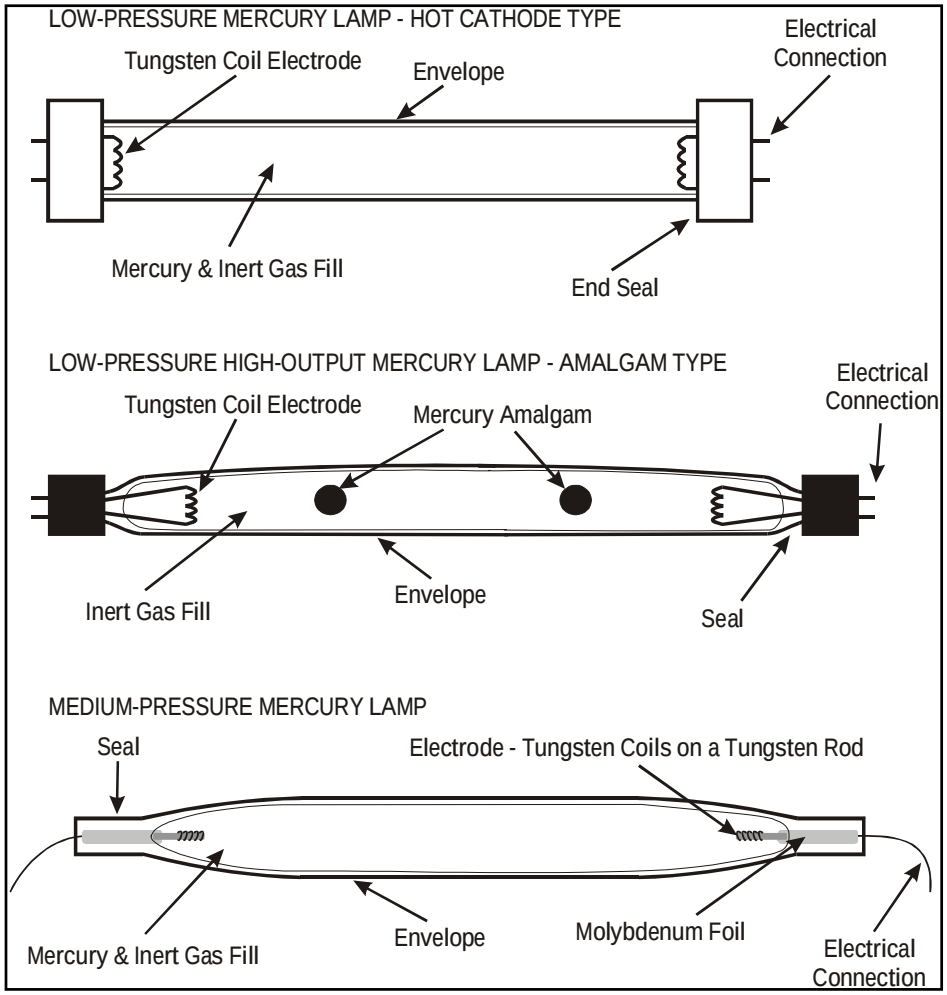
A.3.1 Mercury Lamps

This section describes mercury lamps, including how they are constructed, their components, efficiency, spectral output, and aging. A majority of the material in this section was derived from Sources and Applications of Ultraviolet Radiation by Roger Phillips (1983). Section 2.4.2 (Table 2.1) compares the operating characteristics of LP, LPHO, and MP mercury lamps.

A.3.1.1 Lamp Construction

Mercury vapor discharge lamps consist of a UV-transmitting envelope made from a tube of quartz sealed at both ends (Figure A.14). An electrode is located at each end of the envelope connected to the outside through a seal. The envelope is filled with mercury and an inert gas.

Figure A.14 Construction of a UV Lamp



Lamp Envelope

The envelope of the lamp should transmit germicidal UV light, act as an electrical insulator, and not react with the lamp's fill gases. A non-crystalline form of quartz, vitreous silica, is often used for the lamp envelope because of its high UVT and its resistance to high temperatures. However, some LP lamps use UV-transmitting glass instead of quartz. Envelopes are approximately 1 to 2 mm thick, and the diameter is selected to optimize the UV output and lamp life.

As quartz is exposed to high temperatures, it begins to crystallize. Crystallization reduces the UVT of the quartz and changes its coefficient of expansion, which causes internal stresses. Envelopes for MP lamps must be able to withstand thermal shocks associated with 600 to 900 °C operating temperatures without the quartz transforming to its crystalline form. LP lamps have lower operating temperatures where crystallization is not a concern, which is why some LP lamps use UV-transmitting glass rather than quartz for the lamp envelope.

Envelopes of MP lamps may be covered with a reflective coating at the ends. This is to keep the ends warm and prevent the condensation of mercury behind the electrodes.

The UV transmittance of the envelope affects the spectral output of MP mercury lamps, especially at lower wavelengths. Lamp envelopes can be made from doped quartz, or quartz that is altered to absorb specific wavelengths, in order to prevent undesirable non-germicidal photochemical reactions. If the lamp envelope is not made from doped quartz, the lamp sleeves can also be used to restrict the wavelengths emitted (described in section A.3.3).

Electrodes

With a LP mercury lamp, electrode design depends on whether the lamp operates with a glow or arc discharge. With a glow discharge, free electrons are formed from the bombardment of the electrode by cations. The electrode used is typically a cylinder of iron or nickel. Lamps of this type of electrode operate near 150 °C and are termed cold-cathode lamps. With an arc discharge, free electrons are emitted thermally from a hot electrode operating near 900 °C and are referred to as hot-cathode lamps. The electrode is made of a coil of tungsten wire embedded with oxides of calcium, barium, or strontium. The high melting point of tungsten prevents evaporation of electrode materials that could coat the inside of the lamp and reduce output of UV light. The oxides embedded within the tungsten coil reduce the temperature needed for the emission of electrons. LP and LPHO lamps used in UV disinfection are usually hot-cathode lamps.

In order to reduce the start voltage of a hot-cathode lamp, each electrode may have two electrical connections to pass current through the electrode. Resistive heating of the electrode raises the electrode's temperature, thereby facilitating rapid transition from a glow discharge to an arc discharge at a lower voltage. Rapid transition from a glow to an arc discharge reduces electrode sputtering and improves lamp life. The process of transitioning from glow to arc discharges and how it produces UV light is described in section A.1.1.1.

Electrode design and operation is critical for reliable long term operation. In order for lamps to operate at an optimal temperature, electrode design should promote heat transfer. The

electrodes of a MP mercury lamp consist of a tungsten rod wrapped in a coil of tungsten wire. To improve thermal emission of electrons, thorium or alkaline-earth oxides are embedded within the coils, and the tungsten rod may contain thorium oxide. The electrode must warm-up within seconds to allow transition from a glow to an arc discharge and minimize sputtering of tungsten onto the envelope. The electrode operating temperature must be high enough to promote thermal emission of electrons and low enough to prevent the evaporation of tungsten.

The electrode of a MP lamp is connected to the external electrical supply via a thin molybdenum foil sealed in the quartz at the lamp ends. The molybdenum foil is ductile and therefore does not crack the quartz when the lamp expands and contracts due to changes in operating temperature. If the temperature of the seal increases beyond 350 °C, the molybdenum will oxidize and the seal will fail. Because the seal is located behind the electrode, its temperature is lower than the temperature of the arc.

Mercury Fill

The mercury fill present in UV lamps can be in the solid, liquid, or vapor phase. At typical LP and LPHO lamp operating temperatures, mercury remains predominantly in the liquid or solid amalgam phase with a small proportion in the vapor phase (which is responsible for producing UV light). An amalgam is an alloy of elemental mercury with another metal (typically indium or gallium in lamp applications) that can be either solid or liquid at room temperature, depending on the relative proportions of the two metals. Amalgams are typically used in LP and LPHO lamps, while MP lamps contain liquid elemental mercury.

Vapor pressure (the pressure of mercury in the vapor phase) depends on the temperature. LP lamps operate with an envelope temperature near 40 °C, resulting in a mercury vapor pressure near 0.007 torr (1.4×10^{-4} psi), which is optimal for the production of UV light at 254 nm. MP lamps operate at a much higher envelope temperature (600 to 900 °C), resulting in a mercury vapor pressure ranging from 100 to 10,000 torr (2 to 200 psi). In MP lamps, the concentration of mercury in the vapor phase is controlled by the amount of mercury in the lamp, as opposed to LP and LPHO lamps where an excess of mercury is placed in the lamp and only a portion of the elemental mercury enters the vapor phase.

With a conventional LP lamp, increasing the operating current will not produce a higher UV output. Instead the operating temperature will increase causing an increase in vapor pressure and the UV light output of the lamp will decrease. LPHO lamps hold the mercury vapor pressure constant at the optimal value, allowing the UV light output to increase as current increases until a saturation value is reached. Methods of controlling the vapor pressure within the lamp include using either a mercury amalgam attached to the lamp envelope, a cold spot on the lamp wall, or a mercury condensation chamber located behind each electrode. With each method, the temperature of the mercury within the lamp, and hence the vapor pressure, is controlled, allowing efficient production of UV light at higher currents.

Inert Gas Fill

In addition to mercury, lamps are filled with an inert gas (typically argon) at 1 to 50 torr (0.02 to 1 psi). The inert gas aids in starting the gas discharge and reduces deterioration of the electrode. When the lamp is started at room temperature, the concentration of mercury atoms is

low and there are few collisions between free electrons and mercury. However, there are a significant number of collisions between free electrons and argon atoms. These collisions excite the argon atoms to a metastable higher energy state that does not return quickly to a ground state. Collisions between the excited metastable argon and mercury or free electrons ionizes the mercury and argon, respectively. The free electrons released by ionization reduce the start voltage and aid in the formation of the gas discharge. However, if lamps are manufactured with a non-ideal argon pressure (>50 torr; 1 psi), the collisions between electrons and argon cause energy losses, and therefore the electrons never achieve sufficient kinetic energy to excite the mercury atoms.

A.3.1.2 Low-Pressure Lamp Efficiency

LP lamps are designed and manufactured to efficiently convert electrical energy to germicidal UV light. An optimal LP lamp design typically includes the following components:

- 3.6 cm lamp envelope diameter
- 0.007 torr mercury fill (1.3×10^{-4} psi)
- 3 torr argon fill (0.06 psi)
- 400 mA operating current
- 40 °C operating temperature
- 0.5 W/cm power input per arc length

Under such conditions, the power input efficiency is as follows:

- 60 percent converted to UV light at 185 and 254 nm
- 3 percent converted to other wavelengths
- 15 percent to electrode losses
- 22 percent to thermal losses from the arc

A.3.1.3 Low-Pressure High Output Lamp Efficiency

Theoretically, LPHO lamps have the same efficiency as LP lamps because they operate at similar vapor pressures. However in practice, LPHO lamp efficiency can be significantly lower, depending on lamp construction, ballast operation, power settings, and lamp cooling. The energy input to a LPHO lamp can be converted to energy in the following forms:

- 30 to 45 percent converted to UV light at and 254 nm

- 5 to 25 percent converted to light at other wavelengths, primarily 185, 313, 365, and 436 nm
- 50 to 65 percent to thermal losses from the arc

A.3.1.4 Medium-Pressure Lamp Efficiency

For the purposes of UV disinfection, the efficiency of a MP lamp can be defined as the ratio of its germicidal output to its electrical input. Equation A.22 defines germicidal efficiency as a function of power input, lamp output, and the action spectra of a given microorganism.

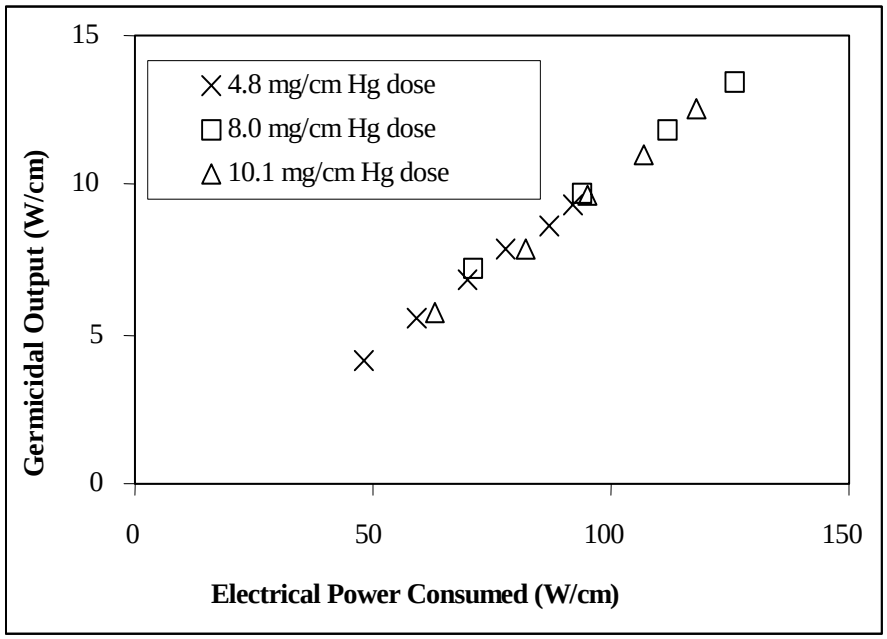
$$\eta = \frac{P_G}{P_E} = \frac{\sum_{\lambda=200nm}^{300nm} P(\lambda)G(\lambda)}{P_E} \qquad \text{Equation A.22}$$

where

η	=	Germicidal efficiency of the lamp
P_G	=	Germicidal lamp output (W)
P_E	=	Electrical power input (W)
λ	=	Wavelength (nm)
$P(\lambda)$	=	Lamp output measured over 1 nm increments at wavelength λ (W)
$G(\lambda)$	=	Action spectra of the microorganism at wavelength λ (unitless)

Figure A.15 presents the output versus electrical input between 248 and 320 nm for three MP lamps containing different mercury doses. For the lamps considered, lamp efficiency varied slightly with input power to the lamp but did not vary with mercury dose. Lamp efficiency on average was 10 percent. Because lamp data used to generate Figure A.15 were based only on lamp output from 248 to 320 nm, the lamp efficiency may be underestimated.

Figure A.15 Germicidal Output from 248 to 320 nm of Three MP Lamps Calculated for MS2 as a Function of Electrical Power Input (adapted from Phillips 1983)



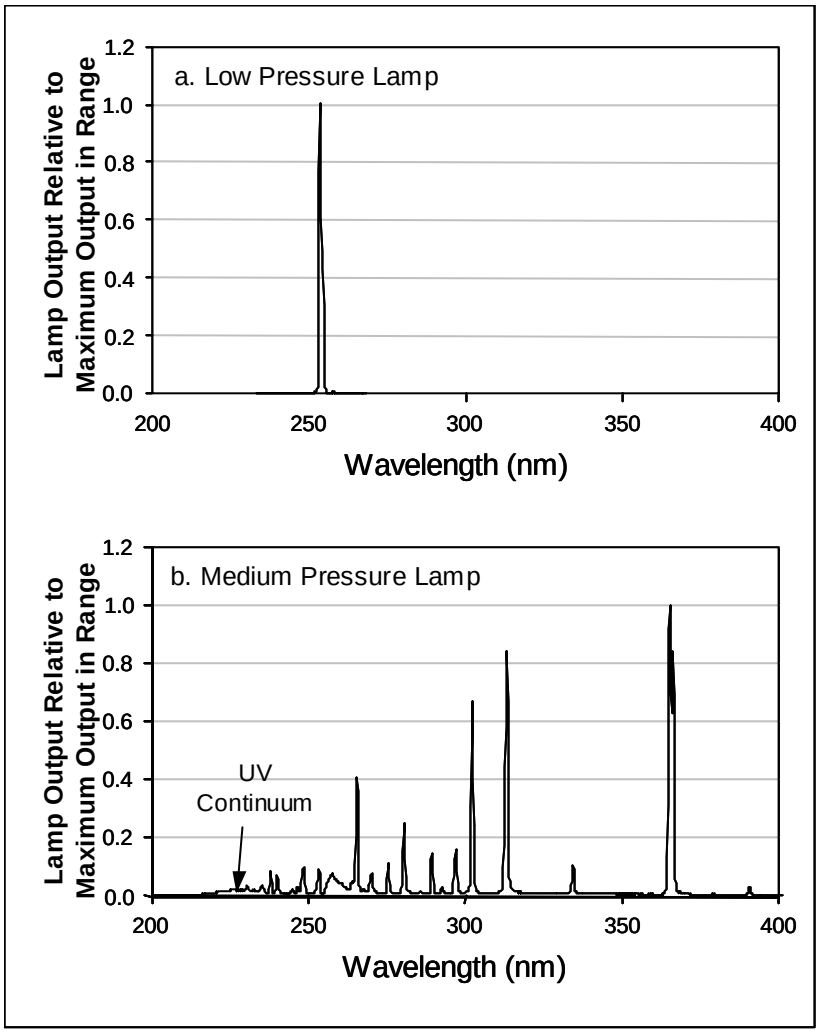
A.3.1.5 Spectral Output of Lamps

LP lamps emit primarily resonant light at 253.7 nm (Figure A.16a) that is formed from electron transitions from the first excited states to the ground state of mercury. They also emit light at 185 nm with intensity varying from 12 to 34 percent of the UV intensity at 253.7 nm depending on the operating current, wall temperature, and inert gas fill. UV light at 185 nm will react with oxygen and promote the formation of ozone within the lamp sleeve. Ozone is a corrosive and toxic compound that absorbs UV light. As such, LP lamps for UV disinfection applications are manufactured to reduce or eliminate the emission of UV light at 185 nm. Other wavelengths of light including 313, 365, 405, 436, and 546 nm also are emitted from LP lamps at low intensities due to higher energy electron transitions within the mercury.

The spectral output of LPHO lamps is similar to LP lamps. Although all of the wavelengths emitted are identical, the intensity of light from LPHO lamps is higher.

The spectral output of MP mercury lamps involves peaks overlying a continuum (Figure A.16b). The combination of free electrons and mercury cations within the arc creates a broad continuum of UV energy lines between 200 and 245 nm. This continuum does not occur with LP lamps, where non-radiating recombination occurs at the envelope walls. Electron transitions within the mercury produce numerous narrow peaks of electromagnetic energy in the visible and ultraviolet range. These transitions result in a broadening of the emitted light and a shift in its peak, usually to longer wavelengths. For example, the peak from 260 to 270 nm arises primarily due to the 254 nm electron transition.

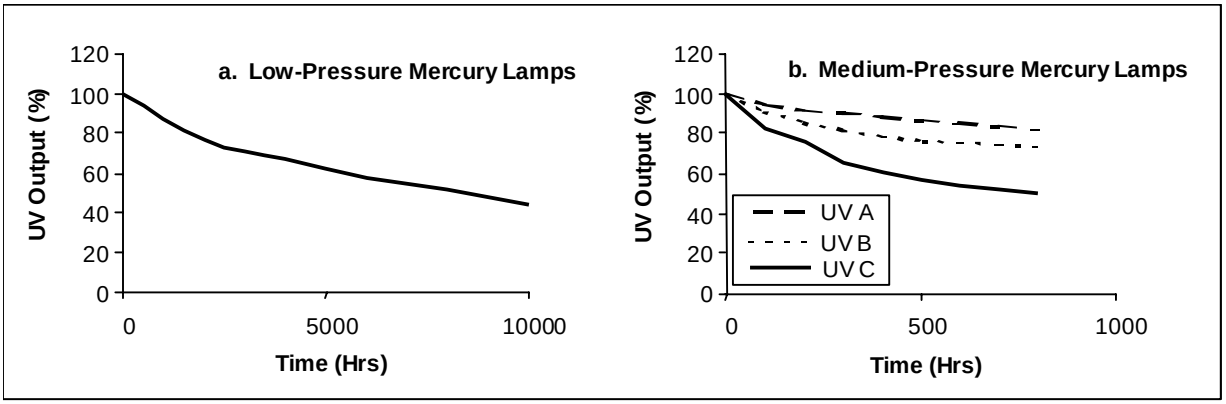
Figure A.16. UV Output of LP (a) and MP (b) Mercury Lamps (Sharpless and Linden 2001)



A.3.1.6 Lamp Aging

Over time, UV lamps can degrade, resulting in a reduction in output where lower germicidal wavelengths degrade faster than higher wavelengths. Lamp output will decrease over time as a function of lamp hours in operation, number of on/off cycles and power applied per unit (lamp) length. The rate of decrease in lamp output slows as the lamp ages (Figure A.17).

Figure A.17. Reduction in UV Output of LP and MP Lamps Over Time (adapted from Schenck 1981)



Lamp aging can be affected by the following factors:

- Ballast operations, including power setting, frequency, and harmonic distortion of the voltage and current driving the lamp
- Water temperature and heat transfer from lamps
- Vibration of the lamp sleeves caused by water flowing through the reactor
- The frequency of on-off cycles

With LP and MP lamps, sputtering of the electrode during the glow phase of start-up can coat the inside surface of the lamp envelope with tungsten. The tungsten coating is black in color, non-uniform, concentrated within a few inches of the electrode, and can absorb UV light (Figure A.18). Sputtering from the electrode can be reduced by the following conditions:

- Pre-heating the electrode before applying the start voltage
- Driving the lamp with a sinusoidal current waveform
- Using a lamp with a higher argon content
- Minimizing the number of lamp starts during operation

Figure A.18. Aged UV Lamp (right) in Comparison to a New UV Lamp (left) (Mackey et al. 2003)

If a MP lamp is not sufficiently cooled during operation, tungsten and oxides between the tungsten coils may evaporate and coat the inside of the envelope. LP lamps using UV-transmitting glass may have mercury combine with sodium in the glass to create a UV absorbing coating. Any deposits on the inner or outer surfaces of the lamp envelope and by metallic impurities within the envelope will absorb UV light. The absorption of UV light can raise the temperature, which may lead to localized overheating of the lamp envelope. If the lamp envelope is quartz, the increase in temperature can lead to devitrification (crystallization), contributing to an additional decrease in UVT.

With MP lamps, reaction of the electrode with any water molecules that have entered the lamp envelope as a result of lamp seal failure will form an oxide and hydrogen and also increase the start voltage. The molybdenum seal of a MP lamp will oxidize and fail if the seal temperature exceeds 350 °C. High operating temperatures of a MP lamp can also lead to bubbles and distortion of the lamp envelope materials and devitrification (crystallization), which leads to a decrease in UVT. The coefficient of expansion of crystalline quartz is higher than that of non-crystalline quartz, and rapid changes in temperature will also stress the envelope, which may lead to lamp breakage.

A.3.2 Lamp Power Supply and Ballasts

UV lamps are typically operated with an AC supply. Unlike an incandescent lamp, a mercury vapor lamp cannot be connected directly to the electrical service because it has a non-linear voltage to ampere characteristic (Persson and Kuusisto 1998). In order for the mercury vapor lamp to function properly, a ballast must be inserted into the circuit to limit the current flow through the lamp. When placed in series with the lamp, the ballast provides an impedance to the power supply with a positive voltage-current characteristic. The power supply and ballast are designed to provide the following features:

- Reliable and rapid starting of the gas discharge

- Re-ignition of the gas discharge every half cycle of the power supply
- An appropriate current waveform
- A high power factor
- Stable light output

Resistors, capacitors, inductors, or combinations of these can be used as ballasts; however, resistors are not used because they consume power and therefore reduce electrical efficiency. Lamp ballasts are often termed either magnetic (also known as electromagnetic) or electronic. Magnetic ballasts can be inductive or capacitive and operate at the line frequency. Electronic ballasts operate at frequencies higher than that of the line voltage and involve solid state devices or a mixture of solid state devices, inductors, and capacitors.

A.3.2.1 Magnetic Ballasts

There are two types of magnetic ballasts: capacitive (those with capacitors) and inductive (those with inductors). Each ballast type is designed to control the current to the lamp.

With a capacitive ballast, the current through the lamp is primarily a function of the capacitance used and does not vary significantly with the applied voltage or the lamp properties. An advantage of the capacitive ballast is that the power delivered to the lamp and the lamp output are independent of line voltage. A disadvantage is that electrode sputtering can increase, which accelerates electrode aging. Capacitive ballasts are more efficient than inductive ballasts, but less efficient than electronic ballasts. Because of the stored energy in the capacitor and the coil, capacitive ballasts are less prone to failure as a result of small fluctuations in power quality.

With the inductive ballast, the current through the lamp is a function of the inductance, the applied voltage, and the lamp properties. As electrical current flows through the inductor, it generates a magnetic field. The magnetic field opposes the electrical current, and the strength of the field is proportional to the current passing through the inductor. Therefore, as the current increases, so does the resistance to the current. This interaction limits the total current flow to the lamps to a specific amperage. The highest power achieved with the inductive ballast is lower than with the capacitive ballast. However, electrode sputtering is less than with capacitive ballasts, leading to extended electrode life. With capacitive ballasts, the UV lamp output varies with the line voltage. Inductive ballasts provide more stable current output and better resolution and control than capacitive ballasts, but are generally less efficient, larger, heavier, and more expensive.

Magnetic ballasts are currently the most common type of ballast used for medium pressure lamps due to their durability and proven operating stability in the higher power applications. Medium pressure reactors typically incorporate some form of power adjustment to optimize energy efficiency and control dose delivery. Because of the manner in which magnetic ballasts operate, power can only be adjusted by incorporating capacitors or inductors into the circuit. Adjustment occurs in a series of steps, and the number of steps is limited by the number of capacitors or inductors that are included in the ballast.

A.3.2.2 Electronic Ballasts

Electronic ballasts, sometimes referred to as solid state ballasts, contain semiconductors and other electronic components such as low-pass filters, rectifiers, buffer capacitors, and high frequency oscillators that allow the ballast to behave like a switching power supply. A chopped electrical current with up to 50,000 pulses per second of electricity is supplied to the lamp, whereas a magnetic ballast typically produces only 100 to 120 pulses per second. With an electronic ballast, the frequency of electrical pulses supplied to the lamp is longer when the lamp is cold. As the lamp approaches its optimum operating temperature, the electronic ballast provides shorter and less frequent pulses of current to the lamp.

Electronic ballasts are a newer technology than magnetic ballasts and are therefore less proven. Although they have limited operational experience, electronic ballasts offer increased efficiency, smaller size and weight, and the opportunity for nearly continuous power adjustment over a wide range of settings. Reliability has improved significantly since electronic ballasts were initially developed. Currently, manufacturers of low pressure reactors and smaller medium pressure reactors often use electronic ballasts in their design. Because of the reduction in stored energy, electronic ballasts are more susceptible to failure due to power inconsistencies; however, by incorporating a buffer capacitor, minor power disturbances can be smoothed out, reducing the occurrence of lamp failure.

A.3.2.3 Comparison of Ballast Types

Electronic and magnetic ballasts each have specific advantages and disadvantages. Manufacturers consider these advantages and disadvantages when determining the technology to incorporate into their equipment designs. The final selection takes into account the relative importance of each of the advantages and disadvantages for a given application. A single manufacturer may have equipment designs based on both ballast types. For example, one UV manufacturer uses electronic ballasts for its smaller units and magnetic ballasts for its larger units. A summary of some of the advantages and disadvantages of each ballast technology is shown in Table A.4.

Table A.4. Comparison of Magnetic and Electronic Ballasts.

	Magnetic Ballast	Electronic Ballast
Comparative Advantages	• Less potential for power interference due to stored energy • More resistant to power surges • More resistant to high temperatures. • Less prone to interference with electronic devices • Less prone to sputtering (inductive less than capacitive) • Proven technology (in use for nearly 70-years) • Less expensive	• More efficient • Lighter weight • Smaller size • Less potential for heat generation • Less potential for noise • Continuous power adjustment • Longer lamp operating life
Comparative Disadvantages	• Less efficient (capacitive more efficient than inductive) • Heavier weight • Larger size • More potential for heat generation • More potential for noise. • Step-function power adjustment (number of steps proportional to number of inductors/capacitors) • Shorter lamp operating life	• More potential for power interference due to stored energy (can be minimized by incorporating a capacitor) • Less resistant to power surges • Less resistant to high temperatures • More prone to interference with electronic devices • More potential for sputtering • Newer technology (limited operating experience, especially in larger sizes) • More expensive

A.3.2.4 Lamp Startup

The voltage applied to the lamps must be sufficiently high to start and operate the lamps. Step-up transformers are needed to increase the voltage above the mains to start cold-cathode lamps. Hot-cathode lamps are classified as either instant or switch start. Instant-start lamps have a single connection with each electrode. Starting instant-start lamps needs the application of a high voltage. As the electrodes warm-up, the needed voltage drops. Switch-start lamps have two electrical connections with each electrode, and the electrodes are preheated for 1 to 2 seconds before the start voltage is applied. This reduces the start voltage and lengthens the lamp life. Because of their relatively high impedance, MP lamps typically need a higher voltage than LP lamps for starting and stable operation. Operating voltage ranges from 5 to 30 volts/cm, depending on arc length, mercury dose, lamp diameter, and electrode losses. With the exception of short lamps, step-up transformers are needed to operate MP lamps and high voltage pulses are used to start them.

A.3.2.5 Voltage Frequency Converters

With LP and LPHO lamps, frequency converters may be used to increase the voltage frequency from that of the mains (typically 60 Hz) to 20 to 100 kHz. Typically, the efficiency of UV light output from electrical power increases by as much as 10 percent as the frequency increases above 500 Hz. Furthermore, the higher frequency reduces electrode deterioration, makes the lamps easier to start, and extends the lamp life. These benefits, however, can be offset by power losses associated with the frequency converter.

A.3.3 Lamp Sleeves

In UV reactors, lamps are housed within lamp sleeves. Sleeve length is sufficient to include the lamp and associated electrical connections. Sleeve diameter is typically 1 inch (2.5 cm) for LP mercury lamps and 2 to 4 inches (5 to 10 cm) for MP lamps. Sleeve walls are typically 2 to 3 mm thick and absorb some UV light. Sleeves made of doped quartz are used to prevent the transmission of low-wavelength UV light, thereby reducing undesirable photochemical reactions.

Lamp sleeves have several functions other than housing the lamps. They maintain the lamp temperature at an optimal value and control heat transfer from the lamps. Heat transfer from the MP lamp prevents failure of the molybdenum seal, distortion of the lamp envelope, and evaporation of the tungsten electrode. Also, lamp sleeves isolate the lamp and its electrical connections from the water. Lastly, they protect the lamp from mechanical forces such as water hammer and protect the lamp from thermal shock arising from differences in water and lamp envelope temperature.

Typically, LP lamps are centered using Teflon® rings, and MP lamps are centered using ceramic or metal disks. The positioning of the lamp along the length of the sleeve can influence dose delivery by the reactor.

Sealing the lamp sleeve assembly prevents water condensation within the sleeve and contains any ozone formed between the lamp envelope and lamp sleeve. Components within the sleeve should withstand exposure to UV light, ozone, and high temperatures. If the components are not made of the appropriate material, exposure can cause component deterioration and off-gassing of any impurities present in the quartz from manufacturing. Off-gassed materials can form UV-absorbing deposits on the inner surfaces of the lamp sleeve. Off-gassing and ozone formation will be a greater issue with MP lamps because they operate at a higher temperature and emit low-wavelength ozone-forming UV light. Off-gassing can be minimized through proper manufacturing of the lamp sleeves.

The UVT of a lamp sleeve influences the intensity of UV light transmitted from the lamp into the water. The UVT is a function of the reflectance and absorbance of UV light by the sleeve, as per Equation A.23.

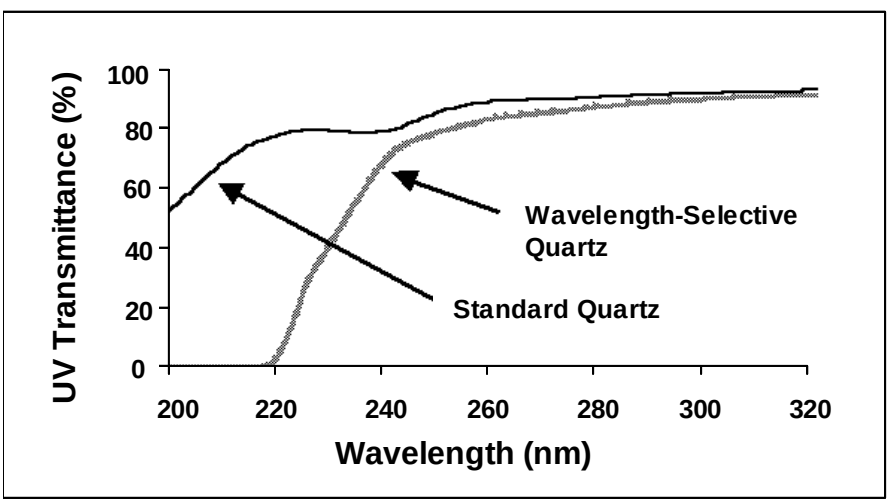
$$UVT_s(\lambda) = [1 - R_{AS}(\lambda)][1 - R_{SW}(\lambda)]e^{(-\alpha(\lambda)L)}$$ Equation A.23

where

$UVT_S(\lambda)$	=	Sleeve UVT at wavelength λ
$R_{AS}(\lambda)$	=	Reflectance of UV light at the air-sleeve interface at wavelength λ
$R_{SW}(\lambda)$	=	Reflectance of UV light at the sleeve-water interface at wavelength λ
$\alpha(\lambda)$	=	Sleeve absorption (Base e) at wavelength λ
L	=	Pathlength of light through the sleeve

Because the refractive indices of the lamp sleeve and water are similar, the reflectance of UV light at the sleeve-water interface (R_{SW}) is often considered negligible in this equation. The absorption coefficient of the sleeve varies strongly with wavelength and the material of the sleeve. For a zero degree incidence angle, Figure A.19 presents the UVT over the germicidal range of two types of quartz: standard and wavelength-selective. Quartz can be manufactured to select for a variety of wavelengths depending on the desired application. For UV disinfection applications, wavelength-selective quartz is primarily used to prevent the transmission of low wavelength (<200 nm) UV light into the water.

Figure A.19. UV Transmittance of Two Types of Quartz Commonly Used to Make Lamp Sleeves (GE Quartz 2001)



In order to reduce fouling on the sleeve surfaces, some UV reactors using LP lamps have sleeves made of Teflon® or Teflon®-coated quartz. However, Teflon® sleeves have a lower UV transmittance, and their transmittance degrades faster than conventional quartz.

Failure mechanisms for sleeves include fractures and fouling. Fractures arise from internal stresses created during the production of the quartz and external mechanical forces. Annealing the quartz at high temperatures during production removes internal stresses. Visual inspection using polarized light can also reveal whether or not sleeves are stress free. Fractures

may arise from mechanical forces such as wiper jams, water hammer, resonant vibration, and impact by foreign objects. Fouling may occur on both internal and external surfaces and is discussed in more detail in section A.4.1.4. Exposure of quartz contaminated with metal cations from the manufacturing process can cause solarization and an increase in UV absorption.

A.3.4 Cleaning Systems

Due to fouling on the lamp sleeves, cleaning the external surface of sleeves is important to maintain dose delivery. UV reactor manufacturers have developed different approaches for cleaning lamp sleeves, depending on the application. Both manual and automatic cleaning regimes are used. A reactor must be shut down and drained prior to manual cleaning. The sleeves are removed once the reactor is drained and wiped with a cloth and cleaning solution. Manual cleaning is primarily used for smaller systems with relatively few sleeves and lower fouling potential.

Automatic cleaning approaches are typically used for larger systems. They may be classified as off-line chemical cleaning (OCC) or on-line mechanical cleaning (OMC). OCC systems, also referred to as flush and rinse systems, involve a sequence of events controlled by the UV reactor. In OCC systems, the reactor is shut down, drained, and flushed with a cleaning solution. Solutions used to clean sleeves include citric acid, phosphoric acid, or a food grade proprietary solution provided by the UV reactor manufacturer. The reactor is rinsed and returned to operation after sufficient time to dissolve the substances fouling the sleeves is allowed. OCC cleaning approaches are typically used by reactors with LPHO lamps.

In OMC systems, the UV reactor remains on-line while the lamp sleeves are cleaned. OMC systems have mechanical or physical-chemical wipers that are built-in to the UV reactor. The wipers are either driven by screws attached to electric motors or pneumatic pistons. Mechanical wipers may consist of steel brush collars or Teflon® rings that move along the lamp sleeve. Physical-chemical wipers have a collar filled with cleaning solution that move along the lamp sleeve. The wiper physically removes fouling on the lamp sleeve surface while the cleaning solution within the collar dissolves fouling materials. UV reactors with MP lamps typically use wipers because the higher lamp temperatures accelerate fouling under certain water qualities.

The time between sleeve cleaning will depend on the rate of fouling. Sleeve cleaning can be initiated manually, at regular intervals, or triggered by a calculated UV dose or measured UV intensity, depending on the reactor control logic. In physical-chemical wipers, solution replacement varies with the rate of fouling and is on the order of months. Replacing the cleaning solution is necessary because reaction with the foulant and dilution with water reduces the ability of the cleaning solution to dissolve the foulant.

A.3.5 UV Intensity Sensors

UV intensity sensors are photosensitive detectors that are used to indicate dose delivery by providing information related to UV intensity at different points in the UV reactor. UV intensity sensors include the following components arranged as shown in Figure A.20.

- **Monitoring windows** and **light pipes** deliver light to the photodetector. Monitoring windows are typically quartz discs and light pipes are cylindrical probes made of quartz (quartz silica probe).

- **Diffusers** and **apertures** reduce the UV light incident on the photodetector, thereby reducing UV intensity sensor degradation. Diffusers also modify the UV intensity sensor's angular response.

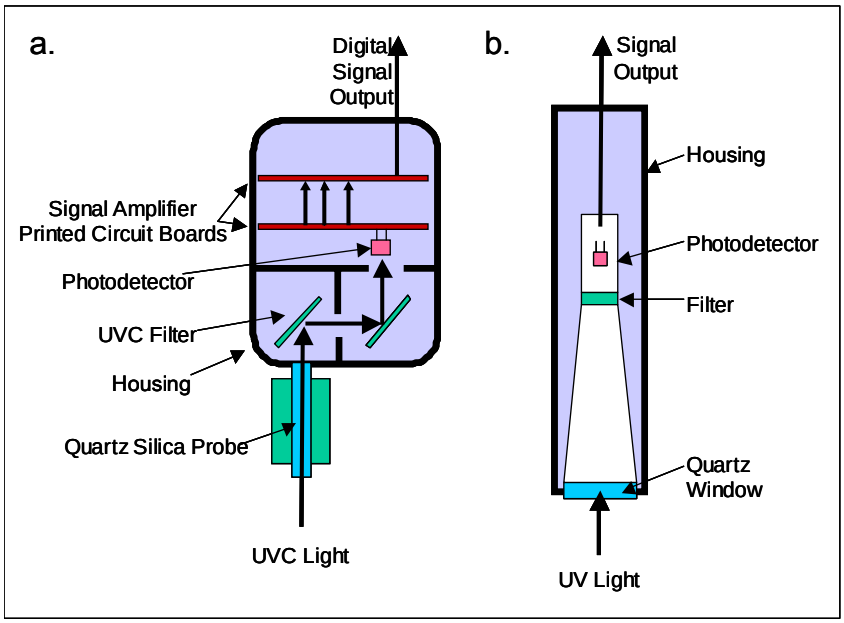
- **Filters** limit the light delivered to the diode, often restricting it to germicidal wavelengths.

- **Photodetectors** are solid-state devices that produce a current proportional to the irradiance on the detector's active surface. The responsivity of typical photodetector to UV light is on the order of 0.1 to 0.4 milliamps/mW (mA/mW).

- **Amplifiers** convert the output of the photodetector from a low-level current to a standardized output proportional to the irradiance (e.g., converts intensity to a 4 to 20 mA output for use in process control interfaces).

- The **housing** of the UV intensity sensor protects the components from the external environment. The housing should be electrically grounded to shield the photodetector and amplifier, thereby reducing electrical noise and bias.

Figure A.20. Interior UV Intensity Sensor Schematics (courtesy of (a) Severn Trent Services and (b) Wedeco-Ideal Horizons)



Note that the sensor shown in Figure A.20b is cylindrical in shape. All dimensions are standardized as detailed in the German standards for UV disinfection.

A.3.5.1 UV Intensity Sensor Properties

UV intensity sensor properties that impact the measurement of UV intensity and dose delivery monitoring include angular response, acceptance angle, spectral response, working range, detection limit and resolution, linearity, temperature response, long term drift, calibration factor, and measurement uncertainty. An ideal UV intensity sensor will have a linear response over the working range, provide a response unaffected by ambient temperature, be stable over time, have zero measurement noise and bias, respond only to germicidal UV light, and have zero measurement uncertainty.

Angular response is a plot of the sensor measurement as a function of the incident angle of UV light at the sensor's window. Angular response is affected by the UV intensity sensor's aperture size, the size of the photodetector's active surface, the distance between the aperture and the active surface, and the impact of any diffusers and reflecting surfaces within the UV intensity sensor. An ideal sensor has a cosine response (Equation A.24) because a cosine response results in an accurate measure of the light incident on the surface of the photodetector.

$$I_m = I_i \cos(\theta) \qquad \text{Equation A.24}$$

where

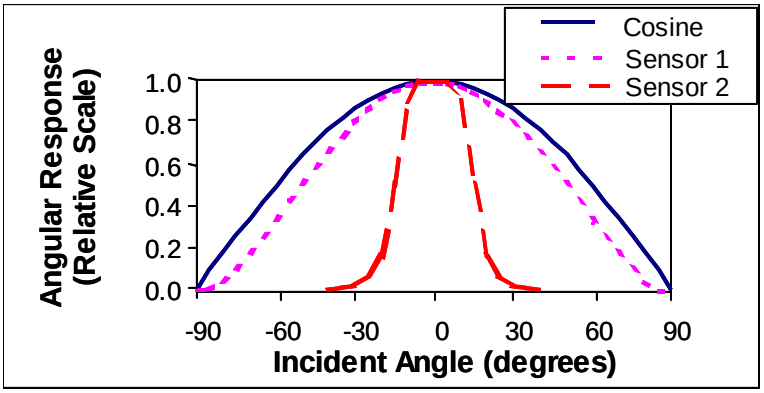
I_m = Intensity measured by photodetector

I_i = Intensity incident on photodetector's surface

θ = Incident angle at the photodetector surface

In practice, sensors deviate from cosine response; some potential responses are shown in Figure A.21.

Figure A.21. Angular Response of Two UV Intensity Sensors Relative to Ideal Cosine Response



The opening or **acceptance angle** of the UV intensity sensor is the angle over which the sensor detects UV light. The opening angle is typically measured by either the threshold detection of UV light or detection at some percentage of the maximum detection value (e.g., 50 percent). The acceptance angle is a characteristic of the sensor but does not affect sensor performance.

The **spectral response** is a measure of the output of the UV intensity sensor as a function of wavelength. The sensor spectral response depends on the response of the photodetector and filters and the UVT of the monitoring windows, light pipes, and filters. Some sensors use filters to limit the spectral response to the wavelengths within the germicidal range (200 to 300 nm) because it can be advantageous for sensors to only respond to UV light that causes damage to microorganisms.

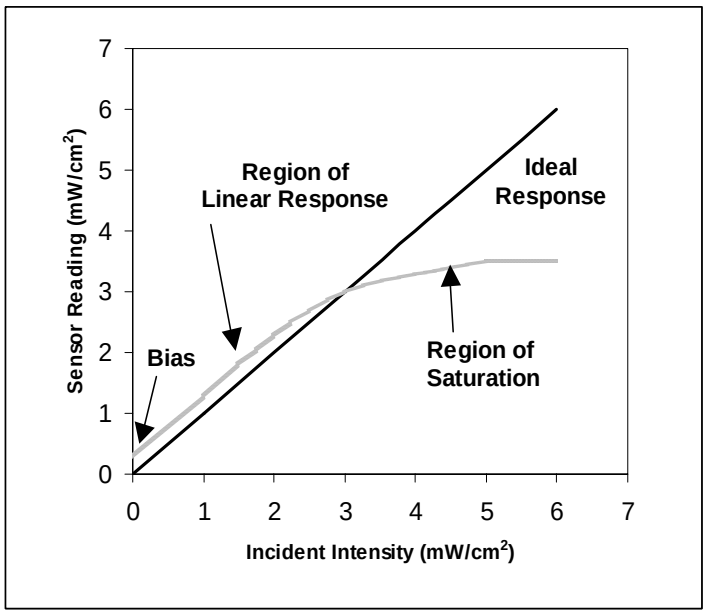
The **working range** of the UV intensity sensor is the range that the sensor is able to measure. The low end of the working range is defined by the detection limit of the measurement. The high end of the measurement range is limited by the saturation of the photodetector and the amplifier. Saturation is the point at which the sensor can no longer respond to an increase in intensity.

The **detection limit** of the UV intensity sensor is the lowest UV intensity that can be detected and quantified at a known confidence level. The detection limit is calculated as a confidence of repeated measurements of low intensity UV light, usually at a specific percentage confidence interval. The **measurement resolution** is the smallest difference in UV intensity that can be differentiated at a given confidence limit. The detection limit and the resolution depend on the measurement noise and on any digitalization of the analog output from the UV intensity sensor by the system's electronics. The measurement noise is the root-mean-square (RMS) of the random variation in the sensor measurement over time. The measurement bias is the time-averaged sensor measurement obtained with no incident light. The measurement bias and noise

of a photodetector are increased by electromagnetic fields within the UV reactor if the sensor is not properly shielded and grounded.

An ideal UV intensity sensor responds proportionally to the intensity incident on the sensor (Figure A.22). The **linearity** of the UV intensity sensor is a measure of the deviation of the sensor response from that proportional relationship. Linearity is affected by bias and saturation. The linearity is reported as the ratio of the measured response to the known incident intensity, usually at a specific percentage confidence interval.

Figure A.22 Example of Sensor Linearity



UV intensity sensor measurement is also affected by ambient **temperature**. The changes in sensor response arise from thermal expansion of the optical components, the photodetector, and the amplifier. UV intensity sensor electronics can compensate to reduce the effects of temperature.

The **long-term drift** of the UV intensity sensor is the change in response as a function of time. Exposure to UV light damages optical and electronic components within the UV intensity sensor. The damage caused by UV light is typically greater at higher UV intensities and lower wavelengths. Degradation of the filter can increase the filter's bandwidth (the wavelength range passed by the filter), thereby increasing the UV intensity sensor measurement even though the UV lamp output has not increased. Degradation of the monitoring windows and light pipes may cause a decrease in UVT due to solarization. Off-gassing from damaged components can coat optical components, reducing the measured intensity.

The **calibration factor** of the UV intensity sensor is a value used to convert the standard electrical output of the UV intensity sensor (mA or volts) to UV intensity (mW/cm^2 or W/m^2). The calibration factor is the ratio of the known intensity of the UV light to the electrical output of the sensor. Sensors used in UV reactors equipped with LP or LPHO lamps are calibrated with

UV light at 254 nm. Sensors used in UV reactors equipped with MP lamps can either be calibrated with light only at 254 nm or can be calibrated with polychromatic UV light from a MP lamp.

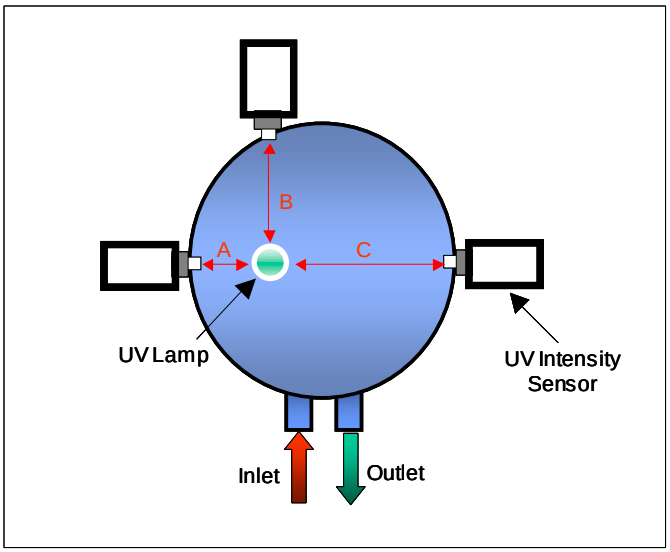
The **uncertainty** of a UV intensity sensor represents the difference in intensity between that measured by the sensor and an accepted reference sensor. This uncertainty incorporates the uncertainty that arises due to variability in calibration, linearity, spectral response, angular response, temperature response, and long-term drift.

A.3.6 UV Transmittance Monitors

As stated previously, UVT is an important parameter in determining the efficiency of UV disinfection. Therefore, monitoring UVT (or UV absorbance, A_{254}, to calculate UVT) is critical to the success of a UV disinfection application. UVT can be determined either by grab samples with a laboratory instrument or by an on-line instrument. Several commercial UV reactors use the measurement of UVT to help monitor and control the calculated UV dose in the reactor.

In general, commercial on-line UVT monitors calculate transmittance by measuring UV intensity at various distances from a lamp. One such monitor is schematically displayed in Figure A.23. In this monitor, a stream of water passes through a cavity containing a short LP lamp with three UV intensity sensors located at various distances from the lamp. The difference in sensor readings is used to calculate UVT.

Figure A.23. UV Transmittance Monitor Design (courtesy of Severn Trent Services)



A.3.7 Temperature Sensors

Energy input per unit volume is relatively high for a UV reactor. The water flowing through a reactor efficiently absorbs the waste heat and maintains operating temperatures within a desirable range. Nevertheless, temperatures can become elevated under the following circumstances:

- Water level in the reactor drops and lamps are exposed to air.
- Water stops flowing in the reactor.

Most temperature sensors are located at the top of the UV reactor. The temperature sensor can either measure the water temperature or the reactor shell temperature. In either case, if the temperature exceeds a setpoint value, it will register a high-temperature alarm. The temperature alarms can be integrated into a supervisory control and data acquisition (SCADA) system such that the alarm results in an operations change to reduce the potential for lamp breakage. For instance, the reactor can be shut down or valves can open or close to change the flow of water to the reactor.

A.3.8 Reactor Configuration

This section describes the configuration of UV lamps and UV intensity sensors as well as the hydraulic considerations of the overall reactor design.

A.3.8.1 Lamp Placement

The lamp configuration in a reactor is designed to optimize dose delivery. UV lamps may be oriented parallel, perpendicular, or diagonal to flow. Depending on the installation of the reactor, this can result in lamps oriented horizontally, vertically, or diagonally relative to the ground. Orienting MP lamps horizontal relative to the ground prevents overheating at the top of the lamps and reduces the potential for lamp breakage due to temperature differentials.

In a reactor with a square-cross section, typically lamps are placed with lamp arrays perpendicular to flow. This pattern may be staggered to improve disinfection efficiency. With a circular cross-section, lamps typically are evenly spaced on one or more concentric circles parallel to flow. The water layer between lamps and between the lamps and the reactor wall influences dose delivery. If the water layer is too small, the reactor wall and adjacent lamps will absorb UV light. If the water layer is too large, water will pass through regions of lower UV intensity and experience a lower UV dose. The optimal spacing between lamps depends on the UVT of the water, the output of the lamp, and the degree of hydraulic mixing within the reactor.

A.3.8.2 UV Intensity Sensor Placement

UV intensity sensors may be located to view either one or more lamps. The measurement of UV intensity from a given lamp depends on the following conditions:

- Output of the lamp
- UVT of the water
- Distance from the lamp to the UV intensity sensor
- Incident angle of the light on the UV intensity sensor

As such, a given measurement by a UV intensity sensor viewing more than one lamp can have many interpretations, and such measurements should be properly understood to avoid misinterpretation. Also, UV intensity sensors may be located to view the output from the center or ends of the lamp. The optimal sensor placement will give a representative or conservative measure of the lamp output, given that lamp aging and sleeve fouling is non-uniform along the length of the lamp.

The number of UV intensity sensors used in a reactor can vary from one per lamp to one per reactor. The appropriate number of sensors will depend on the type of lamp used, the variance in lamp-to-lamp output (especially after the lamps have aged), and the impact of that variance on dose delivery and dose monitoring. The implications of the number of sensors used per reactor are discussed in the background to the validation protocol (section F.3.5)

UV intensity sensors may view the lamps either from a UV intensity sensor port located on the reactor wall or through a lamp sleeve located within the reactor. UV intensity sensors are classified as wet or dry. A dry UV intensity sensor views the UV light through a monitoring window as shown in Figure A.20b. A wet UV intensity sensor is in direct contact with the water flowing through the reactor and is shown in Figure A.20a. While checking the on-line UV intensity sensor with a reference UV intensity sensor is easier with a separate monitoring window, condensation on the window can interfere with the measurement of UV intensity.

A.3.8.3 Hydraulic Considerations

The flow through UV reactors is turbulent with residence times on the order of tenths of a second for MP lamps or seconds for LP lamps. In theory, optimal dose delivery by a UV reactor is obtained with plug flow hydrodynamics and complete mixing perpendicular to the flow. In practice, however, UV reactors do not have these ideal hydrodynamics.

Lamp placement, inlet and outlet conditions, baffles, and mixers all affect hydrodynamics within a reactor. Turbulence and eddies form in the wake behind lamp sleeves oriented perpendicular to flow. Staggered lamp arrays promote mixing within the reactor, thereby minimizing short-circuiting of flow.

Inlet and outlet conditions can have a significant impact on reactor hydrodynamics. Ninety-degree inlet and outlets promote short-circuiting, eddies, and dead zones within the reactor. Straight inlet conditions with gradual changes in cross sectional area can be used to develop flow for optimal dose delivery.

Some manufacturers insert baffles to improve hydrodynamics in the reactor. Perforated plates can be used to even the flow throughout the reactor's cross-section. Plates with a single opening are used to direct flow towards high intensity regions within the reactor. Mixers used within reactors are designed to promote either turbulent or vortex mixing.

Improvements to the hydrodynamics through the reactor are often obtained at the expense of headloss. Perforated baffle plates and turbulent mixers can increase dose delivery but will significantly increase headloss. However, inlet and outlet conditions surrounding the reactor can be changed to reduce headloss without changing the disinfection effectiveness within the reactor. Also, using vortex mixers allows the spacing between lamps to increase, thereby reducing headloss through the reactor.

A.3.9 Monitoring UV Disinfection Performance

Some method of monitoring the performance of an operating UV installation is required to demonstrate to the utility and primacy agency that adequate disinfection is being achieved (40 CFR 141.729(d)). Because the concentration of pathogenic organisms cannot be measured continuously in the UV-treated water and the dose cannot be measured directly in real time, various strategies have been developed to demonstrate adequate dose delivery. Any dose monitoring method selected must be evaluated during reactor validation (described in Appendix C) and the outputs measured during validation will be part of the monitoring setpoints.

Currently, there are three fundamental approaches to monitor UV disinfection performance in a UV reactor:

1. **UV Intensity Setpoint Approach.** In this approach, measurements made by the UV intensity sensor are used to control the UV reactor. The UV intensity sensor is located in a position that allows it to properly respond to both changes in UV intensity output of the lamps and also UVT of the water. The UV intensity sensor output and the flowrate are used to monitor dose delivery. The setpoint value for UV intensity over a range of flowrates is determined during validation (see Chapter 4).

2. **UV Intensity and UVT Setpoint Approach.** This approach is similar to the UV intensity sensor setpoint approach, except that the UV sensor is placed close to the lamp such that it only responds to changes in UV lamp output. UVT is monitored separately. For a specific flowrate, the UV intensity and UVT measurements are used to monitor dose delivery. The setpoints for UV intensity and UVT over a range of flowrates are determined during validation (see Chapter 4).

3. **Calculated UV Dose Approach.** In this approach, the UV intensity sensor is placed close to the lamp, which is similar to the UV intensity and UVT setpoint approach. Flowrate, UVT, and UV intensity are all monitored, and the outputs are used to calculate UV dose via a validated computational algorithm developed by the UV reactor manufacturer.

The strategy for dose monitoring depends on the manufacturer and is typically proprietary. Dose monitoring recommendations are discussed in section 5.4.

A.4 Water Quality Impacts and Byproduct Formation

Constituents in the water affect the performance of UV reactors. In addition, most disinfectants form byproducts, and the goal of the overall disinfection process is to maximize disinfection while minimizing byproduct formation.

A.4.1 Water Quality Impacts

UV absorbance, particle content, and constituents that foul lamp sleeves and other wetted components are the most significant water quality factors impacting UV disinfection effectiveness. In spite of these effects, the impact of water quality on dose delivery can be adequately addressed in virtually all drinking water applications if carefully considered during the design of the UV reactors.

A.4.1.1 UV Absorbance

The most important water quality parameter affecting reactor performance is UV absorbance. As UV absorbance increases, the intensity throughout the reactor decreases for a given lamp output. This results in a reduction in UV dose delivered to the microorganism and measured UV intensity. Section 3.1.3.1 discusses how to incorporate the impact of UV absorbance into UV reactor design.

UV absorbers in typical source waters include humic and fulvic acids, other aromatic organics (e.g., phenols), metals (e.g., iron), and anions (e.g., nitrates and sulfites) (Yip and Konasewich 1972; DeMers and Renner 1992). Both soluble and particulate forms of these compounds will absorb UV light. UV absorbance will vary over time due to changing concentrations of these compounds. Temporal variability in UV absorbance is greater in rivers and small lakes than in large lakes and reservoirs. UV absorbance will vary seasonally due to rainfall, lake stratification and destratification (turnover), and changes in biological activity of organisms within the water source.

Water treatment processes can reduce the UV absorbance of water. Coagulation, flocculation, and sedimentation remove soluble and particulate material, and filtration removes particles. Oxidants such as chlorine and ozone reduce soluble material, precipitate metals, and reduce UV absorbance. Activated carbon absorption also reduces soluble organics. Because these treatment processes reduce UV absorbance, the lowest UV absorbance occurs at the end of the treatment train, and therefore UV disinfection is most effective when applied after filtration. Chemicals used in the water treatment process can also increase the UV absorbance of the water, and their impacts are discussed in section A.4.1.3.

A.4.1.2 Particles

Particle content can also impact UV disinfection performance. Particles may absorb and scatter light, thereby reducing the UV intensity delivered to the organisms. Particle-associated microorganisms also may be shielded from UV light, effectively reducing disinfection

performance as discussed in section A.2.6.5 and causing a tailing or flattening of the dose-response curve when higher inactivation levels are desired. Particles in source waters are diverse in composition and size and include large molecules, microorganisms, clay particles, algae, and flocs. Sources of particles include wastewater discharges, erosion, runoff, microbial growth, and animal waste. The particle concentration will vary over time both seasonally and over the short term. Storm events, lake turn over, and spring runoff are some events that increase the concentration of particles.

Recent research by Linden et al. (2002b) indicated that the UV dose-response of microorganisms added to filtered drinking waters is not altered by variation in turbidity of filtered water that met regulatory requirements (40 CFR 141.73). For unfiltered raw waters, Passantino and Malley (2001) found that source water turbidity up to 10 NTU does not impact the UV dose-response of separately added (seeded) organisms. In these experiments, however, organisms were added to waters containing various levels of treated or natural turbidity. Therefore, it was not possible to examine microorganisms associated directly with particles in their natural or treated states. Consequently, these drinking water studies can only suggest the impact of turbidity on dose-response as it relates to the impact of UV light scattering by particles rather than particle-association or clumping of microorganisms.

Water treatment unit processes such as coagulation, flocculation, sedimentation, and filtration are designed to remove particles from water. Organisms within coagulated and flocculated particles will be more difficult to inactivate; however, they will typically be removed during filtration.

A.4.1.3 Water Treatment Chemicals

Water treatment chemicals affect the UVT of the water, the formation of conglomerate particles, and the fouling potential of the water.

Water treatment processes upstream of the UV reactors can be operated to control and increase UVT, thereby optimizing the design and costs of the UV reactor. Chemicals such as chlorine, ozone, and hydrogen peroxide oxidize UV-absorbing compounds but may also absorb UV light with ozone showing the most pronounced effect on UV absorbance. Oxidant residuals can be quenched with chemicals such as sodium thiosulfate or sodium bisulfite. However, the use of these chemicals can also increase the UV absorbance of water.

Table A.5 lists the UV absorption coefficients of common water treatment chemicals and their "impact threshold concentration", defined as the concentration that will decrease the UVT from 91 to 90 percent. Of these chemicals, ozone and ferric iron have the greatest potential of impacting the UV absorbance of water.

Table A.5 UV Absorbance Characteristics of Common Water Treatment Chemicals (Adapted from Bolton et al. 2001)

Compound	Molar Absorbtion Coefficient (M^{-1} cm^{-1})	Mass-based Absorbance (L/mg cm^{-1})	Impact Threshold Concentration [1] (mg/L)
Ozone (O_3) (aqueous)	3,250	0.0677	0.071
Ferric iron (Fe^{3+})	4,716	0.0844	0.057
Permanganate (MnO_4^-)	657	0.0055	0.91
Thiosulfate ion ($S_2O_3^{2-}$)	201	0.00178	2.7
Hypochlorite ion (ClO^-)	29.5	0.000573	8.4
Hydrogen peroxide (H_2O_2)	18.7	0.00055	8.7
Ferrous iron (Fe^{2+})	28	0.0005	9.6
Sulfite ion (SO_3^{2-})	16.5	0.000206	23
Zinc ion (Zn^{2+})	1.7	0.000026	187
Ammonia (NH_3)	NSA	NSA	N/A
Ammonium ion (NH_4^+)	NSA	NSA	N/A
Calcium ion (Ca^{2+})	NSA	NSA	N/A
Hydroxide ion (OH^-)	NSA	NSA	N/A
Magnesium ion (Mg^{2+})	NSA	NSA	N/A
Manganese ion (Mn^{2+})	NSA	NSA	N/A
Phosphate species	NSA	NSA	N/A
Sulfate ion (SO_4^{2-})	NSA	NSA	N/A

NSA No significant absorbance
N/A Not applicable
[1] Concentration in mg/L resulting in UVT decrease from 91 percent to 90 percent (A_{254} increase from 0.041 cm^{-1} to 0.046 cm^{-1})

A.4.1.4 Fouling Potential

Wetted components within a UV reactor can become fouled over time. Fouling on the external surfaces of the lamp sleeve reduces the transmittance of UV light from the lamps into the water, thereby reducing dose delivery. Fouling on UV intensity sensor windows reduces the intensity of UV light measured by the sensors, resulting in under prediction of dose delivery. Fouling on the inside surfaces of the reactor reduces reflection of UV light from those surfaces, which reduces the amount of UV light available for disinfection.

Fouling on the wetted surfaces of a UV reactor has been attributed to the following events:

- Compounds whose solubility decreases as temperature increases will precipitate (e.g., $CaCO_3$, $CaSO_4$, $MgCO_3$, $MgSO_4$, $FePO_4$, $FeCO_3$, $Al_2(SO_4)_3$). These compounds will foul MP lamps faster than LP lamps due to differences in operating temperature.

- Compounds with low solubility will precipitate (e.g., $Fe(OH)_3$, $Al(OH)_3$).

- Particles will deposit on the lamp sleeve surface due to gravity settling and turbulence-induced collisions (Lin et al. 1999a).

Precipitation will depend on the water temperature, pH, alkalinity, ion concentration, total hardness, and the particle concentration. Residual concentrations of coagulants like ferric sulfate can also affect fouling. The fouling will vary spatially along and around the lamp sleeve, and will depend on the operating temperature of the lamp. Precipitation of compounds whose solubility decreases with increasing temperature is more notable with lamps operating at higher temperatures (e.g., MP lamps; Sheriff and Gehr 2001). Organic fouling can occur when a reactor is left off and full of water for an extended period of time (Toivanen 2000).

Fouling rates on lamp sleeves are reported to follow first order kinetics after an initial induction period (Lin et al. 1999b). Currently, there is not sufficient information to predict quantitatively the fouling based on water quality. The potential for fouling and the frequency of sleeve cleaning will be site and equipment specific. The fouling observed during several pilot- and full-scale UV facilities is shown in section 2.5.1 (Table 2.3).

The Langelier Saturation Index (LSI) or the calcium carbonate precipitation potential (CCPP) can be used to help indicate fouling potential. The LSI is defined as the difference between the pH of the water and the pH at which calcium and carbonate are at equilibrium with solid $CaCO_3$. The CCPP is the amount of calcium carbonate that will precipitate when equilibrium conditions in the water have been reached. Both the LSI and CCPP are functions of temperature, pH, calcium hardness, total dissolved solids (TDS), and alkalinity. For UV disinfection, the temperature of the lamp sleeve surface should be used to calculate the LSI and CCPP. The LSI and CCPP will depend on upstream processes, such as pH adjustment and lime softening, and may vary daily or seasonally.

A.4.1.5 Algae Growth

Visible light emitted from UV lamps may promote algae growth in UV reactors and the surrounding piping. Depending on the species, algae growth could cause taste and odor problems in the finished water. Algae growth is a greater issue with MP lamps than LP lamps because MP lamps produce more light in the visible range. Algae growth also depends on water temperature, pH, and nutrient concentration (Sterner and Grover 1998).

A.4.2 Disinfection Byproducts

UV disinfection byproducts (DBPs) arise either directly through photochemical reactions or indirectly through reactions with products of photochemical reactions. Photochemical reactions will only take place if a chemical species absorbs UV light, and the resulting excited state reacts to form a new species. The resulting concentration of new species will depend on the concentration of the reactants and the UV dose.

When UV light is absorbed by an atom, electrons within the atom are excited to higher energy states. An excited atom may return to its original ground state releasing the absorbed energy as light, or it may interact with other atoms forming or breaking bonds. The formation or

breaking of bonds between atoms results in the formation of a new chemical species. Chemical reactions promoted by light are termed photochemical reactions. In some cases, the products of photochemical reactions are radical species. Radical species may react with other chemicals to form new chemical species (i.e., UV DBPs).

In drinking water, research has focused on the impact of UV light on the formation of halogenated DBPs following subsequent chlorination and the transformation of organic material to more degradable components. For ground water and filtered drinking water, UV disinfection at typical doses is not shown to impact the formation of trihalomethanes (THM) or haloacetic acids (HAA), two categories of DBPs currently regulated by EPA (Malley et al. 1995; Kashinkunti et al. 2003). Several studies have shown low-level formation of degradable, non-regulated DBPs (e.g., aldehydes) as a result of applying UV light to wastewater and raw drinking water sources. However, a study performed with filtered drinking water indicates no significant change in aldehydes, carboxylic acids, or total organic halides (TOX) (Kashinkunti et al. 2003). The difference in results can be attributed to the difference in water quality, most notably the higher concentration of organic material in raw waters and wastewaters.

Akhlaq et al. (1990) reported that UV doses of 250 mJ/cm^2 from an LP lamp do not break down alginic acid, a model compound for polysaccharides in drinking water. They concluded that UV disinfection does not increase the assimilable organic carbon (AOC) of drinking water. With UV doses ranging from 18 to 161 mJ/cm^2, Kruithof et al. (1989) reported no increase in AOC or mutagenicity of a granular activated carbon (GAC) filtrate.

Malley et al. (1995) evaluated the impact of UV doses of 60, 130, and 200 mJ/cm^2 on DBP formation in ground waters and treated surface waters. They reported no change in pH, turbidity, dissolved organic carbon, A_{254}, color, nitrate, nitrite, bromide, iron, or manganese. Formaldehyde increased from 1.2 to 12.1 μg/L with one highly colored ground water. Formaldehyde increased from less than 2 μg/L up to 14 μg/L with untreated surface waters but only 2 to 3 μg/L with treated surface waters. A small but insignificant increase in AOC was observed with all waters.

Zheng et al. (1999) observed an 8 to 17 percent decrease in THM and a 9 to 19 percent increase in HAA when MP UV light was applied at a dose of 2000 mJ/cm^2 after chlorination. However, at a lower dose of 100 mJ/cm^2, they observed a 1 to 7 percent decrease in THM and no change in HAA.

A low conversion of nitrate to nitrite by UV light has been observed (approximately 1 percent; Sharpless and Linden 2001). Von Sonntag and Schuchmann (1992) also reported 0.001 and 0.072 mg/L nitrite formed from 50 mg/L nitrate exposed to 25 mJ/cm^2 from LP and MP lamps, respectively. Conversion is lower with LP lamps than MP lamps because the UV absorbance of nitrate is higher below 240 nm than it is at 254 nm.

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Appendix B. Derivation of UV Dose-Response Requirements

In support of the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), the U.S. Environmental Protection Agency (EPA) developed UV dose requirements for *Cryptosporidium*, *Giardia*, and virus inactivation. The requirements represent the UV dose necessary to achieve a given inactivation level, similar to the concentration * time (CT) requirements for chemical disinfectants.

The UV dose requirements were developed to account for uncertainty associated with the dose-response of microorganisms (*Cryptosporidium*, *Giardia*, and virus) in controlled experimental conditions. In practical application, other sources of variability and uncertainty are introduced due to the hydraulic effects of the UV installation, UV reactor, and UV intensity sensors. The validation protocol, as described in Chapter 4 and Appendix C, addresses these and other areas of variability and uncertainty by applying safety factors to the UV dose requirements derived in this appendix. Therefore, the dose requirements presented in this appendix are not the actual dose levels at which utilities will be required to validate and operate UV reactors for a given log inactivation.

This appendix explains the derivation of the UV dose requirements through a three-step process of data collection, qualitative review to establish working data sets, and mathematical analyses.

B.1 Data Collection

EPA collected UV dose-response research data for adenovirus, *Giardia lamblia*, *Giardia muris*, and *Cryptosporidium parvum*. Adenovirus was evaluated because, of the data available, it is considered the most resistant to inactivation by UV light of the pathogenic waterborne viruses. In compiling data, EPA reviewed published and unpublished studies conducted over the past 50 years as provided in published literature, electronic databases, research reports, and conference proceedings. The experimental conditions varied among batch and continuous flow UV apparatuses, types of UV lamps, and water quality conditions. Table B.1 summarizes these studies.

Table B.1 Summary of Data Collected (cont)

General		Microbial Information						Experimental Information			
Reference	Peer Reviewed Literature (Y/N)	Organism	Species	Host	Strain	Type	Assay Used	Experiment Type	Lamp Type	UV Dose Measurement	Water Quality[1]
Gerba 2000	No	Adenovirus	N/A	Human	N/A	2	Cell Culture (PLC/PRF/5)	Batch	LP	Radiometer	Lab
Gilead and Ginsberg 1966	Yes	Adenovirus	N/A	Human	N/A	12	Cell Culture (KB cells)	Batch	LP	None	Lab
Hara et al. 1990	Yes	Adenovirus	N/A	Human	N/A	19	Cell Culture (Vero)	Batch	LP	Not given	Lab
Malley 2000b	No	Adenovirus	N/A	Human	N/A	41	Cell Culture (Hep-2) and RT-PCR	Batch	MP	MP-Calculated (DNA), Radiometer	Lab
Meng and Gerba 1996	Yes	Adenovirus	N/A	Not given	N/A	40 41	Cell Culture (PLC/PRF/5)	Batch	LP	Radiometer	Lab
Shin et al. 2001a	No	Adenovirus	N/A	Human	N/A	5	Cell Culture (A549)	Batch	LP	Radiometer	Lab
Thompson et al. 2002	Yes	Adenovirus	N/A	Human	N/A	2 15	Cell Culture (A-549)	Batch	LP	Radiometer	Low Turbidity Reclaimed Wastewater
Thurston et al. 2002	No	Adenovirus	N/A	Human	N/A	40	Cell Culture (PLC/PRF/5)	Batch	LP	Radiometer	Lab and Ground-water

Table B.1 Summary of Data Collected (cont)

General		Microbial Information						Experimental Information			
Reference	Peer Reviewed Literature (Y/N)	Organism	Species	Host	Strain	Type	Assay Used	Experiment Type	Lamp Type	UV Dose Measurement	Water Quality[1]
Craik et al. 2000	Yes	*Giardia*	*muris*	Bovine	N/A	N/A	Mouse Infectivity (C3H/HeN)	Batch	MP	MP-Calculated (DNA)	WTP Filtered Water
Danielson et al. 2001	No	*Giardia*	*muris*	Bovine	N/A	N/A	Mouse Infectivity	Batch	LP/ LPHO	Radiometer	Lab
Hayes et al. 2001	No	*Giardia*	*muris*	Hamster	N/A	N/A	Mouse Infectivity	Batch	LP	Radiometer	Lab
Oppenheimer et al. 2002	No	*Giardia*	*muris*	Mouse	N/A	N/A	Mouse Infectivity	Batch	LP/MP	Not Given	Unfiltered
Campbell and Wallis 2002	Yes	*Giardia*	*lamblia*	Human	N/A	N/A	Gerbil Infectivity	Batch	LP	Radiometer	Lab
Linden et al. 2002	No	*Giardia*	*lamblia*	Bovine	N/A	N/A	Gerbil Infectivity	Batch	LP	Radiometer	Lab
Malley 2000a	No	*Giardia*	*lamblia*	Bovine	N/A	N/A	Gerbil Infectivity	Batch	P-UV	Bioassay	Reclaimed Wastewater
Mofidi et al. 2002	Yes	*Giardia*	*lamblia*	Bovine	N/A	N/A	Mouse Infectivity Gerbil Infectivity	Batch	LP	Radiometer	WTP Filtered Water

Table B.1 Summary of Data Collected (cont)

General		Microbial Information						Experimental Information			
Reference	Peer Reviewed Literature (Y/N)	Organism	Species	Host	Strain	Type	Assay Used	Experiment Type	Lamp Type	UV Dose Measurement	Water Quality[1]
Bukhari et al. 1999	Yes	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Mouse Infectivity (CD-1)	Continuous Flow	MP	Math Model (PSS)	WTP Filtered Water
Clancy et al. 2000	Yes	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Mouse Infectivity (CD-1)	Batch	MP/ LP	MP-Calculated (DNA) Radiometer	Lab / Backwash supernatant recycle
Clancy Env 2000	No	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Mouse Infectivity (CD-1)	Batch	LP/MP	Radiometer MP-Calculated (DNA)	Unfiltered
Clancy et al. 2002	Yes	*Crypto.*	*parvum*	Bovine	TAMU Moredum Iowa Maine Glasgow	N/A	Mouse Infectivity	Batch	LP	Radiometer	Lab
Craik et al. 2001	Yes	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Mouse Infectivity (CD-1)	Batch	LP/ MP	Radiometer - calculated	Lab or WTP Filtered Water
Hargy et al. 2000	Yes	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Mouse Infectivity (CD-1)	Continuous Flow	MP	Math Model (PSS)	Untreated Surface Water
Landis et al. 2000	No	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Cell Culture (HCT-8)	Batch	LP	Radiometer	Lab
Mackey et al. 2000	No	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Mouse Infectivity (CD-1)	Continuous Flow	LPHO	Bioassay	WTP Filtered Water

Table B.1 Summary of Data Collected (cont)

General		Microbial Information						Experimental Information			
Reference	Peer Reviewed Literature (Y/N)	Organism	Species	Host	Strain	Type	Assay Used	Experiment Type	Lamp Type	UV Dose Measurement	Water Quality[1]
Mofidi et al. 1999	No	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Cell Culture (HCT-8) and RT-PCR	Batch	MP/ P-UV	MP - calculated Joulemeter	WTP Filtered Water
Oppenheimer et al. 2002	No	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Mouse Infectivity (CD-1)	Batch	LP/MP	Not Given	Unfiltered
Shin et al. 2001b	Yes	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Cell Culture (MDCK)	Batch	LP	Radiometer	Lab
Kashinkunti et al. 2002	No	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Cell Culture (MDCK)	Batch	LP	Radiometer	WTP Filtered Water
Sommer et al. 2001	No	*Crypto.*	*parvum*	Bovine	Iowa	N/A	Cell Culture (HCT-8)	Batch	LP	Radiometer	WTP Filtered Water

N/A – Not applicable; LP – low pressure lamp; LPHO – low pressure-high output lamp; MP – medium pressure

[1] Water Quality Definitions:

Lab - Tap water treated in the lab by de-ionization and buffering (in some cases).
Reclaimed Wastewater - Tertiary treated wastewater.
Low Turbidity Wastewater - Tertiary treated wastewater with turbidity less than 1 NTU.
Unfiltered - Water that meets EPA's filtration avoidance criteria.
Untreated Surface Water - Water from an untreated surface water (e.g., lake, river).
WTP Filtered Water – Filtered water from a water treatment plant.
Lab Filtered Surface Water - Filtered water from a water treatment plant that is filtered subsequently in the lab

B.2 Data Review – Criteria for Inclusion in Statistical Analysis

EPA evaluated the data presented in Table B.1 to determine the data sets to be used in analyzing dose-response for each target microorganism. To be included in the statistical analysis, the experimental design had to be sufficiently documented with respect to experimental conditions, methodology, and calculation of results to allow an accurate assessment of UV dose-response. For instance, studies were not included if the report did not provide sufficient information to determine the UV dose measurement method or whether the reported UV dose accounted for appropriate parameters (e.g., UV absorbance). The statistical dose-response analysis combines data across different experimental designs and conditions; therefore, it is important to ensure the differences between studies do not affect the UV dose-response relationship.

B.2.1 Appropriate Experimental Design and Conditions

Research studies with the following criteria were selected for the statistical analyses:

- Batch experimental design
- Low pressure (LP) lamps as the UV light source
- Filtered water, high quality unfiltered water, laboratory water, or low turbidity reclaimed wastewater
- UV dose of the target microorganism inactivation directly measured and not derived from the inactivation response of another microorganism

Data from continuous flow studies were not included in the analyses because flow-through UV reactors apply a distribution of UV doses as opposed to a single dose. Moreover, UV dose in a reactor is difficult to calculate precisely due to the variability in hydraulic detention time and UV intensity distributions in reactors.

Studies were not included if the researchers utilized a UV light source that did not have a widely accepted dose measurement methodology, such as pulsed UV lamps. Medium pressure (MP) lamps pose a challenge of dose measurement due to the polychromatic nature of the MP UV light and the absence of a standard method for calculating dose from MP lamps. The results of a t-test indicated the LP and MP UV dose-response data, as reported, were statistically different[1]; therefore, only LP lamp data were used in the statistical analyses.

Given the potential interference of particles in water and the fact that utilities installing UV disinfection would need to meet finished water turbidity levels, EPA restricted media to water with turbidity values less than or equal to 1 nephelometric turbidity unit (NTU).

[1] The t-test was calculated with *Cryptosporidium* data at low doses. The *Giardia* data and higher dose *Cryptosporidium* data had too many data reported as "greater than a value" (referred to as censored data) and thus, could not be used in a t-test. The adenovirus data had too few MP data to conduct a t-test.

Studies utilizing non-standard microbial assay methods (i.e., not generally accepted in standard microbiological methods references) or studies not providing an evaluation of pathogen infectivity were not included.

Note that many research studies evaluated multiple experimental conditions, but only the subset of data meeting the criteria specified for this statistical analysis were used.

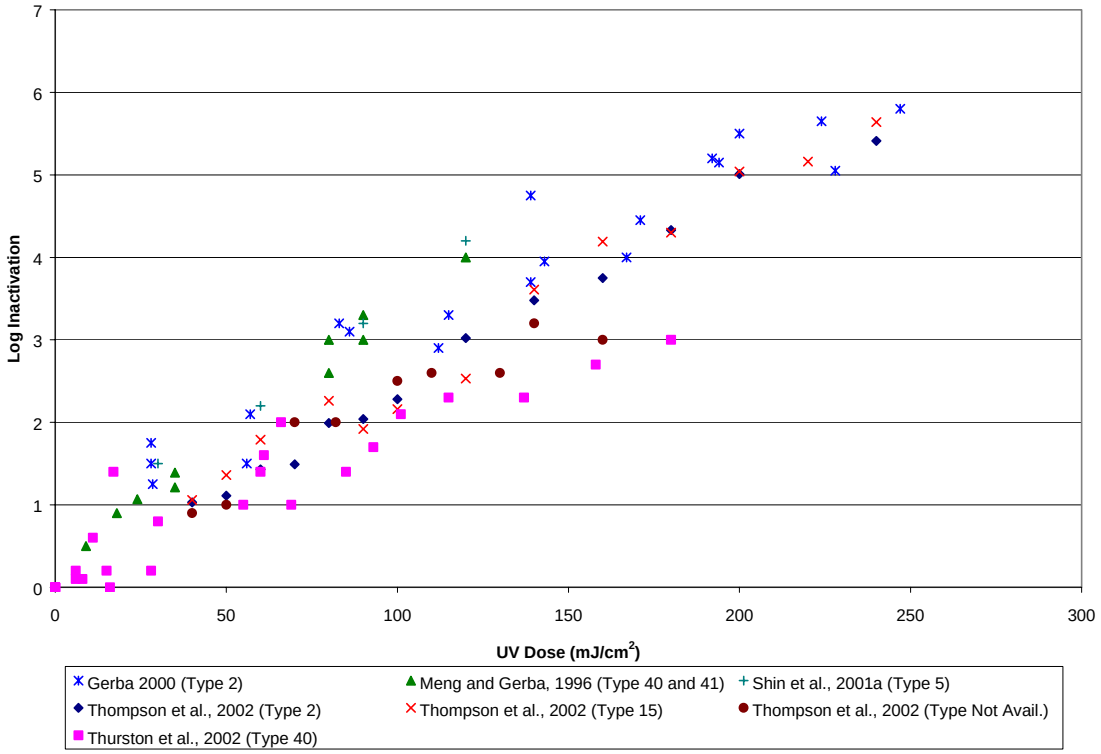
B.2.2 Research Studies and Data Included in Statistical Analysis

UV dose-response data sets for adenovirus, *Cryptosporidium parvum*, and *Giardia lamblia* and *Giarida muris* that met the criteria specified previously are presented in this section.

B.2.2.1 Viruses

For adenovirus, 4 of the 9 studies met the criteria discussed for inclusion in the statistical analysis. Figure B.1 shows the data of the selected studies.

Figure B.1 Observed Adenovirus Data from Selected Research Studies



B.2.2.2 Protozoa

For *Cryptosporidium parvum*, 9 of the 13 studies met the criteria for inclusion in the statistical analysis. For *Giardia* (including both *lamblia* and *muris*), 6 of the 8 studies were included. Figures B.2 and B.3 show the *Cryptosporidium parvum* and *Giardia* data of the selected studies, respectively. The data are both censored and uncensored and noted as such on each graph. Censored data are those with log inactivation of "greater than" a particular value rather than an absolute value (termed uncensored).

Figure B.2 *Cryptosporidium* Data from Selected Research Studies

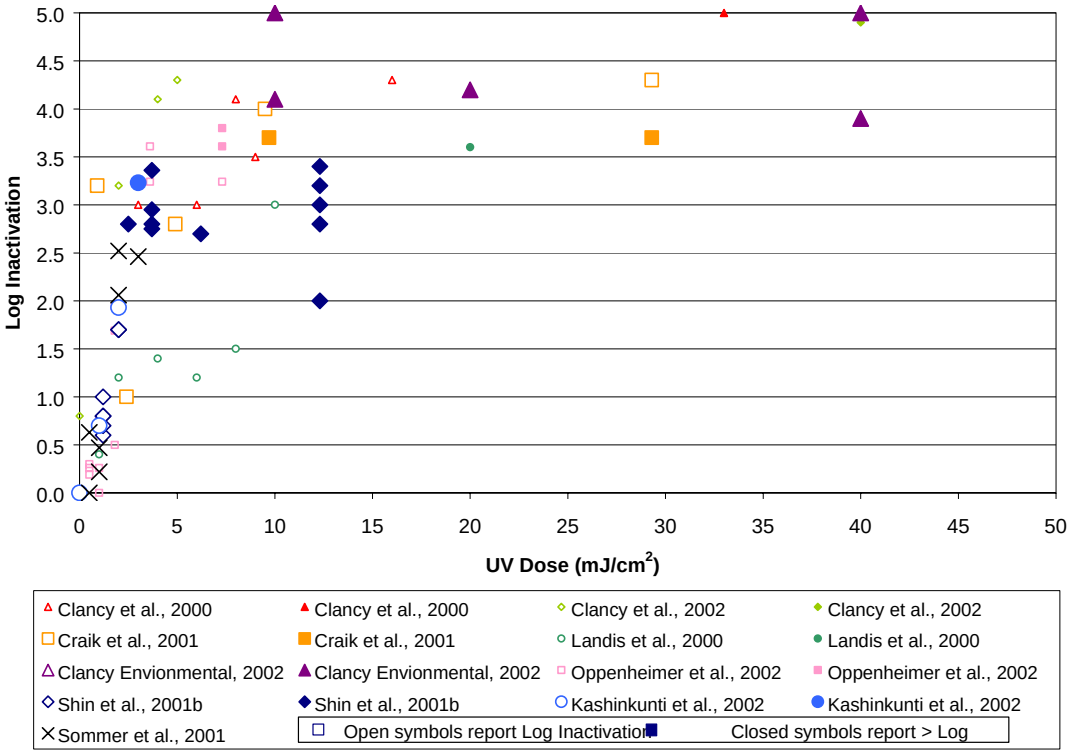
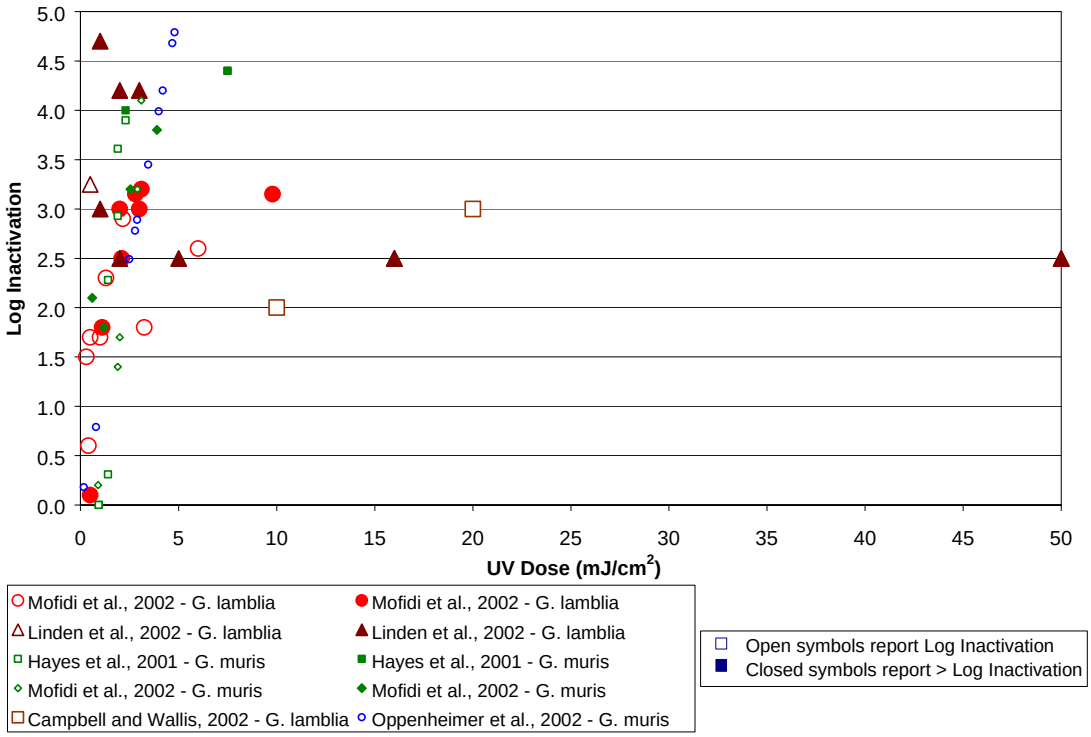


Figure B.3 *Giardia* Data from Selected Research Studies



B.3 Statistical Analysis

To determine the relationships between UV dose and log inactivation of *Cryptosporidium*, *Giardia*, and virus, a mathematical model with hierarchical Bayesian parameter estimation techniques was used. This model performs a meta-analysis that summarizes and integrates the findings of multiple research studies. It can be considered as a compromise of two extreme methods of combining data from different sources. One extreme method treats the data from different sources as identical replications and computes a regression as if the data were from a single source. The second extreme method treats each individual study as totally unrelated to other studies. In this second method, the separately estimated regression coefficients are pooled only to reflect the possible range. The Bayesian meta-analysis treats the studies as exchangeable, but not identical or completely unrelated (Hedges 1997). Regression coefficients for each study are estimated using the same calculations and allowed to differ between studies. A Bayesian hierarchical modeling approach represents a more general and reasonable approach for combining information (Gelman et al. 1995; Condon 2001).

B.3.1 Model Description

The model used to relate UV dose to *Cryptosporidium*, *Giardia*, and virus log inactivation is described by Equation B.1. Qian et al. (2003) provides a complete description of the model and further statistical analyses.

$$
\begin{aligned}
&Y_{ijk} \sim N(\mu_{ij}, \tau_1) I(C_{ijk}) \\
&\mu_{ij} = \exp(\beta_i) \log_{10}(X_{ij} + 1) \\
&\beta_i \sim N(\overline{\beta}, \tau_2) \\
&\tau_{1,2} \sim gamma(0.001, 0.001) \\
&\overline{\beta} \sim N(0, 0.0001)
\end{aligned}
\qquad \text{Equation B.1}
$$

where

Y_{ijk}	=	Log inactivation of the kth observation exposed to the jth UV dose level in the ith study
$N(\mu_{ij},\tau_1)$	=	Normal distribution with mean μ and precision τ
$I(C_{ijk})$	=	Censor operator with C_{ijk} as the estimated lower bound of the log inactivation value for the kth observation exposing to the jth UV dose level in the ith study
X_{ij}	=	j^{th} dose level of study i,
β_i	=	Regression coefficient for study i
$\overline{\beta}$	=	Integrated regression coefficient, combining information from all studies

When an observation is known to be greater than a value (right-censored), the reported value is used as a lower bound value (C_{ijk}.). The prior distributions on precision (inverse of variance), $\tau_{1,2}$, are modeled using gamma(0.001, 0.001), which is considered "non-informative" (the log variance is almost uniform). The prior distribution on $\overline{\beta}$ is N(0, 0.0001), a practically flat distribution.

One of the benefits of using a Bayesian modeling approach is it allows known information that can better explain the data relationships to be incorporated into the model. In this model, two known pieces of information were incorporated: (1) as UV dose increases the number of microorganisms inactivated increases—incorporated by taking the exponential of β_i in the second line of Equation B.1, which restricts the slope of the regression between log inactivation and UV dose to a positive value; and (2) when the UV dose is zero, no microorganism inactivation due to UV light occurs—incorporated by setting the intercept of the regression line to zero (the second line in Equation B.1 has no intercept term).

A Markov Chain Monte Carlo simulation method is used for estimating the model parameters. To impute the censored data, an iterative procedure is used. At a given iteration, a random sample of log inactivation is taken from a normal distribution with the mean and variance calculated by the current estimates of β_i and $\tau_{1:2}$. If the generated value is less than the reported value (the lower bound), it is not used and a new value is generated until one that is larger than the reported value is found. The model is then refitted with new estimates of β_i and $\tau_{1,2}$. This process is repeated many times (200,000 in this case). Mathematical theories indicate that the effect of a set of random initial values for all model coefficients and the censored values

will gradually disappear, and the samples will converge to their respective posterior marginal distributions after a number of iterations. In this case, the first 140,000 iterations were discarded and 1,000 samples for each of the unknown quantities (i.e., coefficients, predictions, and censored values) were taken from the remaining 60,000 iterations. The computation is implemented under WinBUGS (Spiegelhalter et al. 1996).

The Bayesian hierarchical model of Equation B.1 estimates the integrated model coefficients using the coefficient estimates from each study. As the model indicated, $\overline{\beta}$ is assumed to be the mean of the parent distribution of β_i. This integration accounts for the uncertainty of each study and "weights" each study accordingly.

B.3.2 *Cryptosporidium* and *Giardia* Modeled Results

The modeled results for *Cryptosporidium* and *Giardia* are shown graphically in Figures B.4 and B.5, respectively. The graphs show the estimated regression for each study. The model incorporates the coefficients from each study and calculates the predicted median and 80 percent credible intervals, shown by the black solid line (median) and dark dotted lines (credible intervals).

Figure B.4 *Cryptosporidium* Modeled Data and Predictive Credible Intervals

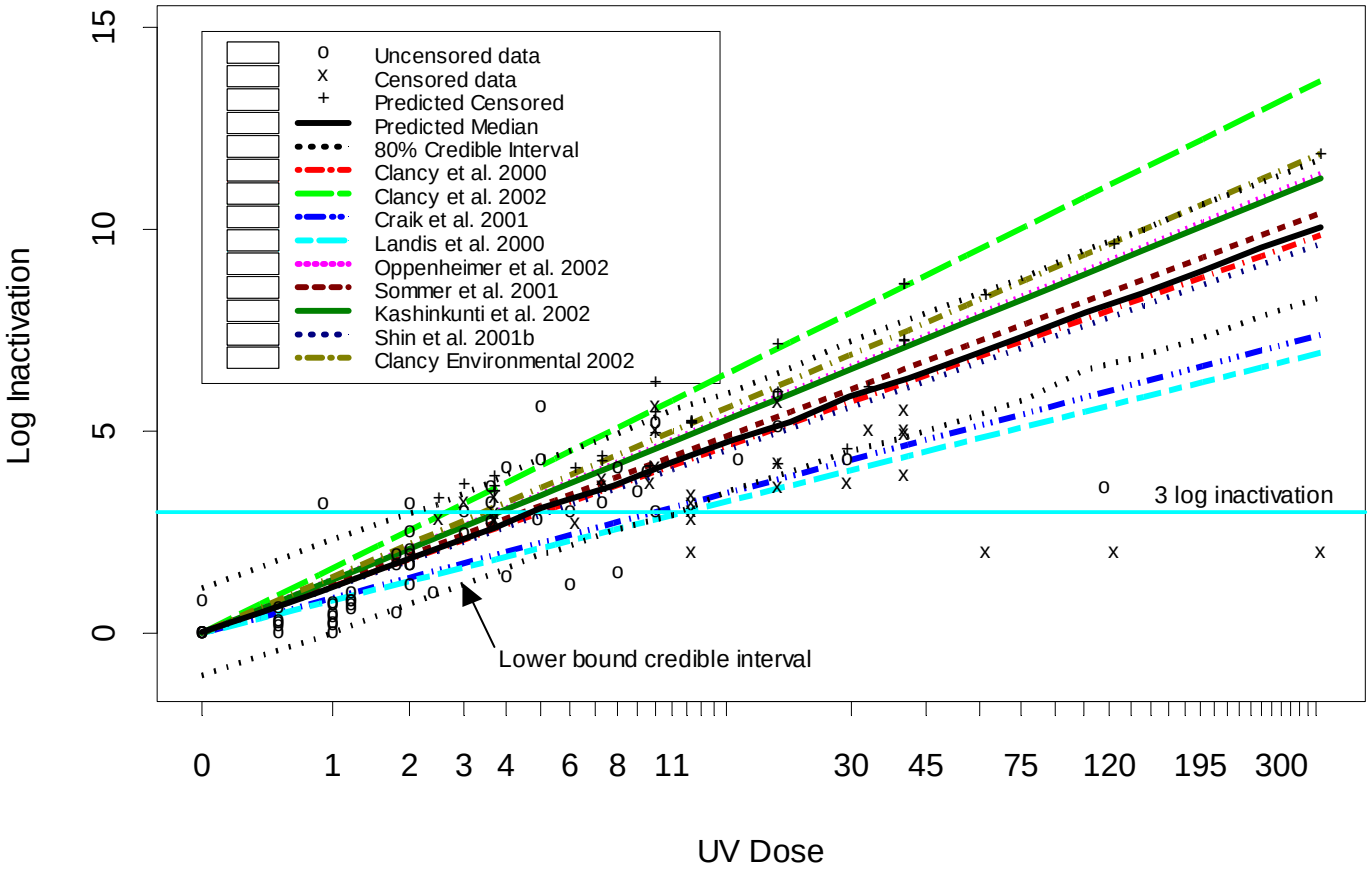
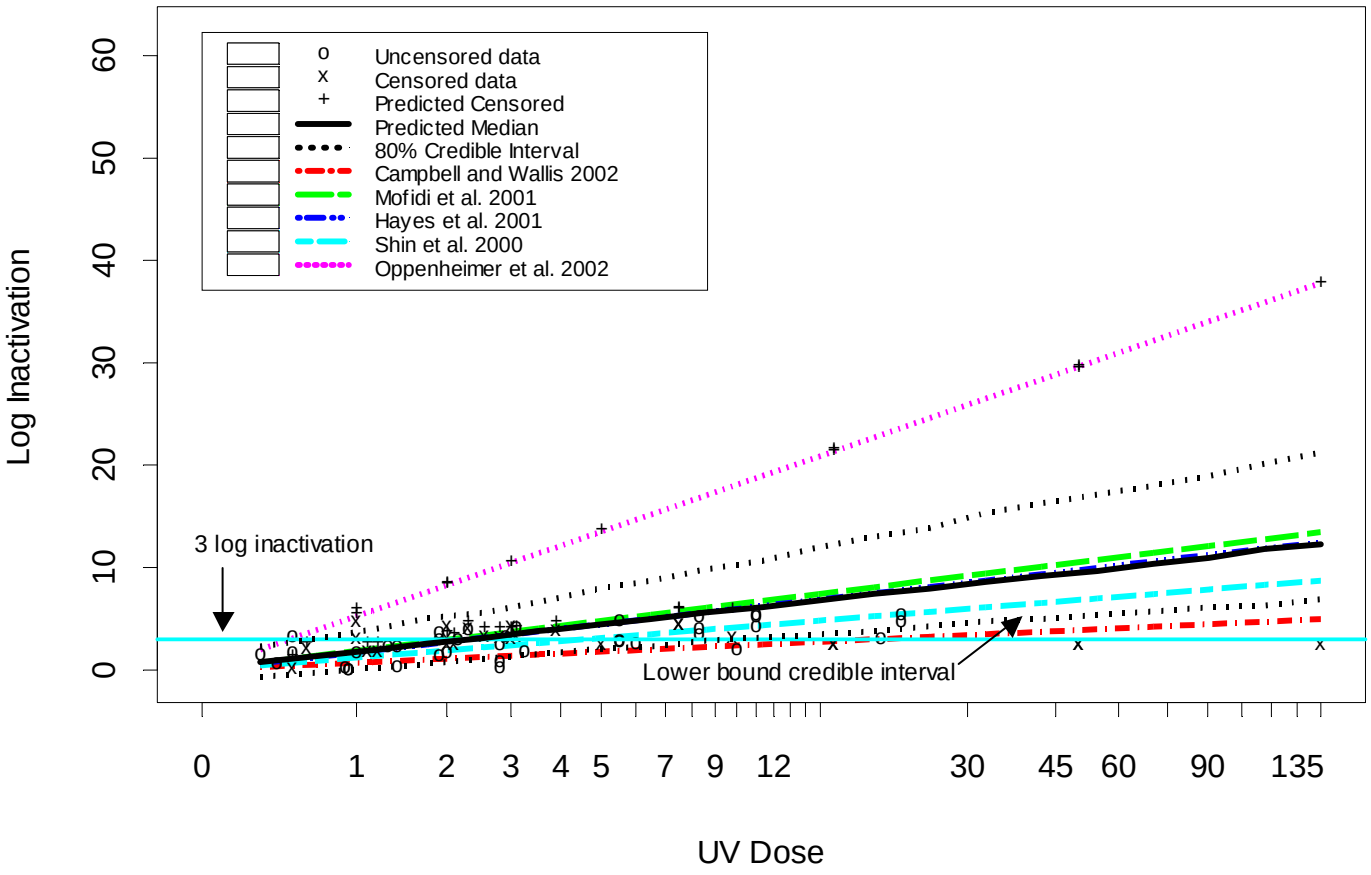


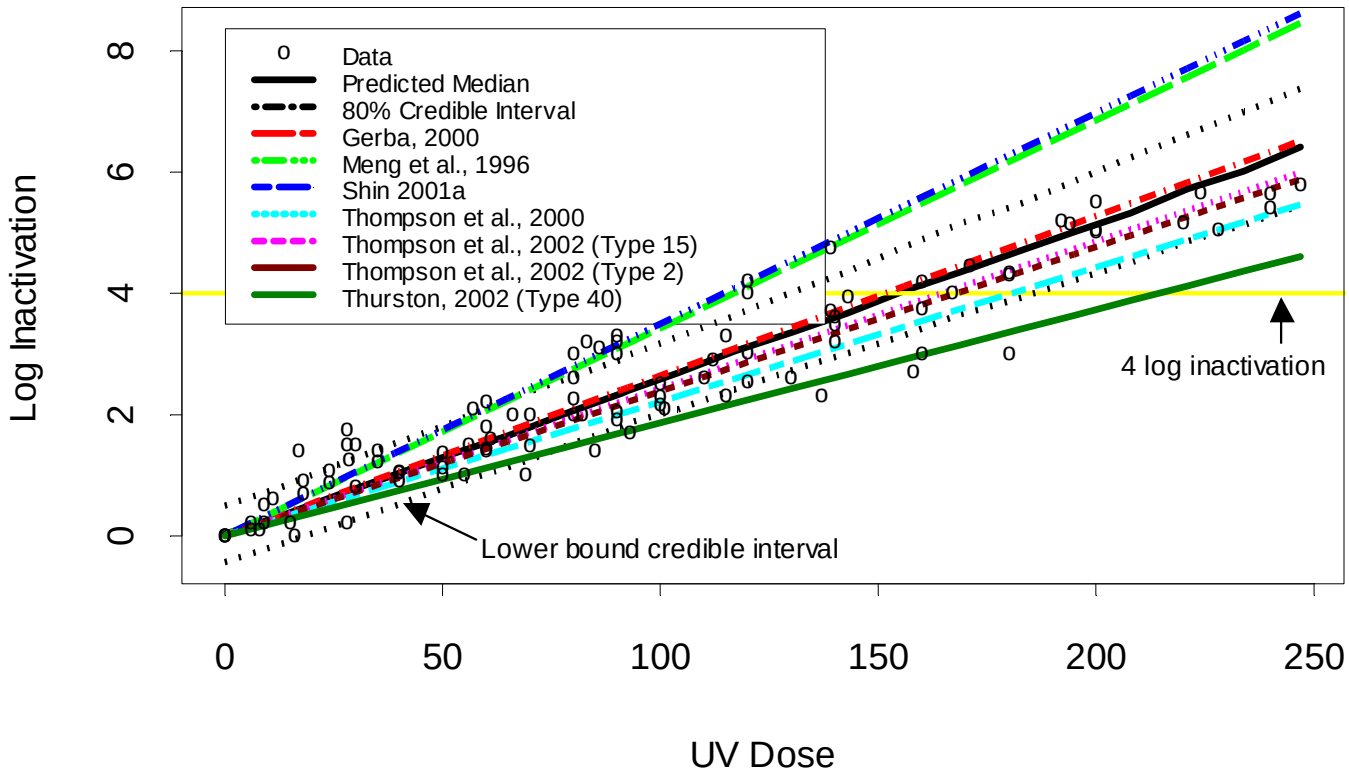
Figure B.5 *Giardia* Modeled Data and Predictive Credible Intervals



B.3.3 Virus Modeled Results

The model for the virus data is slightly different from the *Cryptosporidium* and *Giardia* model described in Equation B.1. First, there were no censored data points; as a result, the term $I(C_{ijk})$ is not included. Second, based on the data, a log transformation on the UV dose is not necessary, i.e., the mean is modeled by $\beta_i X_{ij}$. Figure B.6 displays the modeled results for adenovirus.

Figure B.6 Virus Modeled Data and Predictive Credible Intervals



B.3.4 Calculating UV Dose Requirements from Modeled Results

Table B.2 presents the UV dose requirements for *Cryptosporidium*, *Giardia*, and viruses. Each of the graphs presented in Figures B.4 through B.6 show the 80 percent credible interval. The UV dose requirements for given log inactivation levels were calculated from the fitted model's lower bound of the credible interval (as called out in Figures B.4-B.6). Using the lower bound means that at a given UV dose, the corresponding log inactivation is expected to be achieved 90 percent of the time.

Table B.2 UV Dose Requirements for Inactivation of *Cryptosporidium*, *Giardia* and Viruses During Validation Testing

	Log Inactivation							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	-	-
Giardia	1.5	2.1	3.0	5.2	7.7	11	-	-
Virus	39	58	79	100	121	143	163	186

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Appendix C. Validation of UV Reactors

To receive credit for *Cryptosporidium*, *Giardia*, or virus inactivation using UV light, the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) requires systems to demonstrate that the UV reactor can deliver the required dose through validation testing (40 CFR 141.729(d)). Furthermore, validation testing must determine a set of operating conditions that can be monitored by the control system to ensure that the UV dose required for a given pathogen inactivation credit is delivered during operation. At a minimum, these operating conditions must include flowrate, UV intensity measured by a UV intensity sensor, and lamp status. The validated operating conditions must account for the following factors (40 CFR 141, Subpart W, Appendix D):

- Lamp aging
- Lamp sleeve fouling
- UV transmittance of the water
- Inlet and outlet piping or channel configurations of the UV reactor
- Dose distributions arising from the velocity profiles through the reactor
- Failure of UV lamps or other critical system components
- Measurement uncertainty of on-line sensors

Unless the State approves an alternative approach, validation testing must involve the following components:

- Full-scale testing of a UV reactor, which conforms uniformly to the reactors used by the system
- Inactivation of a test microorganism whose dose-response characteristics have been quantified with a low-pressure (LP) mercury vapor lamp

This appendix presents one approach for validating UV reactors. Other approaches or modifications to this approach may be used at the discretion of the State. This appendix begins with an overview of the approach for conducting validation testing and interpreting validation results. This is followed by a description of the materials, equipment, and personnel used to conduct validation testing and a description of the steps involved in validating UV reactors. The appendix ends with descriptive examples showing how validation test results can be related to inactivation credit.

Appendix F provides more detailed background information on validation testing and includes several examples.

C.1 Overview

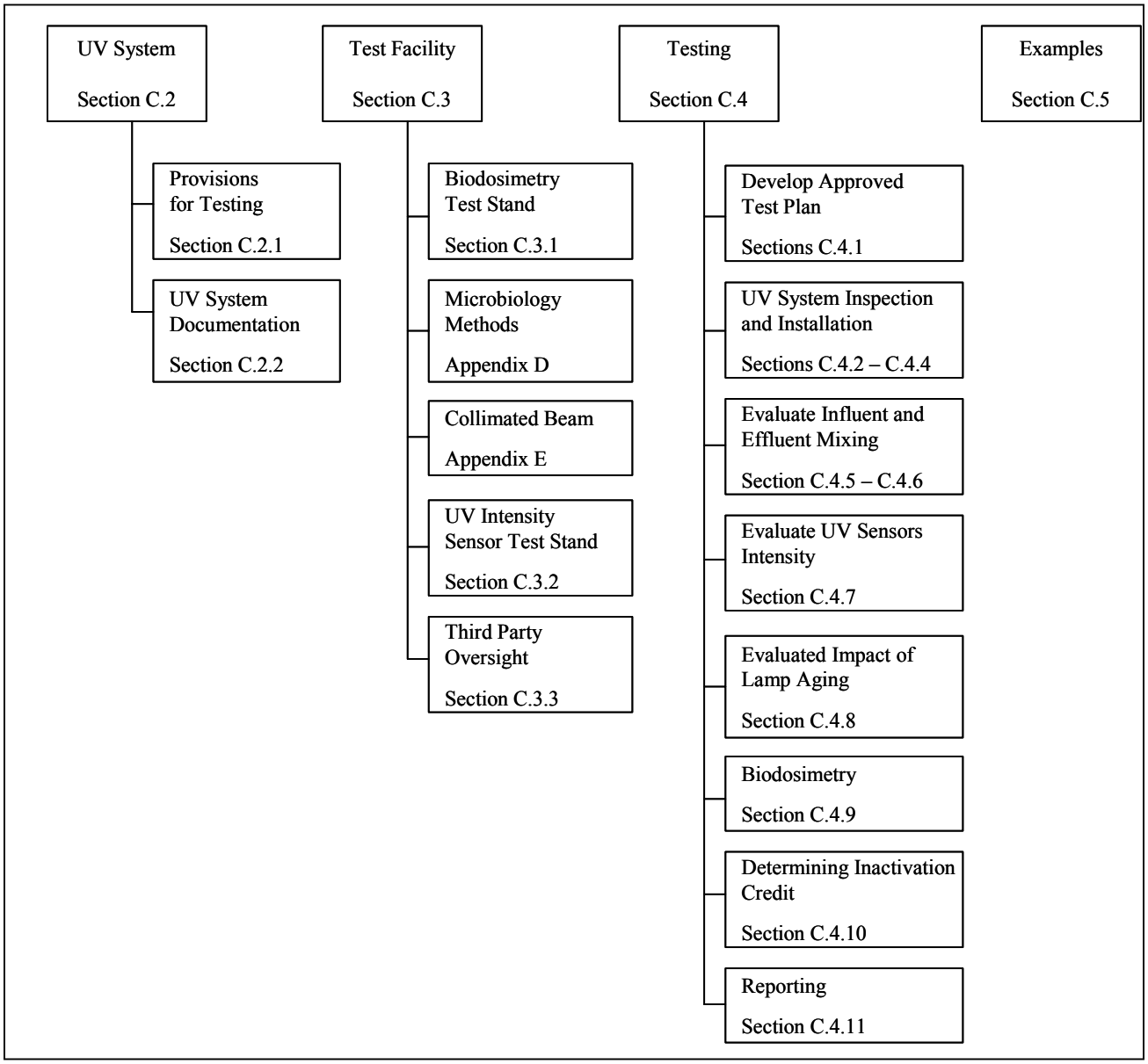
UV reactor validation should provide confidence that the UV reactor is appropriately sized for a given disinfection application and should allow a water treatment plant (WTP) to receive inactivation credit based on on-line measurements of flow, UV intensity, lamp status, and, in some cases, UV transmittance (UVT) of the water at 254 nm. To ensure a UV reactor is appropriately-sized for a given WTP, validation testing should provide data on dose delivery and monitoring under design conditions of flow, UVT, and lamp output. This should be done either by validating UV reactor performance under those conditions or by validating UV reactor performance over a range of conditions that can be interpolated to obtain performance under design conditions. To allow a WTP to obtain inactivation credit with UV disinfection, validation testing should provide data relating on-line measurements of flow, UV intensity, lamp status, and UVT to UV dose levels required to achieve target pathogen inactivation credit. This should be done over the range of those on-line measurements expected with operation of the UV reactor at the WTP.

UV manufacturers typically produce UV reactors as part of a product line where each reactor is manufactured to the same specifications. If a representative UV reactor from that product line undergoes validation testing, the test results can be applied to all other UV reactors within that product line if those reactors are manufactured to the same specifications as the validated reactor. If the design specifications of the product line that impact dose delivery and monitoring change, this new UV reactor design must be re-validated.

C.1.1 Test Protocol

The validation protocol in this guidance document builds on well-established protocols used in Europe and North America. A UV manufacturer typically delivers a UV reactor to a test facility. Test personnel inspect the UV reactor and document features of the design that impact dose delivery and monitoring (e.g., reactor dimensions and sensor properties). The UV reactor is installed within a biodosimetry test stand with inlet and outlet piping that should result in equal or worse dose delivery than with the reactor installed at the WTP. The UV reactor is operated under various test conditions of flow, UVT, and lamp power. The test condition of UVT is typically obtained using a UV-absorbing compound injected into the flow upstream of the UV reactor. A challenge microorganism is injected into the flow upstream of the UV reactor. The concentration of viable challenge microorganisms is measured in samples collected at the reactor's inlet and outlet. The results are used to calculate the log inactivation of the challenge microorganism achieved by the UV reactor. The UV dose-response of the challenge microorganism present in the inlet sample is measured using a bench-scale device termed a collimated beam apparatus. The UV dose-response curve is used to relate the log inactivation observed through the reactor to a UV dose value termed the Reduction Equivalent Dose (RED). A safety factor is applied to the results to account for any bias and random uncertainty associated with the validation of the UV reactor and the on-line monitoring approach used to indicate dose delivery both during validation and during operation at the WTP. Last, a validation report is prepared that describes the UV reactor tested, the test protocol, the test results, and the inactivation credits that can be assigned to the UV reactor under given conditions of flow, UVT, and lamp output. Figure C.1 presents the organization of this validation protocol and the sections within this appendix that address each of these issues.

Figure C.1 Elements of UV Reactor Validation



C.1.2 Relating RED to Target Pathogen Inactivation Credit

Chapter 1 (Table 1.4) presents the UV dose needed to achieve various inactivation credits for *Cryptosporidium*, *Giardia*, and viruses. The dose values provided in Chapter 1 were obtained by analyzing UV dose-response data measured using a bench-scale collimated beam device. To account for variability in the dose-response of the pathogen, an 80 percent predictive credible interval was used to determine dose values needed to achieve a given log inactivation of the pathogen. The derivation of the UV dose requirements is presented in Appendix B. This assessment, however, does not account for the measurement uncertainty associated with UV reactor validation and on-line dose monitoring. To account for this uncertainty, the RED

measured during reactor validation should be equal to or greater than a target RED defined using the following equation:

$$RED_T = B_{RED} \times B_{Poly} \times (1 + e) \times D_P \qquad \text{Equation C.1}$$

where

RED_T	=	Target RED that should be demonstrated during validation
B_{RED}	=	RED bias
B_{Poly}	=	Polychromatic bias
e	=	Expanded uncertainty expressed as a fraction
D_P	=	UV dose in Chapter 1 (Table 1.4) required for a given level of target pathogen inactivation credit.

The RED bias term accounts for the difference between the dose delivered to the target pathogen and the dose measured using a challenge microorganism. If the challenge microorganism is more resistant to UV light than the target pathogen, the RED measured during validation will be greater than the dose delivered to the pathogen. The magnitude of the difference will depend on the dose distribution of the UV reactor and the inactivation kinetics of the challenge microorganism and the target pathogen. If the challenge microorganism is as sensitive or more sensitive to UV light than the target pathogen, the RED bias has a value of 1.00. A recommended approach for obtaining the value of the RED bias is given in section C.4.10.2.

The polychromatic bias term accounts for spectral differences in the lamp output, lamp sleeve UV transmittance, UVT, and action spectrum of the challenge microorganism between validation and operation of a UV reactor equipped with medium-pressure (MP) lamps. These differences can cause the dose delivered at the WTP to differ from the dose measured during validation. Depending on the spectral response and positioning of the UV intensity sensor and the dose distribution of the UV reactor, the dose delivered at the WTP can be less than dose measured during validation and indicated by the monitoring system. The polychromatic bias term accounts for this issue. The polychromatic bias only applies to UV reactors that use polychromatic UV lamps. With UV reactors using LP or low-pressure high-output (LPHO) lamps, the polychromatic bias equals 1.00. A recommended approach for obtaining the value of the polychromatic bias is given in section C.4.10.2.

The expanded uncertainty, *e*, accounts for the uncertainty in the measurements taken during validation and used with dose delivery monitoring. In this protocol, the numeric value of the expanded uncertainty is estimated using an 80 percent confidence level by summing the individual measurement uncertainties associated with on-line sensors used in the field and during validation, influent and effluent challenge microorganism concentrations, challenge microorganism UV dose-response, and quantification of the UV output from the lamps. This approach is described in section C.4.10.2.

Two approaches, termed Tier 1 and Tier 2, are presented in section C.4.10 for applying the RED bias, polychromatic bias, and the expanded uncertainty to define the target RED values.

The Tier 1 approach, described in section C.4.10.1, is a standardized approach that uses prescribed values for the RED bias, the polychromatic bias, and the expanded uncertainty to

define RED targets to be demonstrated during validation. To use the Tier 1 approach, the dose monitoring and validation should meet defined criteria on reactor design, challenge microorganism UV dose-response, UV absorber used during validation, sensor properties, monitoring approach, and microbiology.

The Tier 2 approach, described in section C.4.10.2, allows the user to calculate the values of the RED bias, the polychromatic bias, and the expanded uncertainty, and to use those values to define the RED target to be demonstrated during validation. The approach does not prescribe criteria for reactor design, challenge microorganism dose-response, the UV absorber used during validation, sensor properties, monitoring approach, or microbiology.

C.1.3 Other Validation Protocols

Validation of UV reactors used in drinking water applications has been practiced in North America and Europe using well-established protocols that include the following, shown in chronological order of development:

- National Sanitation Foundation/American National Standards Institute (NSF/ANSI) Standard 55
- Austrian Standards Institute (ÖNORM ; Österreichisches Normungsinstitut) M 5873-1
- German Association for Gas and Water (DVGW; Deutsche Vereinigung des Gas- und Wasserfaches) W294
- National Water Research Institute/American Water Works Association Research Foundation (NWRI/AwwaRF) UV Guidelines

UV validation conducted as per DVGW and ÖNORM demonstrates that a UV reactor will deliver a RED of 40 mJ/cm^2 measured using *Bacillus subtilis* spores. Validation as per these protocols should meet criteria for the UV reactor and its validation. UV validation conducted as per NWRI/AwwaRF Guidelines and NSF Standard 55 both use MS2 bacteriophage (MS2) as a challenge microorganism. NSF standard 55 specifies a target RED of 40 mJ/cm^2 while NWRI/AwwaRF Guidelines does not specify a target RED. Validation testing as per NWRI/AwwaRF Guidelines and NSF Standard 55 should be assessed for consistency with the guidance for test conditions provided in section C.4.9. Results should be interpreted as per the guidance provided in sections C.4.9 and C.4.10.

C.1.4 Planning UV Validation

In general, validation testing will be conducted either for a UV manufacturer who wishes to validate a given UV reactor for the drinking water market or for a utility that wishes to validate a UV reactor for a specific application. Regardless of the end user, parties conducting validation testing should develop a test plan that addresses the following questions:

- Where will validation take place?
- What test conditions of flow, UVT, and lamp output should be tested?
- What UV absorbers and challenge microorganisms should be used?
- What inlet and outlet conditions will be used during validation?
- Who will provide the challenge stock solutions and assay water samples?
- How will UV intensity sensor properties during validation be verified?
- Who will conduct collimated beam testing?
- What is the expected safety factor and is it acceptable?
- Who will provide third party oversight?
- What State review and approval is needed for the test protocol?

When planning how validation testing will be done, utilities and manufacturers should determine if they want to evaluate validation results under Tier 1 or Tier 2. They should assess if the planned validation will meet the Tier 1 criteria and develop preliminary estimates of the safety factor that would be applied under Tier 2. They should explore opportunities to optimize validation testing by identifying approaches that minimize the values of the RED bias, polychromatic bias, and expanded uncertainty terms used to determine the safety factor. To provide flexibility in using Tier 1 and 2, one approach would be to ensure validation meets Tier 1 criteria and then to optimize for Tier 2.

C.1.4.1 UV Validation for Manufacturers

UV manufacturers will conduct validation either for a specific WTP or to allow broad application of their UV reactor to many WTPs. If validation is being done to allow broad application of the UV reactor, the test conditions of flowrate, UVT, and lamp output will likely span a larger range than the test conditions that would be used when validating for a specific WTP. The UV manufacturer may also validate the UV reactor for a range of dose targets that allow the UV reactor to achieve credit for a range of pathogen log inactivation values. The number of test conditions and dose targets chosen should be sufficient to allow interpolation of validation data to conditions of flowrate, UVT, and lamp output specific for a given WTP application.

For broad application of validation results, inlet and outlet conditions should be chosen to provide a conservative yet practical representation of inlet/outlet piping used at WTPs. For example, if the UV reactor is typically applied in a filter gallery, it may make sense to test with a 90 degree bend immediately upstream of the reactor to represent a “worst case” scenario. On the other hand, if a UV reactor is typically installed with 5 or 10 pipe diameters of straight pipe upstream of the reactor inlet, it may make sense to test with a 90-degree bend immediately

upstream of a 5 pipe diameters of straight pipe. UV manufacturers can use computational fluid dynamics (CFD) as a tool to understand the impact of inlet and outlet conditions on the dose delivery of their UV reactors in order to best identify the inlet and outlet conditions most representative of a wide range of applications.

In order to facilitate regulatory approval in the States, validation testing should be conducted using recognized and accepted protocols. Alternatively, the UV manufacturer should solicit feedback and approval for the validation test plan from the State(s) before testing.

C.1.4.2 UV Validation for Utilities

Utilities have the option of validating UV reactors either at a UV test facility or on-site at their WTP. Utilities considering on-site validation should address recommendations on water quality, disposal, and test train requirements provided in section C.3.1. Potential issues include obtaining water with a sufficiently high UVT that allows validation over the entire UVT range expected at the WTP, providing sufficient mixing of additives prior to entering the UV reactor and mixing of the challenge microorganisms after the reactor, and obtaining permits for the disposal of the water used for validation. Utilities considering off-site validation at a test facility should ensure that the inlet and outlet conditions used during validation are representative of those conditions used at the WTP. Recommendations for inlet and outlet conditions to be used during UV validation are provided in section C.3.1.5.

If on-site validation is considered, the utility should identify who will provide microbiological support for validation testing. The utility could use either their own microbiological lab or a third party lab. Regardless of the approach, the microbiology lab should have demonstrated experience working with the challenge microorganism and be able to provide timely analysis of water samples collected during validation testing. Appendix D provides detail on the microbiological lab qualifications and includes growth and assay methods for two commonly used challenge microorganisms.

With on-site validation, the utility should also identify how it will verify the performance of UV intensity sensors used during validation. Because utility staff typically do not have experience in optoelectronic instrumentation, they should use a third party laboratory to benchmark sensor performance. Sections C.3.2 and C.4.7 describe the laboratory needs and the measurements used to benchmark sensor performance.

C.2 UV Reactor

This section describes the hardware and documentation that the UV manufacturer should provide to the validation facility.

C.2.1 Provisions for Testing

The UV manufacturer should provide for validation a UV reactor with the following characteristics:

- A UV reactor that matches the technical description in the documentation provided as per section C.2.2.
- UV lamps that have undergone appropriate burn-in. The recommended burn-in period is 100 hours.
- Lamps aged to give end-of-lamp-life conditions if the reactor is to be tested with aged lamps.
- Provisions to reduce lamp output as per section C.4.9.4.
- Provisions to measure the UV output of each lamp and the electrical power delivered to the lamps as per section C.4.9.2.
- On-line and reference UV intensity sensors that meet the technical description provided in the documentation.
- A safety cut-off switch to prevent overheating if LPHO or MP lamps are used.

C.2.2 UV Reactor Documentation

Prior to validation testing, the UV manufacturer should provide to the party conducting the tests documentation identifying and describing the UV reactor. Documentation should include all reactor and component information that impacts dose delivery and monitoring including the following:

- Technical descriptions of the reactor and all internal components, including lamps, sleeves, UV intensity sensors, baffles, and cleaning mechanisms. The technical description should include dimensions and placement of all wetted components.
- Technical descriptions of the inlet and outlet piping to the reactor undergoing validation, including the length and cross-sectional dimensions of any pipes, channels, and bends, and dimensions of any hydraulic structures affecting flow. If reactors are validated in series, technical descriptions of the piping between reactors should be provided.
- Lamp specification stating the lamp manufacturer and product number, electrical power rating, length from electrode to electrode, spectral output of new and aged lamps, mercury content, and envelope diameter. The spectral output should be specified for 5 nm intervals or less over a wavelength range that includes the response range of the UV intensity sensors and the germicidal range.
- Sleeve specifications indicating sleeve dimensions, material, and UV transmittance from 200 to 400 nm.
- Technical description of the placement of the lamp within the sleeve.

- Specifications for the reference and on-line UV intensity sensors indicating manufacturer and product number, external dimensions, and measurement properties. Measurement properties include spectral and angular response, working range and linearity, calibration factor, temperature stability, long-term stability, and measurement uncertainty. Data and calculations should be provided showing how the total measurement uncertainty of the sensor is derived from the individual sensor properties. Table C.1 gives an example of the calculation of sensor measurement uncertainty from the uncertainty that arises due to each sensor property.

Table C.1 Example of a UV Intensity Sensor Uncertainty Datasheet

Property	Uncertainty (%)
Calibration	8
Linearity	5
Temperature response	3
Angular response	5
Spectral response	1
Long term drift	10
Total Uncertainty[1]	**15**

[1] Total uncertainty is calculated as the square root of the sum of the squared individual uncertainties. In this example, total uncertainty is $(8^2+5^2+3^2+5^2+1^2+10^2)^{1/2}$ = 15%.

- Specifications for the UV intensity sensor port indicating all dimensions and tolerances that impact the positioning of the sensor relative to the lamps.

- If the sensor port contains a monitoring window separate from the sensor, specifications giving the window material, thickness, and UV transmittance from 200 to 400 nm should be provided.

- Technical description of the algorithm used by the reactor to monitor dose delivery, including the use of sensors, signal processing, and calculations.

Documentation should also be provided on the proper installation and operation of the reactor to ensure proper and safe validation testing, including:

- Flowrate, headloss, and pressure rating of the reactor

- Assembly and installation instructions

- Electrical requirements including required line frequency, voltage, amps, and power

- Operation and maintenance manuals that include cleaning procedures, required spare parts, and safety requirements. Safety requirements should include information on electrical lockouts, eye and skin protection from UV light, safe handling of lamps, and mercury cleanup recommendations in the event of a lamp breakage

Lastly, the UV manufacturer should consider providing the following information relevant to the test procedure:

- Specifications for the challenge microorganism to be used during validation that includes protocols required for growth and enumeration, expected UV dose-response, and suitability for use in validation testing as discussed in section F.1.4.

- Specifications for the UV absorber to be used during validation.

- A description of the test conditions of flowrate, UVT, and lamp output used to validate the reactor, and the expected measurements of UV intensity and challenge microorganism RED.

C.3 Test Equipment, Facilities, and Personnel

This section describes the test equipment, laboratory facilities, and personnel that are typically used during validation testing, including the following components:

- Biodosimetry test stand for measuring challenge microorganism inactivation by the UV reactor

- UV intensity sensor test stand for measuring sensor properties

- Third party oversight

Appendix D provides information on the microbiological laboratory with specific information on the growth and assay of MS2 bacteriophage and *B. subtilis* spores. Appendix E provides information on collimated beam apparatus used to measure the UV dose-response of the challenge microorganism.

C.3.1 Biodosimetry Test Stand

The biodosimetry test stand is used to measure the inactivation of a challenge microorganism by the UV reactor operating under controlled conditions of flowrate, UVT, and lamp output.

Figure C.2 presents a block diagram of such a test stand with the following features:

- Water supply with rate-of-flow control and backflow prevention

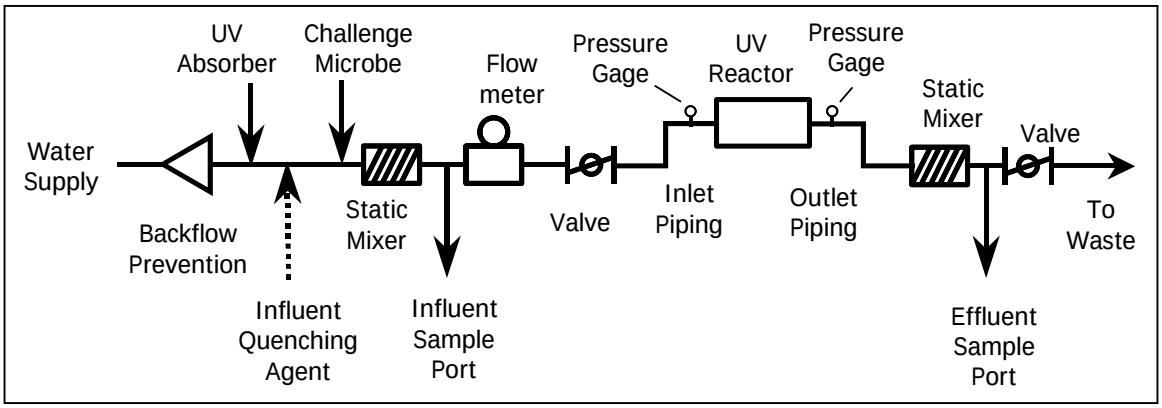
- Dosing pumps and ports for injecting the challenge microorganism, the UV-absorbing compound, and, if required, a disinfectant residual-quenching agent

- Influent-mixing device (static mixer or length of pipe) upstream of the reactor to ensure the challenge microorganism and UV-absorbing compound are well-mixed prior to entering the reactor

- Influent sampling port after the influent-mixing device and before the reactor

- Inlet and outlet piping to the reactor that results in a dose delivery equal to or less than the dose delivery expected with the installation of the reactor at a WTP
- UV reactor under test
- Ports to allow head-loss measurements across the UV reactor
- Effluent-mixing device (static mixer or length of pipe) downstream of the reactor to ensure that the challenge microorganisms that survive inactivation by the reactor are well-mixed prior to sampling
- Effluent sampling port after the effluent-mixing device
- Water disposal facilities

Figure C.2 Block Diagram of the Biodosimetry Test Stand



C.3.1.1 Water Supply

Validation testing should prove that the monitoring of dose delivery by the UV reactor is valid over the full range of UVT values expected with the application of the UV reactor at the WTP. Typically, the UVT of the water supply used for validation is high and UV absorbing chemicals are added upstream of the reactor to simulate different, lower UVTs over the test range. For validation results to be generally applied to all WTPs, the water supply should have a UVT at 254 nm greater than 97 percent (UV absorption coefficient less than 0.013 cm^{-1} with a 10 nm path length).

Whether coagulants are naturally present (e.g., reduced iron in ground water) or added as part of water treatment, they can affect the challenge microorganism concentration, the turbidity, and the UVT of water samples collected during reactor validation (Petri et al. 2000). Coagulation of the challenge microorganism can lead to reduced counts and poor sample-to-sample repeatability. To avoid these effects, the water supply should not contain coagulants that interfere with the validation results. Alternatively, chelating agents or coffee can be used as an additive to counter these effects (Petri et al. 2000).

The water passing through the reactor should not contain disinfectant residuals that inactivate the challenge microorganism during testing. If the water does contain a disinfectant residual, a quenching agent should be injected into the water upstream of the microorganism injection port. The quenching agent should have a minimal impact on the UVT.

The water supply (volume and flowrate) should be sufficient to allow testing over the rated flow range of the UV reactor. A flow-control device (e.g., variable speed pump or valve) can be used to vary the flow over that range. A flowmeter with a known measurement uncertainty should monitor the flowrate through the UV reactor.

Backflow prevention should be used with a potable water supply. Backflow prevention can be obtained using reduced pressure zone (RPZ) backflow preventers, air gaps, or check valves.

C.3.1.2 Dosing of Additives

Challenge microorganisms, UV-absorbing compounds, and possibly disinfectant quenching agents may be injected into the flow upstream of the UV reactor during validation. If pumps are used to inject the additives, they should provide a pulseless flowrate or have a cycle time an order of magnitude less than the residence time of the reactor. The flowrate generated by the pump should be stable over the time required to take samples as per section C.4.9.5. An injection port using standardized injector technologies can be used to disperse the additives into the flow.

C.3.1.3 Mixing of Reactor Influent and Effluent

Additives passed through the reactor should be well-mixed through the cross-section of the pipe prior to the reactor influent sampling port. The challenge microorganisms surviving UV disinfection should be well-mixed through the pipe cross-section prior to the reactor effluent sampling port. Mixing can be achieved either using static mixers or by relying on the turbulent mixing present in the lengths of pipe upstream of the sampling ports. If the water passed through the UV reactor is obtained from a large tank, the additives can be premixed in the tank to obtain a uniform concentration for testing.

C.3.1.4 Sample Taps

The sample taps should be located to provide representative samples of undisinfected water entering the reactor and the disinfected water leaving the UV reactor. If the influent sample tap is located too close to the reactor influent, the samples collected may be exposed to UV light, resulting in underestimation of the influent concentration of the challenge microorganism. If the effluent sample tap is located too close to the reactor effluent, the effluent samples will be collected before full exposure to UV light and the effluent concentration of the challenge microorganism will be overestimated. The UVT of the water can be used to calculate how far UV light from the reactor penetrates the water upstream and downstream of the reactor. The sampling points should be located far enough from the UV reactor that the germicidal UV

intensity at the point of sampling is less than 0.1 percent of the germicidal intensity within the UV reactor.

Sample taps may sample from a single point within the flow or from multiple points at the same time. Samples taken from multiple points within the flow should have the same concentration of additives and microorganisms within the measurement error.

Sampling taps should remain open over the duration of the test. Sample collection should meet standards of good practice as defined by Standard Methods Section 9060 (APHA et al. 1995). Samples should be collected in bottles that have been cleaned and sterilized. Samples collected should be immediately stored on ice within a cooler in the dark until needed for analysis.

C.3.1.5 UV Reactor Inlet and Outlet Conditions

As stated previously, the inlet and outlet structures to the UV reactor during validation should result in equal or worse dose delivery than with the reactor installed at the WTP. EPA recommends using any one or combination of the following approaches:

- Inlet and outlet conditions used at the WTP match those used during validation for at least 10 pipe diameters upstream and 5 pipe diameters downstream of the reactor.

- UV reactor is validated either with a 90-degree bend immediately upstream of the reactor inlet or a with 90-degree bend followed by a length of straight pipe immediately upstream of the reactor inlet. The reactor is installed at the WTP with a length of straight pipe immediately upstream of the reactor equal to 5 pipe diameters plus any length used after the 90-degree bend during validation. To avoid jetting effects, piping upstream of the straight pipe length should not have expansions for at least 10 pipe diameters and any valves located in that length of pipe should always be fully open during operation of the reactor. With this approach, it is assumed that the 90-degree bend immediately upstream of the reactor inlet provides worse hydraulics than the installation. This approach assumes that the reactor design has not been optimized for the 90-degree bend inlet.

- Velocity of the water measured at evenly-spaced points through a given cross section of the flow upstream and downstream of the reactor is within 20 percent of the theoretical velocity with both the validation test stand and the installation. The theoretical velocity is defined as the flowrate divided by the cross-sectional area.

CFD-based dose modeling can be used, in tandem with one of the above-mentioned approaches, to show that dose delivery with the installation is better than dose delivery during validation for given conditions of flowrate, UVT, and lamp output. To account for uncertainty in CFD predictions of dose delivery (Petri and Olson 2001, Wright and Hargreaves 2002), CFD predictions of dose delivery during validation should be at least 20 percent greater than predictions of dose delivery at the WTP.

C.3.1.6 Quality Assurance and Quality Control

Flowmeters, injection pumps, pressure gauges, and other measuring devices used should bear evidence of being in calibration. Accuracy of instrumentation should be checked by comparison with standard measurements. The documentation describing the test facility should be provided and verified including the following items:

- A description of the validation test stand, including all piping, valves, flowmeters, mixers, pumps, sampling locations, and measurement instrumentation
- The measurement uncertainty and the last calibration date of all measurement instrumentation
- Comparisons of on-line instrumentation with standard measurements

C.3.2 UV Intensity Sensor Test Stand

The properties of the on-line and reference UV intensity sensors should be measured by an independent laboratory that is equipped to confirm sensor calibration and measure the sensor's angular and spectral response, linearity over the working range, and temperature response. Measurements should be National Institute of Standards and Technology (NIST) traceable or equivalent with quantified measurement uncertainties. Personnel who test UV intensity sensors should be qualified to undertake optical testing, understand the test protocols for the sensors as provided by the manufacturer, and be aware of all safety requirements associated with UV-irradiation devices.

C.3.3 Third-Party Oversight

Validation of UV reactors and their components should be conducted at facilities and by personnel that are acceptable to the State. At a minimum, personnel independent of the manufacturer of the UV reactor should oversee validation testing. A registered professional engineer with knowledge and experience in testing and evaluating UV reactors should witness the validation testing to verify that the documented validation protocol was followed and the reported data and results are accurate. The engineer should be responsible for supervising the preparation of the engineering report on validation testing and should review and approve that report prior to its release. The engineer should not have a personal stake in the outcome of the validation testing or any conflict of interest with respect to the ultimate use of the UV reactor being tested. Where necessary, the engineer should use other third parties to provide expert opinion on various aspects of UV validation testing.

C.4 Testing

This section describes the recommended steps for validating the UV reactor provided by the UV manufacturer. At the discretion of the State, variations or alternatives to the procedures or steps may be accepted.

C.4.1 Develop Approved Test Plan

The first step in validating a UV reactor should be the development and review of a test plan. The test plan should be developed with input and approval from the utility, manufacturer, third party oversight, and the State. The test plan should resolve the questions identified in section C.1.4.

C.4.2 UV Reactor Inspection

Prior to installing the UV reactor in the biodosimetry test stand, the UV reactor should be inspected to confirm that it matches the descriptions and dimensions provided in the manufacturer's documentation as described in section C.2.2.

C.4.3 UV Reactor Installation

The UV reactor and its inlet and outlet piping should be installed at the test facility in accordance with the manufacturer's installation and assembly instructions. If reactors are installed in series, the piping between the reactors should conform to specifications provided by the UV reactor manufacturer. The piping should be inspected to ensure compliance with the manufacturer's documentation.

C.4.4 Headloss and Integrity Evaluation

The physical integrity of the UV reactor and the test train should be checked before conducting further testing. Personnel who operate the UV reactor during all tests should be familiar with its operation and maintenance manual and with any safety requirements.

Procedure

1. Pass water through the reactor at the minimum and maximum flowrates.
2. Measure and record the headloss across the reactor at each flowrate.
3. On completion of the test, visually inspect the sleeves, UV intensity sensors, and/or monitoring windows for mechanical integrity.
4. If the headloss across the reactor exceeds specifications provided by the manufacturer, or if component integrity has been compromised, investigate the cause and resolve the issue before further testing.

C.4.5 Evaluation of the Mixing of Additives

The mixing of the UV-absorbing chemical and the challenge microorganism prior to entering the UV reactor should be confirmed. Mixing can be confirmed by comparing the UV absorbance of the water at 254 nm (A_{254}) of samples collected at the influent and effluent

sampling ports using the following procedure. *This test should not be necessary if a static mixer is used between the injection port and the reactor entrance and the flowrate through the static mixer meets manufacturer specifications.*

Procedure

1. Prepare a stock solution of the UV-absorbing compound.

2. Pass water through the reactor at the minimum flowrate.

3. Inject sufficient UV-absorbing compound into the flow of water passing through the reactor to give a UVT less than the minimum that will be used during challenge testing.

4. Collect water samples from the influent and effluent sampling ports at 1-minute intervals and measure the UVT. The sample volume should be less than 5 mL and collected over a time not exceeding 2 seconds.

5. Calculate the A_{254} from the measured UVT. Mixing of the injected compounds should be sufficient if the average A_{254} of the influent samples and the average A_{254} of the effluent samples agree within 2 percent and the standard deviation of each is less than 5 percent. If these conditions are not met, the mixing between the injection port and the influent sampling port should be increased and retested.

C.4.6 Evaluation of the Mixing of Surviving Microorganisms

Mixing of the surviving challenge microorganisms leaving the UV reactor should be confirmed. Mixing can be confirmed by comparing the challenge microorganism concentration of samples collected at the effluent sampling port and a sampling port downstream of the effluent sampling port using the following procedure. *This test should not be necessary if a static mixer is located between the reactor exit and the effluent sampling port and the flowrate through the static mixer meets manufacturer specifications.*

Procedure

1. Prepare a stock solution of the challenge microorganism and a stock solution of the UV- absorbing compound.

2. Pass water through the reactor at the minimum flowrate that will be used during challenge testing.

3. Operate the UV reactor with the lamps power set at 100 percent.

4. Inject the challenge microorganism into the water flowing through the reactor.

5. Collect at least three UV-disinfected samples spaced 1 minute apart from the effluent sampling point and from a location at least 5 pipe diameters downstream of the effluent sampling point.

6. Measure the concentration of the challenge microorganism in each sample in triplicate.

7. If the concentration in the effluent samples is below the detection limit, repeat steps 2 to 6 with the UV absorber injected into the flow to reduce the dose delivery by the reactor.

8. Repeat steps 3 to 7, passing the water through the reactor at the minimum flowrate that will be used during the challenge test.

9. The mixing should be sufficient if there is no statistical difference at a 95 percent confidence level between the geometric means of the samples collected from the two effluent sample points. If statistical differences are observed, the mixing between the reactor and the effluent sampling port should be increased and the test repeated.

C.4.7 UV Intensity Sensor Evaluation

The measurement uncertainty of the UV intensity sensors used on the UV reactors should be confirmed. This may be achieved either by comparing the UV intensity sensor measurements made on the reactor to a reference measurement, or by measuring the properties of the sensors using a UV intensity sensor test stand. The following sections discuss each of these approaches.

C.4.7.1 Assessing Uncertainty Using Reference Sensors

If the measurement uncertainty of the reference intensity sensor is known, the following procedure can be used to check the uncertainty of the UV intensity sensors used during validation.

Procedure

1. Pass water through the reactor without the addition of UV-absorbing chemicals.

2. Using at least three recently calibrated reference sensors, install each sensor on the UV reactor at each port and record the measured UV intensity. Repeat using each duty sensor. If the sensors can be rotated, then measure the minimum and maximum sensor readings with rotation.

3. Record the water temperature as an indicator of the operating temperature of the sensors.

4. Repeat the test with the UVT decreased to the minimum value expected during testing.

5. For a given lamp output and UVT, the difference between the reference sensor measurements should follow Equation C.2:

$$\left|\frac{I_{Ref\,1}}{I_{Ref\,2}} - 1\right| * 100 \le \left(\sigma^2_{Ref\,1} + \sigma^2_{Ref\,2}\right)^{1/2} \qquad \text{Equation C.2}$$

where
I = Intensity measured by a reference sensor designated by the subscript
σ = Measurement uncertainty of reference sensor designated by the subscript (%)

6. For a given lamp output and UVT, the difference between the reference and duty sensor measurements should follow Equation C.3:

$$\left|\frac{I_{Duty}}{I_{Ref}} - 1\right| * 100 \le \left(\sigma^2_{Ref} + \sigma^2_{Duty}\right)^{1/2} \qquad \text{Equation C.3}$$

where
I_{Ref} = Intensity measured by the reference sensor
I_{Duty} = Intensity measured by the duty sensor
σ_{Ref} = Measurement uncertainty of the reference sensor (%)
σ_{Duty} = Measurement uncertainty of the duty sensor (%)

7. UV intensity sensors that do not meet these criteria should be replaced. Alternatively, the UV manufacturer can re-evaluate their stated measurement uncertainty and use a higher value.

C.4.7.2 Assessing Uncertainty Using a Sensor Test Stand

The measurement uncertainty of the UV intensity sensors can be assessed by a laboratory capable of confirming sensor calibration and properties with a known measurement uncertainty. The laboratory should measure linearity, spectral and angular response, and temperature response. Results should be used to calculate the measurement uncertainty. Sensors that do not meet manufacturer specifications should be replaced. Alternatively, the UV manufacturer can re-evaluate their stated measurement uncertainty and use a higher value.

C.4.8 Evaluation of Lamp and Sleeve Aging on Dose Monitoring

With operation over time, UV lamps and sleeves can experience non-uniform aging along their length and around their circumference. Lamps can also experience spectral shifts in output and sleeves can experience spectral shifts in UV transmittance. If these effects have a significant impact on how the dose delivery indicated by the monitoring system compares to the delivered dose, validation should be conducted using both new and aged lamps and sleeves. The following procedure compares dose delivery monitoring with new and aged lamps to identify if validation

should be conducted with both new and aged lamps and sleeves. Alternatively, data on the UV output of new and aged lamps and the UV transmittance of new and aged sleeves can be compared and used to demonstrate if validation should be conducted with new and aged lamps and sleeves. In both approaches, an aged lamp or sleeve is one that has reached the end of its useful service life.

Procedure

1. Prepare a stock solution of the challenge microorganism.

2. Fit the UV reactor with aged lamps and sleeves.

3. Pass water through the reactor at a constant UVT and at the maximum flowrate that will be used during challenge testing.

4. Operate the UV reactor at peak lamp power.

5. Inject the challenge microorganism into the flow passing through the reactor.

6. Collect at least three microbiological samples spaced one minute apart from the influent and effluent sampling ports.

7. Record the UV intensity sensor measurements.

8. Fit the UV reactor with new lamps that have undergone 100-hour burn-in and new sleeves.

9. Lower the lamp power to give a UV intensity sensor reading equivalent to the reading obtained in step 7.

10. Repeat steps 5 and 6.

11. If the mean log inactivation achieved with new lamps differs from the mean log inactivation achieved with aged lamps, lamp aging impacts the relationship between dose delivery and UV intensity sensor reading, and validation with aged lamps and sleeves should be considered.

C.4.9 Dose Delivery Validation

Dose delivery validation via biodosimetry provides an assessment of dose delivery and monitoring by the UV reactor under specific conditions of flowrate, UVT, and lamp output.

C.4.9.1 Preparation of Challenge Microorganism Stock Solution

The challenge microorganism is used to measure the dose delivery of the UV reactor during validation. Because MS2 and *B. subtilis* spores are typically used, methods for their

preparation and assay are provided in this manual in Appendix D. Other peer-reviewed methods may be used. A rationale for selecting challenge microorganisms other than MS2 and *B. subtilis* spores is provided in section F.1.

The challenge microorganism stock solution should be prepared in accordance with peer-reviewed methods. The source of the challenge microorganism, the source of the host (if used), a description of all media used, the steps involved in propagating the challenge microorganism, and the steps involved in purifying the challenge microorganism to create a mono-disperse stock solution should be documented. The volume of stock solution needed should be estimated prior to testing based on the test plan and the expected stock concentration.

C.4.9.2 Reactor Preparation

If the number of sensors is less than the number of lamps, the UV intensity sensors should be directly monitoring the lamps with the highest output and those lamps should be the closest lamps to the sensor. The lamps with the highest output can be identified by taking measurements using either a dedicated test stand or the UV reactor. One approach for using the UV reactor is described below. *This preparation should not be necessary if the UV reactor has one UV intensity sensor per lamp.*

Procedure

1. Install a lamp within a lamp sleeve located near one of the reactor's UV intensity sensors.

2. Pass water through the reactor at a constant flowrate and UVT.

3. With only the lamp under evaluation on, record the measured UV intensity.

4. Repeat the test for each lamp and rank the results.

5. Install the lamps in the UV reactor so that the lamps with the highest output are closest to the UV intensity sensors monitoring those lamps.

C.4.9.3 Flowrates

At a minimum, the reactor should be validated at the minimum and maximum flowrates as defined by the UV manufacturer. Other flowrates within that range can be tested. For interpolation of validation results as a function of flowrate, a recommended approach for selecting intermediate flowrates is to approximate a geometric series using Equation C.4:

$$Q_n = Q_{Max}\beta^{1-n}$$ Equation C.4

where

Q_n	=	nth flowrate to be tested
Q_{max}	=	Maximum flowrate to be tested
β	=	Rate term with a recommended value between 1.5 and 2
n	=	Number of flowrates to be tested

The value of β should not exceed 2 and should be sufficient to obtain at least three measured data points for interpolation.

Example. Interpolation will be used to predict RED as a function of flowrate for a UV reactor rated over a flow range of 2 to 20 mgd. If a rate term of 2 was used with Equation C.4, the UV reactor would be validated at flowrates of 20, 10, 5, 2.5, and 2 mgd. If a rate term of 1.5 was used with Equation C.4, the UV reactor would be validated at flowrates of 20, 13, 8.9, 5.9, 4.0, 2.6, and 2 mgd.

C.4.9.4 Lamp Power and UV Transmittance

At a given flowrate, the UV reactor should be validated under conditions of UVT and lamp output that demonstrate the UV reactor is sized to deliver a given dose and the UV reactor's dose monitoring system provides a valid measure of that dose. Typically, the UVT of the source water used during validation is high and UV absorbing chemicals are added to that water to achieve the UVT used during validation testing. Different levels of lamp output can be obtained using one or more of the following approaches:

- Using new and aged lamps
- Using different lamp types with the same spectral output (e.g., using LP and LPHO lamps)
- Changing the ballasts' power settings
- Using specially modified ballasts capable of operating at different power levels
- Changing the supply voltage to the lamp ballasts

If lamp aging affects the relationship between the inactivation achieved by the UV reactor and the measurements made by the on-line UV intensity sensor, aged lamps should be used when validation testing involves reduced lamp output.

The conditions of lamp power and UVT used during validation should depend on the monitoring approach of the UV reactor. The next three sections describe recommended approaches for defining these test conditions for UV reactors that use the following monitoring approaches:

- UV intensity setpoint approach
- UV intensity and UVT setpoint approach
- Calculated dose approach

Section F.2 provides background on the development of these approaches.

UV Intensity Setpoint Approach

With the UV intensity setpoint approach, measurements of UV intensity and flowrate are used directly to indicate dose delivery. Dose delivery at or above a given level is indicated when the measured intensity reads above an alarm setpoint value defined as a function of flowrate.

With the UV intensity setpoint approach, the UV intensity sensor is positioned within the UV reactor to respond to the impacts of both lamp output and UVT. As such, dose delivery can be monitored without the need to measure the UVT.

Strategies for implementing this approach include:

1. Using a single UV intensity setpoint value from minimum to maximum flow to verify dose delivery at some minimum level.

   Example. A UV intensity setpoint of 10 mW/cm^2 is used to verify a minimum MS2 RED of 40 mJ/cm^2 from 1 to 5 mgd.

2. Several UV intensity setpoint values are used, each one applying over a specific flow range.

   Example. UV intensity setpoints of 10 and 20 mW/cm^2 are used to verify a minimum MS2 RED of 40 mJ/cm^2 from 1 to 2.5 mgd and from 2.5 to 5 mgd, respectively.

3. UV intensity setpoint values are interpolated as a function of flowrate.

   Example. UV intensity setpoints defined by the following equation are used to indicate an MS2 dose of 39 mJ/cm^2 from 1 to 2.4 mgd:

   Intensity setpoint (mW/cm^2) = 15.6 x flow rate (mgd) + 3.9

4. UV intensity setpoints are defined as a function of flowrate for multiple levels of dose delivery.

   Example. A UV intensity setpoint of 10 mJ/cm^2 is used to verify a minimum RED of 40 mJ/cm^2 from 1 to 5 mgd. A UV intensity setpoint value of 7 mW/cm^2 is used to verify a minimum RED of 25 mW/cm^2 from 1 to 5 mgd.

With UV reactors using this monitoring approach, validation testing provides data on the relationship between dose delivery and measured intensity at a given flowrate. Dose delivery at a given flowrate and UV intensity is measured under two conditions of lamp power and UVT, described as follows:

1. Lamps at peak power and the UVT decreased to give a UV intensity sensor reading at a setpoint value.

2. High UVT and the lamp power lowered to give a UV intensity sensor reading at a setpoint value.

The RED assigned to the reactor is the lower value observed between the two test conditions.

If the lamp power cannot be sufficiently lowered to obtain a UV intensity sensor reading at the setpoint value, an alternative to the second test condition is to test with the lowest possible lamp power setting and the UVT decreased until an intensity reading at the setpoint is obtained. This alternative second test condition is acceptable if the following conditions are met:

- The adjusted lamp power results in a lamp output equal to or lower than the lamp output used for sizing the UV reactor for a WTP. The lamp output used for sizing the UV reactor is the product of the lamp-aging factor and the fouling factor.

- The RED measured with the second condition is equal to or greater than the RED measured with the first test condition or the UVT with the second test condition is less than the UVT expected at the WTP.

There are several approaches for defining the UV intensity setpoint values evaluated during validation testing:

1. If a UV reactor is being validated for an application with specific design conditions of flowrate, lamp output, and UVT, the intensity setpoint at design flow is equal to or greater than the intensity reading obtained with the reactor operating under these design conditions.

2. A UV reactor manufacturer can usually provide model estimates of dose delivery as a function of flowrate and UV intensity. The model estimates would be used to define the intensity setpoint values associated with a target dose delivery. Since model estimates may not be accurate, trial and error testing may be used to establish the optimal intensity setpoint necessary for a target level of dose delivery. Alternatively, testing can be used to define the relation between dose delivery and measured intensity, and interpolation can be used to define the optimal setpoint associated with a target dose delivery.

During the validation of a UV reactor using the intensity setpoint monitoring approach, the UVT used will likely be less than the design UVT and the lamp output will be less than the design lamp output. While it may appear that these test conditions are more stringent than the design conditions, it should be recognized that design conditions do not represent the worst-case

conditions that can occur at a WTP. For example, lamps can age below their expected end-of-life output, lamp sleeves can foul internally, wiper mechanisms can fail, and dose-pacing strategies can reduce lamp output. These factors in combination can result in a UV output well below the design output. If the design UVT is selected at a 95 percent confidence level, then a UVT below the design value is expected 5 percent of the time. Because intensity setpoints should provide a valid measure of dose delivery, regardless of the combination of lamp output and UVT values, a UV reactor using intensity setpoint monitoring should be validated over the full range of conditions giving rise to the setpoint, even if they exceed design conditions.

Example. A UV reactor that uses the intensity setpoint approach for monitoring is sized using a design UVT of 90 percent, a lamp aging/fouling factor of 70 percent, and a flow of 5 mgd. With lamp power and UVT adjusted to 70 and 90 percent, respectively, the UV intensity sensor reads 14 mW/cm^2. The UV reactor is tested at a flow of 5 mgd using the following conditions of lamp output and UVT that give rise to a UV intensity of 14 mW/cm^2:

- 100 percent lamp power, 87 percent UVT
- 27 percent lamp power, 98 percent UVT

By testing the reactor using these conditions, dose delivery associated with a setpoint of 14 mW/cm^2 is validated.

UV Intensity and UVT Setpoint Approach

With the UV intensity/UVT setpoint approach, measurements of UV intensity, UVT, and flowrate are used to indicate dose delivery. Dose delivery at or above a given level is indicated when both the measured UV intensity and UVT read above their respective alarm setpoint values. Strategies for implementing this approach include:

1. Using a single UV intensity setpoint value and UVT setpoint value from minimum to maximum flowrate to indicate dose delivery at some level.

   Example. A minimum MS2 RED of 40 mJ/cm^2 from 1 to 5 mgd is verified when the measured UV intensity is equal to or greater than 10 mW/cm^2 and the measured UVT is equal to or greater than 85 percent.

2. Several sets of UV intensity and UVT setpoint values are used, each set applying over a specific flow range.

   Example. For an MS2 RED of 40 mJ/cm^2, a UV intensity setpoint value of 10 mW/cm^2 and a UVT setpoint value of 80 percent are used from 1 to 2.5 mgd. A UV intensity setpoint value of 20 mW/cm^2 and a UVT setpoint value of 85 percent are used from 2.5 to 5 mgd.

3. Sets of UV intensity and UVT setpoint values are interpolated as a function of flowrate.

4. Sets of UV intensity and UVT setpoint values are defined as a function of flowrate for multiple levels of dose delivery.

With UV reactors using this monitoring approach, validation testing provides data on the dose delivery with the reactor operating at the setpoint values and proof that the sensor is appropriately positioned for this monitoring approach. As such, each set of UV intensity and UVT setpoints should be tested using two conditions as follows:

1. UVT decreased to give a reading at the UVT setpoint followed by a decrease in lamp power to give a UV intensity sensor reading at the UV intensity setpoint.

2. Lamp power at 100 percent and UVT decreased to give a UV intensity sensor reading at the intensity setpoint.

The first condition provides data on dose delivery with the reactor operating with UV intensity and UVT at the setpoint values. The second condition provides data on the positioning of the UV intensity sensor. If the RED measured with the second test condition is greater than the RED measured with the first, the UV intensity sensor is not appropriately positioned for this monitoring strategy and this monitoring strategy cannot be used (see section F.2 for a rational for this criteria).

There are several approaches for defining the UV intensity and UVT setpoints used during validation testing.

1. At design flow, the UVT setpoint is the design UVT. The intensity setpoint is the UV intensity measured with the lamp output and UVT adjusted to their design values.

2. At other flowrates, model estimates of dose as a function of UVT and lamp output can be used to identify the setpoint values that will be assessed during validation testing. Trial and error testing or interpolation of test results can be used to refine and optimize those values for a given target dose delivery.

Example. A UV reactor that uses the UV intensity and UVT setpoint approach for monitoring is sized for a WTP using a design UVT of 90 percent, a design lamp fouling/aging factor of 70 percent, and a design flowrate of 5 mgd. Operating under those conditions, the intensity sensor measures 14 mW/cm^2. The UV reactor is validated under two test conditions at a flowrate of 5 mgd:

- 70 percent lamp power and 90 percent UVT resulting in a UV intensity reading of 14 mW/cm^2

- 100 percent lamp power and 75 percent UVT resulting in a UV intensity reading of 14 mW/cm^2

The first condition provides data on the dose delivery of the reactor operating at the setpoint. The second condition provides data to assess the positioning of the UV intensity sensor.

Calculated Dose Approach

With the calculated dose approach, dose delivery is calculated from measurements of UV intensity, UVT, and flowrate using an algorithm developed by the UV reactor manufacturer. For UV reactors that use this approach, the UV reactor should be tested over a range of combinations of flowrate, UVT, and lamp power that result in a given calculated dose. At a given flowrate, that range should include the following combinations:

- Maximum power and decreased UVT
- Maximum UVT and decreased lamp power
- One or two intermediate combinations of UVT and lamp power

If the algorithm for calculating dose accounts for lamps operating at different power levels or specific lamps operating either on or off, test conditions should include combinations of these conditions.

Example. A UV reactor that uses a calculated dose for compliance will be used at a WTP with a design UVT of 90 percent, a design lamp fouling/aging factor of 70 percent, and a design flowrate of 5 mgd. The target RED is 40 mJ/cm^2. At 5 mgd, test conditions that result in a calculated dose of 40 mJ/cm^2 by the monitoring system are as follows:

- 100 percent lamp power, 80 percent UVT
- 58 percent lamp power, 90 percent UVT
- 34 percent lamp power, 98 percent UVT

C.4.9.5 Measuring Challenge Microorganism Inactivation by the UV Reactor

The reactor should be operated at each of the test conditions of flowrate, UVT, and lamp power in accordance with sections C.4.9.3 and C.4.9.4. Prior to sampling, steady-state conditions should be confirmed by monitoring the UV intensity sensor measurements and the UVT. The challenge microorganism should be injected into the flow upstream of the reactor and well-mixed prior to its entering the UV reactor. At least three influent and effluent samples should be collected for each test condition. The time interval between sample collections should be greater than or equal to the residence time between the inlet and outlet sampling ports. Water samples should be collected by personnel who are familiar with good sampling practices as specified in Standard Methods (APHA et al. 1995) and the guidance for collecting UV-irradiated samples. Sample volumes should be sufficient for assessing the challenge microorganism concentrations in the influent and effluent.

Before and after the samples are collected, the flowrate through the reactor, all UV intensity sensor measurements, on-line UVT measurements, and any calculated dose values should be measured and recorded. With the validation of LP or LPHO UV reactors, the UVT

should be measured and recorded with each influent sample. With MP reactors, the UVT from 200 to 400 nm should be measured and recorded. The electrical power delivered to the lamps by each ballast should also be measured and recorded. The challenge test should be repeated if the flowrate, UV intensity, lamp power, or UVT changes by more than the error of the measurement over the course of sampling.

The challenge microorganism concentration in the samples should be measured within 24 hours of collection using a peer-reviewed method. Suggested methods for measuring MS2 and *B. subtilis* spore concentrations in water samples are provided in Appendix D. Reported challenge microorganism concentrations should include dilutions, volumes used, and the number of plaques or colonies counted on each plate.

C.4.9.6 Quality Assurance and Quality Control Samples

During testing of the UV reactor, samples should be collected to ensure quality assurance and control (QA/QC) including:

- **Trip controls** - sample bottles of challenge microorganism stock solution of known concentration that travel with the stock solution from the microbiological laboratory to the location of reactor testing and back to the laboratory. The concentration of the challenge microorganism in the trip controls measured at the beginning and end should be the same at a 90 percent confidence level.

- **Reactor blanks** - influent water samples taken without any addition of challenge microorganism to the flow passing through the reactor. The concentration of the challenge microorganism measured with the blank should not interfere with the determination of RED delivered by the reactor.

- **Reactor controls** - influent and effluent water samples taken with the UV lamps (in the reactor) turned off. The challenge microorganism concentrations in both samples should be the same at a 90 percent confidence level.

- **Method blanks** - sample bottle of sterilized reagent grade water that undergoes the challenge microorganism assay procedure. The concentration of challenge microorganism with the method blank should be non-detectable.

C.4.9.7 Challenge Microorganism Dose-Response

The UV dose-response of the challenge microorganism within samples collected from the reactor influent should be measured with the collimated beam apparatus as described in Appendix E. At least two dose-response curves should be generated. One sample should have UVT unadjusted by UV-absorbing additives and one sample should have UVT adjusted to give the minimum UVT used in section C.4.9.4. A one-liter influent sample should be sufficient for measuring the challenge microorganism UV dose-response.

The collimated beam tests should be conducted within 24 hours of sample collection. Based on the expected dose-response of the challenge microorganism, UV doses should be applied to achieve log reductions of approximately 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0. For each log reduction, at least three aliquots of the influent sample should be irradiated. Three aliquots should also be collected as zero dose samples. Aliquots should be packed on ice and stored in the dark until they are assayed. Aliquots should be assayed within 24 hours of irradiation.

The log inactivation for each applied dose delivered by the collimated beam should be calculated using Equation C.5:

$$Log\ Inactivation = \log\left({N_0}/{N} \right) \qquad \text{Equation C.5}$$

where

N_0 = Average concentration of the challenge microorganism in the zero dose aliquots

N = Challenge microorganism concentration in an aliquot of sample

Fitting Dose-Response Data

The dose-response of the challenge microorganism should be plotted as UV dose versus log inactivation. An equation that best expresses the UV dose as a function of log (N_0/N) should be obtained using regression analysis. A linear equation should best-fit first-order kinetics. A quadratic equation should provide a better fit with tailing, and other equations should be used if inactivation kinetics involves shoulders (DVGW 1997, ONORM 2001). Equation coefficients obtained from the regression analysis should be significant at a 95 percent confidence level. The differences between the values measured and predicted by the equation should be randomly distributed around zero and not show a dependence on dose. Confidence intervals for the fit should be determined at an 80 percent confidence level. The equation should be used for interpolating dose-response data but should not be used for extrapolation outside of the measured UV dose range.

Example. The dose-response of MS2, presented in the following table, was measured using a collimated beam apparatus.

UV Dose (mJ/cm^2)	Log Inactivation	Log Inactivation
0	0.016	-0.119
10	0.805	1.06
30	1.87	2.16
60	3.40	3.62
100	4.71	4.83

Regression analysis was used to fit the equations to the MS2 dose-response data:

$$Dose = A \times Log\ Inactivation + B$$

and

$$Dose = C \times Log\ Inactivation + D \times (Log\ Inactivation)^2$$

The following table lists the coefficients derived from the regression analysis, the p-statistics for those coefficients, and the R-squared value for the fit.

Equation	Coefficient	Value	p-statistic
$Dose = A \times Log\ Inactivation + B$ R-squared = 0.967	A	20.5	3.13×10^{-7}
	B	-6.01	0.15
$Dose = C \times Log\ Inactivation + D \times (Log\ Inactivation)^2$ R-squared = 0.995	C	8.90	1.22×10^{-4}
	D	2.47	4.39×10^{-5}

In evaluating the two equations, a first check was done to determine if the equation coefficients were significant at a 95 percent confidence level. While the R-squared value for the first equation was high, the p-statistic for coefficient B was greater than 0.05, indicating that it was not significant at a 95 percent confidence level. Thus, the first equation was not a good fit to the dose-response data. On the other hand, the p-statistics for coefficients C and D with the second equation were both less than 0.05, indicating that they were significant at a 95 percent confidence level. Thus, Equation 2 was a valid fit to the dose-response data.

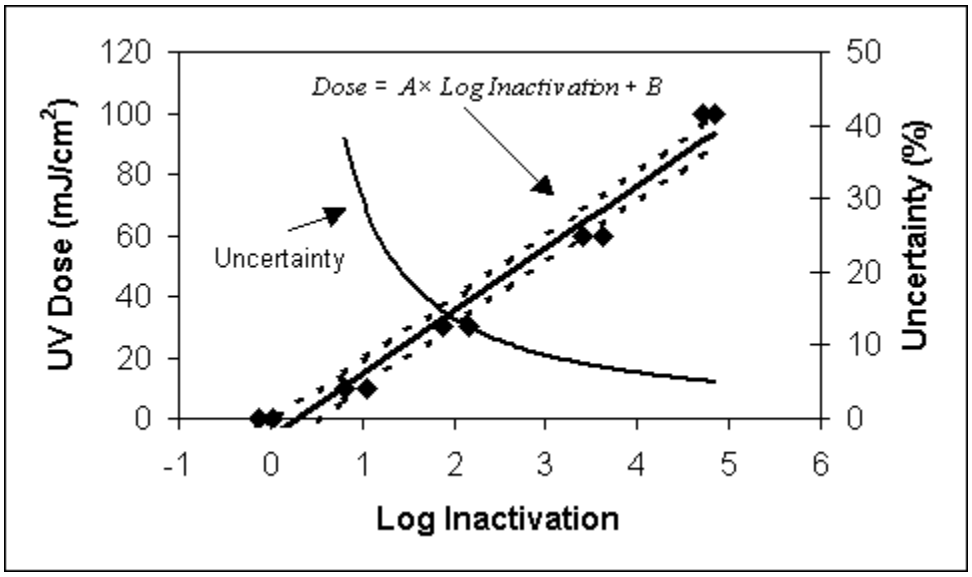
A second check of the two equations was to determine if the difference between the measured and predicted dose was randomly distributed as a function of the log inactivation. Figure C.3 presents the dose-response data and the fits to the data with confidence levels. As shown, the first equation under-predicts UV dose at low and high levels of inactivation and over-predicts dose at mid levels of dose. On the other hand, the second equation does not show a bias in the prediction of dose as a function of log inactivation. This second check further demonstrates that the second equation was a valid fit to the dose-response data while the first equation was not valid.

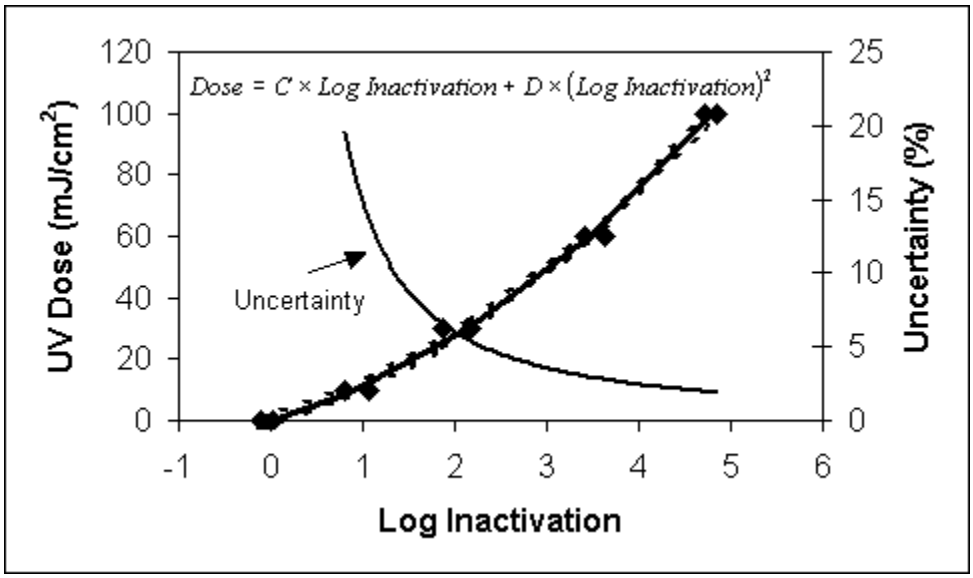
To illustrate the importance of using an appropriate equation to fit the dose-response data, the following table compares the dose predicted using the two equations for 2-log inactivation.

Equation	UV Dose for 2 log inactivation (mJ/cm^2)	
	Mean	Lower Bound
$Dose = A \times Log\ Inactivation + B$	35	30
$Dose = C \times Log\ Inactivation + D \times (Log\ Inactivation)^2$	28	26

As shown, the first equation over-predicts the mean dose needed for 2-log inactivation by 27 percent, as compared to the second equation. Large errors can occur predicting the UV dose associated with a given log inactivation if the equation used to fit the data is not appropriate.

Figure C.3 UV Dose Plotted as a Function of MS2 Log Inactivation and Fitted Using Two Equations





Combining Dose-Response Data

During validation, the UV dose-response of the challenge microorganism is used to relate the inactivation measured through the reactor under each test condition to an RED value. Typically, it is assumed that the dose-response measured with a subset of the test conditions assessed during validation can be used to calculate the RED for all test conditions. This assumption is valid if the dose-response of the challenge microorganism does not vary from test condition to test condition. To prove this assumption, the regression coefficients generated for each set of dose-response data should be equal at a 95 percent confidence level (Draper and Smith 1981). If the coefficients are the same, the equation fitting the combined dataset should be used for determining the RED. If the coefficients are different, the cause of the difference should

be determined. Difference in UV dose-response could occur if the dose-response was determined with different batches of the challenge microorganism or if water quality interferences are impacting the dose-response (e.g., MS2 coagulation). The following example presents an approach that can be used to determine if two sets of UV dose-response data can be combined.

Example. The following table gives the dose-response data for MS2 measured on two influent samples during validation testing.

UV Dose (mJ/cm^2)	Log Inactivation (N_0/N)			
	Influent Sample 1		Influent Sample 2	
0	0.02	0.09	0.24	-0.10
10	0.33	0.709	0.54	0.40
20	1.1	1.4	1.0	1.4
40	1.8	2.4	2.3	2.3
60	2.7	3.2	3.2	3.3
80	3.5	4.4	3.4	3.9
100	3.9	4.4	4.3	4.8

Each dataset can be described using the following equation:

$$\text{Dose} = A \times \text{Log}\left(\frac{N_0}{N}\right) + B \times \left(\text{Log}\left(\frac{N_0}{N}\right)\right)^2$$

To determine if the two datasets could be combined, a general equation is defined for both datasets as:

$$\text{Dose} = A \times \text{Log}\left(\frac{N_0}{N}\right) + B \times \left(\text{Log}\left(\frac{N_0}{N}\right)\right)^2 + C \times d \times \text{Log}\left(\frac{N_0}{N}\right) + D \times d \times \left(\text{Log}\left(\frac{N_0}{N}\right)\right)^2$$

The term d is set to zero with the first dataset and set to one with the second dataset. Multiple regression analysis using the full dataset is used to determine the values of coefficients A, B, C and D with the following results:

Coefficient	Value	p-statistic
A	17.5	0.000
B	1.03	0.202
C	-2.43	0.553
D	0.435	0.689

As shown by the p-statistic, the term A was statistically significant at the 95 percent confidence level ($p \leq 0.05$) and the terms B, C, and D were not ($p \geq 0.05$). The regression analysis was repeated in a step-wise fashion, removing the term with the highest p-value from the equation. With the second regression, the terms A and B were statistically significant and the term C was not. With the third regression, the terms A and B were both statistically significant. Because neither terms C nor D were significant, it can be concluded that the regression

coefficients generated by the fits to each dose-response are equal at a 95 percent confidence level. Thus, the two datasets can be combined.

C.4.9.8 Reactor Log Inactivation and RED

For each condition of flowrate, UVT, and lamp output as defined in sections C.4.9.3 and C.4.9.4, the arithmetic mean and standard deviation of the log of the influent and effluent challenge microorganism concentrations should be calculated. For each test condition, the log inactivation should be calculated using equation C.6:

$$Log\ Inactivation = log(N_I) - log(N_E) \qquad \text{Equation C.6}$$

where
$log(N_I)$ = Mean challenge microorganism log concentration of the influent samples
$log(N_E)$ = Mean challenge microorganism log concentration of the effluent samples

The uncertainty of the log inactivation should be calculated using Equation C.7:

$$U_{in} = \frac{\left(\frac{(t_I\sigma_I)^2}{n_I} + \frac{(t_E\sigma_E)^2}{n_E}\right)^{1/2}}{Log\ Inactivation} \times 100\% \qquad \text{Equation C.7}$$

where
U_{in} = Percent uncertainty of the log inactivation through the UV reactor
t_I = t-statistic of the influent samples at an 80 percent confidence level
σ_I = Standard deviation of the challenge microorganism log concentration of the influent samples
n_I = Number of influent samples
t_E = t-statistic of the effluent samples at an 80 percent confidence level
σ_E = Standard deviation of the challenge microorganism log concentration of the effluent samples
n_E = Number of effluent samples

The RED should be calculated from the log inactivation using the equation describing the UV dose-response curve of the challenge microorganism. The percent measurement uncertainty of the RED can be calculated using Equation C.8:

$$U_{RED} = \left(U_{in}^{\ 2} + U_{DR}^{\ 2} + U_{D}^{\ 2}\right)^{1/2} \qquad \text{Equation C.8}$$

where

U_{RED} = Percent uncertainty of the measured RED

U_{DR} = Percent uncertainty of the regression equation fitting the challenge microorganism's UV dose-response data at an 80 percent confidence level (see section C.4.8.7, Figure C.3)

U_D = Percent uncertainty of the collimated beam dose calculation that is not captured in the variability of the measured dose-response data (see Appendix E). This typically includes the uncertainty of the radiometer and the Petri factor

Example. A UV reactor was validated using MS2. The UV dose-response measured using a collimated beam apparatus is given in Figure C.3. The dose-response was fitted using the following equation:

$$\text{Dose} = 8.90 \times \text{Log Inactivation} + 2.47 \times (\text{Log Inactivation})^2$$

The uncertainty of the radiometer used with the collimated beam apparatus was 8 percent. The Petri factor was measured with an uncertainty of 2 percent. Thus the uncertainty of the collimated beam dose calculation, U_D is calculated as follows:

$$U_D = \left(8^2 + 2^2\right)^{1/2} = 8.2\%$$

The following table presents the microbiology results obtained with the influent and effluent samples collected with one of the test conditions assessed during validation.

The mean and standard deviation of the influent and effluent log concentrations of the MS2 are 6.32 ± 0.075 and 4.26 ± 0.13, respectively. The log inactivation through the reactor is calculated as follows:

$$\textit{Log Inactivation} = 6.32 - 4.26 = 2.06$$

Table C.2 Estimated Log Inactivation and Corresponding RED Values Using Bioassay Results

Before UV	**Plate Counts - Dilution = 10^4**			**Plate Counts - Dilution = 10^5**			**Concentration**	
	1	**2**	**3**	**1**	**2**	**3**	**PFU/mL**	**log**
Sample 1	148	180	TNTC	15	18	20	1.77×10^6	6.24
Sample 2	173	TNTC	TNTC	11	32	22	2.17×10^6	6.33
Sample 3	TNTC	192	150	37	15	22	2.47×10^6	6.39
After UV	**Plate Counts - Dilution = 10^2**			**Plate Counts - Dilution = 10^3**			**Concentration**	
	1	**2**	**3**	**1**	**2**	**3**	**PFU/mL**	**Log**
Sample 1	166	181	TNTC	17	18	42	2.57×10^4	4.40
Sample 2	133	TNTC	101	13	28	10	1.70×10^4	4.23
Sample 3	165	141	123	17	14	12	1.43×10^4	4.15

The t-statistic for 3 samples and an 80 percent confidence level is 1.88. The percent uncertainty of the log inactivation is calculated as follows:

$$U_{in} = \frac{\left(\frac{(1.88 \times 0.075)^2}{3} + \frac{(1.88 \times 0.13)^2}{3}\right)^{1/2}}{2.06} \times 100 = 7.91\%$$

The RED associated with a log inactivation of 2.06 is calculated as follows:

$$\text{Dose} = 8.90 \times 2.06 + 2.47 \times (2.06)^2 = 28.8\,\text{mJ/cm}^2$$

The percent uncertainty of the regression equation, U_{DR}, at a log inactivation of 2.06 is 6 percent. The percent uncertainty of the RED is calculated as follows:

$$U_{RED} = \left(7.9^2 + 6^2 + 8.2^2\right)^{1/2} = 12.9\%$$

C.4.9.9 Interpretation of Results

Interpretation of the results should depend on the monitoring approach used to guarantee dose delivery:

- With the UV intensity setpoint approach, the UV reactor should be rated at the lowest inactivation observed for each setpoint condition evaluated.
- With the UV intensity and UVT setpoint approach, the UV reactor should be rated at the inactivation observed with UV reactor operation under setpoint conditions.
- With the calculated dose approach, the UV reactor should be rated at the lowest inactivation observed for each calculated dose setpoint evaluated.

C.4.9.10 Interpolation of Results

The RED measured by validation testing can be interpolated as a function of flowrate, UVT, and UV intensity by fitting an equation to the data being interpolated. If the RED is interpolated as a function of the measured intensity or the inverse flowrate, the equation used should pass through the origin (0,0). The equation coefficients should be significant at a 95 percent confidence level. The differences between the values measured and predicted by the equation should be randomly distributed around zero. The equation should be used for interpolating between measured data but should not be used for extrapolation.

The uncertainty of the equation used to interpolate the RED should be assessed by determining the 80 percent confidence level. If significant, the uncertainty should be included as an uncertainty term in the determination of the expanded uncertainty, as described in section C.4.10.2.3.

C.4.10 Determining Inactivation Credit

This guidance presents two approaches, termed Tier 1 and Tier 2, which can be used to relate the RED demonstrated during reactor validation to target pathogen inactivation. Other approaches or modifications to this approach may be used at the discretion of the State.

With both approaches, the RED demonstrated during validation should be equal to or greater than a target RED that is related to the dose tables in Chapter 1 using a safety factor. With Tier 1, fixed safety factors have been defined and applied to the dose tables in Chapter 1 to define target RED values. The Tier 1 safety factors are based on specific Tier 1 criteria for the UV reactor and its validation protocol. The Tier 1 approach can be used with a given UV reactor provided it meets all the Tier 1 criteria. With Tier 2, the safety factors are calculated based on the validation results for, and certain properties of, the UV reactor that are calculated from the validation results and certain properties of the UV reactor undergoing validation.

C.4.10.1 Tier 1 Approach

For a UV reactor using LP or LPHO lamps, Table C.3 presents the Tier 1 RED values that should be demonstrated during validation to achieve the specified log-inactivation credits for *Cryptosporidium*, *Giardia*, and virus. Table C.4 presents the Tier 1 RED values for MP reactors. The Tier 1 RED values are applicable with all UV reactors that meet the Tier 1 criteria provided in this section.

Example. To receive 2.5 log *Cryptosporidium* inactivation credit, a LP reactor under Tier 1 should demonstrate an RED of 28 mJ/cm^2.

Table C.3 Tier 1 RED Targets for UV Reactors with LP or LPHO Lamps

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

Table C.4 Tier 1 RED Targets for UV Reactors with MP Lamps

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

Tier 1 criteria for the UV reactor are as follows:

- UV reactors equipped with MP lamps should be equipped with one sensor per lamp. UV reactors equipped with LP or LPHO lamps should be equipped with at least one sensor per bank of lamps.

- The standard deviation of the UV output of LP or LPHO lamps should be 15 percent or less of the mean output. The standard deviation should be determined using either life test or field data on aged lamps.

- UV intensity sensors should view a point along the length of the lamp that is within 25 percent of the arc length away from the electrode.

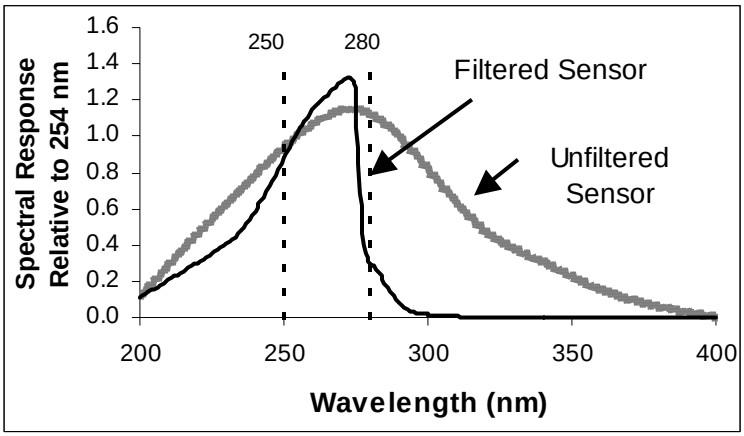
- UV intensity sensors should have a spectral response that peaks between 250 and 280 nm. When mounted on the UV reactor and viewing the lamps through water, the measurement of UV light greater than 300 nm made by the sensor should be less than 10 percent of the total measurement made by the sensor. Conformance to these criteria can be demonstrated using UV intensity field modeling. Figure C.4 presents an example of how two sensors would conform to this criterion.

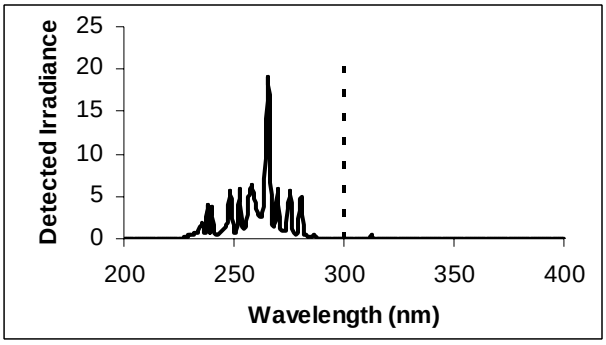
- The UV intensity sensors used during validation and the duty and reference sensors used during operation of the UV reactor at the WTP should provide NIST traceable measurements with a measurement uncertainty of ± 15 percent or less at an 80 percent confidence level.

- During operation of the UV reactor at the WTP, measurements made by the duty UV intensity sensor should be checked using a reference UV intensity sensor. The difference between the measurement made by the duty and reference sensors should meet the following criteria:

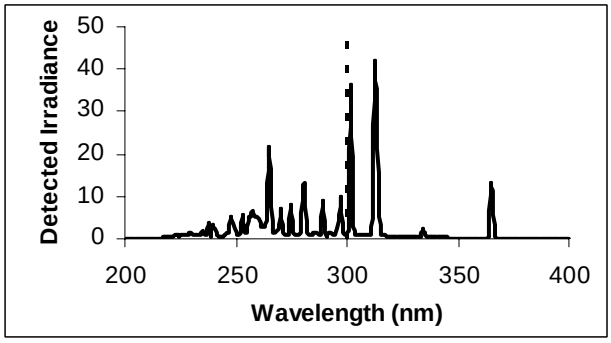
$$\left(\frac{I_{Duty}}{I_{Ref}} - 1\right) \times 100 \le \left(\sigma_{Ref}^2 + \sigma_{Duty}^2\right)^{1/2} \qquad \text{Equation C.9}$$

Figure C.4 Comparison of the Spectral Response of Two UV Intensity Sensors Estimated Using UV Intensity Field Modeling

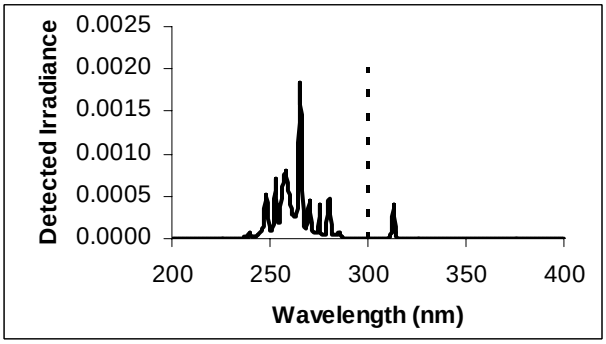




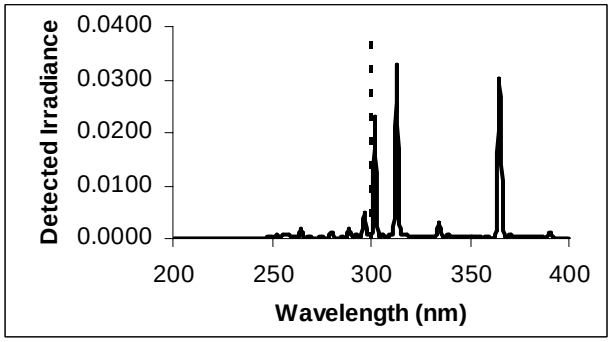
Filtered Sensor. Detected UV light with a 0 cm sensor-to-lamp water layer. Detected UV > 300 nm is 0.7% of total UV light detected.



Unfiltered Sensor. Detected UV light with a 0 cm sensor-to-lamp water layer. Detected UV > 300 nm is 41% of total UV light detected.



Filtered Sensor. Detected UV light with a 20 cm sensor-to-lamp water layer. Detected UV > 300 nm is 5% of total UV light detected.



Unfiltered Sensor. Detected UV light with a 20 cm sensor-to-lamp water layer. Detected UV > 300 nm is 85% of total UV light detected.

- If the dose monitoring strategy uses an on-line UVT monitor, the A_{254} calculated from the measured UVT should have a measurement uncertainty of ± 10 percent or less at an 80 percent confidence level.

Tier 1 criteria for the flow measurements are as follows:

- The flow measurements during validation and during operation of the UV reactor at the WTP should have a measurement uncertainty of ± 5 percent or less at an 80 percent confidence level.

Tier 1 criteria for the collimated beam apparatus are as follows:

- The calculated dose delivered by the collimated beam apparatus should have a measurement uncertainty of ± 15 percent or less at an 80 percent confidence level.

Tier 1 criteria for the challenge microorganism dose-response are as follows:

- Over the range of doses within one log of the log reduction demonstrated during validation, the UV sensitivity of the challenge microorganism should be less than or equal to 25 mJ/cm^2 per log inactivation (the dose-response of a resistant strain of MS2). For example, if you measure log inactivation values between 1.5 and 3.5 log, the test organism you use should have a dose-response less than or equal to 25 mJ/cm^2 per log inactivation between 0.5 and 4.5 log inactivation.

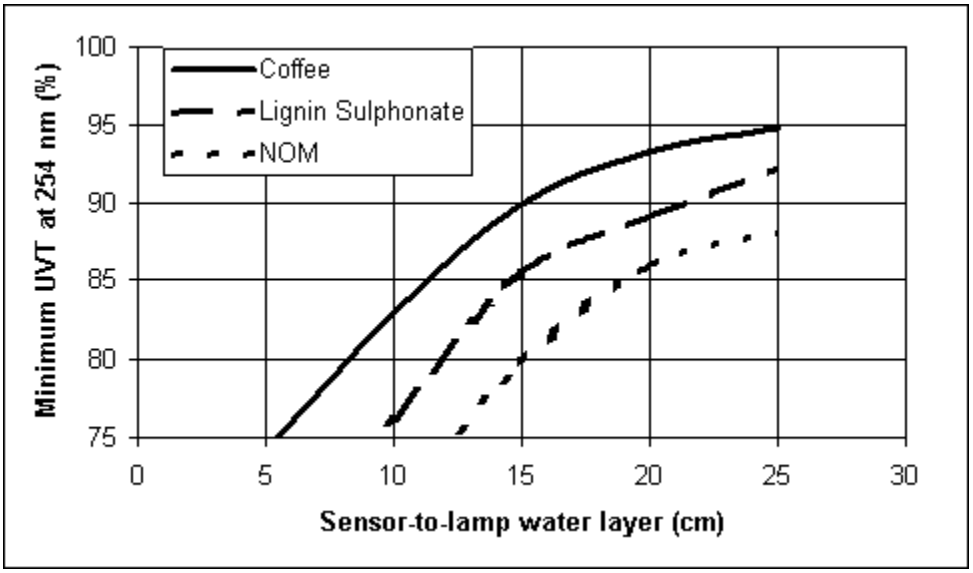
- If the dose-response of the challenge microorganism has a shoulder, that shoulder should not occur over a dose range greater than 50 percent of the RED demonstrated during validation. The shoulder is defined by extrapolating the exponential reduction region of the dose-response curve to the dose-axis.

- If the dose-response demonstrates tailing, the tailing should not occur until one log reduction greater than the highest log reduction demonstrated during validation.

Tier 1 criteria for the UVT used for validating UV reactors using medium-pressure lamps are as follows:

- The UVT at 254 nm of the water during validation should be greater than the values specified in Figure C.5 for a given sensor-to-lamp water layer and UV-absorbing chemical (the polychromatic bias should be 1.0). The sensor-to-lamp water layer is defined as the distance traveled through water by UV light passing from the lamp to the sensor. The values in Figure C.5 were taken from Figure C.7 for a polychromatic bias of 1.2.

Figure C.5 Criteria for the Minimum UVT of MP UV Reactors under Tier 1



Tier 1 criteria for the challenge microorganism dose-response data are as follows:

- A plot of dose versus log inactivation should have an 80 percent confidence level of 10 percent or less at the log inactivation demonstrated by the UV reactor.

Tier 1 criteria for the challenge microorganism measurements through the reactor are as follows:

- Five influent and five effluent samples should be collected per test condition evaluated as per section C.4.9.5.

- The standard deviation of the challenge microorganism concentration measured with the influent and the effluent samples should be less than or equal to 0.20 log.

Tier 1 criteria for the interpolation of challenge microbe results are as follows:

- The uncertainty of the interpolation should be 10 percent or less at an 80 percent confidence level.

C.4.10.2 Tier 2 Approach

The safety factor used to relate the RED demonstrated during validation to the dose required to inactivate the target pathogen should be defined using Equation C.10:

$$SF = B_{RED} \times B_{Poly} \times (1 + e) \qquad \text{Equation C.10}$$

where
SF = Safety Factor
B_{RED} = RED bias
B_{Poly} = Polychromatic bias
e = Expanded uncertainty as a fraction

The following sections describe an approach for defining each of these terms.

Determining the RED Bias

If a single challenge microorganism is used to demonstrate dose delivery during validation, the RED bias should be determined using Figure C.6 and the following procedure. (Section F.1 provides the background on the development of Figure C.6 and the procedure for determining the RED bias.)

Procedure

1. Calculate the UV sensitivity of the target pathogen as the dose requirement specified in Chapter 1 divided by the corresponding log inactivation credit.

2. Calculate the UV sensitivity of the challenge microorganism as the calculated RED divided by the log inactivation.

3. If the target pathogen is more resistant to UV light than the challenge microorganism, the RED bias equals 1.0. Otherwise, calculate the RED bias using Equation C.11:

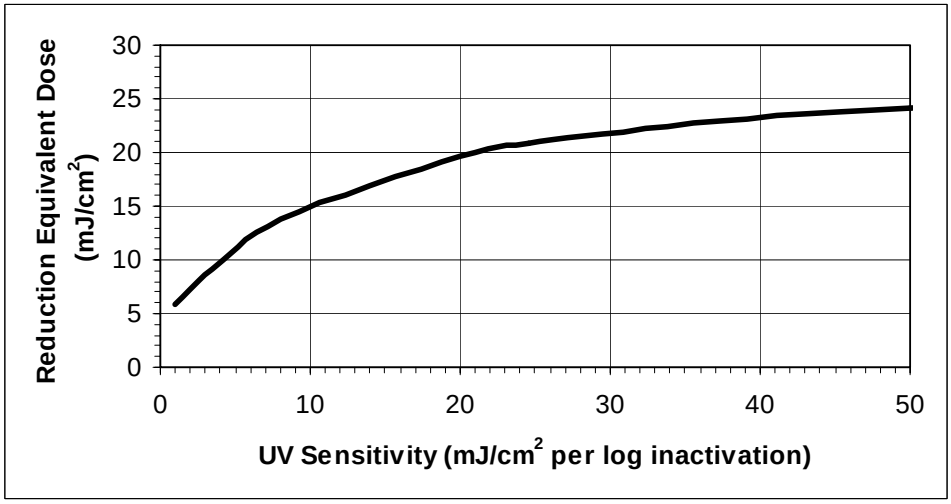
$$RED\ Bias = \frac{RED_C}{RED_P} \qquad \text{Equation C.11}$$

where
RED_C = RED of the challenge microorganism obtained from Figure C.6
RED_P = RED of the target pathogen obtained from Figure C.6

Example. An MS2 inactivation of 2 log corresponding to an RED of 36 mJ/cm^2 is measured during validation. A 2-log *Cryptosporidium* credit is required. The UV dose required to achieve that level of inactivation from Chapter 1 is 5.8 mJ/cm^2. Thus, the UV sensitivity of MS2 and *Cryptosporidium* is defined as 36/2.0 = 18 and 5.8/2.0 = 2.9 mJ/cm^2 per log inactivation, respectively. Because MS2 is more resistant than *Cryptosporidium*, the RED bias is greater than one. In Figure C.6, REDs of 19 and 8.2 correspond to UV sensitivities of 18 and 2.9 mJ/cm^2 per log, respectively. Thus, using Equation C.11, the RED bias is 19/8.2 = 2.3.

Example. An MS2 inactivation of 4 log and a corresponding RED of 80 mJ/cm^2 is measured during validation. A 2.0-log adenovirus credit requiring a dose of 100 mJ/cm^2 is required. Thus, the UV sensitivity of the challenge microorganism and pathogen are 20 and 50 mJ/cm^2 per log inactivation, respectively. Because the UV sensitivity of adenovirus is greater than that of the challenge microorganism, the RED bias equals 1.0.

Figure C.6 RED versus Microorganism UV Sensitivity for Use in Determining the RED Bias



If two challenge microorganisms with different UV sensitivities are used during validation to demonstrate dose delivery, the RED delivered to the target pathogen can be determined by interpolation using the following procedure. (Section F.1.3 provides the background on the use of two challenge microorganisms to demonstrate RED delivered to a target pathogen.)

Procedure

1. For a given test condition of flowrate, UVT, and lamp output, calculate the UV sensitivity of the challenge microorganisms as their respective measured REDs divided by their corresponding log inactivations.

2. Determine the UV sensitivity of the target pathogen as the dose listed in Chapter 1 divided by the log inactivation.

3. Calculate the RED delivered to the target pathogen using the following equation:

$$RED_P = RED_{C1} + (RED_{C2} - RED_{C1})\frac{(D10_P - D10_{C1})}{(D10_{C2} - D10_{C1})} \qquad \text{Equation C.12}$$

where

RED_P = Estimate of the target pathogen's RED

RED_{C1} = The RED measured with the first challenge microorganism

RED_{C2} = The RED measured with the second challenge microorganism

$D10_P$ = UV sensitivity of the target pathogen (mJ/cm^2 per log inactivation)

$D10_{C1}$ = UV sensitivity of the first challenge microorganism (mJ/cm^2 per log inactivation)

$D10_{C2}$ = UV sensitivity of the second challenge microorganism (mJ/cm^2 per log inactivation)

4. Calculate the percent uncertainty of the estimated RED of the target pathogen using Equation C.13:

$$U_{REDp} = \frac{\left[\left(RED_{C1} U_{RED,C1}\right)^2 + \left(\frac{D10_p - D10_{C1}}{D10_{C2} - D10_{C1}} \right)^2 \left\{ \left(RED_{C1} U_{RED,C1}\right)^2 + \left(RED_{C2} U_{RED,C1}\right)^2 \right\} \right]^{1/2}}{RED_P}$$

Equation C.13

where

U_{REDp} = Percent uncertainty of the RED estimated for the pathogen

$U_{RED,C1}$ = Percent uncertainty of the RED measured with the first challenge microorganism (see Equation C.8)

As an alternative two-microorganism approach, the log inactivation measured with the challenge microorganisms can be interpolated as a function of the microorganisms' first-order inactivation coefficients.

Example. A UV reactor was validated using MS2 and ϕX174 at 1 and 2 mgd. The UV sensitivities of the MS2 and ϕX174 were 18 and 2 mJ/cm^2 per log inactivation, respectively. The following table gives the RED and percent uncertainties measured with MS2 and ϕX174. At the lower flowrate of 1 mgd, the ϕX174 was inactivated to below the detection limit and the measured RED was estimated as greater than 10 mJ/cm^2. The table also gives the RED delivered to *Cryptosporidium* estimated using Equation C.12 and the percent uncertainty of that RED estimated using Equation C.13. These estimations assumed a UV sensitivity of *Cryptosporidium* of 4.0 mJ/cm^2 per log inactivation based on the dose in Chapter 1 for a 3.0-log inactivation credit.

Flow (mgd)	MS2		ϕX174		*Cryptosporidium*	
	RED (mJ/cm^2)	Uncertainty (%)	RED (mJ/cm^2)	Uncertainty (%)	RED (mJ/cm^2)	Uncertainty (%)
1	40	6	> 10	0	14	3.2
2	20	11	9	4	10	2.9

Determining the Polychromatic Bias

For a UV reactor using a germicidal UV intensity sensor (the spectral response meets Tier 1 criteria), the polychromatic bias can be assigned a value of one if the UV intensity sensor is located where dose delivery is proportional to measured UV intensity or closer to the lamps than that location. This can be shown experimentally by demonstrating under fixed conditions of flow and measured UV intensity that the RED obtained with peak UVT and lowered lamp power is greater than or equal to the RED measured with peak lamp power and lowered RED.

If data are not available showing the UV intensity sensor location meets the above criteria, the polychromatic bias should be determined by calculating, at a given flowrate, UVT,

and measured UV intensity, the ratio of RED during validation to the RED at the WTP. This calculation should be done conservatively by assuming ideal dose delivery where dose is the product of the average intensity within the reactor and the theoretical mean residence time. The calculation should include the following factors:

- The spectral UV transmittance of the water during validation and at the WTP.
- The spectral lamp output during validation and expected at the WTP with aged lamps.
- The spectral sleeve UV transmittance during validation and expected at the WTP with aged and fouled sleeves.
- The spectral response of the sensor used during validation and at the WTP.
- The action spectra of the challenge microorganism used during validation and the action spectra of the target pathogen taken from the literature.

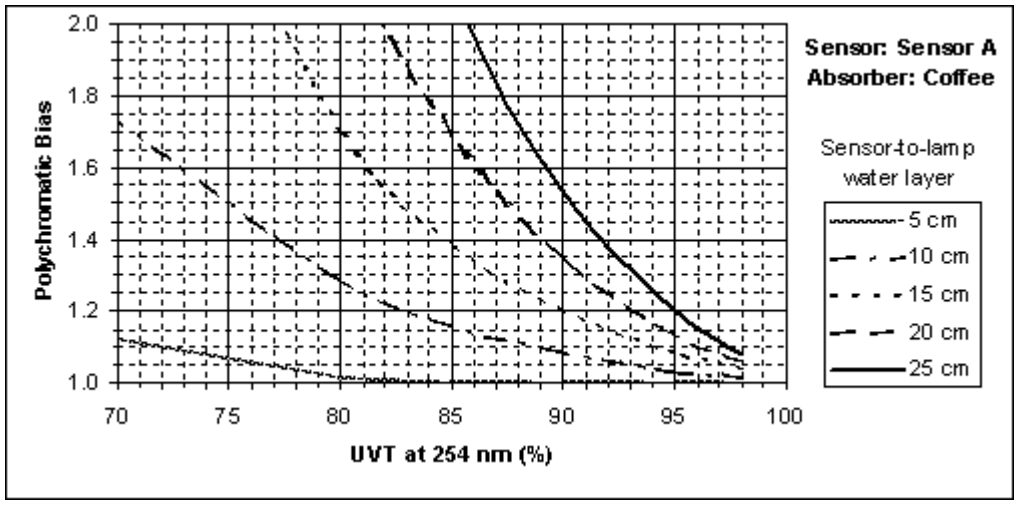
If the above ratio is less than one, the polychromatic bias should be assigned a value of one.

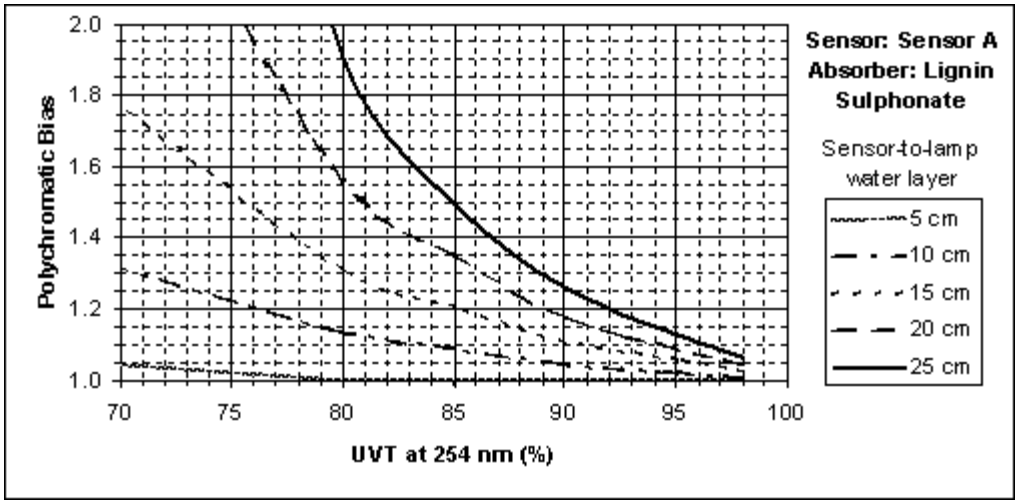
Figures C.7 to C.9 present the polychromatic bias for reactors with UV intensity sensor spectral response curves shown in Figure C.10. Each figure presents, for a given sensor spectral response, the polychromatic bias as a function of the UVT, the sensor to sleeve water layer, and the UV absorbing chemical used during validation (coffee, lignin sulphonate, and natural organic matter (NOM)). The spectral UV absorption coefficient of the UV absorbers and the WTP water used to define the polychromatic bias values is provided in Figures C.11 and C.12. Figures C.7 to C.9 can be used to determine the polychromatic bias if the spectral response of the UV intensity sensor used in the figure is representative of the spectral response the UV reactor's intensity sensor. Alternatively, the polychromatic bias can be calculated using a model that meets the above-mentioned criteria.

The polychromatic bias shown in Figures C.7 to C.9 was determined for an annular reactor with a reactor radius of 18.8 cm and a sleeve radius of 3.81 cm. The UV intensity field was calculated using a radial intensity model. Section F.4.2 presents details on the models used to develop Figures C.7 to C.9.

The polychromatic bias values in Figures C.7 to C.9 only account for differences between the spectral UV absorbance during validation and the spectral UV absorbance at the WTP. They do not account for the impact of spectral shifts in the optical properties of the UV reactor (e.g., lamp output, sleeve UVT). If spectral shifts in UV reactor properties occur with operation of the UV reactor at the WTP, the polychromatic bias should be multiplied by terms that account for those shifts. Section F.4.3 describes spectral shifts and provides estimates of the polychromatic biases that can occur with those shifts.

Figure C.7 Polychromatic Bias as a Function of Water UVT and Sensor-to-Lamp Water Layer for UV Reactors using Sensors with Germicidal Response (response A in Figure C.10) Validated using Coffee, Lignin Sulphonate, or NOM





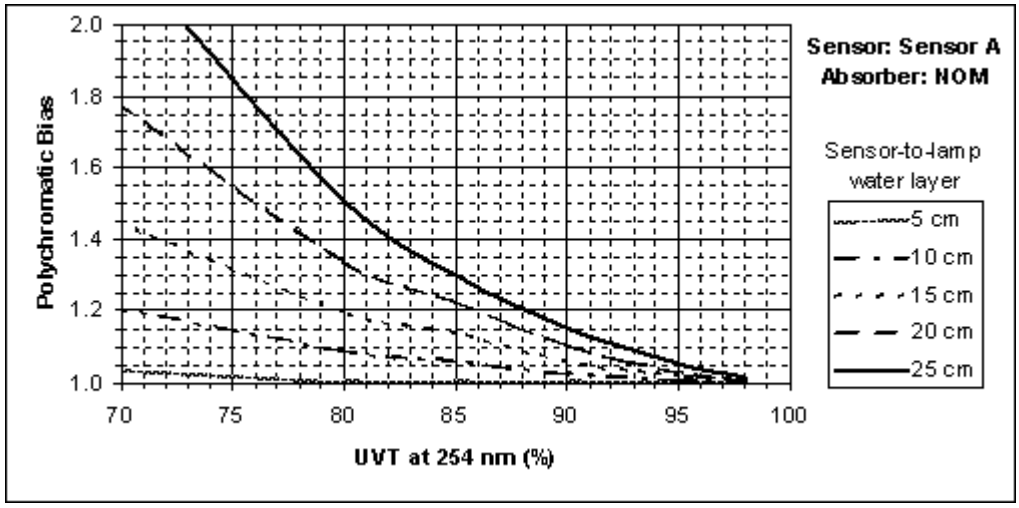
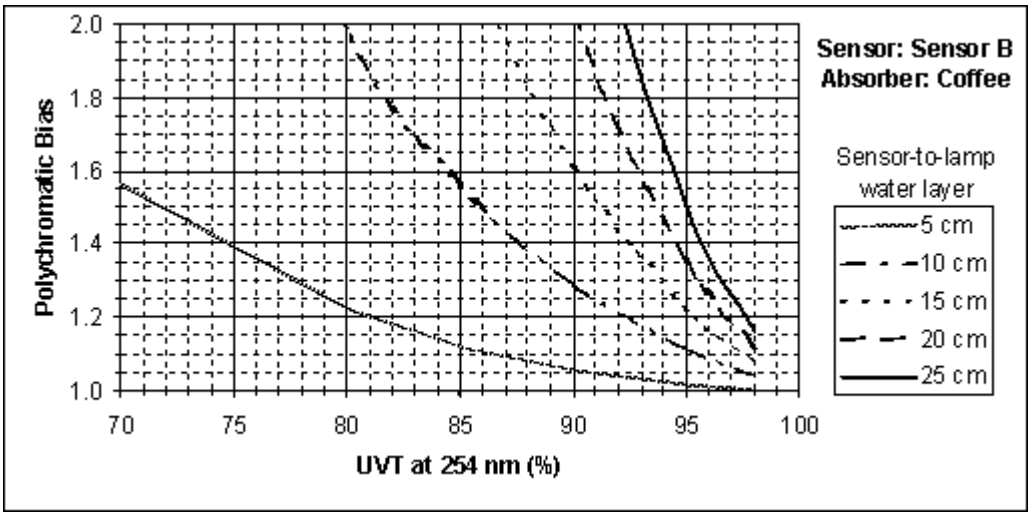
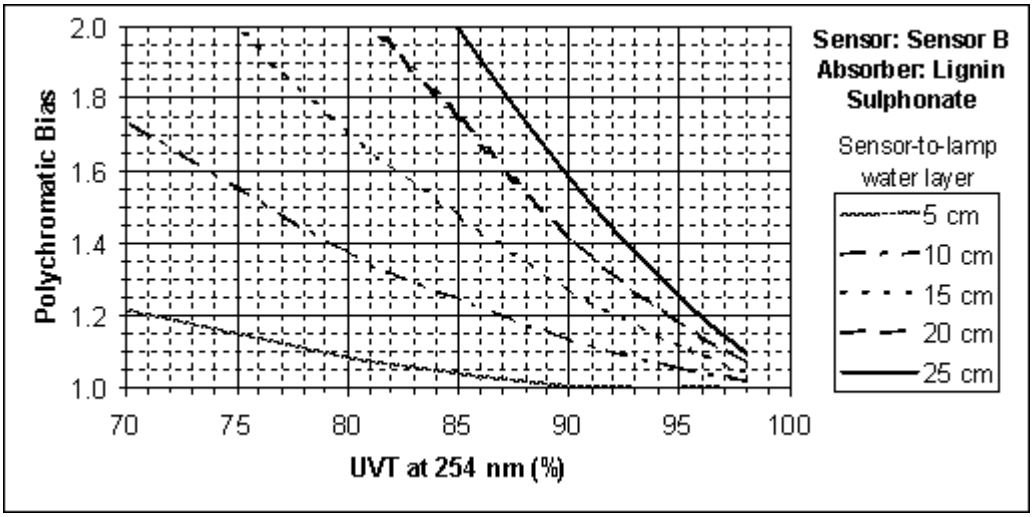


Figure C.8 Polychromatic Bias as a Function of Water UVT and Sensor-To-Lamp Water Layer for UV Reactors Using Sensors with SiC Response (Response B In Figure C.10) Validated Using Coffee, Lignin Sulphonate, or NOM





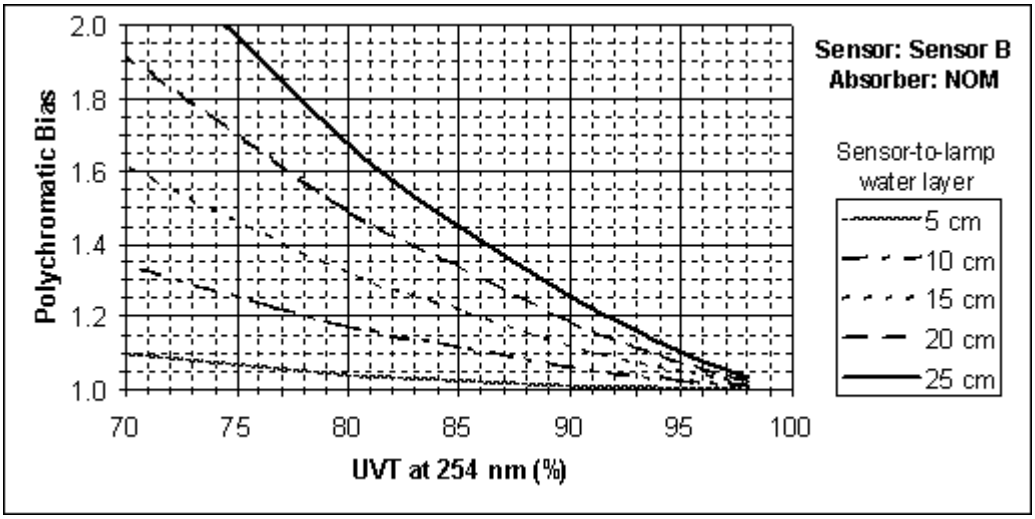
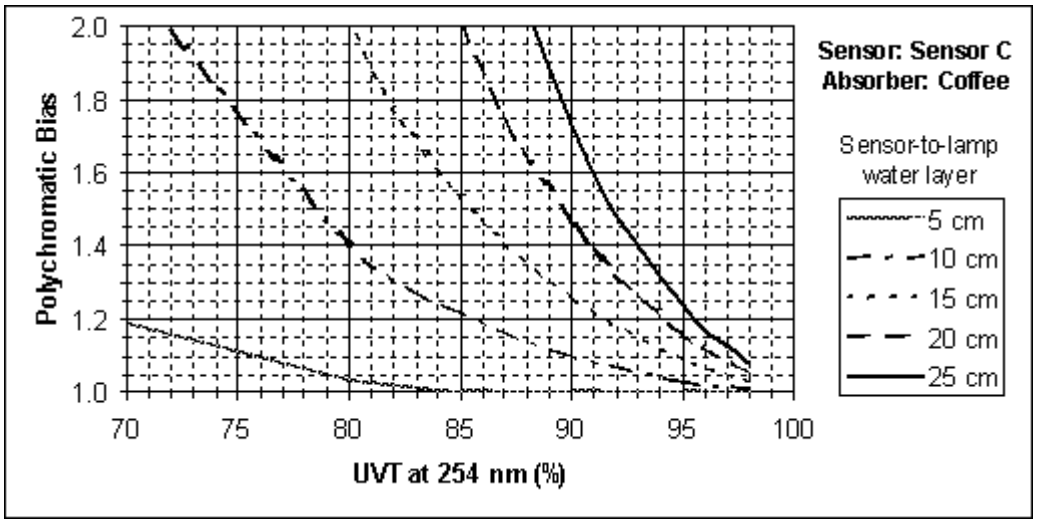
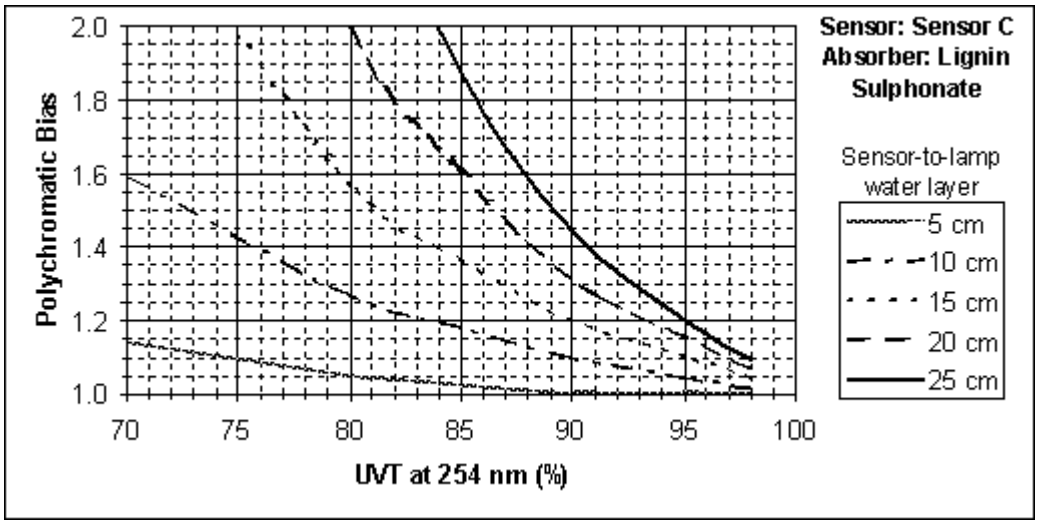


Figure C.9 Polychromatic Bias as a Function of Water UVT and Sensor-To-Lamp Water Layer for UV Reactors Using Sensors with Germicidal Response (Response C In Figure C.10) Validated Using Coffee, Lignin Sulphonate, or NOM





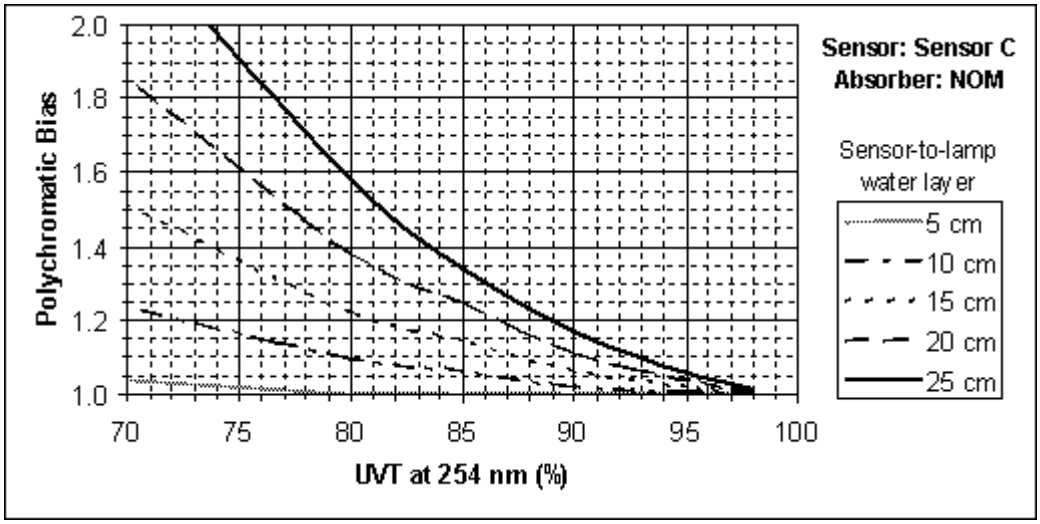


Figure C.10 Spectral Response of Sensors Used in Defining Figures C.7 to C.9

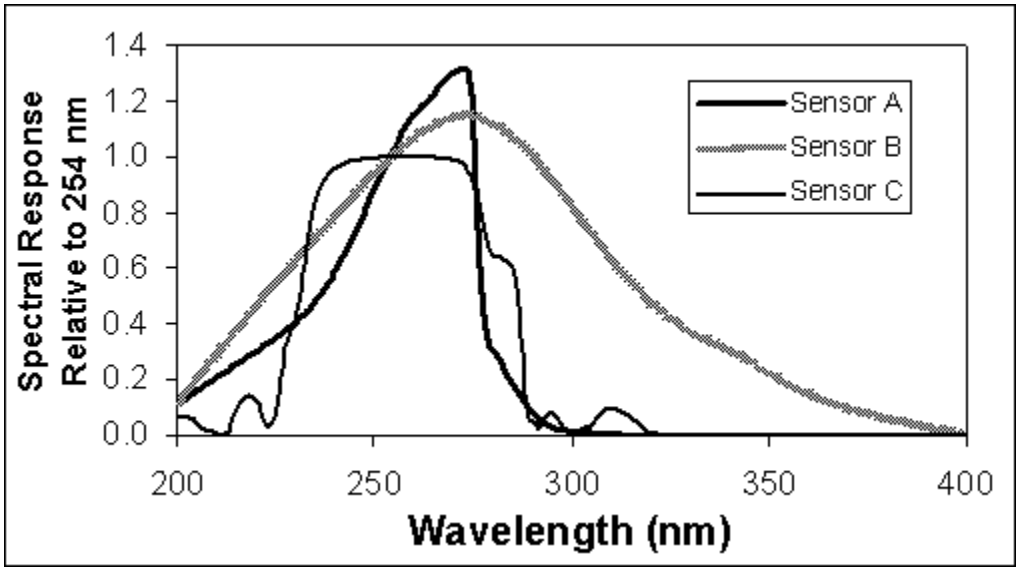


Figure C.11 UV Absorption Coefficient of Coffee, Lignin Sulphonate, and the Target Water used to Define Figures C.7 to C.9

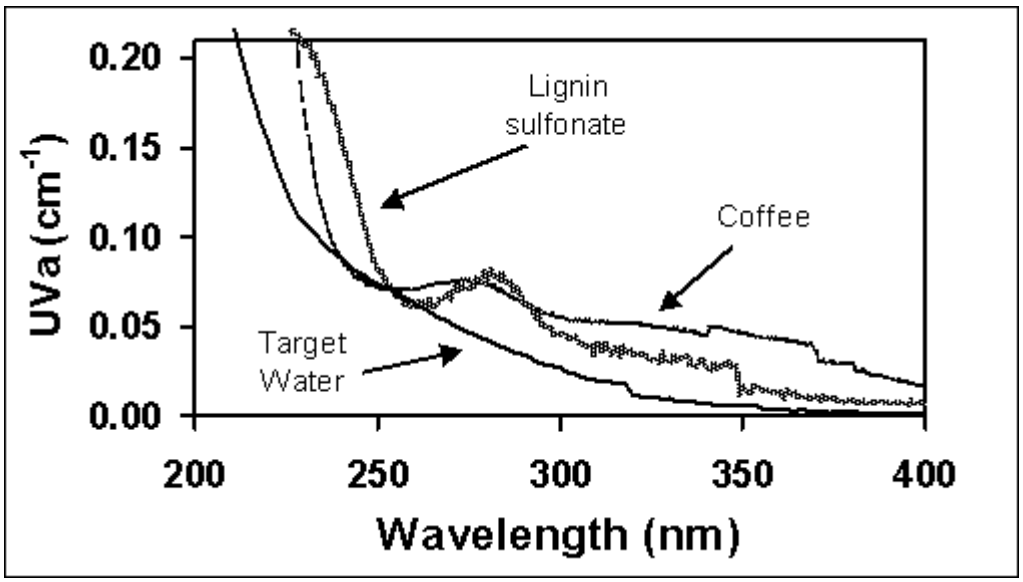
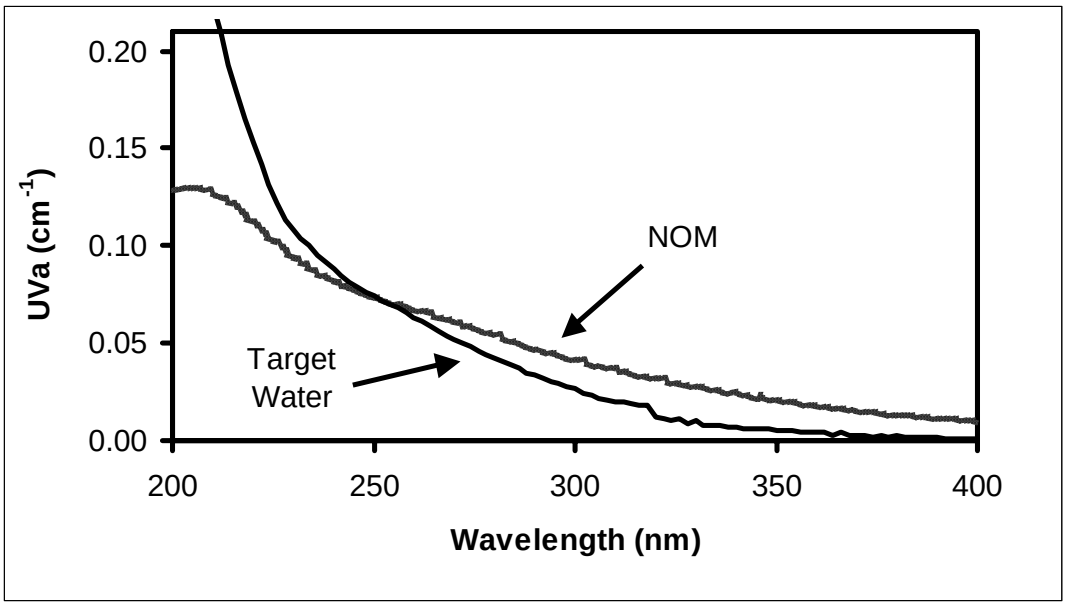


Figure C.12 Spectral UV Absorbance of NOM and the Target Water Used to Define Figures C.7 to C.9



Example. A UV reactor equipped with "Sensor B" located 10 cm from the lamp sleeve (10 cm water layer) is validated using coffee as a UV absorbing chemical. The UV reactor is validated at three intensity setpoints, each tested at lowered UVT values of 95 percent, 90 percent, and 85 percent. The polychromatic bias values taken from Figure C.8 are 1.11, 1.29, and 1.56, for UVT values of 95 percent, 90 percent and 85 percent, respectively.

Example. A UV reactor equipped with "Sensor A" located 15 cm from the sleeve (20 cm water layer) is being considered at a WTP with a design UVT of 80 percent. From Figure C.7, the polychromatic bias with coffee, lignin sulphonate, and NOM are 1.7, 1.3, and 1.2, respectively. Comparing these values, a strong incentive exists to select the UV absorber that minimizes the polychromatic bias.

Determining the Random Uncertainty

The random uncertainty associated with monitoring and validation should be calculated at an 80 percent confidence level using the uncertainty of the terms listed in Table C.5. The expanded uncertainty should be calculated as the square root of the sum of squares of uncertainties of each term.

If one challenge microorganism is used during validation, the uncertainty of the RED is calculated using Equation C.8. If two challenge microorganisms are used, the uncertainty of the RED is calculated using Equation C.13. The uncertainty of the interpolation is obtained from the confidence bands of the equation used for the interpolation (see section C.4.9.10). The uncertainty of the UV intensity sensors used during validation and used at the WTP should be obtained from manufacturer data with supporting documentation as per Table C.1 in section

Table C.5 Factors Impacting Expanded Uncertainty of Dose Delivery Monitoring and Validation

Uncertainty
Measured RED
Any interpolation of RED as a function of flowrate, UVT, or UV intensity
Sensors used during validation (UV intensity, UVT)
On-line and reference sensors used at the WTP (UV intensity, UVT)
Lamp output quantification

C.2.2. If the dose monitoring approach uses a UVT monitor, include the measurement uncertainty of the UVT monitor obtained from data provided by the manufacturer.

The uncertainty of lamp output quantification is zero if each lamp is monitored by an individual UV intensity sensor. Otherwise, the uncertainty can be calculated using Equation C.14:

$$Uncertainty = \frac{1.28\sigma}{\sqrt{n_1}\sqrt{n_2}} \qquad \text{Equation C.14}$$

where

σ = Standard deviation of lamp-to-lamp output expressed as a percentage of the mean

n_1 = Number of banks of lamps in series in the reactor

n_2 = Number of sensors monitoring each bank

The variability of UV output from lamp-to-lamp can be obtained from either life test or field data on aged lamps.

Example. A UV reactor consists of two banks of four lamps. Each bank is equipped with two UV intensity sensors. Dose delivery is monitored using the UV intensity setpoint approach. The manufacturer provides data showing the standard deviation of lamp-to-lamp output is 12 percent of the mean output at the end of lamp life. Thus, the lamp output quantification uncertainty is $1.28\times12/(2^{0.5}\times2^{0.5}) = 7.7$ percent. When operating at a WTP, the on-line UV intensity sensors have a measurement uncertainty of 20 percent. The on-line sensors will be checked using a reference sensor with an uncertainty of 5 percent. During validation, the flowmeter and UV intensity sensors had an uncertainty of 0.5 percent and 5 percent. The collimated beam dose calculation has an uncertainty of 8 percent. The regression fit to the dose-response of the phage has an uncertainty of 10 percent. The UV reactor is tested at peak flowrate with the results shown in Table C.6. The uncertainty of the measured log inactivation is determined as 4.4 percent. As summarized in Table C.7, a total uncertainty of 26 percent is calculated as the square root of the sum of the squares of the individual uncertainties.

Table C.6 Sample Calculation of the Log Inactivation Uncertainty

Influent		Effluent	
N	**Log N**	**N**	**Log N**
3.60×10^5	5.56	154	2.19
4.90×10^5	5.69	206	2.31
4.10×10^5	5.61	263	2.42
Mean	5.62	**Mean**	2.31
St Dev.	0.067	**St Dev.**	0.116
T-statistic	2.92	**T-statistic**	2.92
Uncertainty	0.0729	**Uncertainty**	0.126
		Inactivation	
		Log Inactivation	3.31
		Uncertainty	0.145
		Uncertainty (%)	4.40

Table C.7 Sample Calculation of the Expanded Uncertainty

Uncertainty	**Uncertainty (%)**	**Uncertainty Squared**
Log Inactivation by reactor	4.4	19
Collimated beam dose calculation	8	64
Regression fit to UV Dose-Response Data	10	100
Validation UV intensity sensor	5	25
WTP on-line UV intensity sensor	20	400
WTP reference UV intensity sensor	5	25
Quantification of lamp-to-lamp variability	7.7	59
Expanded Uncertainty	**26**	**692**

Determining the Safety Factor

The safety factor relating the RED measured during validation to the pathogen inactivation requirements should be calculated as the product of the RED bias, the polychromatic bias, and the expanded uncertainty as per Equation C.10.

Example. MS2 inactivation of 2.0 log corresponding to an RED of 40 mJ/cm^2 is measured during validation with a LP reactor. The expanded uncertainty of 35 percent is calculated. Because LP lamps are used, the polychromatic bias is 1.00. An RED bias of 2.0 is determined using the observed UV sensitivity of MS2 and the UV sensitivity associated with a 3.0-log *Cryptosporidium* inactivation credit. A safety factor of $(1+0.35) \times 2.0 \times 1.0 = 2.7$ is calculated. Hence, the *Cryptosporidium* RED demonstrated by validation is 40 / 2.7 = 15 mJ/cm^2. Because the demonstrated *Cryptosporidium* RED is greater than the 3.0-log requirement of 12 mJ/cm^2, the UV reactor is validated for a 3.0-log *Cryptosporidium* inactivation credit.

Example. The UV reactor in the above example is instead equipped with MP lamps monitored with UV intensity sensors matching the spectral response of Sensor A. The UV intensity sensors view the lamp through a 15 cm water layer. The UV reactor is validated using lignin sulphonate at a maximum UVT of 80 percent. Using Figure C.7, the polychromatic bias

of 1.3 is determined. Thus, the safety factor is (1+0.35) × 2.0 × 1.3 = 3.5 and the *Cryptosporidium* RED demonstrated by validation is 40/3.5 = 11.4 mJ/cm^2. In this case, the demonstrated RED is less than the required RED of 12 mJ/cm^2 for 3.0-log *Cryptosporidium* inactivation credit, and the UV reactor should not be considered validated for 3.0-log inactivation of *Cryptosporidium*. However, for a 2.5-log *Cryptosporidium* inactivation requiring a dose of 8.5 mJ/cm^2, the RED bias is 2.1, resulting in a safety factor of 3.7 and a demonstrated *Cryptosporidium* RED of 40 / 3.7 = 10.8 mJ/cm^2. Because the demonstrated RED of 10.8 mJ/cm^2 is greater than the target RED of 8.5 mJ/cm^2, the UV reactor can be considered validated for a 2.5 log *Cryptosporidium* inactivation credit.

C.4.11 Validation Test Report

The engineer responsible for third-party oversight should collect all documentation and test results and prepare summary and detailed reports.

C.4.11.1 Summary Report

The summary report should describe the UV reactor validated under this protocol in general terms including the following components:

- Inlet and outlet conditions
- Number of UV lamps and their location within the reactor
- Lamp characteristics including type, electrical power consumption, and spectral output
- Monitoring and controls approach used for dose compliance
- Number of UV intensity sensors and their locations
- UVT monitor, if used
- Safety features used to ensure water disinfection

The summary report should provide the challenge microorganism UV dose-response, including the regression fit and the confidence intervals. The report should tabulate each reactor test condition evaluated, including the flowrate, UV intensity setpoint, UVT setpoint (if used), calculated dose (if used), log inactivation achieved, and calculated RED. The number of samples evaluated, the standard deviation of the influent and effluent samples, and the uncertainty of the inactivation through the reactor should also be tabulated.

If interpolation of bioassay results is part of dose monitoring, tables or charts should present the results of the interpolation.

If the reactor is evaluated under Tier 1, documentation should be provided supporting that the validation met Tier 1 criteria. The report should state the pathogen credits that the UV reactor can achieve based on the Tier 1 designation.

If the UV reactor is evaluated under Tier 2, documentation should be provided describing the Tier 2 analysis including the determination of the RED bias, polychromatic bias, and expanded uncertainty. For the expanded uncertainty, each term used in the calculation should be provided. The report should state the pathogen credits that the UV reactor can achieve based on the Tier 2 results.

Based on the values used to determine the safety factor applied to the validation data (Tier 1 or 2), the summary report should specify all criteria for the measurement uncertainty of the UV intensity sensors, and UVT monitors used at the WTP.

C.4.11.2 Detailed Report

The detailed report should provide a comprehensive description of the test methodology that includes the following components:

- Identity and qualifications of personnel involved in the validation test
- UV reactor specifications
- UV intensity sensor specifications and calibration documentation
- Physical test set-up
- Summary of QA/QC procedures
- Materials and methods employed during the test
- Complete test results, including raw data and analyses performed

C.5 UV Reactor Validation Examples

This section provides examples of UV reactor validation for the following reactors and monitoring approach combinations:

- LP reactor using a single intensity setpoint (section C.5.1)
- LP reactor using multiple setpoints as a function of flowrate (section C.5.2)
- LP reactor using multiple setpoints as a function of flowrate and dose (section C.5.3)

- MP reactor using a single intensity setpoint and UVT setpoint (section C.5.4)
- MP reactor using the calculated dose method for monitoring (section C.5.5)

C.5.1 LP Reactor Using a Single Intensity Setpoint

A UV reactor consists of two banks in series of nine LPHO lamps oriented perpendicular to flow. Dose delivery is monitored using the UV intensity setpoint approach. Each bank is equipped with one UV intensity sensor.

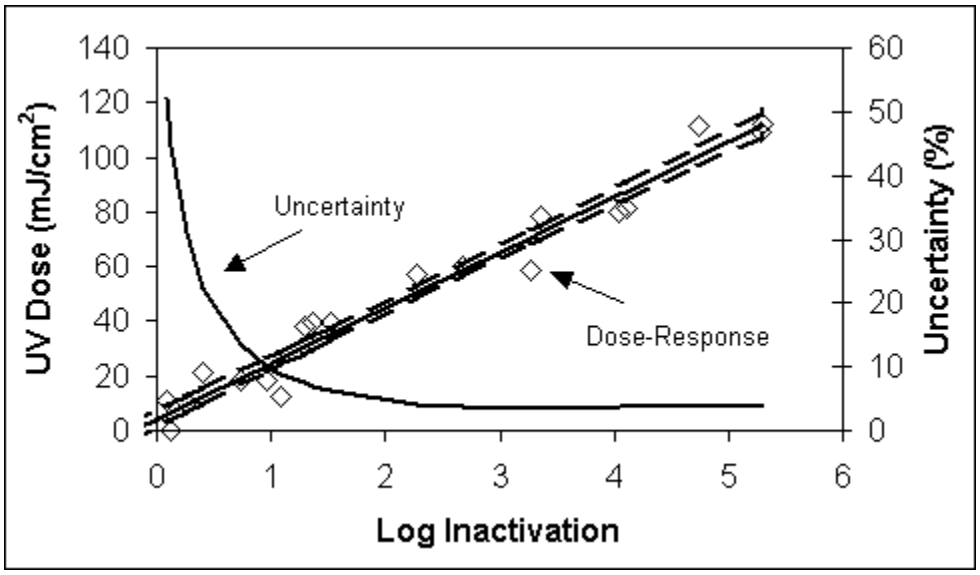
The UV reactor is considered for use at a WTP. The application requires a 2.5 log inactivation credit of *Cryptosporidium*. The design flowrate and UVT at the WTP are 500 gpm and 90 percent, respectively. The UV manufacturer states the lamp fouling/aging factor for the reactor is 70 percent. During operation at a WTP, the on-line and reference UV intensity sensors are expected to have a measurement uncertainty of 15 and 5 percent, respectively. The reactor will operate at the WTP using a single intensity setpoint to indicate dose delivery over a flow range of 100 to 500 gpm.

The reactor is validated using coffee as the UV absorber and MS2 as the challenge microorganism. Figure C.13 gives the dose-response of the MS2 measured during validation with a collimated beam. The dose-response is fitted using the following equation:

$$\text{Dose} = 20.3 \times \log\left(\frac{N_0}{N}\right) + 4.3$$

Figure C.13 also provides 80 percent confidence levels for the fit and the percent uncertainty of the UV dose calculated from those confidence levels.

Figure C.13 Dose-Response of the MS2 Challenge Microorganism Used in Example C.5.1



A reference sensor is used to monitor UV intensity during validation testing. The intensity setpoint to be validated is determined by operating the reactor under design conditions of 70 percent lamp output and 90 percent water UVT. Under these conditions, the UV intensity sensor reads 5.0 mW/cm^2.

Table C.8 gives the validation test conditions and results. The reactor is tested at flowrates of 100 and 500 gpm with the intensity sensor reading 5.0 mW/cm^2. At each flowrate, the reactor is tested under conditions of low UVT - high lamp output and high UVT - low lamp output. Each test condition is evaluated using five influent and five effluent samples.

Table C.8 Validation Test Conditions and Results for Example C.5.1

Test Conditions			Test Results				
Flow (gpm)	UVT (%)	Lamp (%)	UV Intensity (mW/cm^2)	Influent (log)	Effluent (log)	Inactivation (log)	RED (mJ/cm^2)
100	98	44	4.98	4.97 ± 0.08	< 0	> 4.97	> 105
100	84	100	4.90	5.02 ± 0.10	< 0	> 5.02	> 106
500	98	44	4.98	5.03 ± 0.06	4.02 ± 0.08	1.00	24.6
500	84	100	4.92	5.02 ± 0.10	3.52 ± 0.18	1.49	34.6

Note. Influent and effluent data presented as mean ± standard deviation.

Based on the results, the reactor is rated at an MS2 RED of 24.6 mJ/cm^2 for a flow range of 100 to 500 gpm and a sensor setpoint of 5 mW/cm^2.

A Tier 2 analysis was used to assess if the reactor achieved 2.5 log *Cryptosporidium*.

RED Bias. Since a 2.5 log inactivation of *Cryptosporidium* requires a dose of 8.5 mJ/cm^2, the UV sensitivity of *Cryptosporidium* is defined as 8.5/2.5 = 3.4 mJ/cm^2 per log inactivation. Since 1.00-log MS2 inactivation occurred with a dose of 24.6 mJ/cm^2, the UV sensitivity of MS2 is defined as 24.6 mJ/cm^2 per log inactivation. In Figure C.6, an RED of 9.2 and 21 mJ/cm^2 occurs with a UV sensitivity of 3.4 and 24.6 mJ/cm^2 per log inactivation, respectively. Accordingly, the RED bias is 21/9.2 = 2.28.

Polychromatic Bias. The polychromatic bias equals 1.0 because the UV reactor uses LPHO lamps.

Expanded uncertainty. A t-statistic of 1.53 is associated with 5 samples and an 80 percent confidence level. Using the standard deviations for the influent and effluent counts in Table C.8, the uncertainty of the log inactivation through the reactor is calculated as follows using Equation C.7:

$$\text{Error} = \frac{\left(\frac{(0.06 \times 1.53)^2}{5} + \frac{(0.08 \times 1.53)^2}{5}\right)^{1/2}}{1.00} * 100\% = 6.8\%$$

The uncertainty of the collimated beam dose calculation was determined to be 8.9 percent. At a UV dose of 24.6 mJ/cm^2, the uncertainty in the dose calculation based on the confidence bands in Figure C.13 is 9.6 percent.

The uncertainties of the sensors used during validation and at the WTP are as follows:

- Validation UV intensity sensor 5 percent
- WTP on-line UV intensity sensor 15 percent
- WTP reference UV intensity sensor 5 percent

The total uncertainty of the sensors is calculated according to the following equation:

$$\text{Error} = \left(5^2 + 15^2 + 5^2\right)^{1/2} = 16.6\%$$

The UV vendor states the standard deviation of the UV output from lamp to lamp is 25 percent. Given two banks of lamps and one UV intensity sensor per bank, the uncertainty of the lamp output is calculated as follows using Equation C.14:

$$\text{Error} = \frac{1.28 \times 25}{\sqrt{1}\sqrt{2}} = 22.6\%$$

Including each of these random uncertainty terms, the expanded uncertainty is calculated as follows:

$$\text{Error} = \left(6.8^2 + 8.9^2 + 9.6^2 + 16.6^2 + 22.6^2\right)^{1/2} = 31.7\%$$

Safety factor. Using Equation C.10, the safety factor is calculated as follows:

$$SF = (1 + 0.317) \times 2.28 \times 1.00 = 3.00$$

Based on this safety factor value and the *Cryptosporidium* dose target for 2.5-log inactivation credit, the MS2 RED demonstrated during validation should be as follows:

$$\text{MS2 RED} = 3.00 \times 8.5 = 25.5\ \text{mJ/cm}^2$$

Because the demonstrated RED of 24.6 mJ/cm^2 is less than this value, the reactor cannot get 2.5-log *Cryptosporidium* inactivation credit operating at a sensor setpoint of 15 mW/cm^2. However, with a 2.0-log *Cryptosporidium* credit target, the RED bias would be 2.6, resulting in a safety factor of 3.42 and an MS2 RED target of 19.8 mJ/cm^2. Because the demonstrated MS2 RED is greater than this value, the reactor can get 2.0 log *Cryptosporidium* credit operating at a setpoint of 15 mW/cm^2 over a flow range of 100 to 500 gpm.

The reactor does not meet Tier 1 criteria because the standard deviation of the UV output from lamp-to-lamp is greater than 15 percent. If the reactor did meet all Tier 1 criteria, the reactor would receive credit for 2.0-log *Cryptosporidium* based on a comparison of the demonstrated MS2 RED of 24.6 mJ/cm^2 with the dose criteria in Table C.3.

C.5.2 LP Reactor with a Intensity Setpoint Interpolation as a Function of Flow

A UV reactor consists of four banks of six LPHO lamps oriented perpendicular to the flow. Dose delivery is monitored using the UV intensity setpoint approach. Each bank is equipped with two UV intensity sensors.

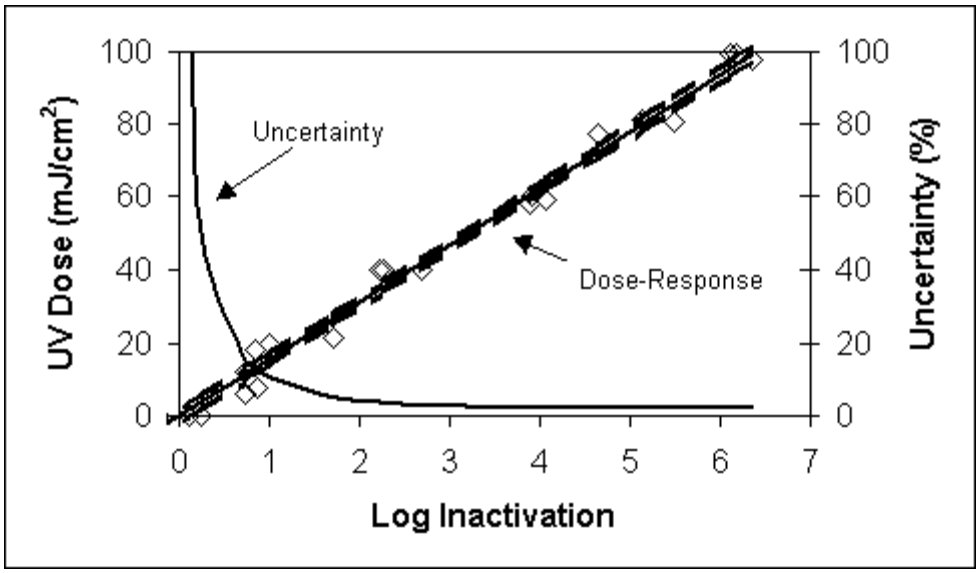
The UV reactor is rated by the manufacturer for flows ranging from 0.9 to 2.4 mgd. The manufacturer states that sensor setpoints of 6.0, 7.5, 10, and 14 mW/cm^2 should indicate a 3.0-log *Cryptosporidium* inactivation credit at flows of 0.9, 1.2, 1.7 and 2.4 mgd, respectively.

During operation at a WTP, the on-line and reference UV intensity sensors will have a measurement uncertainty of 15 and 5 percent respectively.

The reactor is validated using lignin sulphonate as the UV absorber and MS2 as the challenge microorganism. Figure C.14 gives the dose-response of the MS2 measured during validation with a collimated beam. The dose-response is fitted using the following equation:

$$\text{Dose} = 15.6 \times \log\left(\frac{N_0}{N}\right) - 0.144$$

Figure C.14 Dose-Response of the MS2 Challenge Microorganism Used in Example C.5.2



Confidence intervals are fitted to the data at an 80 percent level.

Table C.9 gives the validation test conditions and results. The reactor is tested at four flowrates, 0.9, 1.2, 1.7 and 2.4 mgd, with the lamp power and UVT adjusted to give a UV intensity sensor reading at the setpoint values. At each flowrate, the reactor is tested under conditions of reduced UVT - maximum lamp output and maximum UVT - reduced lamp output. A reference sensor with an uncertainty of 5 percent is used during validation to measure UV intensity. Each test condition is evaluated using five influent and five effluent samples.

Table C.9 Validation Test Conditions and Results for Example C.5.2

Test Conditions			Test Results					
Flow (mgd)	UVT (%)	Lamp (%)	UV Intensity (mW/cm^2)	Influent (Logs)	Effluent (Logs)	Inactivation		RED (mJ/cm^2)
						Log	Uncertainty (%)	
0.90	98	37	6.15	5.99 ± 0.096	2.95 ± 0.080	3.04	3.8	47.5
0.90	70	100	6.06	5.94 ± 0.127	3.21 ± 0.087	2.73	5.4	42.5
1.2	98	45	7.48	6.09 ± 0.100	2.98 ± 0.108	3.11	4.5	48.5
1.2	75	100	7.46	6.04 ± 0.070	3.34 ± 0.088	2.70	4.0	42.1
1.7	98	61	10.1	6.03 ± 0.150	3.27 ± 0.112	2.76	6.5	43.1
1.7	83	100	10.1	5.98 ± 0.116	3.45 ± 0.120	2.52	6.2	39.4
2.4	98	83	13.8	6.03 ± 0.102	3.37 ± 0.090	2.67	4.9	41.6
2.4	92	100	13.7	6.02 ± 0.136	3.37 ± 0.062	2.66	5.4	41.4

Table C.10 presents the MS2 RED and reactor setpoint assigned to each flowrate based on the validation results. A Tier 2 analysis was used to determine the *Cryptosporidium* inactivation credit that can be assigned to the reactor given the validation test results.

Table C.10 Summary of Validation Results for Example C.5.2

Flow (mgd)	UV Intensity Setpoint (mW/cm^2)	MS2 RED (mJ/cm^2)
0.90	6.06	42.5
1.2	7.46	42.1
1.7	10.1	39.4
2.4	13.7	41.4

RED Bias. Since a 3.0-log inactivation credit for *Cryptosporidium* requires a dose of 12 mJ/cm^2, the UV sensitivity of *Cryptosporidium* is defined as 12/3.0 = 4.0 mJ/cm^2 per log inactivation. The UV sensitivity of MS2 is 16 mJ/cm^2 per log inactivation 42.5/2.73 = 16 mJ/cm^2. In Figure C.6, an RED of 10 and 18 mJ/cm^2 is associated with a UV sensitivity of 4.0 and 16 mJ/cm^2 per log inactivation. Accordingly, the RED bias is 18/9.8 = 1.84.

Polychromatic Bias. The polychromatic bias equals 1.0 because the UV reactor uses LPHO lamps.

Expanded uncertainty. The uncertainty of the log inactivation through the reactor, calculated using Equation C.7, is tabulated in Table C.9. A mean value of 5.1 percent is used as the uncertainty of the log inactivation in this analysis. The uncertainty of the collimated beam dose calculation was determined as 8.9 percent. For an RED near 40 mJ/cm^2, the uncertainty in the RED arising from the scatter in the dose-response in Figure C.14 is 4 percent.

The uncertainties of the sensors used during validation and at the WTP are as follows:

- Validation UV intensity sensor 5 percent
- WTP On-line UV intensity sensor 10 percent
- WTP Reference UV intensity sensor 5 percent

The total uncertainty of the sensors is calculated as follows:

$$\text{Error} = \left(5^2 + 10^2 + 5^2\right)^{1/2} = 12.2\%$$

The UV vendor states the standard deviation of the UV output from lamp to lamp is 15 percent. Given four banks of lamps and two sensors per bank, the uncertainty associated with the number of sensors is calculated as follows using Equation C.14:

$$\text{Error} = \frac{1.28 \times 15}{\sqrt{2}\sqrt{4}} = 6.8\%$$

Including each of these random uncertainty terms, the expanded uncertainty is calculated as follows:

$$\text{Error} = \left(5.1^2 + 8.9^2 + 4^2 + 12.2^2 + 6.8^2\right)^{1/2} = 17.8\%$$

Safety Factor. Using Equation C.10, the safety factor is calculated as follows:

$$\text{SF} = (1 + 0.178) \times 1.84 \times 1.00 = 2.17$$

***Cryptosporidium* Credit.** Using this safety factor, the target RED that should be demonstrated during validation is 12 × 2.17 = 26 mJ/cm^2. Because the demonstrated RED of 39.4 mJ/cm^2 is greater than this number, the UV reactor operating at the validated intensity setpoints can get credit for 3.0-log *Cryptosporidium* inactivation.

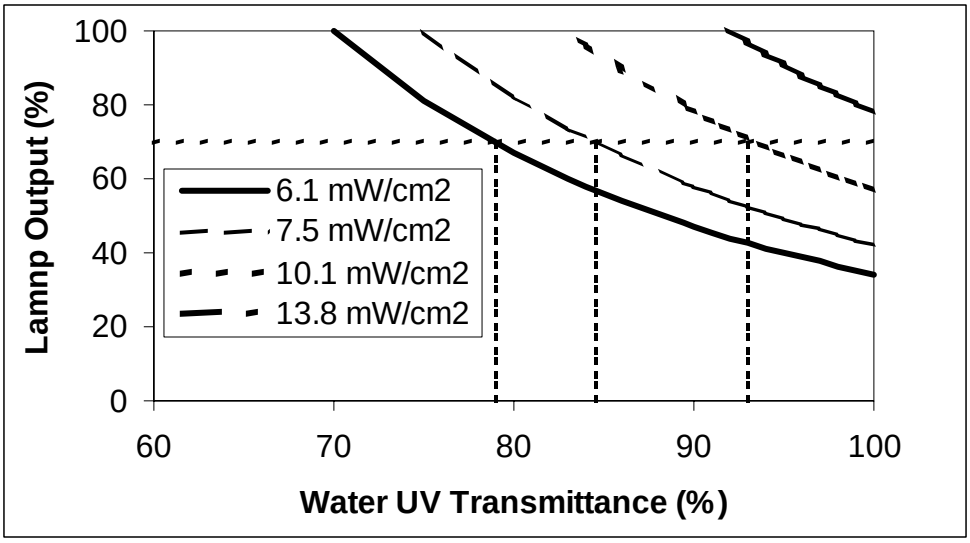
The validation results can be used to define three strategies for operating the UV reactor at a WTP:

1. The UV reactor can operate using one intensity setpoint over the full range of flowrates. In this case, a setpoint of 13.7 mW/cm^2 can be used to indicate a 3.0-log *Cryptosporidium* inactivation at all flows of 2.4 mgd or less.

2. The UV reactor can operate using multiple intensity setpoints where each setpoint functions over a given range of flows. In this case, a setpoint of 13.7 mW/cm^2 would be used at all flows from 1.7 to 2.4 mgd, a setpoint of 10.1 mW/cm^2 would be used at all flows from1.2 to 1.7 mgd, and a setpoint of 7.46 mW/cm^2 would be used at all flows from 0.90 to 1.2 mgd.

3. The UV reactor can be operated using intensity setpoints interpolated as a function of flowrate using the validation data. In this case, using the plot of sensor setpoint versus flowrate in Figure C.15, a setpoint value of 11.7 mW/cm^2 can be used at a flow of 2 mgd to indicate an MS2 RED of 39.4 mJ/cm^2 and hence a 3.0-log *Cryptosporidium* inactivation credit.

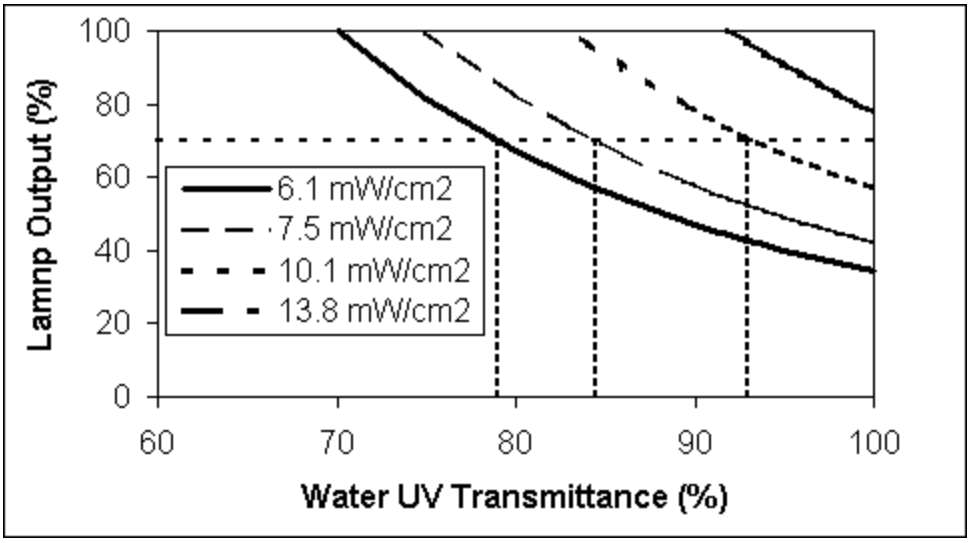
Figure C.15 Interpolation of Intensity Setpoint Values Indicating an MS2 Dose of 39.3 mJ/cm^2



The UV reactor and validation test conditions met all prerequisites to be considered under Tier 1. The Tier 1 requirement for 3.0-log inactivation of *Cryptosporidium* by a LPHO reactor is 36 mJ/cm^2. Since the RED demonstrated during validation is greater than this amount, the reactor can receive 3.0-log *Cryptosporidium* inactivation credit under Tier 1.

Validation data obtained in this example can be related to design criteria by plotting combinations of lamp output and water UVT that result in a given measured UV intensity setpoint value. For example, Figure C.16 plots combinations of lamp output and water UVT that result in the intensity setpoint values validated in Table C.9. Any combination of UVT and lamp output along that curve can be used as design criteria for each setpoint value shown. For example, a setpoint of 10.1 mW/cm^2 indicates 3.0-log *Cryptosporidium* inactivation at a flow of 1.7 mgd. A setpoint of 10.1 mW/cm^2 occurs with a combination of 70 percent lamp output and 93 percent UVT. Thus, the reactor could be used in a design application where the design flow, UVT, and lamp fouling/aging factor are 1.7 mgd, 93 percent, and 70 percent, respectively. The setpoint of 10.1 mW/cm^2 is also obtained with a combination of 80 percent lamp output and 89 percent UVT. Thus, the reactor could also be used in a design application where the design flow, UVT, and lamp fouling/aging factor is 1.7 mgd, 89 percent, and 80 percent, respectively.

Figure C.16 Combinations of Lamp Output and Water UV Transmittance that Result in Given Sensor Setpoint Values



C.5.3 LP Reactor with Intensity Setpoint Interpolation as a Function of Flow and Target Inactivation

A UV reactor consists of twelve rows of twelve LPHO lamps oriented perpendicular to flow. Dose delivery is monitored using the UV intensity setpoint approach. Each row is equipped with one UV intensity sensor.

The UV reactor is rated by the UV vendor for flows ranging from 5 to 20 mgd. During operation at a WTP, the on-line and reference UV intensity sensors will have a measurement uncertainty of 15 and 5 percent, respectively.

The UV manufacturer wants to validate the UV reactor using test conditions that allow interpolation of intensity setpoints as a function of flowrate and measured RED. Table C.11 gives the validation test conditions and results. To allow interpolation of sensor setpoints as a function of flowrate, the reactor is tested at a three flowrates of 5, 10, and 20 mgd. To allow interpolation of sensor setpoints as a function of dose delivery, the reactor is tested at each flowrate at setpoint values that the manufacturer states will result in MS2 RED values of 10, 20, and 30 mJ/cm^2. At each setpoint evaluated, the reactor is tested under conditions of reduced UVT - maximum lamp output and maximum UVT - reduced lamp output. Each test condition is evaluated using five influent and five effluent samples. A reference sensor with an uncertainty of 5 percent is used during validation to measure the UV intensity.

Table C.11 Validation Test Conditions and Results for Example C.5.3

Test Conditions			Test Results					
Flow (mgd)	UVT (%)	Lamp (%)	UV Intensity (mW/cm^2)	Influent (logs)	Effluent (logs)	Inactivation		RED (mJ/cm^2)
						log	Uncertainty (%)	
5	98	31	5.20	6.00 ± 0.074	1.86 ± 0.098	4.14	2.8	42.8
5	66	100	5.10	5.98 ± 0.136	2.68 ± 0.090	3.30	4.7	34.4
5	97.5	20	3.28	6.02 ± 0.088	3.23 ± 0.039	2.80	3.3	29.4
5	57	100	3.27	6.02 ± 0.129	3.87 ± 0.060	2.15	6.3	23.0
5	80	20	1.81	5.97 ± 0.075	4.55 ± 0.176	1.42	12.8	15.8
5	47	100	1.84	5.96 ± 0.118	4.84 ± 0.110	1.12	13.7	12.8
10	98	55	9.20	6.09 ± 0.141	2.31 ± 0.114	3.79	4.6	39.3
10	80	100	9.10	5.96 ± 0.076	2.66 ± 0.121	3.30	4.1	34.4
10	98	33	5.50	6.00 ± 0.068	3.74 ± 0.070	2.26	4.1	24.1
10	68	100	5.60	6.00 ± 0.130	4.04 ± 0.086	1.97	7.6	21.2
10	90.5	20	2.62	5.96 ± 0.066	4.91 ± 0.072	1.05	8.8	12.1
10	53	100	2.63	5.99 ± 0.135	4.92 ± 0.076	1.07	13.7	12.3
20	98	91	15.1	5.97 ± 0.080	2.93 ± 0.104	3.04	4.1	31.8
20	95	100	15.2	5.97 ± 0.117	2.97 ± 0.125	3.00	5.4	31.5
20	98	67	11.2	6.03 ± 0.117	3.62 ± 0.121	2.41	6.7	25.6
20	86	100	11.2	5.91 ± 0.079	3.82 ± 0.038	2.09	4.0	22.4
20	98	33	5.50	6.00 ± 0.167	4.91 ± 0.104	1.09	17.2	12.5
20	68	100	5.60	5.97 ± 0.032	4.89 ± 0.110	1.08	10.2	12.4

During validation, lignin sulphonate and MS2 are used as the UV absorber and challenge microorganism, respectively. Figure C.17 gives the dose-response of the MS2 measured during validation with a collimated beam apparatus. The dose-response is fitted using the following equation:

$$\text{Dose} = 9.91 \times \log\left(\frac{N_0}{N}\right) + 1.70$$

Confidence intervals are fitted to the data at an 80 percent level.

Table C.12 presents the MS2 RED assigned to each reactor setpoint based on the validation results. For a given flowrate, Figure C.18 presents the measured RED interpolated as a function of measured UV intensity.

Figure C.17 Dose-Response of the MS2 Challenge Microorganism Used in Example C.5.3

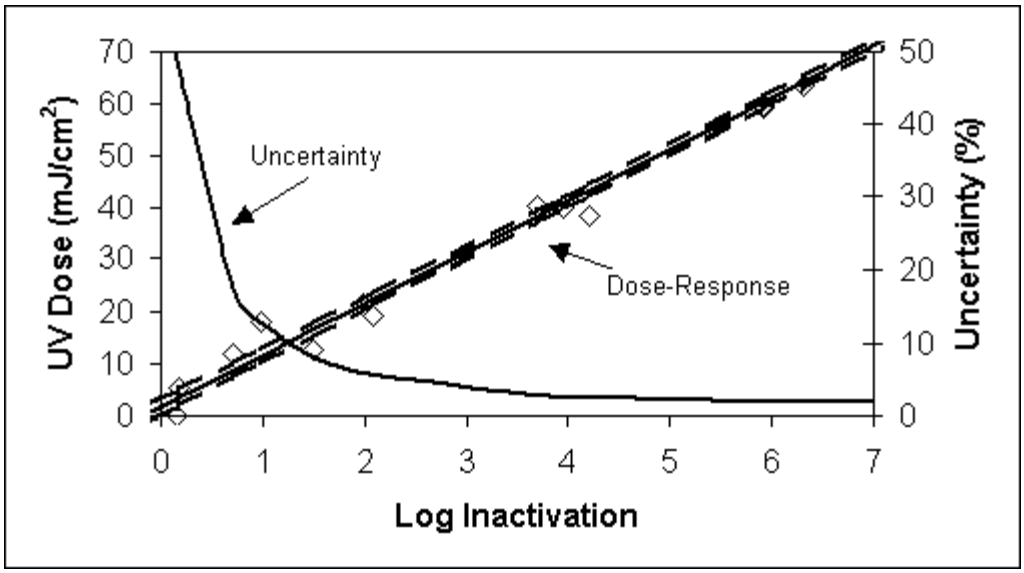


Table C.12 Summary of Validation Results for Example C.5.3

Flow (mgd)	UV Intensity (mW/cm^2)	MS2 RED (mJ/cm^2)
5	5.10	34.4
5	3.27	23.0
5	1.84	12.8
10	9.10	34.4
10	5.60	21.2
10	2.63	12.3
20	15.2	31.5
20	11.2	22.4
20	5.60	12.4

A Tier 2 analysis was used to determine the *Cryptosporidium* inactivation credit that can be assigned to the UV reactor given the validation test results. Because the validation results will be interpolated as a function of dose delivery, the Tier 2 safety factors are determined as a function of measured RED. For 1.5, 2.0, 2.5, and 3.0 log *Cryptosporidium* inactivation, Table C.13 presents the RED bias as a function of the measured RED. RED bias values were determined using the approach cited in section C.4.10.2. The polychromatic bias equals 1.0 because the UV reactor uses LPHO lamps.

Table C.13 RED Bias as a Function of the Target Pathogen Target Inactivation and the Demonstrated RED in Example C.5.3

Demonstrated RED (mJ/cm^2)	Challenge Microorganism UV Sensitivity (mJ/cm^2 per log)	RED Bias for a *Cryptosporidium* log Inactivation of			
		1.5 log	2.0 log	2.5 log	3.0 log
12	11.6	1.98	1.89	1.76	1.65
16	11.3	1.96	1.87	1.74	1.63
20	11.1	1.95	1.86	1.73	1.62
24	11.0	1.94	1.85	1.72	1.61
28	10.8	1.93	1.84	1.71	1.61
32	10.8	1.93	1.84	1.71	1.60
36	10.7	1.92	1.83	1.70	1.60

Figure C.18 Measured RED as a Function of Sensor Setpoint Values for Given Flowrates

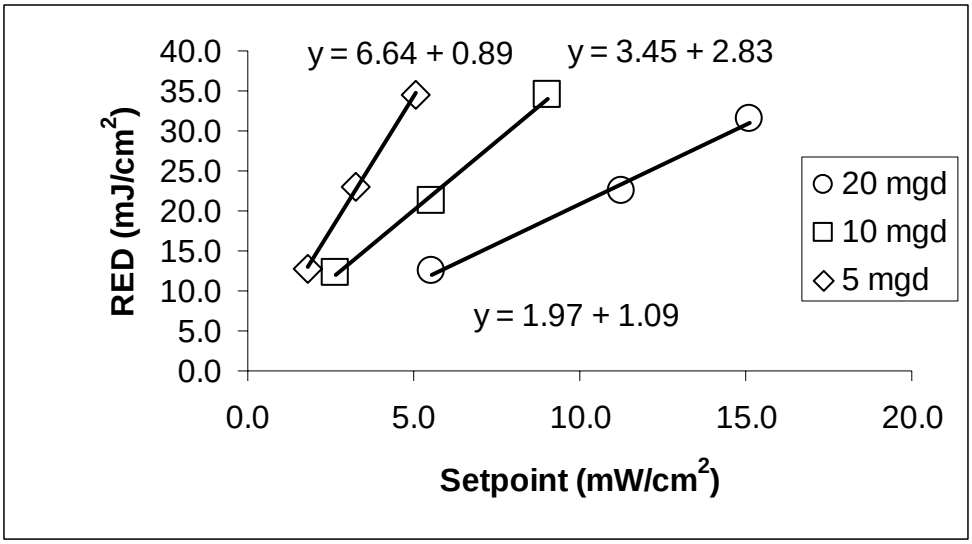


Table C.14 presents the random uncertainty terms and the expanded uncertainty as a function of the demonstrated RED. Using data from Table C.11, Figure C.19 presents the uncertainty of the log inactivation as a function of the demonstrated RED. An empirical fit to this data was used to obtain the uncertainty of the log inactivation as a function of demonstrated RED in Table C.14. The uncertainty of the RED due to the dose-response data was obtained from Figure C.17. The uncertainty of the collimated beam dose calculation was 8.9 percent. The uncertainties of the sensors used during validation and at the WTP are as follows:

- Validation UV intensity sensor 5 percent
- WTP On-line UV intensity sensor 15 percent
- WTP Reference UV intensity sensor 5 percent

The total uncertainty of the sensors is calculated as follows:

$$\text{Error} = \left(5^2 + 15^2 + 5^2\right)^{1/2} = 16.6\%$$

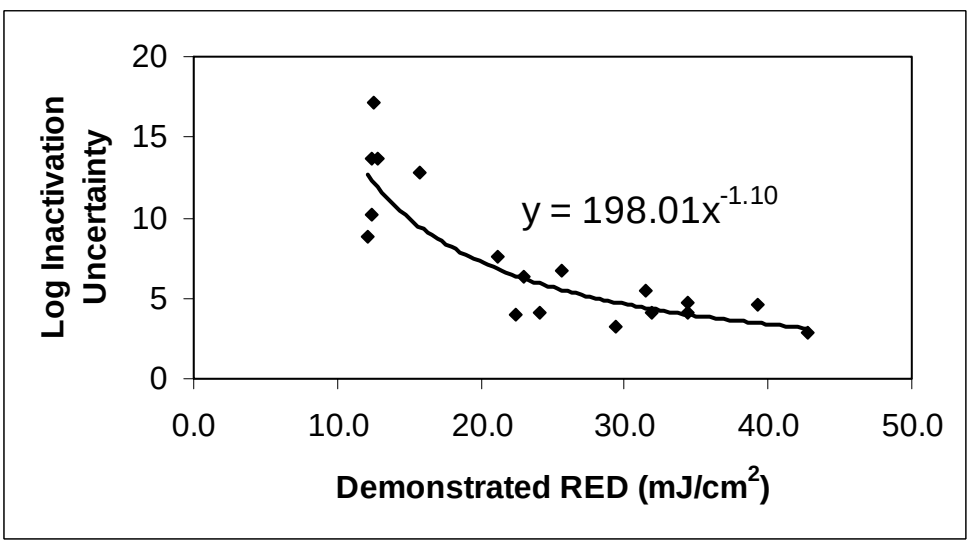
The UV vendor states the standard deviation of the UV output from lamp to lamp is 25 percent. Given four rows of lamps and two sensors per row, the uncertainty associated with the number of sensors is calculated as follows:

$$\text{Error} = \frac{1.28 \times 25}{\sqrt{1}\sqrt{12}} = 9.2\%$$

Table C.14 Random Uncertainty Terms as a Function of the Demonstrated RED for Example C.5.3

Demonstrated RED (mJ/cm^2)	Uncertainty (%)					
	Challenge Microorganism Log Inactivation	Challenge Microorganism Dose-response	Collimated Beam Dose Calculation	Intensity and Flow Sensors	Number of Sensors	Total Expanded Uncertainty
12	12.4	11.7	8.9	16.6	9.2	27.0
14	10.5	9.7	8.9	16.6	9.2	25.3
16	9.1	8.2	8.9	16.6	9.2	24.3
18	8.0	7.1	8.9	16.6	9.2	23.5
20	7.1	6.3	8.9	16.6	9.2	23.0
22	6.4	5.6	8.9	16.6	9.2	22.6
24	5.9	5.1	8.9	16.6	9.2	22.3

Figure C.19 Uncertainty of the Measured Log Inactivation as a Function of Demonstrated RED



Safety factors calculated from the RED bias, polychromatic bias, and expanded uncertainty are tabulated in Table C.15. The safety factors were multiplied by the dose requirements for *Cryptosporidium* to obtain target RED values which are tabulated in Table C.16. For a given demonstrated RED, the UV reactor can achieve a given level of *Cryptosporidium* credit if the demonstrated RED is greater than the target RED. Interpolation of these data can be used to identify the RED required to obtain a given level of *Cryptosporidium* inactivation. Using this approach, an RED of 14.0, 19.1, and 25 mJ/cm^2 is required to show 2.0, 2.5, and 3.0-log *Cryptosporidium* inactivation, respectively.

For each flowrate validated, interpolation of the data in Figure C.18 will provide the UV intensity setpoints that will indicate an RED of 14.0, 19.1, and 25 mJ/cm^2. For a given RED, Figure C.20 presents those intensity setpoints as a function of flowrate. Interpolation of the data in Figure C.20 can be used to identify the intensity setpoint required at a given flowrate. For example, at a flowrate of 15 mgd, intensity setpoints of 4.7, 6.7, and 9.0 mW/cm^2 can be used to indicate *Cryptosporidium* log inactivation of 2.0, 2.5, and 3.0.

Intensity setpoints obtained from Figure C.20 for a given design flow can be related to design values of water UVT and lamp output using an approach similar to that used in section C.5.2 (see Figure C.16).

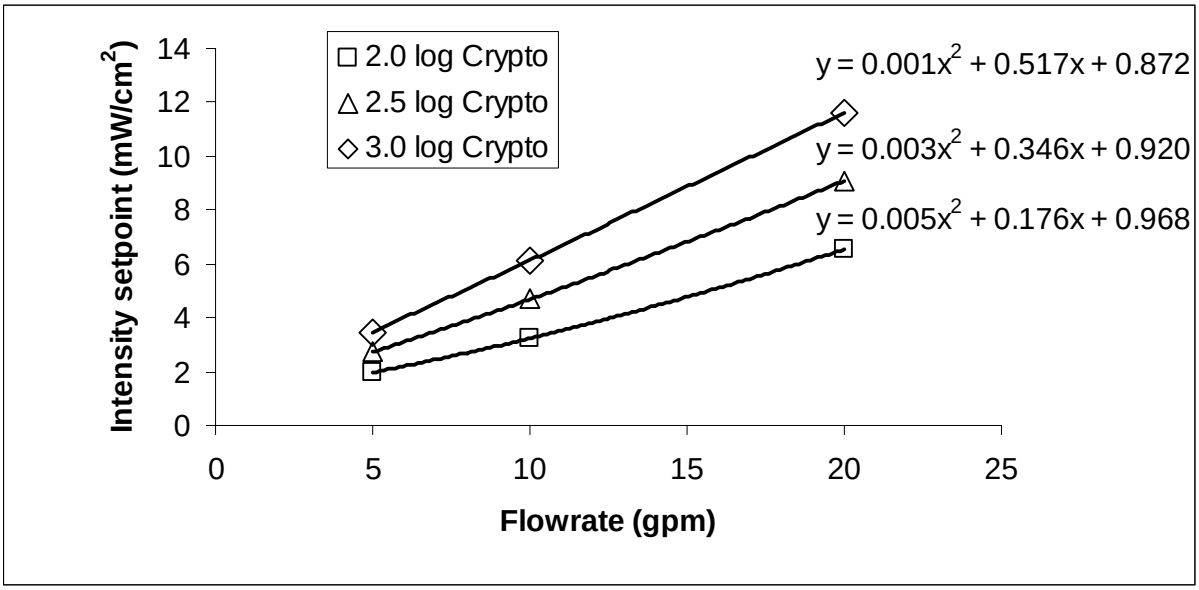
Table C.15 Safety Factors Applicable to Validation Results

Demonstrated RED (mJ/cm^2)	Safety Factors Needed Given a *Cryptosporidium* Inactivation of			
	1.5 log	2.0 log	2.5 log	3.0 log
12	2.54	2.42	2.25	2.11
14	2.48	2.37	2.20	2.06
16	2.44	2.33	2.17	2.03
18	2.42	2.30	2.14	2.01
20	2.40	2.28	2.13	1.99
22	2.38	2.27	2.11	1.98
24	2.37	2.26	2.10	1.97

Table C.16 Comparison of Demonstrated RED and RED Required for Various Log Inactivation of *Cryptosporidium* for Example C.5.3

Demonstrated RED (mJ/cm^2)	RED Needed to Achieve a *Cryptosporidium* Inactivation of			
	1.5 log	2.0 log	2.5 log	3.0 log
12	9.9	14.0	19.1	25
14	9.7	13.7	18.7	25
16	9.5	13.5	18.4	24
18	9.4	13.3	18.2	24
20	9.4	13.2	18.1	24
22	9.3	13.2	17.9	24
24	9.2	13.1	17.9	24

Figure C.20 Intensity Setpoint Values Indicating Various Log Inactivation of *Cryptosporidium* for example C.5.2



C.5.4 MP Reactor Using a Single UV Intensity Setpoint and UV Transmittance Setpoint

A UV reactor consists of two MP lamps oriented parallel to the flow. Each lamp is monitored by a UV intensity sensor. Lamps are spaced 40 cm apart and 20 cm from the wall. The lamp sleeve radius is 5 cm. The sensor is located on the wall, 20 cm away from the lamp. The sensor's spectral response matches that of "Sensor A" in Figure C.10. Dose delivery is indicated using the UV intensity and UVT setpoint approach.

The reactor is rated for a flow from 0.1 to 0.5 mgd. The reactor will be used with a design UVT of 85 percent. The manufacturer states that the lamp output at the end-of-lamp life will be 78 percent of the 100 hr burn-in value. The fouling factor for the reactor is 90 percent. Accordingly, the lamp output factor for the reactor is $0.78 \times 0.90 = 0.70$. A UV intensity setpoint of 2.8 mW/cm^2 is obtained by measuring the UV intensity with the water UVT set to 85 percent and the lamp output lowered to 70 percent.

During operation at a WTP, the on-line and reference UV intensity sensors will have a measurement uncertainty of 10 and 5 percent, respectively.

The UV reactor is validated using lignin sulphonate as a UV absorber and MS2 as a challenge microorganism. The measured dose-response of the challenge microorganism is provided in Figure C.14. Table C.17 gives the validation test conditions and results.

Table C.17 Validation Test Conditions and Results for Example C.5.4 with the Sensor Located 20 cm from the Lamp

Test Conditions			Test results					
Flow (mgd)	UVT (%)	Lamp (%)	UV Intensity (mW/cm^2)	Influent (Logs)	Effluent (logs)	Inactivation		RED (mJ/cm^2)
						Log	Uncertainty (%)	
0.1	85	70	2.9	6.00 ± 0.07	0.00	>6.00	-	> 82.6
0.5	85	70	2.9	6.06 ± 0.08	3.04 ± 0.16	3.03	5.6	47.1
0.5	82.7	100	2.8	5.99 ± 0.11	2.13 ± 0.14	3.85	4.3	60.0
0.5	93.5	20	2.9	6.12 ± 0.11	4.52 ± 0.07	1.60	7.6	24.8

The first two test conditions evaluate dose delivery at minimum and maximum flow with the reactor operating at the intensity and UVT setpoint values. Based on these results, the UV reactor is rated at an MS2 RED of 47.1 mJ/cm^2 when operating at the setpoint conditions.

The last two test conditions evaluate the sensor position and the validity of using the UV intensity and UVT setpoint approach for indicating dose delivery. As indicated, the UV reactor delivers an MS2 RED of 60.0 mJ/cm^2 when operating with peak lamp output and the UVT lowered to 82.7 percent to give a measured intensity at the setpoint. The UV reactor delivers a dose of 24.8 mJ/cm^2 when operating at high UVT and lowered lamp output to give a measured intensity at the setpoint value. In other words, an intensity setpoint of 2.9 mW/cm^2 and a UVT setpoint of 85 percent does not ensure the reactor delivers an MS2 RED of 47.1 mJ/cm^2.

The manufacturer has three options for resolving this problem:

- Relocate the sensor closer to the lamp.
- Switch from the dose monitoring method to the calculated dose approach.
- Switch from the dose monitoring method to the intensity setpoint approach either with the sensor in its current location or with the sensor in a more optimized location.

In this example, the manufacturer chooses to relocate the sensor to 8 cm from the lamp and revalidates the UV reactor. Table C.18 gives the test conditions and results. In this case, a UV intensity of 41.0 mW/cm^2 is measured with the UV reactor operating with a UVT of 85 percent and a lamp output of 70 percent. This value is greater than the UV intensity measured with the sensor on the wall because the sensor is located closer to the lamp. Based on the results, the UV reactor is rated at an MS2 RED of 48.5 mJ/cm^2 when operating at setpoint conditions of 85 percent UVT and a 41.0 mW/cm^2 UV intensity value. With the measured intensity at the intensity setpoint value, the UV reactor delivers an RED greater than 48.5 mJ/cm^2 when operating with a UVT greater than the UVT setpoint value and an RED less than 48.5 mJ/cm^2 when operating with a UVT less than the setpoint value. Thus, the intensity sensor is properly located for using the intensity and UVT setpoint approach for indicating dose delivery and the setpoints will ensure the dose delivery meets an RED of 48.5 mJ/cm^2.

Table C.18 Validation Test Conditions and Results for Example C.5.4 with the Sensor Located 12 cm from the Lamp

Test Conditions			Test Results					
Flow (mgd)	UVT (%)	Lamp (%)	UV Intensity (mW/cm^2)	Influent (Logs)	Effluent (Logs)	Inactivation		RED (mJ/cm^2)
						Log	Uncertainty (%)	
0.1	85	70	41.0	6.00 ± 0.07	0.00	> 6.00	-	> 82.6
0.5	85	70	41.0	6.01 ± 0.10	2.90 ± 0.10	3.12	4.3	48.5
0.5	75	100	41.4	6.03 ± 0.07	3.26 ± 0.18	2.77	6.7	43.0
0.5	98	46	41.1	5.96 ± 0.12	1.59 ± 0.12	4.37	3.7	68.1

A Tier 2 analysis is used to determine the *Cryptosporidium* inactivation credit that can be assigned to the UV reactor given the validation test results.

RED Bias. Since a 3.0 log inactivation of *Cryptosporidium* requires a dose of 12 mJ/cm^2, the UV sensitivity of *Cryptosporidium* is defined as 12/3.0 = 4 mJ/cm^2 per log inactivation. The UV sensitivity of MS2 is 48.5/3.12 = 15.5 mJ/cm^2. In Figure C.6, a RED of 9.78 and 18.0 mJ/cm^2 is associated with UV sensitivities of 4 and 15.5 mJ/cm^2 per log inactivation, respectively. Accordingly, the RED bias is 18.0/9.78 = 1.84.

Polychromatic Bias. The sensor-to-lamp water layer is 3 cm. For a sensor with the response of "Sensor A" in Figure C.10, a polychromatic bias 1.00 is obtained from Figure C.7 for a UVT of 85 percent.

Expanded uncertainty. The uncertainty of the log inactivation through the UV reactor calculated using Equation C.7 is 4.3 percent. The uncertainty of the collimated beam dose calculation was 8.9 percent. The uncertainty in the RED arising from the scatter in the dose-response obtained from Figure C.14 is 3.9 percent at an RED of 48.5 mJ/cm^2. The uncertainties of the sensors used during validation and at the WTP are as follows:

- Validation UV intensity sensor 5 percent
- WTP On-line UV intensity sensor 10 percent
- WTP Reference UV intensity sensor 5 percent

The total uncertainty of the sensors is calculated as follows:

$$\text{Error} = \left(5^2 + 10^2 + 5^2\right)^{1/2} = 12.2\%$$

Because each lamp is monitored, the uncertainty knowing the output of the lamps is 0 percent. Including each of these random uncertainty terms, the expanded uncertainty is calculated as follows:

$$\text{Error} = \left(4.3^2 + 8.9^2 + 3.9^2 + 12.2^2 + 0^2\right)^{1/2} = 16.2\%$$

Safety factor. Using Equation C.10, the safety factor is calculated as follows:

$$SF = (1 + 0.162) \times 1.84 \times 1.00 = 2.14$$

***Cryptosporidium* Credit.** Using this safety factor, the target RED that should be demonstrated during validation is 12 × 2.14 = 26 mJ/cm^2. Because the demonstrated RED is greater than this number, the UV reactor operating at or above the validated intensity and UVT setpoints can get credit for 3.0-log *Cryptosporidium* inactivation.

C.5.5 MP Reactor Using Calculated Dose Monitoring

A UV reactor consists of twelve MP lamps oriented perpendicular to the flow. Each lamp is monitored by a UV intensity sensor whose spectral response matches that of "Sensor A" in Figure C.10. The UV intensity sensors view the UV lamps through a 15 cm water layer. During operation at a WTP, the on-line and reference UV intensity sensors will have a measurement uncertainty of 10 and 5 percent respectively. During validation, a reference sensor is used to measure UV intensity.

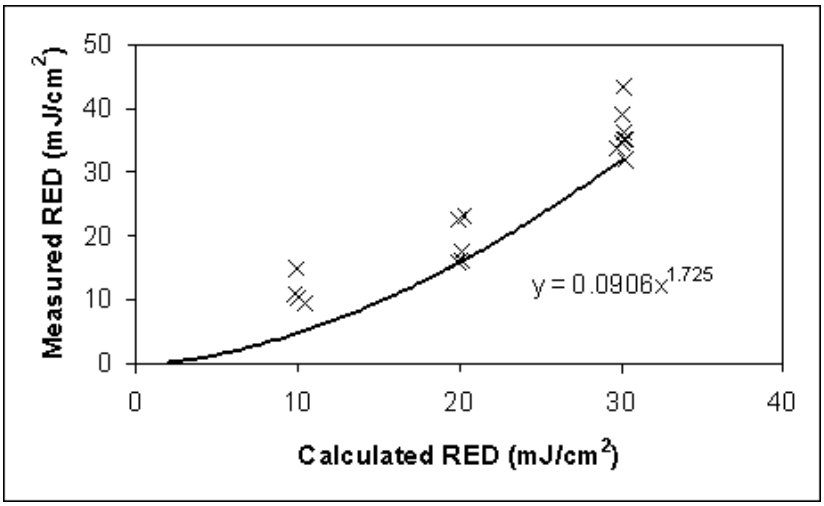
The UV reactor is validated at flows ranging from 10 to 40 mgd using lignin sulphonate as a UV absorber and MS2 as a challenge microorganism. Figure C.3 gives the dose-response of the challenge microorganism. The lamp's power supplies vary lamp power from 30 to 100 percent. The UV reactor is validated at flowrate, UVT, and lamp power combinations that give a calculated UV doses of 30, 20 and 10 mJ/cm^2. Table C.19 gives the validation test conditions and results.

Table C.19 Validation Test Conditions and Results for Example C.5.5

Test Conditions			Test Results				
					Inactivation		
Flow (mgd)	UVT (%)	Lamp (%)	Calculated RED (mJ/cm^2)	Intensity (mW/m^2)	Log	Uncertainty (%)	Measured RED (mJ/cm^2)
40	98	40.5	30.1	22.7	2.38	3.0	35.2
40	90	68	30.2	11.8	2.43	3.2	36.3
40	82.8	100	30.2	5.8	2.38	4.2	35.1
20	90	33.8	30.0	5.9	2.57	3.0	39.1
20	85	44.5	30.1	3.6	2.36	3.6	34.7
20	75	70	29.7	1.2	2.31	3.5	33.8
10	79	30	30.3	1.0	2.22	4.8	32.0
10	75	35.5	30.1	0.6	2.76	2.9	43.3
40	96.5	30	20.1	13.5	1.42	4.0	17.7
40	85	59.5	20.1	4.9	1.34	6.2	16.3
40	73.5	100	19.9	1.3	1.31	7.3	15.9
20	85	30	20.3	2.5	1.75	4.0	23.1
20	75	47	19.9	0.8	1.72	2.9	22.7
40	84.5	30	9.9	2.3	0.96	6.5	10.8
40	75	47	10.0	0.8	1.24	8.1	14.9
40	80	38	10.1	1.4	0.93	7.8	10.4
20	70	30	10.4	0.2	0.86	10.4	9.5

Figure C.21 provides a plot of the measured RED as a function of the calculated RED. As shown, there is a range of measured RED values associated with a given calculated RED. The UV reactor is rated at the lower end of that range for a given calculated dose. A power function ($y=Ax^B$) is used to define the relationship between the calculated RED and the lower bound of the measured RED.

Figure C.21 Relationship Between Measured and Calculated Dose for the MP Reactor in Example C.5.5



A Tier 2 analysis was used to determine the calculated RED values required for 3.0-log credit for *Cryptosporidium*. For various log inactivation credit values for *Cryptosporidium*, Table C.20 gives the RED bias as a function of the MS2 RED predicted from the calculated dose using the power function in Figure 21.

Table C.20 RED Bias as a Function of the Target Pathogen Target Inactivation and the Calculated Dose in Example C.5.5

Calculated Dose (mJ/cm^2)	MS2 RED (mJ/cm^2)	MS2 Log Inactivation	MS2 Sensitivity (mJ/cm^2 per log inactivation)	RED Bias for *Cryptosporidium* log inactivations of				
				3.0 log	2.5 log	2.0 log	1.5 log	1.0 log
10	4.8	0.43	11.2	1.61	1.73	1.86	1.95	1.99
12	6.6	0.58	11.3	1.62	1.74	1.87	1.97	2.00
14	8.6	0.75	11.5	1.63	1.76	1.89	1.98	2.01
16	10.8	0.92	11.7	1.64	1.77	1.90	1.99	2.03
18	13.3	1.11	11.9	1.65	1.78	1.92	2.01	2.04
20	15.9	1.30	12.2	1.67	1.80	1.93	2.03	2.06
22	18.7	1.50	12.5	1.68	1.82	1.95	2.05	2.08
24	21.8	1.69	12.9	1.70	1.84	1.97	2.07	2.11
26	25.0	1.88	13.3	1.72	1.86	2.00	2.10	2.13
28	28.4	2.07	13.7	1.74	1.88	2.02	2.12	2.16
30	32.0	2.25	14.2	1.77	1.91	2.05	2.15	2.19

Table C.21 gives the random uncertainty terms and the resulting total expanded uncertainty as a function of the MS2 RED and calculated dose. Using data from Table C.19, Figure C.22 presents the uncertainty of the log inactivation as a function of measured MS2. An empirical fit to this data was used to predict the uncertainty of the log inactivation as a function of MS2 RED in Table C.21. The uncertainty of the RED due to the dose-response data was obtained from Figure C.3. The uncertainty of the collimated beam dose calculation was 8.0 percent. The uncertainties of the sensors used during validation and at the WTP are as follows:

- Validation UV intensity sensor 5 percent
- WTP On-line UV intensity sensor 10 percent
- WTP Reference UV intensity sensor 5 percent

The total uncertainty of the sensors is calculated as follows:

$$\text{Error} = \left(5^2 + 10^2 + 5^2\right)^{1/2} = 12.2\%$$

Because each lamp is monitored by a UV intensity sensor, the uncertainty associated with quantifying lamp output is zero.

Table C.21 Random Uncertainty Terms as a Function of the Calculated Dose for Example C.5.5

Calculated Dose (mJ/cm^2)	MS2 RED (mJ/cm^2)	Uncertainty (%)				
		Challenge Microorganism Log Inactivation	Challenge Microorganism Dose-response	Collimated Beam Dose Calc	Intensity Sensors	Total Expanded Uncertainty
10	4.8	13.9	1.9	8.0	12.2	20.3
12	6.6	11.1	1.3	8.0	12.2	18.4
14	8.6	9.2	0.9	8.0	12.2	17.3
16	10.8	7.8	0.7	8.0	12.2	16.6
18	13.3	6.8	0.5	8.0	12.2	16.1
20	15.9	5.9	0.4	8.0	12.2	15.8
22	18.7	5.3	0.3	8.0	12.2	15.6
24	21.8	4.8	0.3	8.0	12.2	15.4
26	25.0	4.3	0.2	8.0	12.2	15.3
28	28.4	3.9	0.2	8.0	12.2	15.1
30	32.0	3.6	0.2	8.0	12.2	15.1

Table C.22 gives the polychromatic bias as a function of the UVT. The polychromatic bias values were taken from Figure C.7 for sensor "A" located with a 15 cm water layer and lignin sulphonate as the UV-absorbing chemical.

Figure C.22 Uncertainty of the Measured Log Inactivation as a Function of Demonstrated RED

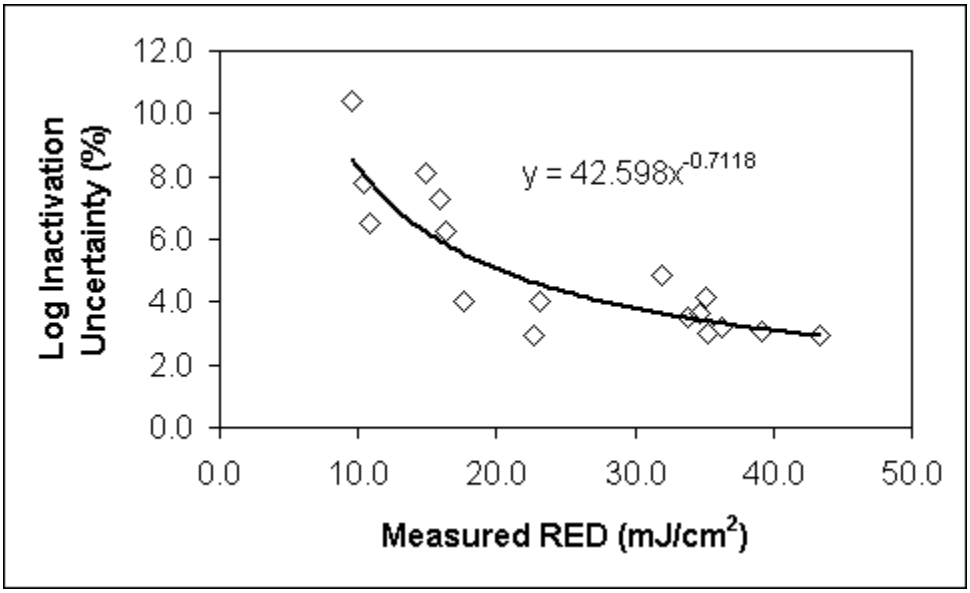


Table C.22 Polychromatic Bias for Example C.5.5

UVT (%)	Polychromatic Bias
98	1.03
95	1.06
90	1.10
85	1.20
80	1.30
75	1.55

Safety factors calculated from the RED bias, polychromatic bias, and expanded uncertainty are tabulated in Table C.23. The safety factors were multiplied by the 3.0-log dose requirement for *Cryptosporidium* of 12 mJ/cm^2 to obtain target RED values which are tabulated in Table C.24. For a given calculated dose, the UV reactor can achieve receive 3.0-log *Cryptosporidium* credit if the measured MS2 RED associated with that calculated dose is greater than the target RED.

Table C.25 presents the calculated dose needed to achieve a given level of *Cryptosporidium* inactivation and the lower limit of UVT over which the calculated dose applies. The values in Table C.22 for 3.0-log inactivation credit were obtained from Table C.21. The values for other log inactivation credit levels were obtained by repeating the analysis in Tables C.23 and C.24.

Table C.23 Safety Factors for 3-Log *Cryptosporidium* Inactivation as a Function of the Calculated Dose for Example C.5.5

Calculated Dose (mJ/cm^2)	MS2 RED (mJ/cm^2)	Safety Factors for 3.0-log *Cryptosporidium* Inactivation for UVT of					
		98%	95%	90%	85%	80%	75%
10	4.8	1.99	2.05	2.13	2.32	2.51	3.00
12	6.6	1.97	2.03	2.10	2.30	2.49	2.97
14	8.6	1.97	2.02	2.10	2.29	2.48	2.96
16	10.8	1.97	2.03	2.10	2.29	2.48	2.96
18	13.3	1.98	2.03	2.11	2.30	2.49	2.97
20	15.9	1.99	2.05	2.12	2.32	2.51	2.99
22	18.7	2.00	2.06	2.14	2.34	2.53	3.02
24	21.8	2.02	2.08	2.16	2.36	2.55	3.04
26	25.0	2.04	2.10	2.18	2.38	2.58	3.08
28	28.4	2.07	2.13	2.21	2.41	2.61	3.11
30	32.0	2.09	2.16	2.24	2.44	2.64	3.15

Table C.24 Comparison of the Target MS2 RED Needed to Demonstrate 3.0-Log *Cryptosporidium* Inactivation Credit to the Calculated Dose and Measured MS2 RED

Calculated Dose (mJ/cm^2)	MS2 RED (mJ/cm^2)	Target MS2 RED (mJ/cm^2)					
		98%	95%	90%	85%	80%	75%
10	4.8	23.9	24.6	25.5	27.8	30.1	35.9
12	6.6	23.7	24.3	25.3	27.6	29.9	35.6
14	8.6	23.6	24.3	25.2	27.5	29.8	35.5
16	10.8	23.6	24.3	25.2	27.5	29.8	35.5
18	13.3	23.7	24.4	25.3	27.6	29.9	35.7
20	15.9	23.9	24.6	25.5	27.8	30.1	35.9
22	18.7	24.1	24.8	25.7	28.0	30.4	36.2
24	21.8	24.3	25.0	25.9	28.3	30.6	36.5
26	25.0	24.5	25.2	26.2	28.6	31.0	36.9
28	28.4	24.8	25.5	26.5	28.9	31.3	37.3
30	32.0	25.1	25.9	26.8	29.3	31.7	37.8

Table C.25 Dose and UVT Alarm Setpoints for Various Log Inactivation Credit Levels of *Cryptosporidium*

3.0 log		2.5 log		2.0 log		1.5 log		1.0 log	
Dose (mJ/cm^2)	UVT (%)	Dose (mJ/cm^2)	UVT (%)	Dose (mJ/cm^2)	UVT (%)	Dose (mJ/cm^2)	UVT (%)	Dose (mJ/cm^2)	UVT (%)
25	98.0	22	94.7	19	88.8	15	93.0	12	89.6
26	95.6	23	88.5	20	83.2	16	84.7	13	80.9
27	90.4	24	83.9	21	79.4	17	79.5	14	76.3
28	85.9	25	80.5	22	76.8	18	76.3	15	77.5
29	82.2	26	78.1	23	75.1	-	-	-	-
30	79.2	27	76.3	-	-	-	-	-	-
-	-	28	75.0	-	-	-	-	-	-

The data in Table C.25 represents calculated dose and UVT alarm setpoints that can be used to ensure the reactor delivers a given log inactivation of *Cryptosporidium*. Alternatively, as shown in Table C.26, a single calculated dose alarm setpoint can be defined over the validated range of UVT.

Table C.26 Dose Setpoints for Various Log Inactivation Credit Levels of *Cryptosporidium*

Cryptosporidium Log Inactivation Credit	Calculated Dose Setpoint (mJ/cm^2)	UVT Range (%)
1.0	14	75 - 98
1.5	18	75 - 98
2.0	23	75 - 98
2.5	28	75 - 98
3.0	30	79 - 98

C.6 References

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Appendix D. Microbiological Methods

D.1 General Recommendations

The challenge microorganism used to validate UV reactors should be cultured and analyzed by a laboratory staffed by professional microbiologists and equipped to perform microbiological examinations as per Standard Methods for the Examination of Water and Wastewater (APHA et al. 1998, sections 1020-1050). Protocols for culturing the challenge microorganism and measuring its concentration should be based on published and peer-reviewed methods and should be clearly defined and followed. Measurement of the concentration of the challenge microorganism before and after exposure to UV light should be initiated within 24 hours of exposure. If the challenge microorganism has the ability to photorepair, exposure of samples to visible light should be kept to a minimum.

Because MS2 bacteriophage (MS2) and *B. subtilis* spores are commonly being used as challenge microorganisms for UV reactor validation, the following sections describe procedures that can be used for preparing stock solutions of MS2 and *B. subtilis* spores and assaying the concentration of those microorganisms in water samples. Procedures for preparing stock solutions can be scaled to provide the volumes needed for UV reactor validation. Alternative procedures and challenge microorganisms can be used if they are acceptable to the State. Section F.1 provides a rational for selecting challenge microorganisms.

D.2 MS2 Bacteriophage Stock Preparation

MS2 (ATCC 15597-B1) can be propagated using a variety of host bacteria including *Escherichia coli* C3000 (ATCC 15597), *E. coli* F-amp (ATCC 700891), and others (Meng and Gerba 1996, Oppenheimer et al. 1993, NWRI/AwwaRF 2000). The following propagation method was adapted from NWRI/AwwaRF (2000):

1. Inoculate sterile tryptic soy broth (TSB) (DIFCO, Detroit, Michigan) with host bacterium transferred from a single colony grown on a nutrient agar plate. Incubate the culture with constant stirring at 35 to 37°C for 18 to 24 hours.

2. Transfer 0.5 mL of the host bacterium culture to 50 mL of fresh TSB and incubate at 35 to 37°C for 4 to 6 hours with continuous shaking at 100 Hz to obtain a culture in its log growth phase (approx. $3x10^8$ cfu/mL) (cfu = colony forming units).

3. Dilute stock MS2 using Tris-buffered saline (pH 7.3) to a concentration of approximately 10^8 pfu/mL (pfu = plaque forming units).

4. Add 1mL of diluted MS2 stock solution to the 50 mL volume of *E. coli* in TSB and incubate overnight at 35 to 37°C.

5. Centrifuge the MS2/*E. coli* culture at 8000 × g (g = 9.82 m/s^2) for 10 minutes at 4°C to remove cellular debris.

6. Filter the supernatant by passing it through a 0.45 μm low protein-binding filter.

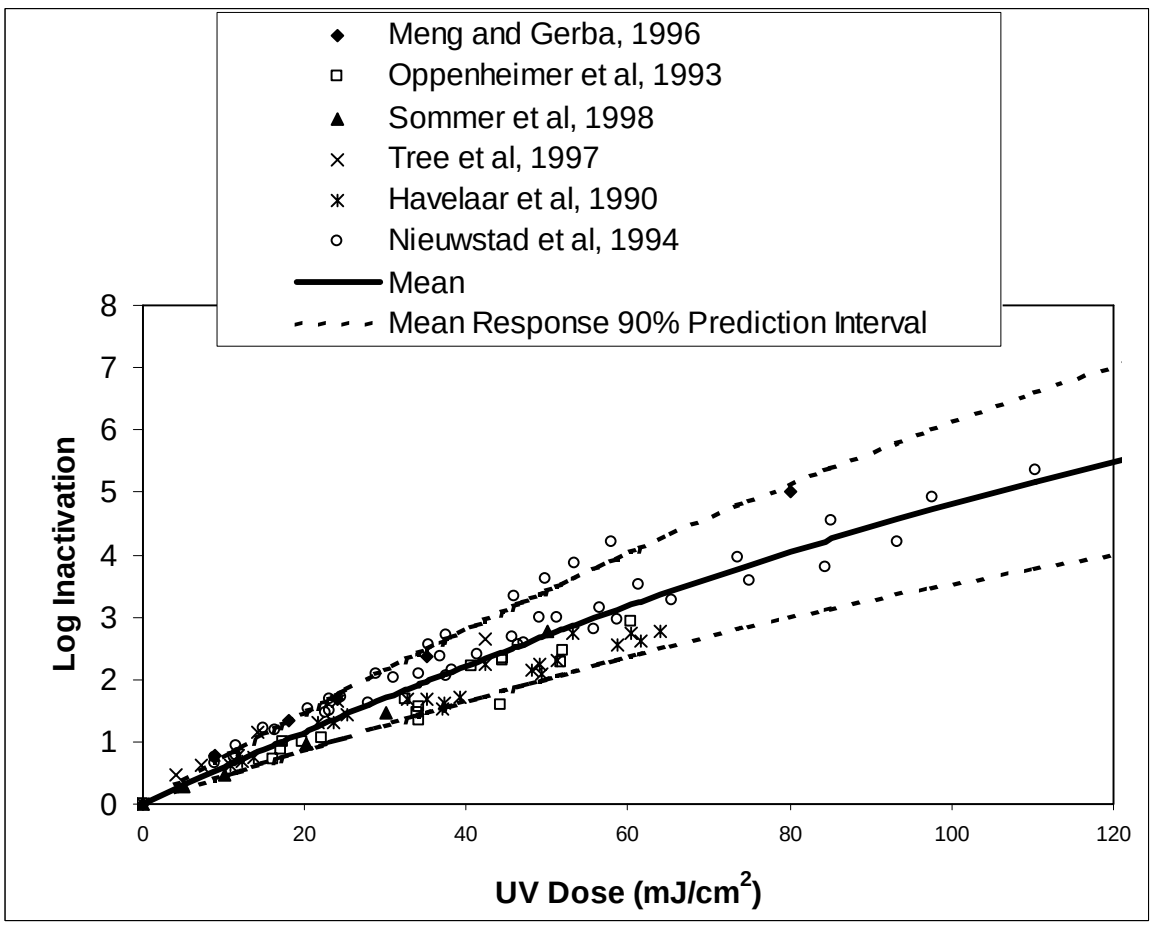
7. Assay the concentration of MS2 in the stock solution as per section D.3.

8. Collect and refrigerate the filtrate at 4°C and use within a one-month period.

Propagation should result in a highly concentrated stock solution of essentially mono-dispersed phage whose UV dose-response follows first order kinetics with minimal tailing. Figure D.1 presents the dose-response of MS2 as reported in the literature. Over the range of REDs demonstrated during validation testing, the mean dose-response of the MS2 stock solution should lie within the 90 percent prediction interval of the mean response in Figure D.1. Over a dose range of 0 to 120 mJ/cm^2, the predictions intervals may be defined using the following equations:

$$Lower\ Bound : \log Inactivation = -1.4 \times 10^{-4} \times Dose^2 + 7.6 \times 10^{-2} \times Dose$$
$$Upper\ Bound : \log Inactivation = -9.6 \times 10^{-5} \times Dose^2 + 4.5 \times 10^{-2} \times Dose$$

Figure D.1 UV Dose-Response of MS2



D.3 MS2 Assay

The concentration of MS2 (ATCC 15597-B1) in water samples can be assayed using the agar overlay technique with *E coli* (ATCC 15597) as a host bacterium (Adams 1959, Yahya et al. 1992, Oppenheimer et al. 1993, Meng and Gerba 1996). The following procedure can be used:

1. Inoculate TSB (Difco, Detroit, MI) with the host bacterium and incubate at 35 to 37°C for 18 to 24 hours to obtain an approximate concentration of 10^8 CFU/mL.

2. Transfer 1 mL of the culture to 50 mL of fresh TSB and incubate at 35 to 37°C for 4 to 6 hours with continuous shaking at 100 Hz to obtain a culture in its log growth phase.

3. Obtain serial dilutions of the MS2 sample using a 0.001 M phosphate-saline buffer or TSB.

4. Combine and gently stir 1 mL of host cell solution, 0.1 mL of diluted MS2 sample, and 2 to 3 mL of molten tryptic soy agar (TSA) (0.7 percent agar, 45 - 48°C) (Difco, Detroit, MI).

5. Pour the mixture onto solidified TSA (1.5 percent agar) contained within Petri dishes. The time between the mixing the MS2 sample with the *E. coli* host and the plating of the top agar layer should not exceed 10 minutes. After plating, the agar should harden in 10 minutes.

6. After the top agar layer hardens, cover, invert the Petri dishes, and incubate 16 to 24 hours at 35 to 37°C.

7. Count the plaques with the aid of a colony counter. Plaques are identified as clear circular zones 1 to 10 mm in diameter in the lawn of host bacteria.

8. Record the number of plaques per dish, and the MS2 sample volume and dilution. If it is not possible to distinguish individual plaques because of confluent growth, record the plate counts as "TNTC" (too numerous to count).

9. Calculate the MS2 concentration in the water samples:

$$Concentration = \frac{\sum n_i}{\sum V_i} \qquad \text{Equation D.1}$$

where
n_i = The number of counts on each plate
V_i = The volume of undiluted sample used with each plate

Example. A water sample containing MS2 was diluted 10, 100 and 1,000-fold using a 0.1 mL aliquot dilution of the sample for each. Each dilution was assayed in triplicate. Plaque

forming units observed on the plates were 2, 5 and 6 for the 1,000-fold diluted sample and 32, 40, and 47 for the 100-fold diluted sample. With the 10-fold dilution, plate counts were too numerous to count. The concentration in the original sample is calculated as follows:

$$Concentration = \frac{(2+5+6+32+40+47)\,pfu}{0.1*3/1000\,mL + 0.1\times 3/100\,mL} = 40{,}000\ pfu/mL$$

D.4 *Bacillus Subtilis* Spore Preparation

Bacillus subtilis spores (ATCC 6633) can be propagated using Schaeffer's media (Munakata and Rupert 1972, Sommer et al. 1995, DVGW 1997). The following propagation method was adopted from DVGW (1997):

1. Prepare Columbia agar (Oxoid CM 331) as a 1 L solution of 23.0 g special peptone (Oxoid L 72), 1.0 g starch, 5.0 g NaCl, and 10.0 g agar (Oxoid L 11) in distilled water. Adjust pH to 7.0 and autoclave 15 minutes at 121ºC.

2. Prepare the sporulation media as a 1 L solution of 280 mg $MgSO_4{\cdot}H_2O$, 1.11 g KCl, 3.1 mg $FeSO_4{\cdot}7H_2O$, and 8.9 g nutrient broth (Oxoid CM 67) in distilled water. Adjust the pH to 7.0 and autoclave it for 15 minutes at 121ºC.

3. Inoculate Columbia agar plates (Oxoid CM 331) with three smears of *B. subtilis* and incubate 24 hours at 37ºC.

4. Inoculate 300 mL of sporulation media with three colonies collected from the agar plates.

5. Incubate the sporulation media 72 hours at 37ºC on a shaker operating at 2 Hz.

6. Sonicate the resulting culture for 10 minutes at 50 kHz and 10ºC.

7. Harvest the spores by centrifuging 80 mL aliquots at 5000 g for 10 minutes and 10ºC.

8. Wash the spores three times by resuspending in 20 mL of distilled water and centrifuging at 5000 × g for 10 minutes at 10ºC.

9. Resuspend the washed spores in 100 mL of 0.001 M phosphate-saline buffer.

10. Inactivate the vegetative *B. subtilis* by heat treatment at 80ºC for 10 minutes.

11. Sonicate the resulting culture for 10 minutes at 50 kHz and 10ºC.

12. Collect the resulting stock solution and assay the *B. subtilis* spore concentration as per section D.5.

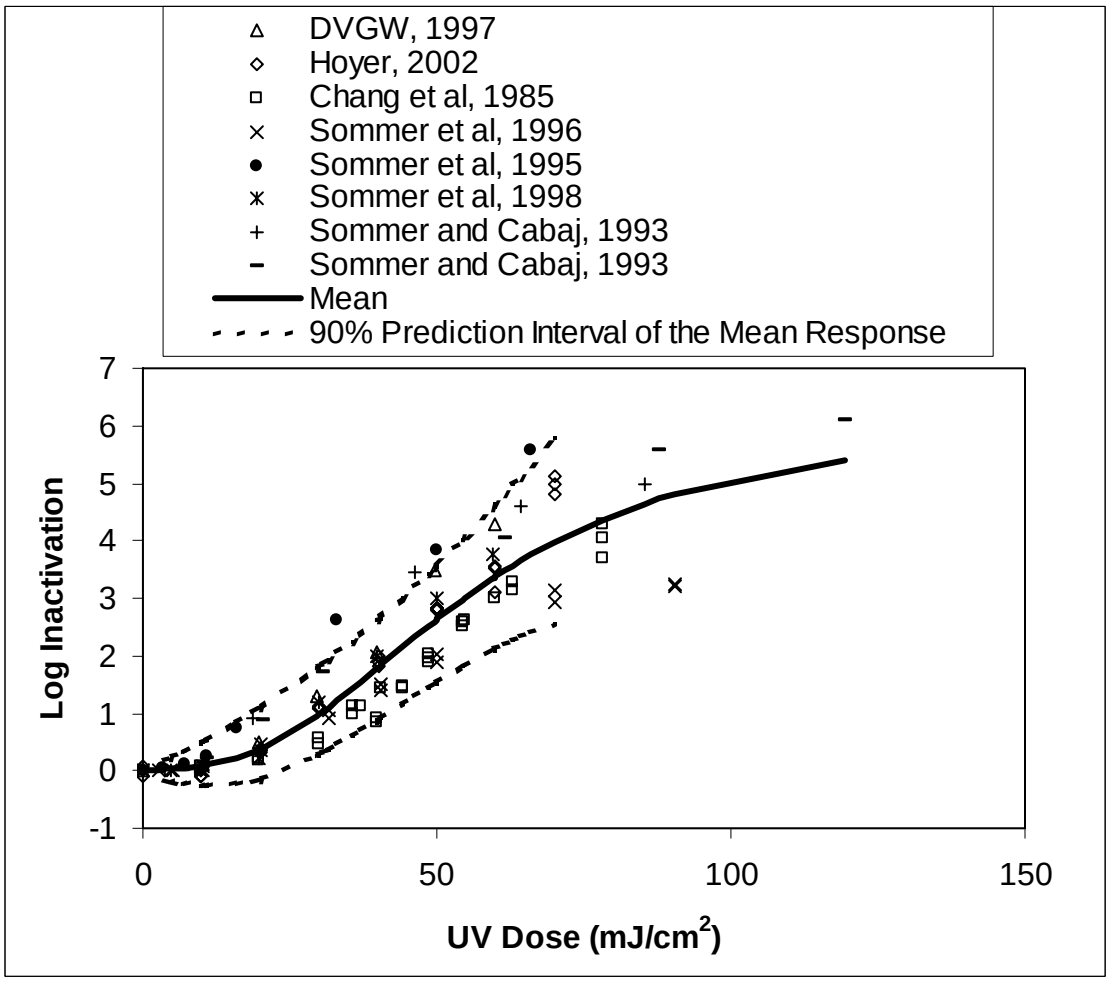
13. Refrigerate the filtrate at 4ºC and use within a one-month period. Sonicate for 10 minutes at 50 kHz and 10ºC before use.

Propagation should result in a highly concentrated stock solution of mono-dispersed *B. subtilis* spores with a UV dose-response that follows the dose-response reported in the literature and presented in Figure D.2. Over the range of reduction equivalent doses (REDs) demonstrated during validation testing, the mean dose-response of the *B. subtilis* stock solution should lie within the 90 percent prediction interval of the mean response provided in Figure D.2. Over a dose range of 0 to 70 mJ/cm^2, the predictions intervals may be defined using the following equations:

$$Lower\ Bound: \log Inactivation = -2.0\times10^{-5}\times Dose^3 + 2.7\times10^{-3}\times Dose^2 - 5.3\times10^{-2}\times Dose$$

$$Upper\ Bound: \log Inactivation = 5.7\times10^{-4}\times Dose^2 + 4.3\times10^{-2}\times Dose$$

Figure D.2 UV Dose-Response of *Bacillus Subtilis* Spores



D.5 *Bacillus Subtilis* Spore Assay

The concentration of *B. subtilis* spores (ATCC 6633) in water samples can be assayed by the plate method using plate count agar. The following procedure was adopted from Deutscher Verein des Gas- und Wasserfaches (DVGW) (1997):

1. Prepare plate count agar (Oxoid CM 325) as a 1 L solution of 5.0 g casein peptone (Oxoid L 42), 2.5 g yeast extract (Oxoid L 21), 1.0 g glucose, and 9.0 g agar (Oxoid L 11) in distilled water. Adjust pH to 6.8 ± 0.2 and autoclave for 15 minutes at 121º C.

2. Obtain serial dilutions of the *B. subtilis* spore sample using 0.001 M phosphate-saline buffer.

3. Vacuum filter 100 mL of diluted sample through a 47 mm x 0.45 µm membrane filter (Gelman Sciences, Ann Arbor, MI).

4. Place filter onto a Petri dish containing hardened agar and cover plates.

5. Incubate plates 24 ± 2 hours at 37 ± 1ºC.

6. Count the number of colonies formed with the aid of a colony counter.

7. Record the number of colonies per dish, and the *B. subtilis* spore sample volume and dilution. If it is not possible to distinguish individual colonies because of confluent growth, record the plate counts as “TNTC”.

8. Calculate the *B. subtilis* spore concentration in the original samples as cfu/mL using Equation D.1.

D.6 References

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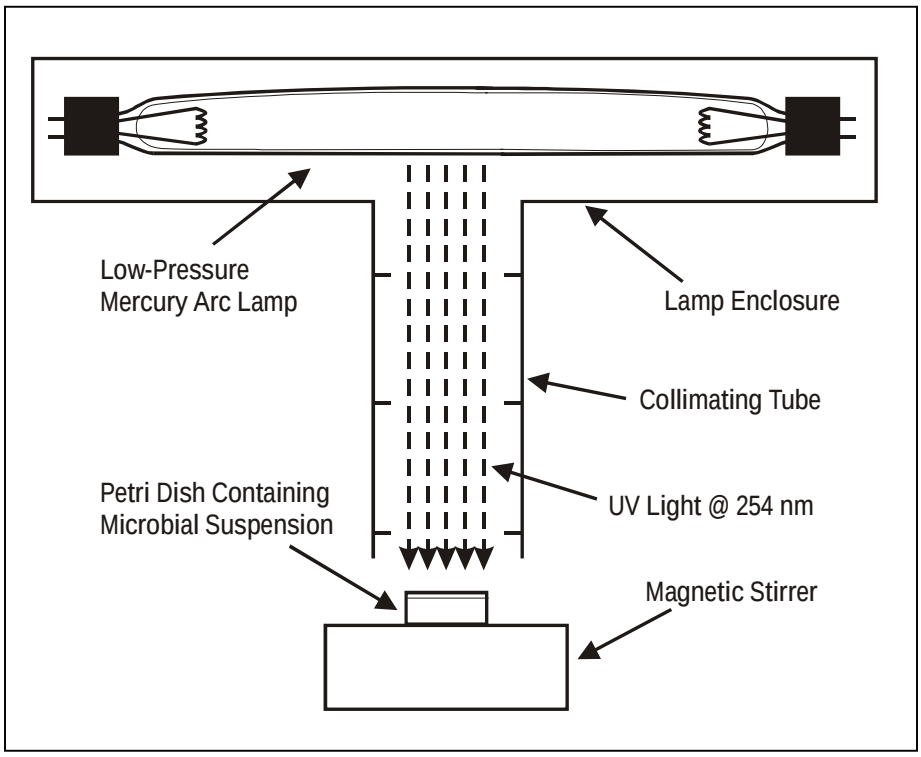
Appendix E. Collimated Beam Apparatus: Measuring Challenge Microorganism UV Dose-Response

The challenge microorganism's UV dose-response should be measured using a bench-scale device referred to here as a “collimated beam apparatus” (Figure E.1). The apparatus delivers UV light to a microbial suspension usually contained within a completely mixed batch reactor. The UV light enters the suspension with a near zero degree angle of incidence and is relatively homogenous across the surface area. UV dose delivered to the suspension is calculated using measurements of incident UV intensity, exposure time, suspension depth, and the absorption coefficient of the suspension. By measuring microbial inactivation in the suspension as a function of UV dose, the microorganism's dose-response is determined.

Figure E.1 Collimated Beam Apparatus



This appendix describes the following components of collimated beam testing:

- Collimated beam apparatus design and operation (section E.1)
- Procedure for irradiating samples using apparatus (section E.2)
- Calculation of UV dose delivered by the apparatus (section E.3)
- Quality Assurance / Quality Control (QA/QC) procedures (section E.4)
- Reporting results (section E.5)

E.1 Apparatus Design and Operation

Because UV dose requirements are based on the pathogen inactivation achieved using 253.7 nm light, the collimated beam apparatus must use a lamp that emits germicidal UV light only at 254 nm (e.g., a low-pressure lamp). To prevent ozone formation, lamps that emit 185 nm light should not be used. The output from the lamp measured using a radiometer or equivalent should not vary more than 5 percent over the exposure time. A stable lamp output can be obtained by driving the lamp with a constant power source and maintaining the lamp at a constant operating temperature. A voltage regulator may be used to obtain a stable power supply to the lamps if the line voltage is not sufficiently stable. A stable temperature can be obtained by controlling the airflow around the lamp.

The UV lamp should be located far enough above the surface of the microbial suspension that uniform irradiance is obtained across the sample's surface and UV light enters the suspension with a near zero degree angle of incidence (Blatchley 1997). A recommended minimum distance from the lamp to the suspension is six times the longest distance across the suspension’s surface. In order to vary the UV intensity incident on the suspension, the distance between the suspension and the lamp can be adjusted.

The uniformity of the intensity field across the sample’s surface should be assessed by measuring the “Petri Factor,” the ratio of the average irradiance across the suspension surface to the irradiance measured at the center (Bolton and Linden 2003). The average irradiance is determined by averaging radiometer measurements taken at each point in a 5 mm spaced grid across an area defined by the suspension's surface. If the radiometer's sensing window is wider

than 5 mm, it should be reduced using a cover slip with a small hole. In general, the collimated beam apparatus should have a Petri Factor greater than 0.9.

The lamp and the light path from the lamp to the suspension should be enclosed to protect the user from exposure to UV light. A box-like enclosure made of aluminum is often used. A length of pipe is often used to enclose the light path from the lamp to the microbial suspension. The inside surface of the pipe should have a low UV reflectance and incorporate apertures to improve UV light collimation (Blatchley 1997). A shutter mechanism is sometimes used to control the exposure of the suspension to UV light. The exposure times should be measured with an uncertainty of 5 percent or less. Exposure times less than 20 seconds are not recommended.

The microbial suspension should be irradiated in an open cylindrical container with a constant cross-sectional area (e.g., Petri dish). The diameter of the container should be smaller than the diameter of the light beam incident on the container. Sample depth should be 0.5 to 2 cm. The material of the container should not adsorb the challenge microorganism enough to impact its measured dose-response.

Sample volumes irradiated in the container should be sufficient for measuring the challenge microorganism's concentration after irradiation. The microbial suspension should be mixed using a stir bar and a magnetic stirrer at a rate that does not induce vortices. The volume and diameter of the stir bar should be small relative to the volume and depth of the sample volume.

The irradiance at the center of the suspension's surface before and after exposure to UV light should be measured using a radiometer calibrated at 254 nm. The radiometer calibration should be National Institute of Standards and Technology (NIST) traceable or equivalent with a known measurement uncertainty. During measurement, the radiometer's calibration plane should match the height of the suspension's surface and be perpendicular to the incident UV light. The calibration plane of the radiometer should be specified in the radiometer’s calibration certificate.

The depth of the suspension, including the stir bar volume, should be measured with an uncertainty of 10 percent or less. The UV absorption coefficient of the microbial suspension at 254 nm should be measured using a spectrophotometer with a measurement uncertainty of 10 percent or less. If scattering of light by the microorganisms and other particulate matter within the suspension is significant, the UV absorption coefficient should be measured using a spectrophotometer equipped with an integrating sphere (Linden and Darby 1998). While 1 cm cuvettes are typically used for measuring UV absorption coefficients, cuvettes with longer pathlengths are recommended to reduce the measurement uncertainty with low UV absorbance samples.

E.2 Procedure

Personnel who perform bench-scale UV irradiation should be experienced with the use and safety requirements of the equipment. Safety goggles and latex gloves should be worn. Skin should be shielded from exposure to UV light. The following procedure is recommended for irradiating a water sample using the collimated beam apparatus:

1. Define the target UV dose.

2. Measure the UV absorption coefficient of the water sample.

3. Place a known volume from the water sample into a container and add a stir bar.

4. Measure the water depth in the container.

5. Measure the UV irradiance delivered by the collimated beam.

6. Calculate the exposure time to deliver the target dose.

7. Block the light from the collimating tube using a shutter or equivalent.

8. Center the container containing the water sample under the collimating tube.

9. Unblock the light from the collimating tube and start the timer.

10. When the target exposure time has elapsed, block the light from the collimating tube.

11. Remove the container and collect the sample for measurement of the challenge microorganism concentration. If the sample is not assayed immediately, store in the dark at 4ºC.
12. Re-measure the UV irradiance and calculate the average of the two measurements.

13. Using Equation E.1, calculate the applied dose using the measured irradiance, UV absorption coefficient, sample depth, and exposure time.

14. Repeat the procedure for various target dose values. The UV dose-response curve is a plot of the microorganism concentration as a function of the applied dose.

E.3 Dose Calculation

Dose delivered to the sample is calculated using Equation E.1:

$$D = E_s P_f (1-R) \frac{L}{(d+L)} \frac{(1-10^{ad})}{ad \ \ln(10)} t \qquad \text{Equation E.1}$$

where

D	=	UV dose in mJ/cm^2
E_s	=	UV irradiance at the center of the suspension's surface in mW/cm^2
P_f	=	Petri Factor
R	=	Reflectance at the air-water interface at 254 nm
L	=	Distance from lamp centerline to suspension surface in cm
d	=	Depth of the suspension in cm
a	=	UV absorption coefficient (Base 10) of the suspension at 254 nm in cm^{-1}
t	=	Exposure time in seconds

The term L/(d+L) accounts for the divergence of the UV light from the collimated beam as it passes through the suspension. The reflectance at the air-water interface estimated using Fresnel's Law is 0.025 given an index of refraction of 1.000 and 1.372 for air and water, respectively.

Alternatively, given a target dose, the exposure time may be calculated by re-arranging Equation E.1 to form Equation E.2:

$$t = D\frac{ad \ \ \ln(10)(d+L)}{E_s P_f L(1-R)(1-10^{ad})} \qquad \text{Equation E.2}$$

where
variables are defined as in Equation E.1

The measurement uncertainty of the dose delivered by the collimated beam should be assessed at an 80 percent confidence interval with consideration of each term in Equation E.1. The measurement uncertainty of each term in Equation E.1 can be determined from the measurement uncertainty stated for the instrumentation used to measure those quantities and the standard deviation of repeated measurements made with that instrumentation (Taylor 1997). If the uncertainty of the measurement of the suspension depth and the UV absorption coefficient is less than 10 percent at a 80 percent confidence level and the product *ad* is less than 0.1, the uncertainty of the term $(1\text{-}10^{-ad})/ad$ can be assumed as 4 percent. This assumption allows the use of the sum of variances approach to calculate the uncertainty of the dose delivered by the collimated beam.

Example. A pipette with an accuracy of 0.2 mL is used to place a 25 mL microbial sample in a Petri dish. The incident irradiance of 1.00 mW/cm^2 is measured using a radiometer. The uncertainty of the radiometer measurement indicated by the calibration certificate is 7 percent. The suspension is irradiated for 60 seconds. The irradiation time is monitored using a stopwatch with an uncertainty of ±1 second. The Petri dish radius, measured using a ruler with 1 mm graduations, is 2.5 ± 0.1 cm. The stir bar volume is estimated as 1 ± 0.1 mL. The UV absorption coefficient of the microbial sample at 254 nm is 0.050 ± 0.005 cm^{-1}. The Petri factor of 0.90 ± 0.02 is calculated for the collimated beam apparatus. The distance from the lamp to the surface of the suspension is determined using a ruler as 25 ± 1 cm.

The depth in the Petri dish is calculated as the sum of the suspension and stir bar volumes divided by the area of the Petri dish.

$$\mathrm{l} = \frac{\text{Volume}}{\text{Area}} = \frac{\left(25 \pm 0.2\,\mathrm{cm}^3\right) + \left(1 \pm 0.1\,\mathrm{cm}^3\right)}{\mathrm{p}\left(2.5 \pm 0.1\,\mathrm{cm}\right)^2} = 1.32 \pm 0.07\,\mathrm{cm}$$

The UV dose is calculated as:

$$D = \frac{(1.00\ \text{mW/cm}^2)(0.90)(1-0.025)}{\left[1+\frac{(1.32\,\text{cm})}{(25\,\text{cm})}\right]} \frac{\left(1-10^{-(0.050\,\text{cm}^{-1})(1.32\,\text{cm})}\right)}{(0.050\,\text{cm}^{-1})(1.32\,\text{cm})\ \ln(10)}(60\text{s}) = 46\ \text{mJ/cm}^2$$

Because the uncertainty of the sample depth (± 0.07 cm) and the measured UV absorption coefficient (± 0.005 cm^{-1}) is less than or equal to 10 percent of the sample depth and the product of the sample depth and UV absorption coefficient is less than 0.1, the uncertainty of the term $(1-10^{-ad})/ad$ is assumed as 4 percent. The uncertainties of the terms in the dose calculation are as follows:

- Incidence irradiance 7 percent
- Petri factor 2 percent
- L/(d+L) 0.3 percent
- Time 2 percent
- $(1-10^{-ad})/ad$ 4 percent

The uncertainty of the dose calculation is calculated using the sum of variances approach as:

$$\text{Uncertainty} = \left(7^2 + 2^2 + 0.3^2 + 2^2 + 4^2\right)^{1/2} = 8.5\%$$

E.4 Quality Assurance and Quality Control

QA/QC measures include:

- Designing the collimated beam apparatus with a Petri factor greater than 0.9
- Selecting instrumentation and methods that minimize the measurement uncertainty of dose delivery by the collimated beam apparatus
- Calibrating all radiometers at regular intervals as recommended by the manufacturer
- Using a reference radiometer or equivalent method to regularly check the measurement accuracy of the radiometer used to measure incident irradiance
- Ensuring irradiance measurements before and after exposure to UV light do not differ by more than 5 percent
- Ensuring replicate UV inactivation curves do not differ significantly

- Ensuring the UV dose-response of the challenge microorganism lies within expected bounds as defined by published dose-response data

E.5 Reporting

The following information should be documented and included with the validation test report:

- Lamp type
- Distance from the light source to the sample surface
- Radiometer make and model
- Measurement uncertainty of the radiometer and date of last calibration
- Comparison of working and reference radiometers
- Volume and depth of the microbial suspension
- UV absorption coefficient of the microbial suspension measured at 254 nm
- Irradiance measurement before and after each irradiation
- Petri factor calculations and results
- Method of dose determination
- UV dose calculations
- Uncertainty assessment

E.6 References

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Appendix F. Background to the UV Reactor Validation Protocol

This appendix provides background material for the validation protocol given in Appendix C. The background material is organized into the following six sections.

- Dose delivery by UV reactors. Section F.1 describes how the RED of a challenge microorganism measured during UV reactor validation is related to the capacity of the UV reactor to inactivate a target pathogen. This section describes why correction factors should be applied to the reduction equivalent dose (RED) of the challenge microorganism to account for systematic errors that arise if the challenge microorganism is more resistant to UV light as compared to the target pathogen. The section concludes by describing approaches for selecting one or more challenge microorganisms to minimize those errors.

- Dose monitoring. Section F.2 describes three approaches whereby measurements of flowrate, UV intensity, and water UV transmittance (UVT) are used by UV reactors to indicate dose delivery. This section discusses the importance of UV intensity sensor placement within a UV reactor and provides a rationale for defining test conditions to validate UV reactors using a given dose monitoring approach.

- UV intensity sensors. Section F.3 describes the properties of UV intensity sensors, how those properties impact the sensor's measurement uncertainty, and how that measurement uncertainty is used to define rejection criteria for using reference sensors to check the accuracy of duty sensors. The section also discusses how non-uniform lamp aging and fouling and the variability in lamp output affects the use of UV intensity sensors.

- Polychromatic considerations. Section F.4 describes systematic errors that can occur with the validation of UV reactors equipped with medium-pressure UV lamps. This section provides approaches for assessing those errors and for defining correction factors that should be applied to validation data.

- Uncertainty of monitoring and dose factors. Section F.5 provides a rationale for defining a safety factor that accounts for the random uncertainty associated with UV reactor validation and monitoring.

- Re-validation. Section F.6 discusses how some changes to a UV reactor design made by a manufacturer would trigger a need to re-validate the UV reactor.

F.1 Dose Delivery by UV Reactors

Dose delivered to an individual microorganism passing through a UV reactor is defined as the integral of UV intensity over time:

$$D = \int_0^{t_r} I dt \qquad \text{Equation F.1}$$

where

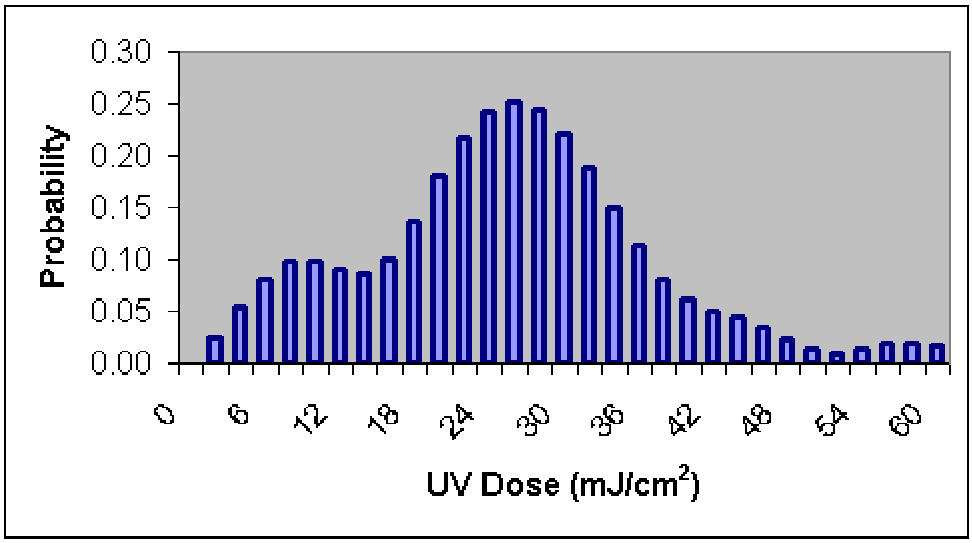
D	=	Dose delivered to the microorganism by the UV reactor
I	=	UV intensity incident on the microorganism as it travels through the UV reactor
t	=	time
t_r	=	Residence time of the microorganism within the UV reactor

Because each microorganism passing through the UV reactor follows a unique trajectory, each microorganism is exposed to a unique dose. For example, microorganisms passing through the UV reactor close to the lamps are exposed to higher UV intensities as compared to microorganisms traveling near the reactor walls or between lamps. Microorganisms caught in eddies or dead zones spend more time within the UV reactor as compared to microorganisms that pass through the reactor quickly due to hydraulic short-circuiting. Because each microorganism is exposed to a different UV dose, dose delivery by the UV reactor is best described using a dose distribution, as opposed to a single dose value. A dose distribution describes the probability that a microorganism passing through a UV reactor will receive a given dose. Figure F.1 presents an example of a dose distribution for a UV reactor.

Model-based and experimental approaches have been identified to determine the dose distribution of a UV reactor. Model-based approaches use computational fluid dynamics (CFD) to predict microorganism trajectories through a UV reactor and hence the dose delivered to each microorganism. Experimental approaches use microspheres that undergo a chemical reaction when exposed to UV light. The microspheres are injected upstream of the UV reactor and are collected downstream. The extent of the UV-induced chemical reaction within each sphere is measured and used to calculate the dose delivered to that sphere as it traveled through the reactor. While promising, both model and experimental-based approaches are subjects of current research. Further effort is necessary to prove these approaches as practical and accurate predictors of UV reactor performance.

Dose delivery by UV reactors is currently measured using biodosimetry (Qualls and Johnson 1983). With biodosimetry, inactivation of a challenge microorganism passed through the UV reactor is measured and related to a single dose value based on the known UV dose-response of that microorganism. This dose value is termed the RED.

Figure F.1 Dose Distribution Delivered by a UV Reactor[1]



[1](Adapted from Chiu et al. 1999)

F.1.1 Relationship Between RED and the Dose Distribution

The RED of a given microorganism depends on the dose distribution delivered by the reactor and the UV inactivation kinetics (dose-response) of the challenge microorganism (Cabaj et al. 1996). A general equation describing this dependence is Equation F.2:

$$f(\mathrm{RED}) = \sum_{i=1}^{j} p_i f(D_i) \qquad \text{Equation F.2}$$

where

RED	=	RED measured using biodosimetry
f	=	Mathematical function describing the inactivation kinetics of the microorganism
j	=	Number of dose values in the dose distribution
D_i	=	i^{th} dose in the dose distribution
p_i	=	Probability of occurrence of dose D_i

For example, if the microorganism has first order inactivation kinetics, the function *f* is shown in Equation F.3:

$$N = f(D) = N_0 \exp(-kD.) \qquad \text{Equation F.3}$$

where

N	=	Microorganism concentration after exposure to dose D
N_0	=	Microorganism concentration with zero UV dose
D.	=	Applied UV dose
k	=	Microorganism's first order inactivation coefficient

Substituting Equation F.3 into F.2 gives the following equation for the RED of a microorganism with first-order inactivation kinetics:

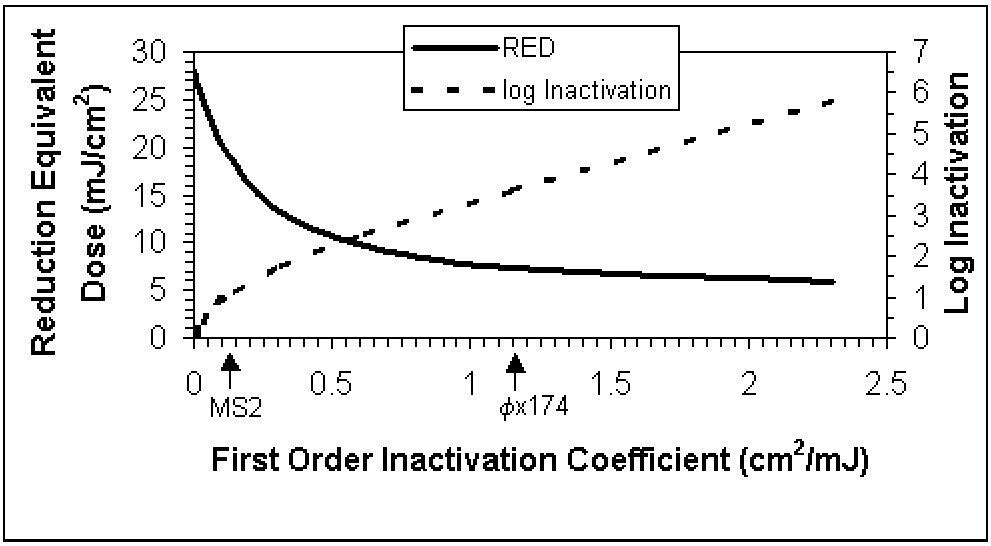
$$RED = -\frac{1}{k}\ln\left(\sum_{i=1}^{j} p_i \exp(-kD_i)\right) \qquad \text{Equation F.4}$$

In equation F.4, the RED depends on the dose distribution of the UV reactor and the first order inactivation coefficient of the microorganism.

Figure F.2 presents the dependence of the RED on the first order inactivation coefficient of the challenge microorganism for the dose distribution shown in Figure F.1. The relation was calculated using Equation F.4. As shown, the RED of a microorganism with a small first-order inactivation coefficient is greater than the RED of a microorganism with a large first-order inactivation coefficient. Because the RED depends on the microorganism's UV inactivation kinetics, the RED of the challenge microorganism is an exact measure of the RED delivered to a pathogen of interest only when the challenge microorganism has the same inactivation kinetics as the pathogen (Wright and Lawryshyn 2000).

Example 1. A UV reactor delivers a dose distribution represented by Figure F.1. The UV reactor is evaluated using biodosimetry. The challenge microorganisms are MS2 bacteriophage (MS2) with a first order coefficient of 0.13 cm^2/mJ and φX174 phage with a first order coefficient of 1.2 cm^2/mJ. As shown in Figure F.2, MS2 would have experienced 1.1 log inactivation, corresponding to an RED of 19 mJ/cm^2. ϕX174 would have experienced 3.6 log inactivation, corresponding to an RED of 7.3 mJ/cm^2. If the pathogen of interest has the same inactivation kinetics as φX174, the RED of MS2 would be 2.5 times greater than the RED delivered to the pathogen, while the RED of φX174 would be an exact measure of the RED delivered to the pathogen.

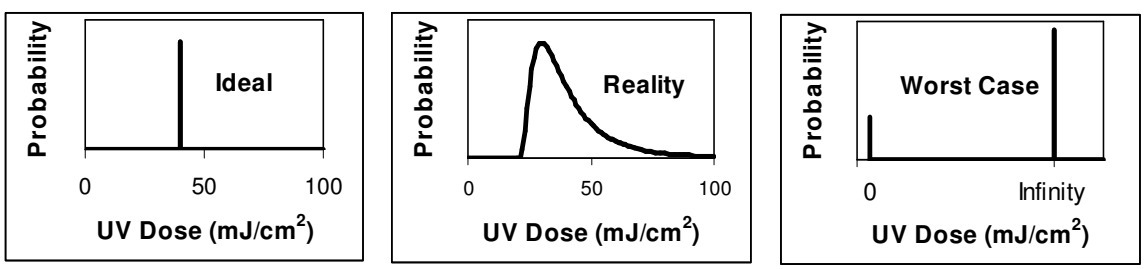
Figure F.2 Microorganism Log Inactivation and RED as a Function of the Microorganism's First Order Inactivation Coefficient for the UV Reactor Represented in Figure F.1



F.1.2 Using RED to Demonstrate Target Pathogen Inactivation

If the UV dose-response of the challenge microorganism differs from that of the target pathogen and the dose distribution of the UV reactor is not known, the results of biodosimetry can only be used to estimate the target pathogen inactivation within a range bounded by the inactivation expected assuming ideal and worst-case hydraulics. Figure F.3 provides a comparison of the dose distribution of reactors with ideal and worst-case hydraulics to a dose distribution that might be seen with a real reactor.

Figure F.3 Comparison of the Dose Distributions of Ideal, Realistic, and Worst-Case UV Reactors



A reactor with ideal hydraulics delivers the same dose to all the microorganisms passing through the reactor. Its dose distribution is represented by a single dose. Examples of a UV reactor with ideal hydraulics include the stirred suspension irradiated during the measurement of UV dose-response by a collimated beam device and a plug flowrate reactor with complete lateral mixing. In both cases, the UV dose delivered is the product of the average UV intensity within

the reactor and the residence time. With an ideal reactor, Equation F.5 shows the net microbial inactivation achieved by the reactor:

$$N/N_0 = \sum_{i=1}^{j} p_i f(D_i) = f(D) \qquad \text{Equation F.5}$$

Accordingly, with an ideal reactor, the RED measured with a challenge microorganism is a measure of the RED delivered to all microorganisms that pass through the reactor. If both the challenge microorganism and the pathogen have first order inactivation kinetics, the log inactivation of the pathogen is calculated using Equation F.6:

$$\log\left(\frac{N}{N_0}\right)_p = -\log(\exp(-k_p RED)) = \frac{RED}{D_{10}^P} \qquad \text{Equation F.6}$$

where

$\log (N/N_0)_p$	=	Log inactivation of the pathogen
k_p	=	First order inactivation coefficient of the pathogen
RED	=	RED observed with the pathogen
D_{10}^p	=	UV sensitivity of the pathogen expressed as mJ/cm^2 per log

The UV sensitivity of the pathogen is related to the first order inactivation coefficient using Equation F.7:

$$D_{10} = \frac{\ln(10)}{k} = \frac{2.30}{k} \qquad \text{Equation F.7}$$

A UV reactor with worst-case hydraulics delivers a UV dose of zero to all microorganisms passing through the reactor. However, in the case of a reactor with a measurable RED, worst-case hydraulics is defined as infinite dose delivered to one fraction of the flowrate and zero dose delivered to the other fraction. Under these conditions, the net microbial inactivation achieved by the reactor is calculated according to Equation F.8:

$$N/N_0 = \sum_{i=1}^{j} p_i f(D_i) = p_1 f(0) + p_2 f(\infty) = p_1 \qquad \text{Equation F.8}$$

As shown, the net inactivation achieved by the worst-case UV reactor with a measurable RED is constant and independent of the inactivation kinetics of the microorganism. With a worst-case UV reactor, the measured inactivation is a measure of the inactivation that would occur with all microorganisms regardless of their UV sensitivity. In other words, the log inactivation of the pathogen is calculated according to Equation F.9:

$$\log\left(\frac{N}{N_0}\right)_p = \log\left(\frac{N}{N_0}\right)_c \qquad \text{Equation F.9}$$

where
$\log (N/N_0)_c$ = log inactivation of the challenge microorganism

Using the above definitions of an ideal and a worst-case reactor, the log inactivation of a pathogen estimated from biodosmetry results will have a value between $log(N/N_o)_c$ and RED/D_p. If the inactivation of the pathogen must be known with absolute confidence, the lower bound of that range should be used. If the challenge microorganism is more resistant to UV light than the pathogen, the lower bound is $log(N/N_o)_c$. If the challenge microorganism is less resistant to UV light than the pathogen, the lower bound is RED/D_p.

Example 2. A UV reactor is challenged using MS2 with a UV sensitivity of 18 mJ/cm^2 per log inactivation. Four log inactivation of the MS2 is observed corresponding to an MS2 RED of $4 \times 18 = 72$ mJ/cm^2. The MS2 results are used to estimate the log inactivation of two pathogens, one with a UV sensitivity of 10 mJ/cm^2 per log inactivation and the other with a UV sensitivity of 25 mJ/cm^2 per log inactivation. The log inactivation of the first pathogen is estimated between 4.0 and 72/10 = 7.2 log and the log inactivation of the second pathogen is estimated between 72/25 = 2.9 and 4.0 log. The biodosimetry results can be used to state with absolute confidence that the inactivation of the first pathogen was at least 4.0 log and the inactivation of the second pathogen was at least 2.9 log.

Example 3. A UV reactor is designed for 3.0 log *Cryptosporidium* inactivation. MS2 is used to measure the performance of the UV reactor. Because MS2 is more resistant to UV light than *Cryptosporidium*, 3.0-log MS2 inactivation must be measured to state with absolute confidence that the reactor achieves 3.0-log *Cryptosporidium* inactivation.

Example 4. A UV reactor is designed for two log adenovirus inactivation. Two-log adenovirus inactivation occurs using a UV dose of 100 mJ/cm^2. The UV reactor is validated using MS2. Because adenovirus is more resistant to UV light than MS2, a RED of 100 mJ/cm^2 must be measured with MS2 to state with absolute confidence that the UV reactor achieves 2 log adenovirus inactivation.

Because UV manufacturers strive to optimize the hydraulic design of their UV reactors, using the worst-case dose distribution represented in Figure F.3 to define the lower bound of pathogen inactivation is overly conservative. An alternative approach is to use the dose distribution of a commercial UV reactor that is representative of worst-case reactor hydraulics. However, defining a worst-case commercial UV reactor is difficult because little data are available in the peer-reviewed UV disinfection literature on dose distributions. Chiu et al. (1999) used measured velocity fields and a random walk model to predict the dose distribution delivered by a wastewater reactor equipped with low-pressure (LP) lamps oriented perpendicular to flowrate. The dose distribution was bimodal due to a short-circuiting path along the reactor walls. Wright and Lawryshyn (2000) compared the dose distribution of four reactor designs using CFD-based dose modeling including the reactor modeled by Chiu et al. Based on this comparison, the dose distribution developed by Chiu et al. is believed to represent a worst-case commercial UV reactor.

Figure F.1 presents a dose distribution adapted from Chiu et al.'s data. For that dose distribution, Figure F.2 presents log inactivation and RED as a function of the microorganism's UV sensitivity expressed as a first-order inactivation coefficient. Figure F.4 presents the same relationship, but with UV sensitivity expressed as dose per log inactivation. Using these figures, the RED delivered to a pathogen by a given UV reactor can be estimated from the measured RED of the challenge microorganism using Equation F.10:

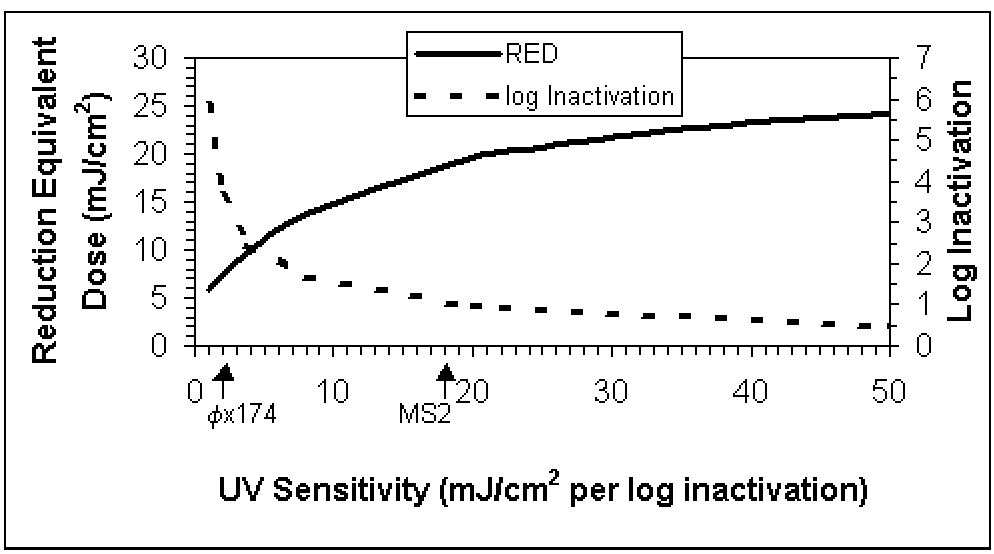
$$RED_p = RED_c \times \frac{RED_p^*}{RED_c^*} \qquad \text{Equation F.10}$$

where

RED_P = RED of the pathogen estimated for the UV reactor of interest
RED_c = RED of the challenge microorganism measured during biodosimetry
RED_p = RED of the pathogen estimated from Figure F.2 or F.4
RED_c = RED of the challenge microorganism estimated from Figures F.2 or F.4

The RED determined using Equation F.10 represents the RED that would be delivered if the reactor under consideration had a dose distribution representative of a worst-case commercial reactor.

Figure F.4 Microorganism Inactivation and RED as a Function of Microorganism UV Sensitivity for the UV Reactor Represented in Figure F.1



Example 5. A UV reactor is challenged using MS2 with a UV sensitivity of 18 mJ/cm^2 per log inactivation. Four log inactivation of the MS2 is observed corresponding to an MS2 RED of 4 × 18 = 72 mJ/cm^2. The MS2 results are used to estimate the log inactivation of two pathogens, one with a UV sensitivity of 10 /cm^2 per log inactivation and the other with a UV sensitivity of 25 mJ/cm^2 per log inactivation. In Figure F.4, the RED delivered to the microorganisms with a UV sensitivity of 10, 18, and 25 mJ/cm^2 per log inactivation is 15, 19,

and 21 mJ/cm^2, respectively. Assuming the UV reactor's performance is bounded by a worst case represented by Figure F.4, the RED delivered to the first pathogen is estimated between 72 mJ/cm^2 and $(72 \times 15)/19 = 57$ mJ/cm^2 and the RED delivered to the second pathogen is estimated between 72 and $(72 \times 21)/19 = 80$ mJ/cm^2. Inactivation of the first pathogen is estimated between 5.7 (57/10) and 7.2 (72/10) log and inactivation of the second pathogen is estimated between 2.9 (72/25) and 3.2 (80/25) log inactivation. This range of inactivation estimated using the worst-case represented in Figure F.4 is notably less than the range estimated in Example 3 using the worst-case represented in Figure F.3.

For regulatory purposes, the lower bound of the range of inactivation and RED estimated for the pathogen should be used when relating challenge microorganism inactivation to target pathogen inactivation. If the challenge microorganism is more sensitive to UV light than the pathogen or if both have the same sensitivity, the RED delivered to the pathogen should be estimated using the RED of the challenge microorganism. If the challenge microorganism is more resistant to UV light than the pathogen, the RED delivered to the pathogen should be estimated using Equation F.10.

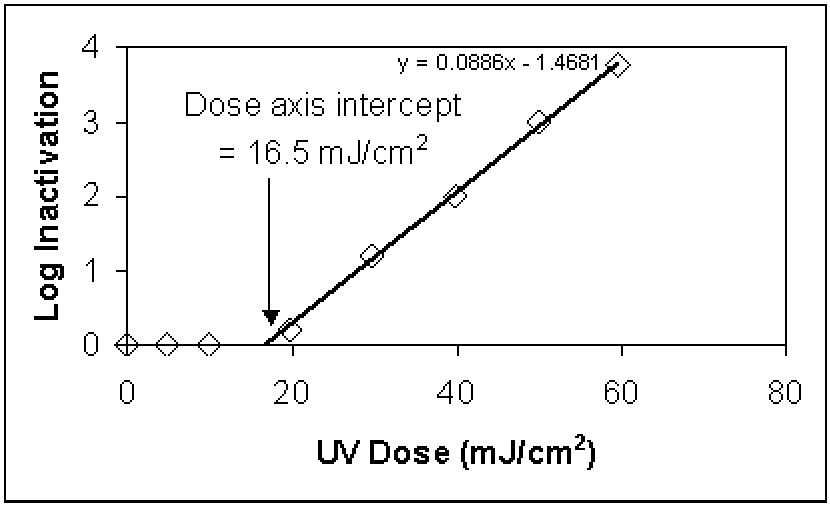
Example 6. A UV reactor is designed for three log *Cryptosporidium* inactivation. The dose needed for 3 log *Cryptosporidium* taken from Chapter 1 (Table 1.4) is 12 mJ/cm^2. Accordingly, the UV sensitivity of *Cryptosporidium* is defined as $12/3 = 4$ mJ/cm^2 per log inactivation. MS2 with a UV sensitivity of 18 mJ/cm^2 per log inactivation is used to measure the performance of the UV reactor. Because MS2 is more resistant to UV light than *Cryptosporidium*, Equation F.10 is used to relate the RED measured using MS2 to the dose delivered to *Cryptosporidium*. From Figure F.4, the RED delivered to the microorganisms with a UV sensitivity of 3.9 and 18 mJ/cm^2 per log inactivation is 9.8 and 19, respectively. Thus an MS2 RED of $12 \times 19/9.8 = 23$ mJ/cm^2 should be demonstrated to show 3 log *Cryptosporidium* inactivation.

Example 7. A UV reactor is designed for one-log adenovirus inactivation. The dose needed for 1-log adenovirus taken from Chapter 1 (Table 1.4) is 58 mJ/cm^2. MS2 with a UV sensitivity of 18 mJ/cm^2 is used to measure the performance of the UV reactor. Because MS2 is less resistant to UV light than adenovirus, an MS2 RED of 58 mJ/cm^2 should be demonstrated to show 1-log adenovirus inactivation.

The RED of microorganisms with shoulders and tailing within the dose-response curve depends on the overlap of the dose distribution with those regions (Cabaj et al.1996, Wright and Lawryshyn 2000). To use Figure F.2 to define safety factors, the inactivation of the challenge microorganism should demonstrate an exponential inactivation as a function of dose over the range of doses in the dose distribution. This creates a dilemma if the dose distribution is not known. To avoid this issue, the dose-response of an appropriate challenge microorganism should not demonstrate a shoulder at a dose beyond 50 percent of the demonstrated RED and should not demonstrate tailing until one log inactivation beyond the demonstrated inactivation. In the case of a challenge microorganism with a shoulder and tailing in the dose-response, the UV sensitivity will be defined as the sensitivity over the region of exponential inactivation that occurs between the shoulder and the onset of tailing. The shoulder of the dose-response is defined by the intersect of the exponential region with the dose axis (see Figure F.5).

Example 8. Figure F.5 presents the measured UV dose-response of *B. subtilis* spores. Because the measured dose-response has a shoulder of 16.5 mJ/cm^2, the *B. subtilis* spores should only be used to demonstrate RED values greater than or equal to $2 \times 16.5 = 33$ mJ/cm^2.

Figure F.5. UV Dose-Response of B. *subtilis* Spores



(Adapted from Sommer et al. 1998)

The RED safety factor provides an incentive to select a challenge microorganism whose UV sensitivity matches that of the target pathogen and a disincentive for overrating UV reactor performance by using challenge microorganisms whose UV sensitivity is much greater than the target pathogen.

F.1.3 Biodosimetry Using Two Challenge Microorganisms

In order to provide a better estimate of the target pathogen's log inactivation and RED, two microorganisms with different UV sensitivities can be used to validate UV reactors. The target pathogen's log inactivation should be estimated by interpolating the log inactivation of the two microorganisms as a function of the UV sensitivity defined on a linear scale as a first-order inactivation coefficient. Alternatively, the target pathogen's RED should be estimated by interpolating the RED of the two microorganisms as a function of the UV sensitivity defined on a linear scale as dose per log inactivation. If interpolation does not meet these provisions, the inactivation of the pathogen will be overestimated.

Example 9. A UV reactor with a dose distribution represented in Figure F.4 is tested using MS2 and ϕX174. The MS2 and ϕX174 have a UV sensitivity of 18 and 2 mJ/cm^2 per log inactivation. Using biodosimetry, 1.1 and 3.6 log inactivation of MS2 and ϕX174 are measured. These log inactivations correspond to RED values of 20 and 7.2 mJ/cm^2, respectively. The RED measured with MS2 and ϕX174 is fit as a function of UV sensitivity resulting in the following equation:

$$RED = 0.731 \times UV\ Sensitivity + 5.83$$

This equation predicts that the RED delivered to *Cryptosporidium*, defined with a UV sensitivity of 3.9 mJ/cm^2 per log inactivation, is 8.7 mJ/cm^2.

If the inactivation of the more UV-sensitive of the two challenge microorganisms is greater than the detection limit of the assay, interpolation should be based on the level indicated by the limitation. Because the inactivation of the UV-sensitive microorganism is underestimated, the interpolation will be conservative and two-microorganism validation may not offer an advantage over single microorganism validation.

Example 10. A UV reactor is evaluated using MS2 and ϕX174 phage. MS2 and ϕX174 are injected into the flowrate upstream of the reactor. Influent and effluent samples are collected and assayed. The assay has a detection limit of 1 pfu/mL. The concentrations of MS2 and ϕX174 in the influent is determined as 1,000,000 and 10,000 pfu/mL, respectively. The concentrations of MS2 and ϕX174 in the effluent samples are 10,000 and 0 pfu/mL, respectively. The results indicate that the concentration of ϕX174 is below the detection limit of the assay. Accordingly, the log inactivation of MS2 and ϕX174 is 2 log and > 4 log, respectively. If the UV sensitivity of MS2 and ϕX174 are determined to be 20 and 2 mJ/cm^2 per log, the MS2 RED is 40 mJ/cm2 and the ϕX174 RED is > 8 mJ/cm^2. The following equation fits the measured RED as a function of UV sensitivity:

$$RED = 1.77 \times UV\ Sensitivity + 4.44$$

This equation predicts that the RED delivered to *Cryptosporidium* defined with a UV sensitivity of 3.9 mJ/cm^2 per log is 11.3 mJ/cm^2. This compares to an RED of 20 mJ/cm^2 that would have been predicted by Equation F.10 using the MS2 data alone. In this case, two-microorganism biodosimetry estimated lower dose delivery to *Cryptosporidium* than single microorganism biodosimetry.

In the past, it has been assumed that the RED measured with a UV-resistant challenge microorganism can be used to demonstrate compliance with a dose target while the log inactivation demonstrated with a UV-sensitive challenge microorganism can be used to demonstrate compliance to a log inactivation target. This approach is not recommended. It is not possible to demonstrate compliance to a 3-log *Cryptosporidium* inactivation by using UV-resistant MS2 to show an RED of 11.7 mJ/cm^2 and using UV-sensitive ϕX174 to show 3-log inactivation.

Example 11. In Example 9, even though the RED measured with MS2 was 18 mJ/cm^2 and the log inactivation measured with ϕX174 was 3.6 log, Figure F.4 shows that *Cryptosporidium*, defined with a UV sensitivity of 3.9 mJ/cm^2 per log, experienced a log inactivation of 2.5 corresponding to an RED of 9.8 mJ/cm^2.

F.1.4 Challenge Microorganism Selection

Ideally, UV reactor performance should be validated with a microorganism whose UV sensitivity matches that of the target pathogen. In this guidance document, the UV sensitivity of the target microorganisms is given by the dose requirements given in Chapter 1 for *Cryptosporidium*, *Giardia*, and virus. Challenge microorganisms currently used to validate UV reactors do not have a UV-sensitivity that matches the UV-sensitivity of the target pathogens as defined in Chapter 1. The UV-resistance of MS2 and *B. subtilis* spores is notably greater than that of *Cryptosporidium* and *Giardia*, and notably less than that of adenovirus. Furthermore, demonstrating 3 or 4-log virus inactivation with these challenge microorganisms necessitates demonstrating REDs greater than 150 mJ/cm^2. These REDs correspond to greater than 6-log inactivation of MS2 and *B. subtilis* spores. Currently, culturing titers of challenge microorganisms needed to demonstrate greater than 6-log inactivation are not practical.

A challenge microorganism should have reproducible UV inactivation kinetics over the dose range of interest. The challenge microorganism should be easily prepared in high titers, easily enumerated by an assay based on microorganism replication, non-pathogenic to humans, and not harmful to the environment. If the challenge microorganism is a phage, the host bacteria used to assay the phage concentration should not be pathogenic to humans. MS-2 phage, non-pathogenic *Escherichia coli*, *B. subtilis* spores, and *Saccharomyces cerevisae* have been used to bioassay UV reactors designed to treat drinking water. Table F.1 summarizes the UV sensitivity of commonly-used and candidate bioassay microorganisms.

Table F.1 UV Sensitivity of Bioassay Microorganisms and Candidates

Microorganism	Dose (mJ/cm^2) Reported to Achieve				Reference
	1 log	2 log	3 log	4 log	
MS-2 phage	16	34	52	71	Wilson et al. 1992
E. Coli	3.0	4.8	6.7	8.4	Chang et al. 1985
B. subtilis spores	28	39	50	62	Sommer et al. 1998
ϕx174 phage	2.2	5.3	7.3	11	Sommer et al. 1998
B40-8 phage	12	18	23	28	Sommer et al. 1998
PRD-1 phage	9.9	17	24	30	Meng and Gerba 1996

F.2 Dose Monitoring

There are three approaches currently used to monitor dose delivery. In this guidance document, the terms used are as follows:

- UV intensity setpoint approach
- UV intensity and UVT setpoint approach
- Calculated dose approach

With the UV intensity setpoint approach, dose delivery is indicated by measured flowrate and UV intensity. The UV reactor complies with a required dose delivery when the measured UV intensity is above an alarm setpoint value defined as a function of flowrate through the reactor. With this approach, the UV intensity sensor should be positioned far enough from the lamp that it provides measurable responses to changing water UV absorbance (and corresponding UVT) as well as lamp output. With the UV intensity and UVT setpoint approach, dose delivery is indicated by measured flowrate, UV intensity, and UVT. The UV reactor complies with a required dose delivery when the measured UV intensity and UVT are above alarm setpoint values, both defined as a function of flowrate through the reactor. With this approach, the UV intensity sensor should be positioned relatively close to the lamp so that it responds primarily to changing lamp output. With the calculated dose approach, dose delivery is indicated by a dose value calculated from measured flowrate, UV intensity, and UVT. The UV reactor complies with a required dose delivery when the calculated dose is above an alarm setpoint value. With this approach, there are no requirements for sensor positioning.

To illustrate the UV intensity setpoint approach and the UV intensity and UVT setpoint approach, Figures F.6, F.7, and F.8 present the relationship between UV dose and measured UV intensity for an annular reactor containing a single LP lamp. UV intensity was calculated using a radial UV intensity model and UV dose was calculated assuming ideal hydraulics (Haas and Sakellaropoulos 1979). UV intensity and dose were calculated for a fixed flowrate of 400 gpm, water UVT ranging from 60 to 98 percent, and lamp output ranging from 20 to 100 percent. In each figure, data are presented as plots of dose versus UV intensity sensor reading for values of UVT specified in the legend. For each of those plots, each point at a given UVT represents, in order of increasing dose, operation at 20, 40, 60, 80, and 100 percent lamp power. The differences between these figures are due to sensor placement.

Figure F.6 Relationship between UV Dose and Intensity for a UV Intensity Sensor Located to Give Dose Proportional to Measured Irradiance

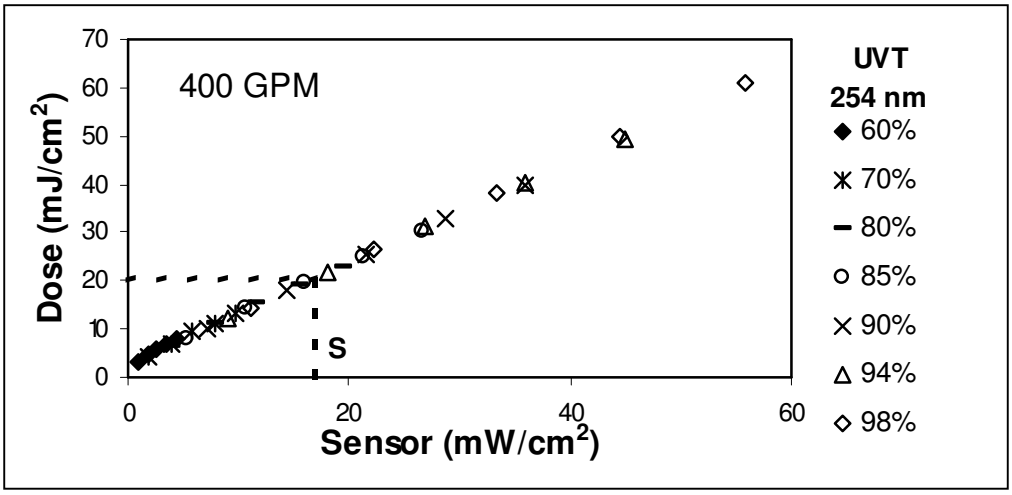


Figure F.7 Relationship between UV Dose and Intensity for a UV Intensity Sensor Located Close to the Lamp

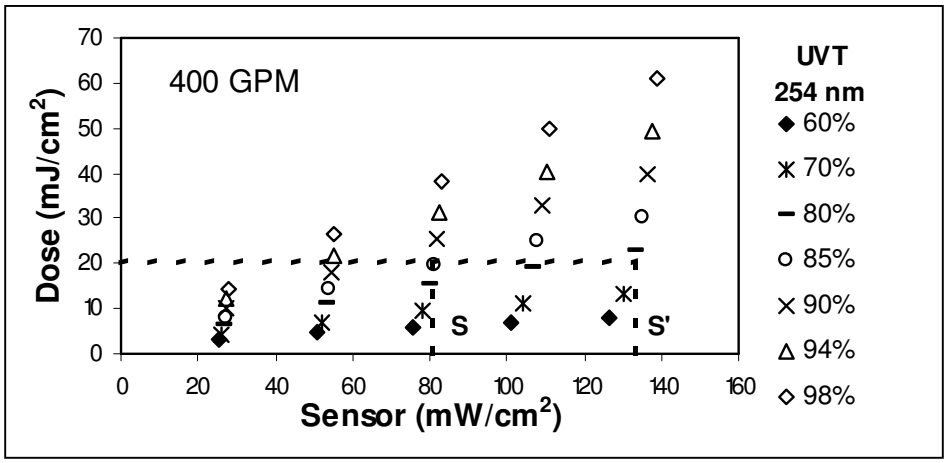
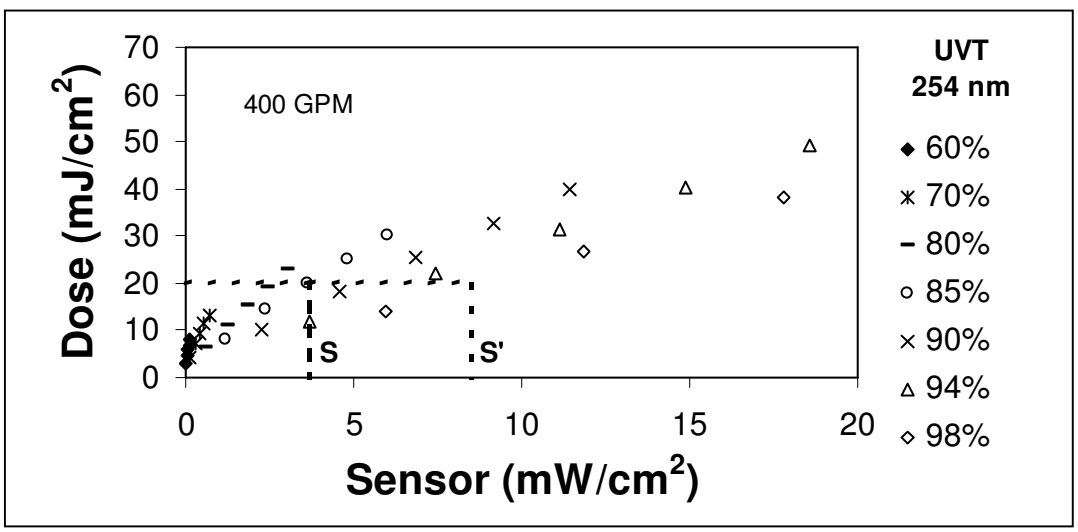


Figure F.8 Relationship between UV Dose and Intensity for a UV Intensity Sensor Located Far from the Lamp



F.2.1 UV Intensity Setpoint Approach

Figure F.6 presents the relationship obtained when the UV intensity sensor is located at a distance from the lamps where UV dose is proportional to measured UV intensity regardless of the UVT and lamp output. With an ideal reactor, this sensor location occurs where the measured intensity equals the average intensity within the reactor. Because of the proportional relationship between dose delivery and measured intensity, a given intensity can be related to a specific level of dose delivery.

Example 12. The UV reactor characterized in Figure F.6 is used in a disinfection application needing a UV dose of 20 mJ/cm^2. At a flowrate of 400 gpm, a UV intensity value *S*

of 18 mW/cm^2 is used as an alarm setpoint to indicate the UV reactor delivers a dose of 20 mJ/cm^2. This alarm setpoint value will indicate a dose of 20 mJ/cm^2 regardless of the UVT of the water and the output of the lamps.

Figure F.7 presents the relationship between dose delivery and measured UV intensity when the UV intensity sensor is placed closer to the lamp than the sensor in Figure F.6. Because the sensor views the lamp through a relatively thin water layer, the sensor response to changing UVT is small compared to that in Figure F.6. Accordingly, the relationship between dose delivery and measured intensity for different values of UVT cannot be described by a single proportional relationship. Unlike Figure F.6, a given UV intensity is not related to a specific level of dose delivery but is related to a range of delivered doses. Accordingly, the measured UV intensity should only be used to indicate dose delivery at the lower end of that range, which occurs under conditions of maximum lamp power and reduced UVT.

Example 13. The UV reactor characterized in Figure F.7 is used in an application needing a UV dose of 20 mJ/cm^2. The UV manufacturer states that a UV intensity value *S* of 80 mW/cm^2 will indicate a dose of 20 mJ/cm^2 under design conditions of 85 percent UVT and 60 percent lamp output. However, as shown in Figure F.7, an intensity of 80 mW/cm^2 corresponds to a dose ranging from 5 to 37 mJ/cm^2. The lower end of this range occurs with lamp powers higher that 60 percent and water UVT lower than 85 percent. For a UV intensity alarm setpoint to ensure a dose of 20 mJ/cm^2 under all possible conditions of the water UVT and lamp output, a setpoint value *S'* of 134 mW/cm^2 should be chosen.

Figure F.8 presents the relationship between dose delivery and measured UV intensity when the UV intensity sensor is located further from the lamps than the sensor in Figure F.6. Because the sensor views the lamp through a relatively thick water layer, the sensor response to changing water transmittance is large compared to that in Figure F.6. Like Figure F.7, the relationship between dose delivery and measured intensity for different values of UVT cannot be described by a single proportional relationship. As such, a given intensity value is related to a range of dose values as opposed to a single value. Again, the measured UV intensity should only be used to indicate dose delivery at the lower end of that range. However, unlike Figure F.7, the lower end of the range occurs under conditions of reduced lamp power and maximum UVT.

Example 14. The UV reactor characterized in Figure F.8 is used in an application needing a UV dose of 20 mJ/cm^2. The UV reactor uses the UV intensity setpoint approach to monitor dose delivery. A UV intensity alarm setpoint value *S* of 4 mW/cm^2 is proposed based on the UV intensity measured under design conditions of 85 percent UVT and 60 percent lamp output. However, an intensity of 4 mW/cm^2 indicates a dose ranging from 9 to 26 mJ/cm^2. To indicate a dose of 20 mJ/cm^2 using the UV intensity setpoint approach, a setpoint value *S'* of 8 mW/cm^2 should be chosen.

The location of the UV intensity sensor within a UV reactor is selected by the manufacturer of the UV reactor. If the UV reactor uses the UV intensity setpoint approach for dose monitoring, the UV manufacturer should optimize the UV intensity sensor's location to give a proportional relationship between dose delivery and measured UV intensity similar to the example given in Figure F.6. If the UV manufacturer does not optimize the UV intensity sensor's location, a given UV intensity will correspond to a range of UV doses values as opposed to a single value. While this does not prevent the UV reactor from using the UV intensity

setpoint approach, the monitoring approach will not be as efficient as with an optimally located sensor because the UV reactor will be overdosing at many combinations of UVT and lamp power that given rise to operation at the setpoint.

F.2.2 UV Intensity and UVT Setpoint Approach

If the UV intensity sensor is not at a location optimal for the UV intensity setpoint approach, measurements of UVT can be used to provide more efficient dose monitoring. UVT alarm setpoints combined with UV intensity alarm setpoints can be used to indicate dose delivery providing the UV intensity sensor is placed relatively close to the lamp. With the sensor located relatively close to the lamp, dose delivery at a given intensity and flowrate decreases with decreasing UVT (Figure F.7). Accordingly, a UVT alarm setpoint combined with a UV intensity alarm setpoint provides a meaningful indicator of dose delivery.

Example 15. The UV reactor characterized in Figure F.7 is used in an application needing a UV dose of 20 mJ/cm^2. If the UV reactor used the UV intensity setpoint approach to monitor dose delivery, an alarm setpoint *S'* of 134 mW/cm^2 would be used to indicate a dose delivery of 20 mJ/cm^2. This approach is not efficient because a UV intensity of 134 mW/cm^2 is associated with a UV dose ranging from 20 to 60 mJ/cm^2. An alternative approach for dose monitoring is to use the UV intensity and UVT setpoint approach. Under this approach, a UV intensity alarm setpoint S of 80 mW/cm^2 combined with a UVT alarm setpoint of 85 percent will indicate a dose delivery of 20 mJ/cm^2. However, the approach is still inefficient because UV dose may range from 20 to 38 mJ/cm^2 with operation of the reactor at the setpoint conditions.

If the UV intensity sensor is located at the optimal position for the UV intensity setpoint approach (Figure F.6), the UVT reading does not provide any additional information on dose delivery that is not provided by the measured UV intensity. However, the measured UVT could be used to indicate whether a UV intensity alarm condition arises from low UVT.

If the UV intensity sensor is located too far from the lamp, dose delivery at a given UV intensity and flowrate increases with decreasing UVT (Figure F.8). As such, the UVT reading cannot be used as an alarm setpoint to indicate dose delivery.

Example 16. The UV reactor characterized in Figure F.8 uses the UV intensity and UVT setpoint approach to show the UV reactor delivers a dose of 20 mJ/cm^2. The intensity alarm setpoint is set to 5 mW/cm^2 and the UVT alarm setpoint is set to 90 percent. If the reactor was operating with a measured UVT and UV intensity of 85 percent and 5 mW/cm^2, the delivered dose would be 28 mJ/cm^2. If the reactor was operating with a UVT and UV intensity of 98 percent and 5 mW/cm^2, respectively, the delivered dose would be 12 mJ/cm^2. Thus the two alarm setpoint values are not ensuring the UV reactor complies with a dose of 20 mJ/cm^2. To remedy this problem, the UV manufacturer should either uses the UV intensity setpoint approach, move the UV intensity sensor closer to the lamps, or use the calculated dose approach to monitor dose delivery.

F.2.3 Calculated Dose Approach

Measurements of flowrate, UV intensity, and UVT can be incorporated into theoretical, empirical, or semi-empirical calculations of dose delivery. For example, the relationships represented in Figures F.6 to F.8 could be defined experimentally and used in an empirical manner to calculate dose. Relationships could also be defined using advanced modeling approaches and used to relate measured intensity to dose delivery for a given flowrate and UVT. In theory, the dose calculation does not necessitate that the sensor be placed at any one location within the reactor. However, if the sensor placed at a location that gives dose delivery proportional to the sensor reading, the dose calculation does not require UVT as an input parameter.

F.2.4 Validating Dose Monitoring

The test conditions used to validate a UV reactor should depend on the approach used to monitor dose delivery.

If the UV reactor uses the UV intensity setpoint approach, the UV reactor is validated by measuring the dose delivery with the UV intensity adjusted to the UV intensity alarm setpoint value. The combination of lamp power and UVT used to achieve operation at the alarm setpoint should be selected to capture the lower end of the dose range associated with the setpoint. If the UV intensity sensor is located closer to the lamp than the optimal location, the UV reactor should be validated at peak lamp power and lowered UVT. If the UV intensity sensor is located further from the lamp than the optimal location, the UV reactor should be validated at peak UVT and lowered lamp power. If the positioning of the UV intensity sensor relative to the optimal location is not known prior to validation testing, the UV reactor should be validated using both test conditions. If the dose values measured with both test conditions are the same, the UV intensity sensor is at the optimal location.

If the UV reactor uses the UV intensity and UVT setpoint approach, the UV reactor is validated by measuring dose delivery with the UV intensity and UVT adjusted to the alarm setpoint values. Validation should also confirm that the UV intensity sensor is located close enough to the lamp that UVT alarm setpoint values provide a meaningful indicator of dose delivery. This is accomplished by showing that dose delivery decreases with decreasing UVT while the UV intensity is held constant at the intensity alarm setpoint value. If dose delivery increases with decreased UVT, the UV intensity sensor is located too far from the lamp and this monitoring approach will not work.

If the reactor uses dose calculations, validation testing confirms that dose delivery is greater than or equal to the calculated dose. Validation testing is conducted at various combinations of flowrate, lamp output, and UVT that result in performance at a target dose. This proves the dose calculation is robust over the range of those variables expected with operation of the reactor at a water treatment plant (WTP).

F.3 UV Intensity Sensors

UV reactors should be equipped with at least one on-line UV intensity sensor that measures the UV intensity at some point within the UV reactor. Measurements made by the on-line UV sensors are used to indicate dose delivery by the UV reactor. Reference sensors are used to check that the measurements made by the on-line sensors are valid.

F.3.1 UV Sensor Properties

The UV sensor may or may not measure the UV light through a monitoring window that is separate from the sensor body. The monitoring windows should have a high UVT over the spectral response range of the UV sensors.

The UV intensity sensor should detect germicidal UV radiation and produce a standardized output signal (e.g., 4 to 20 mA) proportional to the UV irradiance incident on the sensor. UV intensity sensors should be calibrated to an absolute irradiance standard and have a suitable measurement range, angular response, spectral response, linearity, and stability for monitoring and controlling UV dose delivery by the UV reactor. An ideal UV intensity sensor has a linear response to incident UV irradiance that is independent of water temperature and does not degrade with time. Furthermore, the ideal sensor has a fixed angular response and a wavelength response that mimics the germicidal response of microorganisms.

UV intensity sensors provided by the manufacturer should be individually calibrated. UV intensity sensors used to monitor LP lamps are often calibrated using the substitution method (Larason et al. 1998). With this approach, the intensity of a collimated beam of UV light at 254 nm is measured using the UV sensor and compared to that made using a standard measurement, such as a National Institute of Standards and Technology (NIST) traceable sensor or chemical actinometer. The ratio of the standard measurement to the sensor output is the calibration factor. With sensors designed to measure the output of medium-pressure (MP) lamps, the sensor can be either calibrated at 254 nm, calibrated as a function of wavelength, or calibrated using polychromatic light from a MP lamp with a known spectral output. Regardless of the approach used, the calibration should be traceable to some absolute measurement standard and have a quantified measurement uncertainty.

Sensor linearity is determined by comparing the sensor output as a function of incident irradiance to standard measurements of that irradiance. Sensor temperature response is determined by measuring the dependence of sensor output on the sensor's operating temperature with the sensor measuring a constant irradiance. Both linearity and temperature response should be determined over the range of irradiance and temperature expected with the operation of the UV reactor at the WTP. Angular response of a sensor is determined by measuring the dependence of the sensor output on the incident angle of collimated UV light of fixed intensity.

The spectral response of a sensor is determined by measuring the dependence of the sensor output on the wavelength of monochromatic light of known irradiance incident on the sensor. Spectral response is typically presented as a plot of the ratio of sensor output to incident irradiance as a function of the wavelength of light. Because it may be affected by infrared

transmission of glass filters and fluorescence of diffusers that are part of the sensor (Larason and Cromer 2001), UV intensity sensor spectral response should be evaluated from 200 to 1000 nm.

The long-term stability of a UV sensor is best-determined using field data but may be estimated using accelerated life cycle testing. The measurement accuracy of UV sensors can change over time with operation and environmental exposure. Temperature cycling, exposure to UV light, mechanical vibration, and other factors will impact the linear, spectral, angular, and temperature response of a sensor.

The UV sensor manufacturer should conduct regular testing on manufactured UV sensors to develop a database on sensor properties. While some sensor properties may be measured with each sensor, other properties, such as long-term stability, can only be measured on a representative lot size. The sensor manufacturer should have available for inspection the following information:

- Description of the properties measured
- Description of the measurement system used to measure each property
- Description of the measurement standards used
- Documented uncertainty of each measurement
- Description of QA/QC procedures used to ensure the measurements are traceable
- Data collected over time that demonstrates that the properties of the manufactured sensors meet specifications

F.3.2 UV Intensity Sensor Measurement Uncertainty

The measurement uncertainty of a UV intensity sensor quantifies how the measurement of UV intensity made by the sensor when mounted on the UV reactor compares with the true value. For the purposes of this guidance document, UV intensity sensor uncertainty should be determined at a 90 percent confidence level by summing the uncertainty that arises from the calibration, linearity, angular and spectral response, temperature response, and long-term stability.

The uncertainty of sensor calibration depends on the uncertainty of the standards and instrumentation used to calibrate the sensor, such as voltmeters and amplifiers. Uncertainty arises from linearity and temperature response because sensor calibration factors, determined at a given temperature and UV irradiance, are used over a range of temperatures and irradiances with operation of the sensor with the UV reactor. Uncertainty arises with sensor degradation because calibration factors are determined on new sensors.

Uncertainty arises with angular response because sensors, calibrated using collimated UV light, are used in UV reactors to measure UV light impacting from different directions. Uncertainty arises with spectral response because sensors, calibrated at a fixed wavelength, are

used in UV reactors equipped with MP lamps. Variability in spectral and angular response from sensor to sensor will result in a measurement uncertainty not accounted for in calibration. The impact of spectral and angular response variability on sensor measurement uncertainty can be determined either by calculation or by measurement. In the first approach, the sensor spectral and angular response measured on a representative lot size is used as an input to a model that predicts sensor readings in a UV reactor. The variability in the sensor readings predicted by the model is used to define an uncertainty term that is included in the calculation of sensor uncertainty. In the second approach, the variability in measurements made by a representative number of sensors mounted on the UV reactor is used to define the uncertainty.

Example 17. A UV sensor manufacturer calibrates each manufactured UV intensity sensor at 20°C with an uncertainty of 5 percent. UV intensity sensor linearity, temperature response, angular response, and spectral response is evaluated on every tenth sensor manufactured. Linearity ranges from 1 to 3 percent over the measurement range of the sensor. Temperature response ranges from 0.1 to 0.2 percent per C°, or an uncertainty of 4 percent from 0 to 40°C. Models predict that the variability in angular and spectral response from sensor to sensor will cause uncertainties of 8 and 4 percent, respectively. An evaluation of sensors returned from the field indicates that the long-term drift over a one-year period is 10 percent. The measurement uncertainty of the sensors is calculated as the square root of the sum of the squares of the individual uncertainties as per:

$$\text{M}\textit{easurement uncertainty} = \sqrt{5^2 + 3^2 + 4^2 + 8^2 + 4^2 + 10^2} = 15 \text{ percent}$$

F.3.3 On-line and Reference UV Intensity Sensors

Degradation in UV intensity sensor performance can lead to significant under- or over-estimations of dose delivery by the UV reactor's on-line monitoring system. To prevent underdosing, the measurement uncertainty of the UV intensity sensors should be incorporated as a safety factor into the sizing and operation of a UV installation and the performance of the on-line sensor should be regularly checked by use of a reference sensor. Measurements made by the on-line and reference sensor should meet the following equation:

$$\left(\frac{I_{Duty}}{I_{Ref}} - 1\right) \times 100 \leq \left[\sigma_{Ref}^2 + \sigma_{Duty}^2\right]^{1/2} \qquad \text{Equation F.11}$$

where

I_{Ref} = Intensity measured with the reference sensor (W/m^2)
I_{Duty} = Intensity measured with the duty sensor (W/m^2)
σ_{Ref} = Measurement Uncertainty of the reference UV intensity sensor (%)
σ_{Duty} = Measurement Uncertainty of the duty UV intensity sensor (%)

If this condition is not met, the cause for the discrepancy should be determined and resolved. Typically, the discrepancy indicates degradation of the on-line sensor that necessitates recalibration or replacement.

Example 18. A UV reactor uses on-line sensors with an uncertainty of 15 percent. A reference sensor with an uncertainty of 5 percent is used to check the on-line sensors when the UV reactor is operating at the WTP. Measurements made by the on-line sensors are considered out of spec when:

$$\left(\frac{I_{Duty}}{I_{Ref}} - 1\right) \times 100 \leq \left[15^2 + 5^2\right]^{1/2} = 16\,\%$$

F.3.4 Positioning of UV Intensity Sensors

While the UV output along the length and around the circumference of a new UV lamp will be relatively uniform, this may not be true with aged or fouled lamps. Sputtering of electrode material leads to deposits on the inside of the lamp sleeve within 2 or 3 inches from the electrode. Discoloration of the lamp sleeve with lamp aging varies along the length of the lamp. Sleeve fouling varies spatially both along the length and circumference of the lamp sleeve (Lin et al. 1999).

If lamps experience non-uniform aging along their length, the UV intensity sensor should be located to monitor the section along the lamp that experienced the greatest decrease in UV output with aging. The sensor should not be located to monitor the section that experiences the least decrease in UV output.

F.3.5 Number of UV Intensity Sensors

Variability in UV output from lamp to lamp impacts both dose delivery and monitoring. A lamp with a lower output will deliver lower doses to microorganisms passing in its vicinity, thereby shifting the dose distribution to lower values and reducing the net performance of the reactor. The shift in the dose distribution will be more pronounced with a reactor with fewer lamps. Because the dose distribution is affected, the impact on net performance will be greater with a more UV-sensitive microorganism. If the number of UV intensity sensors is less than the number of lamps and the sensors monitor those lamps with the highest output, the monitoring system will overestimate dose delivery by the UV reactor.

The monitoring strategy used to ensure that UV dose delivery meets regulatory targets should account for the variability of UV output from lamp-to-lamp. If each lamp in the reactor is monitored by a UV intensity sensor, dose delivery compliance should be based on the lowest lamp output, unless an accepted and validated dose calculation methodology can account for lamp-to-lamp variability. If the number of sensors used is less than the number of lamps, either the lamp with the lowest output should be monitored and used for dose compliance, or the setpoint used for dose delivery compliance should include a safety factor to account for lamp-to-lamp variability.

Example 19. A UV reactor installed at a WTP is equipped with four lamps and two UV intensity sensors. Because of variability in lamp output, the UV intensity 5 cm from each lamp is 15, 10, 8, and 20 mW/cm^2, respectively. If one sensor monitors the first lamp and the second

monitors the forth lamp, the monitoring system will over-estimate the dose delivery by the UV reactor because microorganisms passing by the second and third lamps will receive lower doses than the microorganisms passing by the first and fourth lamps.

During UV reactor validation, variability in UV output from lamp to lamp should not cause the UV reactor to be overrated. If the number of sensors is less than the number of lamps, the sensors should be monitoring the lamps with the lowest output. If UV intensity sensors record different values during validation, intensity setpoints and calculations should be based on the lowest values recorded.

Example 20. A UV reactor undergoing validation is equipped with four lamps and two sensors. Dose delivery is monitored using the UV intensity setpoint approach. Because of variability in lamp output, the UV intensity 5 cm from each lamp is 10, 15, 8, and 12 mW/cm^2, respectively. To ensure validation results are meaningful, the sensors should be monitoring the first and third lamps.

F.4 Polychromatic Considerations

With UV reactors equipped with LP or low pressure high output (LPHO) lamps, dose delivery and monitoring occurs at a single wavelength of 254 nm. With UV reactors equipped with MP lamps, dose delivery and monitoring involves a response to multiple wavelengths. Dose delivery is an integrated response to UV light from 200 to 320 nm. The output from the UV intensity sensor is an integrated response to UV light over wavelengths spanning the sensor's spectral response. UV absorbance monitors typically measure UV absorbance at a single wavelength of 254 nm. If the spectral properties of the UV reactor that influence dose delivery and monitoring during operation of the UV installation at a WTP are the same as the spectral properties during validation, then the same dose delivery and monitoring characterized during validation will occur at the WTP. However, if the spectral properties are different, dose delivery and monitoring at the WTP will differ from dose delivery and monitoring measured during validation. The following spectral properties may differ:

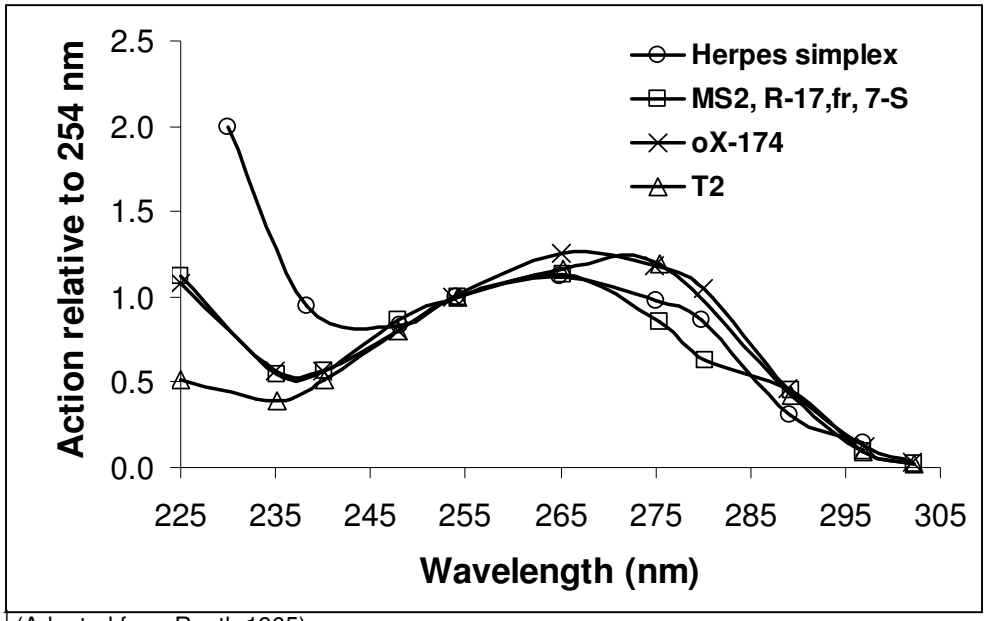
- Action spectra of the challenge microorganism used during validation and the target pathogen
- Spectral UV absorbance of the water during validation and at the WTP
- UV output of the lamps during validation and at the WTP
- UVT of the lamp sleeves during validation and at the WTP

Safety factors should be applied to the validation data for polychromatic UV reactors if spectral differences will lead to under dosing at the WTP. This section describes approaches for assessing the impact of differences in spectral properties and deriving those safety factors.

F.4.1 Action Spectra

The dependence of microorganism inactivation kinetics on UV wavelength may be described using an action spectrum - the UV inactivation sensitivity as a function of wavelength (Figure F.9). Ideally, the action spectrum of the challenge microorganism used to validate a polychromatic UV reactor would either match that of the target microorganism or provide a conservative estimate of inactivation.

Figure F.9 Action Spectra for Various Microorganisms[1]



[1] (Adapted from Rauth 1965)

The impact of various action spectra on UV dose delivery may be estimated by calculating the germicidal lamp output using Equation F.12:

$$P_G = \sum_{\lambda=200}^{320} P(\lambda) G(\lambda) \Delta\lambda \qquad \text{Equation F.12}$$

where

P_G	=	Germicidal output of the MP lamp (W/cm)
λ	=	Wavelength (nm)
$P(\lambda)$	=	Lamp output (W/nm) measured over 1 nm increments at wavelength λ
$G(\lambda)$	=	Relative UV sensitivity of the microorganism at wavelength λ
$\Delta\lambda$	=	1 nm increment

Using the action spectra published for fourteen microorganisms (Rauth 1965, Cabaj et al. 2002, Linden 2001), Table F.2 presents the germicidal lamp output calculated for a MP lamp and the ratio of that output to that of *Cryptosporidium*. A ratio greater than one indicates that the action spectra of the microorganism favors greater inactivation than the action spectra of *Cryptosporidium*. If a challenge microorganism with a ratio greater than one is used to validate a

MP reactor for *Cryptosporidium* inactivation, the ratio should be used as a correction factor to account for the greater inactivation of the challenge that arises from the differences in action spectra. In the case of MS2 and *B. subtilis*, the ratio is close to one and the correction is small. However, based on the data in Table F.2, a correction factor of 1.16 would be needed with UV reactors equipped with MP lamps if ϕX174 was used to show *Cryptosporidium* inactivation.

Table F.2 Germicidal Output Delivered to 14 Microorganisms by a MP Lamp

Microorganism	Type / Nucleic acid (SS = Single Strand, DS = Double Strand)	Germicidal Output (W/cm)	Germicidal Output Relative to *Cryptosporidium*
Cryptosporidium oocysts	DS DNA	5.64	1.00
MS-2, R-17, fr, 7-S	Phage / SS RNA	5.78	1.04
B. subtilis spores	DS DNA	5.58	0.99
ΦX174	Phage / DS DNA	6.53	1.16
Reovirus-3	Animal virus / DS RNA	7.46	1.32
Polyoma	Animal virus / DS DNA	6.74	1.18
T2	Phage / DS DNA	6.05	1.07
VSV	Animal virus / RNA	5.53	0.99
Vaccinia	Animal virus / DS DNA	5.46	0.98
EMC	Animal virus / SS RNA	5.98	1.07
Herpes simplex	Human virus / DS DNA	7.00	1.26

The germicidal output of the MP lamp calculated using the action spectra of *B. subtilis* spores and MS2 is equal to or less than that of most of the 14 microorganisms listed in Table F.2. It is thus reasonable to assume that these microorganisms are acceptable as challenge microorganisms for many pathogens whose action spectrum is not known, like adenovirus and *Giardia*. However, if an alternative challenge microorganism is to be used, its action spectra should be assessed for suitability.

As an alternate approach to measuring the action spectrum and using Equation F.12, the correction factor can also be estimated by comparing the dose-response of the challenge microorganism to that of MS2 measured with a LP and MP lamp. The correction factor would be defined as:

$$\text{Safety Factor} = 1.04\left(\frac{k_{MP}}{k_{LP}}\right)_{\text{Challenge}}\left(\frac{k_{LP}}{k_{MP}}\right)_{MS2} \qquad \text{Equation F.13}$$

where

k_{MP} = Slope of the dose-response measure with the MP collimated beam (cm^2/mJ)

k_{LP} = Slope of the dose-response measure with the LP collimated beam (cm^2/mJ)

1.04 = Germicidal output of MS2 relative to *Cryptosporidium,* from Table F.2

The correction factor that accounts for differences in the action spectra is not the same correction factor that accounts for differences in the UV sensitivity described in section F.1.2. The correction factor described in section F.1.2 applies to all UV reactors regardless of lamp type. The correction factor described in this section is applicable to MP reactors. It should be used in addition to the correction factor described in section F.1.2.

F.4.2 Water Absorption

During UV reactor validation, a UV-absorbing chemical is added to the water passing through the reactor in order to simulate high UV absorbance events that could occur at the WTP. UV-absorbing chemicals that have been used to validate UV reactors include sodium thiosulfate, fluorescein, coffee, tea, and parahydroxybenzoic acid. Ideally, the spectral absorption of the water used to validate UV reactors equipped with MP lamps should match the spectral absorption of the water at the WTP over the wavelength range associated with dose delivery and monitoring (Figure F.10).

Figure F.11 compares the UV absorbance spectra of coffee and lignin sulphonate to that of two drinking water sources (Water A and Water B). For a given UVT at 254 nm, the UV absorption at wavelengths above and below 254 nm is greater with coffee, tea, and lignin sulphonate than with the drinking water sources. If those chemicals are used during validation of a MP reactor, the RED and UV intensity measured at a given flowrate, lamp output, and water UVT will be lower during validation than at the WTP.

Figure F.10 Spectral UV Absorption of Water at Various WTPs

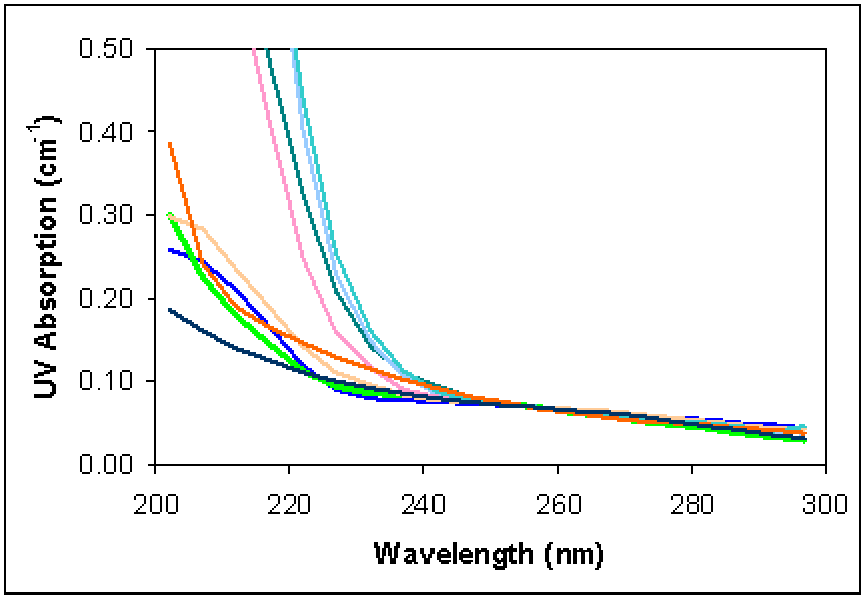
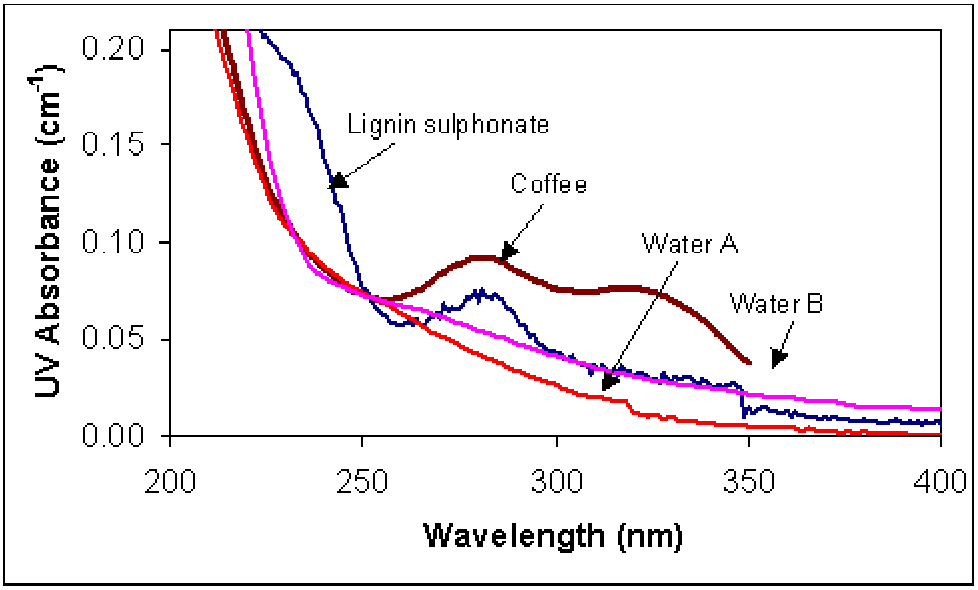


Figure F.11 Comparison of the UV Absorbance Spectrum of Additives used during UV Reactor Validation to the UV Absorbance of Two Finished Waters



The impact of the difference in the UV absorbance spectra on the measured intensity will depend on sensor placement relative to the lamps. If the sensor is located close to the lamps, the sensor reading during validation will be only slightly lower than the reading at the WTP. Accordingly, for a given sensor reading, flowrate, and water UVT, the RED delivered at the WTP will be greater than the RED measured during validation. However, if the sensor is placed far enough from the lamp, the UV intensity measured during validation will be much lower than the reading at the WTP. As such, for a given sensor reading, flowrate, and water UVT, the RED delivered at the WTP will be less than the RED measured during validation. If the UV intensity sensor's spectral response mimics the microorganism's action spectra and the sensor is located at a position where the dose delivery is proportional to the sensor reading, the RED delivered at the WTP will equal the RED measured during validation, even with the differences in the UV absorbance spectra shown in Figure F.11 (Wright et al. 2002). However, this relationship will not hold true if the sensor's spectral response deviates sufficiently from the microorganism's action spectra.

Modeling approaches can be used to predict and compare the RED and UV intensity sensor readings obtained during validation to those expected at a WTP. The modeling approach can be used to define correction factors applicable to validation results to ensure dose monitoring provides valid measurements at the WTP. UV intensity readings should be predicted using polychromatic intensity models that factor in the spectral and angular response of the sensor. While RED predictions could be obtained using CFD-based dose modeling approaches, ideal dose delivery models should be used to provide conservative correction factors. The ideal dose delivery model is conservative because the sensor location within a reactor where the dose delivery is proportional to sensor reading is predicted to occur closer to the lamp with the ideal model than with a CFD-based dose delivery model (Wright et al. 2002). As such, the transition to a correction factor greater than one occurs with closer sensor-to-lamp distance with the ideal dose delivery model than with the CFD-based dose delivery model.

Table F.3 provides predictions of dose delivery and sensor measurements for an ideal annular reactor. The reactor consists of a cylinder with an 18.81-cm radius and a length greater than the arc length of the lamp. The reactor is equipped with a single MP lamp oriented along the central axis of the cylinder (i.e., at a radius of 0 cm). The lamp is housed in a lamp sleeve with a radius of 3.81 cm. The spectral output of the lamp is given in Figure F.12. The spectral UV absorbances used in the model are provided in Figure F.11. UV intensity was modeled using a polychromatic radial intensity model and the dose was calculated as the product of the average germicidal intensity and the hydraulic residence time as per the following equation:

$$D = \sum_{\lambda=200}^{320} P(\lambda) L_{arc} G(\lambda) T_q(\lambda) \left(\frac{\exp(-\alpha_e(\lambda) r_{wl}) - 1}{-Q\alpha_e(\lambda)} \right) \qquad \text{Equation F.14}$$

where

D	=	Dose delivered by the reactor (mJ/cm^2)
L_{arc}	=	Arc length of the lamp (cm)
$T_q(\lambda)$	=	Lamp sleeve UVT
$\alpha_e(\lambda)$	=	Naperian UV absorbance
r_{wl}	=	Reactor water layer, defined as the radial distance from the sleeve to the reactor wall (cm)
Q	=	Flowrate through the reactor (cm^3/s)

UV intensity sensor measurements were modeled at different lamp-to-sensor distances for sensors with the spectral response shown in Figure F.13 as per Equation F.15:

$$I = \sum_{\lambda=200}^{400} \frac{P(\lambda) S(\lambda) T_q(\lambda) \exp(-\alpha_e(\lambda)(r - r_S))}{2\pi r} \qquad \text{Equation F.15}$$

where

I	=	Intensity measured by the sensor
$S(\lambda)$	=	Sensor spectral response normalized to unity at 254 nm
r	=	Distance from the sensor to the lamp (cm)
r_S	=	Lamp sleeve outer radius (cm)

Table F.3 Dose and UV Intensity Sensor Measurements Modeled for a MP Annular Reactor

Performance Parameters		Water A	Water B	Coffee	Lignin Sulphonate
MS2 RED (mJ/cm^2)		72	67	60	61
Sensor	Water Layer (cm)[1]	Measured UV Intensity (254 nm equivalent mW/cm^2)			
SiC	2.0	269	256	238	245
	5.0	136	122	101	110
	10	59.7	48.7	31.6	40.4
	15	31.9	23.6	11.7	18.2
	20	19.2	13.0	4.77	9.34
Filtered SiC	2.0	112	107	103	104
	5.0	48.0	44.8	10.9	11.8
	10	15.3	13.7	3.46	4.06
	15	5.02	4.97	1.18	1.51
	20	2.42	1.95	0.410	0.593

[1] Water layer is defined as the distance between the lamp sleeve and the UV intensity sensor.

Figure F.12 UV Output of a MP Lamp

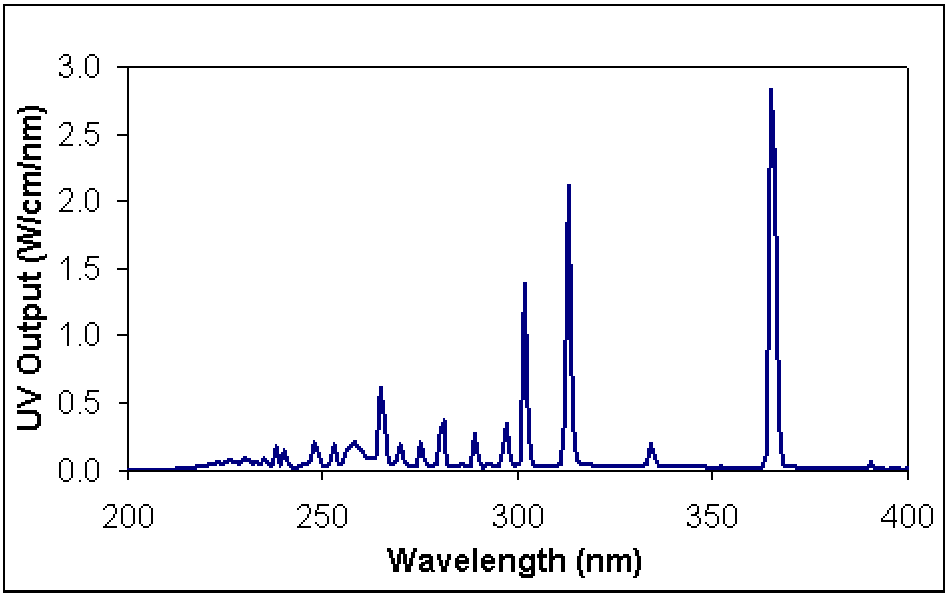


Table F.3 presents the MS2 RED and sensor measurements predicted for the annular reactor operating at a flowrate of 200 gpm, a water UVT of 85 percent at 254 nm, and 100 percent lamp power. As expected, the dose delivered with coffee and lignin sulphonate for a given flowrate, water UVT, and lamp power was less than the dose delivered with both WTP waters.

For a given sensor reading, flowrate, and UVT, Table F.4 presents the ratio of the dose measured during validation to the dose delivered at the WTP calculated using the data from Table F.3. A ratio greater than one indicates that the dose measured during validation will be greater than the dose delivered at the WTP. As expected, the ratio is less than one with the UV

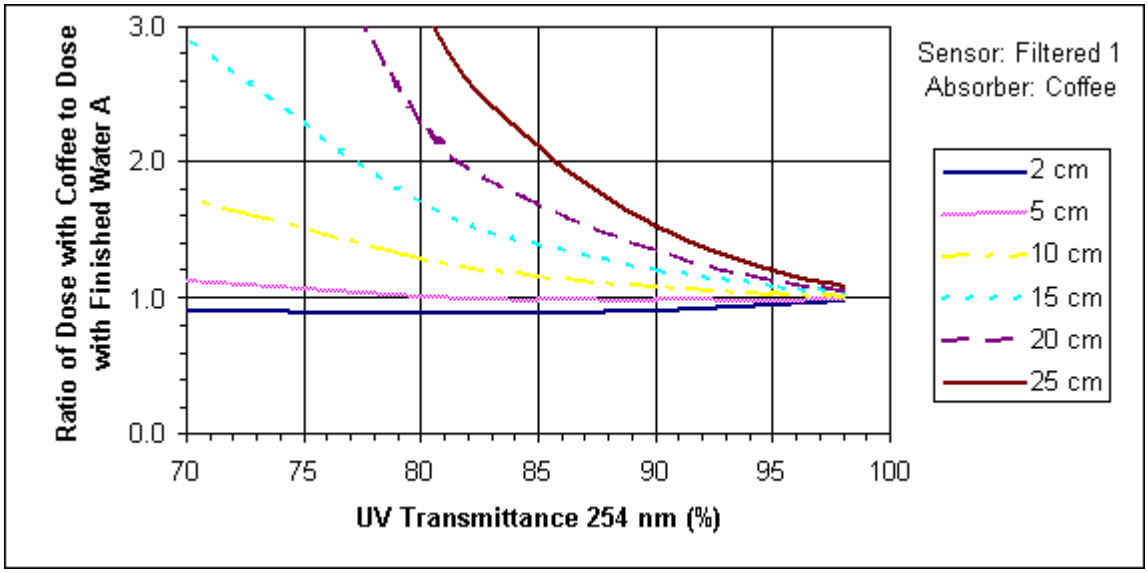
intensity sensor located close to the lamps and greater than one with the UV intensity sensor located far from the lamps. For a given sensor position, the ratio with lignin sulphonate is closer to one than the ratio with coffee indicated that lignin sulphonate better matches the UV absorption spectra of WTP waters. The ratio is also closer to one with a germicidal sensor spectral response compared to the non-germicidal response. This indicates that validation results with a germicidal sensor are more representative of performance at a WTP than validation results with a non-germicidal sensor.

Table F.4 Impact of Water UV Absorbance on the UV Intensity Sensor Value Associated with a Given UV Dose Delivery

UV Sensor	Water Layer (cm)	Ratio of Dose Delivered During Validation to Dose Delivered at the WTP for a Given Sensor Reading			
		Coffee to Water A	Coffee to Water B	Lignin Sulphonate to Water A	Lignin Sulphonate to Water B
SiC	2	0.93	0.96	0.93	0.95
	5	1.12	1.09	1.04	1.01
	10	1.56	1.37	1.25	1.10
	15	2.25	1.80	1.48	1.19
	20	3.34	2.44	1.74	1.27
Filtered SiC	2	0.89	0.93	0.91	0.94
	5	0.98	0.99	0.98	0.99
	10	1.16	1.12	1.09	1.06
	15	1.39	1.29	1.21	1.12
	20	1.70	1.48	1.35	1.18

For the germicidal sensor, Figure F.13 presents the ratio of the dose expected with coffee to the dose expected with finished Water A as a function of sensor position and water UVT. With the sensor located close to the lamp, the ratio is less than one over a wide range of water UVT values. However, the ratio increases above one with increased sensor-to-lamp water layer and, for the most part, increases with decreased UVT.

Figure F.13 Comparison of Dose Expected with Coffee as a UV Absorber to Dose Expected with WTP Water for a MP Reactor Equipped with a Germicidal Sensor



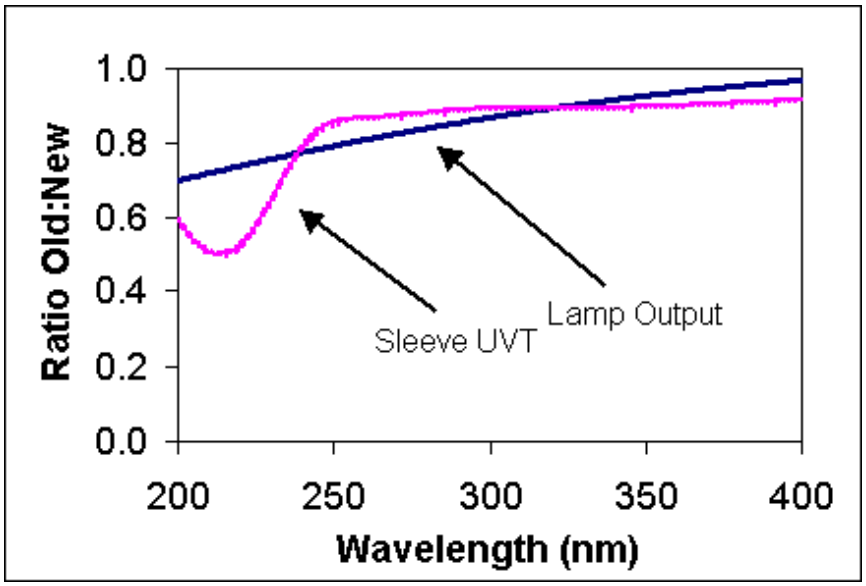
For a given UV reactor equipped with MP lamps, the impact of differences in the spectral UV absorbance between validation and operation at a WTP should be evaluated and used to establish correction factors. The correction factor is calculated for a given flowrate, sensor reading, and UVT, as the ratio of the dose expected during validation to the dose expected at the WTP. If the ratio is less than one, no correction factor is needed.

F.4.3 Spectral Shifts

Spectral shifts in the UV output of MP lamps may occur as MP lamps age. Spectral shifts in the UVT of light through lamp sleeves may occur as sleeves age and undergo internal and external fouling. Spectral shifts in the UVT of sensor windows may occur with window fouling. Spectral shifts associated with the lamp-sleeve assembly will impact both dose delivery and monitoring, while spectral shifts associated with window fouling will impact monitoring only.

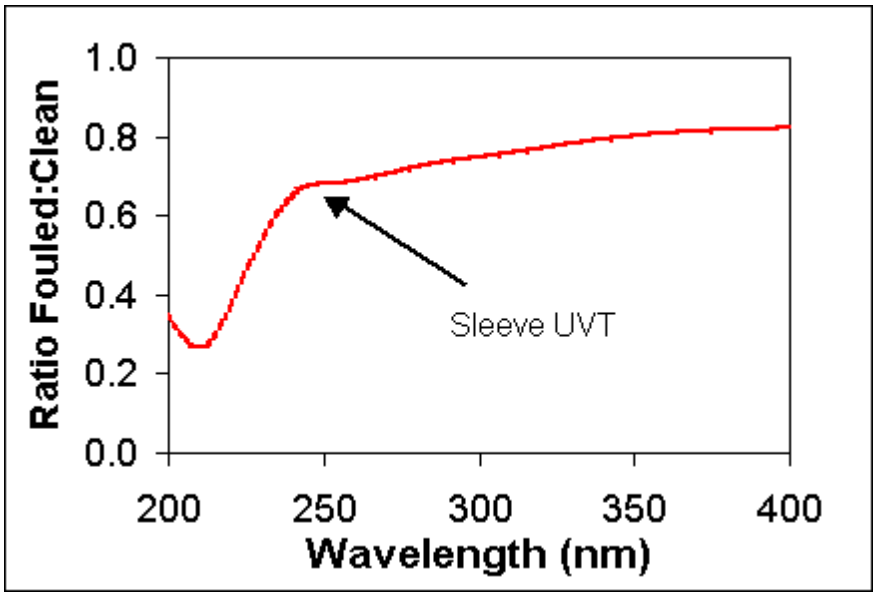
Figure F.14 presents reported data on the spectral shift in MP lamp output and lamp sleeve UVT experienced with aging. Figure F.15 presents data comparing the UVT of clean and fouled lamp sleeves. In both cases, aging and fouling have reduced the output of low-wavelength UV light from the lamp/sleeve assembly more than the output of higher wavelength UV light. The impact of lamp and sleeve aging and sleeve fouling can be assessed by validation testing. Alternatively, the impact can be modeled and used to define a correction factor applicable to validation results generated using new lamps.

Figure F.14 Spectral Shifts in the MP Lamp Output and Lamp Sleeve UVT Reported with Aging[1]



[1] Adapted from Phillips 1983 and Kawar et al. 1998.

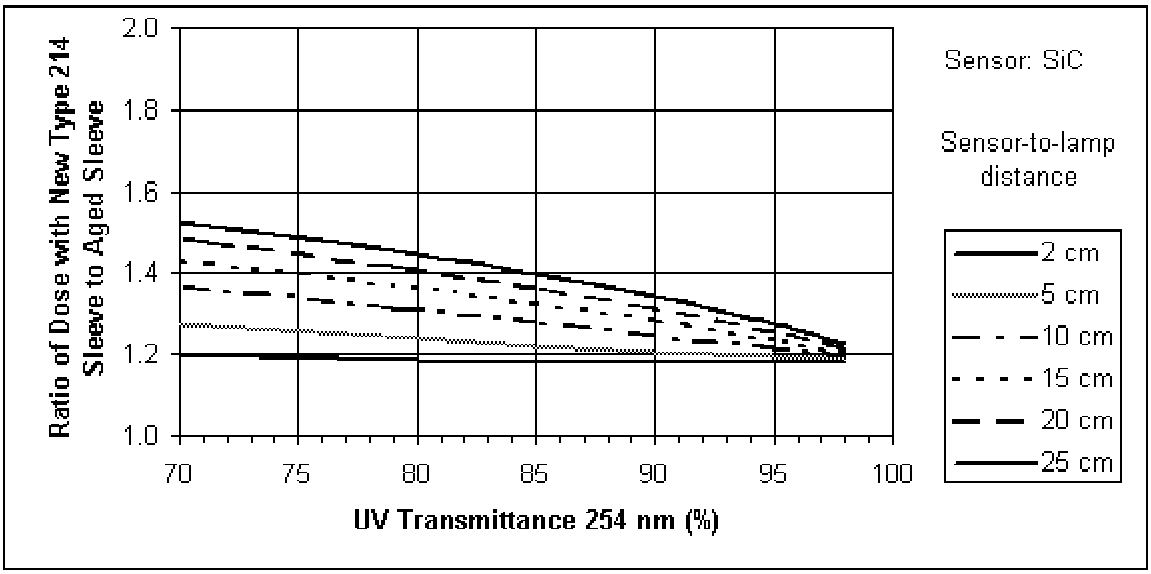
Figure F.15 Comparison of the UVT of New and Fouled Lamp Sleeves



For a measured flowrate, water UVT, and UV intensity, Figures F.16, F.17, and F.18 provide the ratio of the dose delivered with new lamps and sleeves to the dose delivered with aged lamps, aged sleeves, and fouled sleeves, respectively. In each figure, the dose ratio is presented as a function of water UVT and sensor-to-lamp water layer for two different sensors. One sensor had a SiC spectral response while the other had a germicidal response. Dose and UV

response. Dose and UV intensity values were predicted using Equations F.14 and F.15 applied to the annular reactor described in section F.4.2.

Figure F.16 Comparison of Dose Delivered by a MP Reactor with New and Aged Type 214 Lamp Sleeves



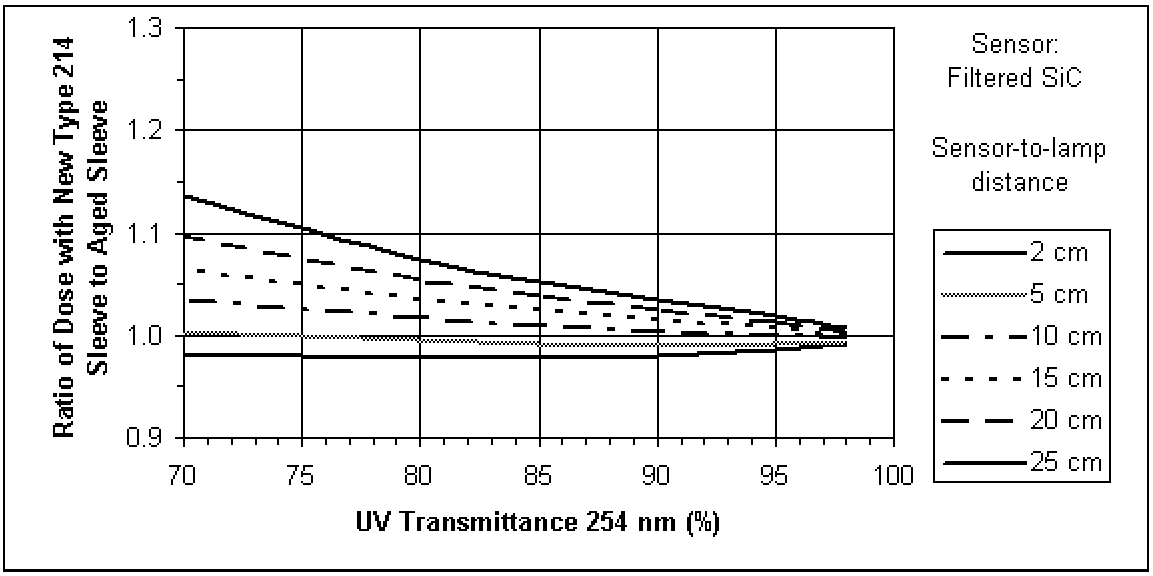
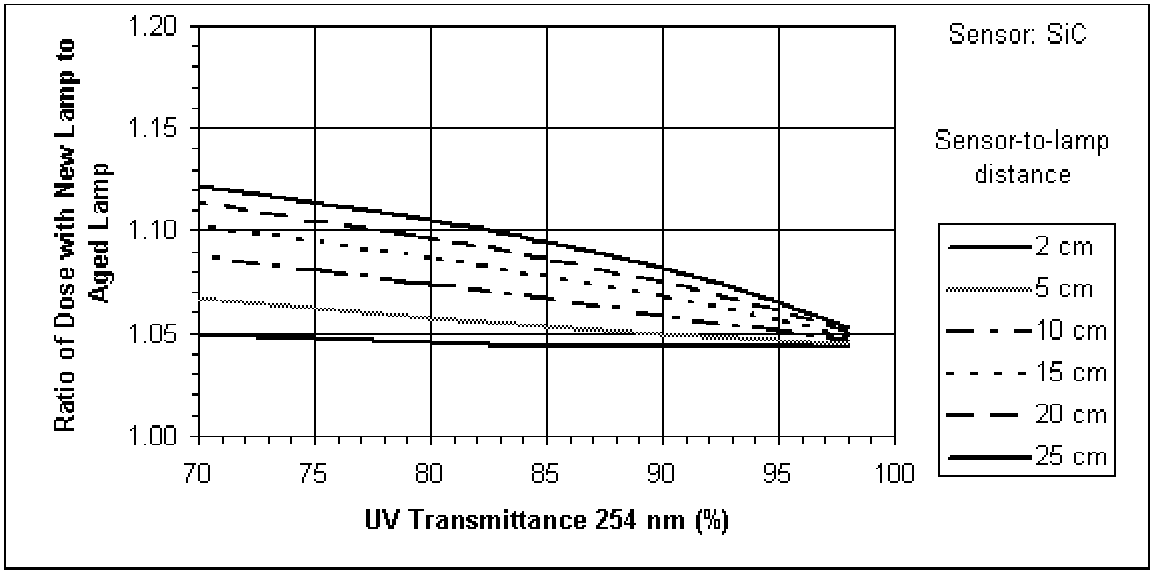


Figure F.17 Comparison of Dose Delivered by a MP Reactor with New and Aged Lamps



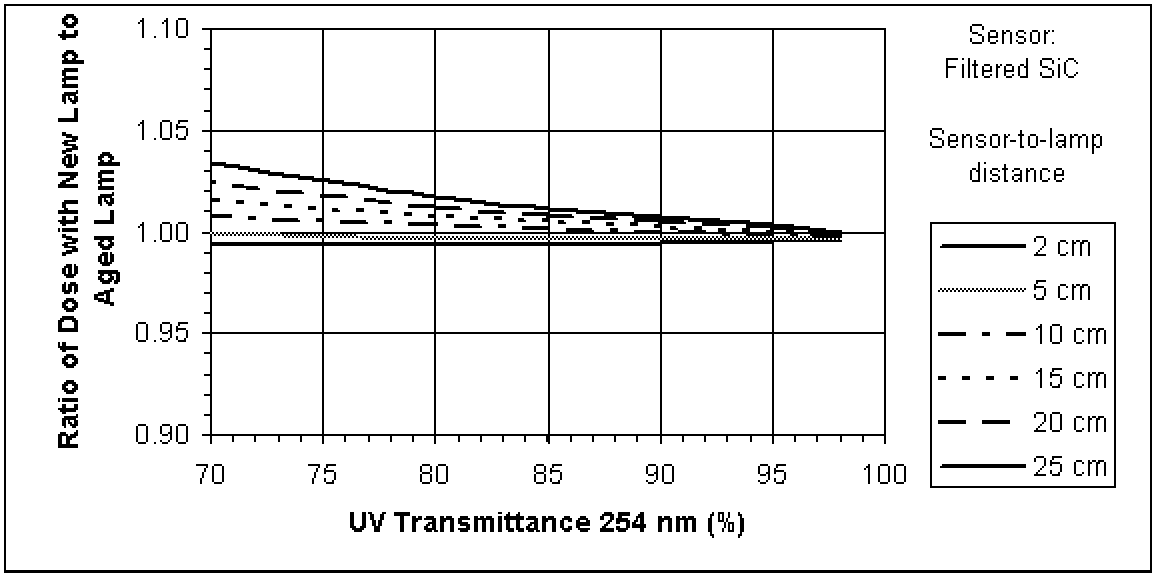
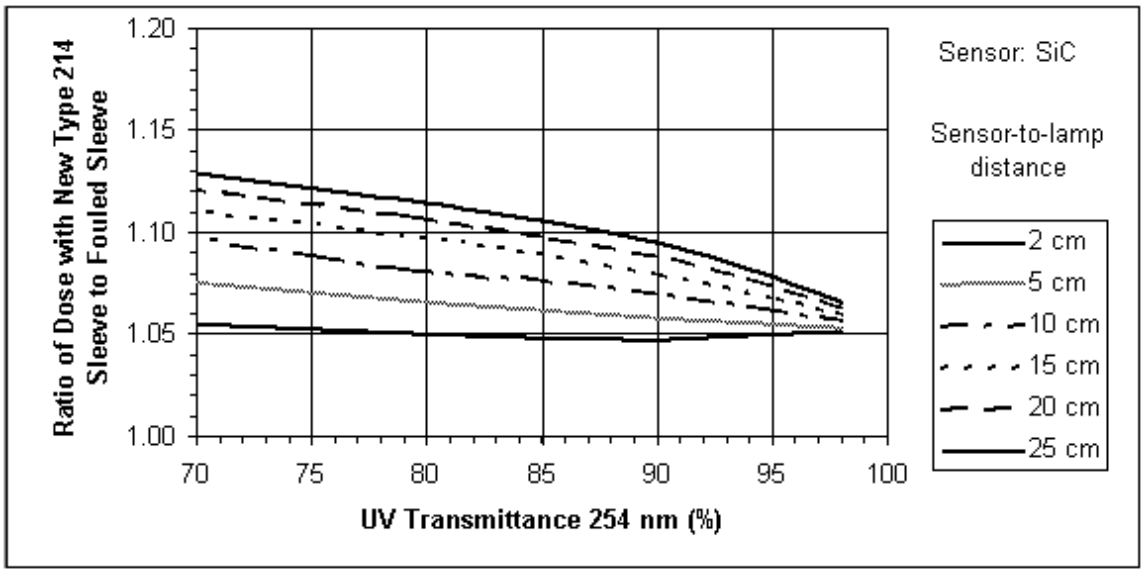
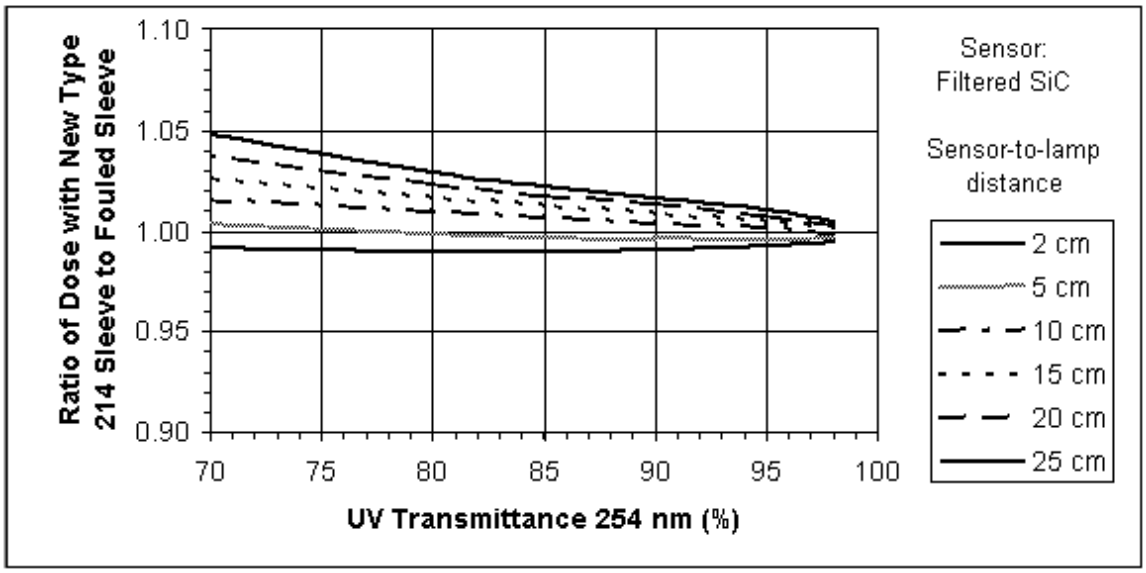


Figure F.18 Comparison of Dose Delivered by a MP Reactor with New Type 214 Lamp Sleeves to Fouled Sleeves





In each figure (Figures F.16 to F.18), the dose ratio increases with decreased water UVT and increased sensor-to-lamp distance. The ratio is closer to one with germicidal sensors compared with sensors with a SiC spectral response.

For a given UV reactor equipped with MP lamps, the impact of spectral shifts in lamp output and sleeve UVT should be evaluated and used to establish correction factors. The correction factor is calculated, for a given flowrate, sensor reading, and UVT, as the ratio of the dose expected with and without the spectral shift expected with operation of the UV reactor at the WTP. If the ratio is less than one, no correction factor is needed.

Spectral shifts associated with lamp and sleeve aging can be avoided by regular replacement of those components. Spectral shifts arising from fouling on external surfaces of lamp sleeves and sensor windows can be minimized with good cleaning practices. However, fouling can also occur on internal surfaces of lamp sleeves and sensor windows.

F.5 Uncertainty of Dose Monitoring and Safety Factors

UV installations should be sized and operated in a manner that accounts for the measurement uncertainty associated with dose delivery monitoring. The objective of dose delivery monitoring is to indicate the level of inactivation of the target pathogen. Safety factors applied to UV installations that account for measurement uncertainty should be chosen to ensure that UV reactors meet inactivation targets at a 90-percent confidence level. A 90 percent confidence level is consistent with the confidence level used to define dose values for *Cryptosporidium*, *Giardia*, and virus in Chapter 1.

F.5.1 Analytical Foundation for Defining Uncertainty

This section derives a measurement equation for UV dose monitoring. This equation is used in this guidance document as the analytical foundation for defining the uncertainty of dose monitoring.

Consider a UV installation operating at a WTP. Assuming first order kinetics, the log inactivation of a target pathogen achieved by the UV reactor at some point in time can be expressed using Equation F.16:

$$\log N_p = \frac{RED_p}{D_{10p}} \qquad \text{Equation F.16}$$

where
$\log N_p$ = Log inactivation of the pathogen
RED_p = RED of the pathogen (mJ/cm^2)
D_{10p} = UV sensitivity of the pathogen (mJ/cm^2 per log inactivation)

If the UV reactor delivers a dose distribution, the log inactivation of the pathogen is related to the inactivation of a challenge microorganism using Equation F.17:

$$\log N_p = B_{RED} \frac{RED_c}{D_{10p}} \qquad \text{Equation F.17}$$

where
RED_c = RED of the challenge microorganism (mJ/cm^2)
B_{RED} = Ratio of the RED of the pathogen to that of the challenge microorganism

Assuming the challenge microorganism RED is proportional to the measured UV intensity, log inactivation of the pathogen can be expressed according to Equation F.18:

$$\log N_p = B_{RED} \frac{\alpha I}{D_{10p}}$$ Equation F.18

where

I = UV intensity measured at the WTP (mW/cm^2)

α = Constant relating challenge microorganism inactivation to measured intensity (J/W)

The constant k is determined during validation as the ratio of the measured RED of the challenge microorganism to the measured intensity. Assuming that inactivation is proportional to flowrate, Equation F.19 can be used:

$$\log N_p = B_{RED} \frac{RED_{cv}}{D_{10p}} \frac{I}{I_v} \frac{Q_v}{Q}$$ Equation F.19

where

RED_{cv} = RED of the challenge microorganism measured during validation

I_v = UV intensity measured during validation

Q_v = Flowrate measured during validation (mgd)

Q = Flowrate measured at the WTP (mgd)

If spectral properties such as lamp output, sleeve UVT, and water UV absorbance during validation differ from those during operation of the UV installation at the WTP, Equation F.19 is expressed as Equation F.21:

$$\log N_p = B_{REF} \frac{RED_{cv}}{D_{10p}} \frac{I}{I_v} \frac{Q_v}{Q} B_{Poly}$$ Equation F.20

where

variables are defined as in Equation F.19

The term B_{Poly} is the ratio of challenge microorganism RED expected at the WTP to the challenge microorganism RED expected during validation for the same conditions of flowrate, water UVT, and UV intensity.

Assuming the dose-response of the challenge microorganism follows first order kinetics, the challenge microorganism RED during validation is calculated using the log inactivation of the challenge microorganism measured through the reactor as per Equation F.21:

$$RED_{cv} = D_{10c} \log\left(N_{in} / N_{ef} \right)_{cv}$$ Equation F.21

where

D_{10c} = UV sensitivity of the challenge microorganism (mJ/cm^2 per log inactivation)

N_{in} = Challenge microorganism concentration measured at the reactor influent

N_{ef} = Challenge microorganism concentration measured at the reactor effluent

The UV sensitivity of the challenge microorganism can be calculated according to Equation F.22 from the UV dose-response measured using the collimated beam apparatus:

$$D_{10c} = \frac{D_{CB}}{\log i} \qquad \text{Equation F.22}$$

where

D_{CB} = Dose delivered by the collimated beam apparatus

$\log i$ = Log inactivation of the challenge microorganism observed with dose D_{CB}

The dose delivered by the collimated beam apparatus is defined by Equation E.1 (section E.3). Substituting Equations F.21 and F.22, and E.1 into Equation F.20 gives the measurement equation for dose monitoring using the UV intensity setpoint approach:

$$\log N_p = B_{RED} B_{Poly} \log\left(\frac{N_{in}}{N_{ef}}\right)_{cv} \frac{I}{I_v} \frac{Q_v}{Q} \frac{E_s P_f (1-R)(1-10^{-al})}{D_{10p} \log i (1+\frac{1}{L}) al \ln(10)} \qquad \text{Equation F.23}$$

F.5.2 Calculating Total Uncertainty

Errors in dose monitoring can be classified as either biases or random uncertainties.

Biases are systematic errors that favor either an over or under estimation of dose delivery. A bias error will occur with dose monitoring if the monitoring approach does not account for differences in the RED measured with the challenge microorganism and the RED delivered to the target pathogen. A bias error will also occur if the monitoring approach does not account for differences between the spectral properties of the UV reactor that impact dose delivery and monitoring during validation and those properties during operation of the UV reactor at the WTP. A bias error will occur if the radiometer, UV intensity sensor, flowmeter, or UVT monitor used during validation always reads either high or low. Bias errors should be accounted for using correction factors. The approaches for defining correction factors to account for bias errors represented by the terms B_{RED} and B_{Poly} in the measurement equation are provided in Sections F.1 and F.4, respectively.

Random uncertainty is associated with every term in the measurement equation (Equation F.23). If the measurement equation consists of linear relationships of independent variables whose random uncertainty is normally distributed, standard approaches can be used to calculate the uncertainty of the measured variable from the uncertainty of each term in the measurement equation. For example, if the measurement equation is $y = x_1 + x_2$ or $y = x_1 - x_2$, the uncertainty of y due to the uncertainty of x_1 and x_2 is calculated using Equation F.24:

$$s = \left(s_1^2 + s_2^2\right)^{1/2}$$ Equation F.24

where
s = Uncertainty of y in absolute units
s_1 = Uncertainty of x_1 in absolute units
s_2 = Uncertainty of x_2 in absolute units

On the other hand, if the measurement equation is $y = x_1 \times x_2$ or $y = x_1 / x_2$, the uncertainty of y due to the uncertainty of x_1 and x_2 is calculated using Equation F.25:

$$s = \left(s_1^2 + s_2^2\right)^{1/2}$$ Equation F.25

where
s = Uncertainty of y in percent
s_1 = Uncertainty of x_1 in percent
s_2 = Uncertainty of x_2 in percent

If the measurement equation involves non-linear relations like $y= x_1 \exp(x_2)$, Monte Carlo approaches should be used to define the uncertainty of y.

Determining the random uncertainty of a measured quantity requires making assumptions about the statistical distribution of measurements. If the distribution is normal, the uncertainty is calculated as the product of the sample standard deviation and the t-statistic. If the number of samples is high, the t-statistic can be approximated by the z-statistic. If the standard deviation of the population is known, the uncertainty is calculated as the product of the population standard deviation and the z-statistic. T and z-statistics are often given in the appendices of statistics texts. The NIST provides recommendations for specifying the uncertainty for quantities that are not normally distributed.

Table F.5 defines an approach for estimating the uncertainties of each term in the measurement Equation F.23. The total random uncertainty of dose monitoring can be estimated by summing the uncertainties associated with each term in Equation F.23 using the above stated rules. Assuming the terms B_{RED} and B_{Poly} are the only bias terms, a safety factor for dose monitoring can be defined according to Equation F.26:

$$SF = B_{RED} \times B_{Poly} \times (1 + e)$$ Equation F.26

where
e = Total random uncertainty associated with the measurement equation.

Table F.5 Terms Used to Define the Uncertainty of Dose Monitoring

Term	Assumption
B_{RED} and B_{abs}	No term used if values are selected as safety factors as described in Sections F.1 and F.4. If terms are calculated, use uncertainty of model predictions to define uncertainty of these terms.
I and I_v	UV intensity measurement uncertainty is often defined by the UV intensity sensor manufacturer. If a reference sensor is used to check the uncertainty of a duty sensor, the uncertainty of the duty sensor should be defined as the rejection criteria used to determine if the on-line sensor is out of tolerance. See Equation F.11.
Q and Q_v	Use measurement uncertainty defined by flowmeter manufacturer
D_{10p}	Accounted for in dose targets provided in Chapter 1
$Log(N_{in}/N_{ef})$	Calculated as a confidence interval using standard deviation and Student's t-statistic associated with samples collected during validation. See Equation C.7
D_{CB}	Calculated as a confidence interval using the measurement uncertainties of the terms in Equation C.2. See Appendix E and Equation C.8.
Log(i)	Use confidence interval of challenge dose-response. See sections C.4.9.7 and C.4.9.8

The safety factor defines the relationship between the dose targets provided in Chapter 1 and the RED that should be delivered by the UV reactor at the WTP.

F.6 Re-validation

If the design of a validated UV reactor changes, the UV reactor should be re-validated if the design change significantly impacts dose delivery or monitoring. Dose delivery and sensor modeling can be used to assess the impact of the design change and justify the need, or lack of need, for re-validation. This section discusses UV reactor modifications and provides guidance on the need for re-validation.

F.6.1 Lamp Assembly

Design changes to the lamp assembly include changes made by the lamp manufacturer to the lamp, selection of a new lamp type by the UV manufacturer, and changes made by the UV manufacturer to the components associated with the lamp assembly. The relationship between dose delivery and monitoring may be impacted by any design change involving modifications to the following components:

- Lamp arc length
- Any reflectors, connectors, and spacers used at the lamp ends
- Lamp envelope diameter
- Lamp envelope UVT from 185 nm to 400 nm

- Mercury content of the lamp
- Argon content of the lamp

The lamp's arc length and the use of components at the ends of the lamps (like reflectors, spacers, and connectors) impact the UV intensity field in the region near the lamp ends. Design changes to these components could impact dose delivery, especially if the lamps are oriented perpendicular to flowrate. Design changes could also impact UV intensity sensor measurements if the lamp ends are within the viewing angle of the sensors. Dose delivery and UV intensity sensor modeling can be used to assess the impacts on changing the lamp arc length or components used at the lamp ends. If the impacts are considered significant, the reactor should be re-validated.

With LP lamps, the UV-emitting plasma occupies the space within the lamp envelope. With MP lamps, the plasma forms a narrow arc that occupies a portion of the space within the lamp envelope. In the presence of electromagnetic fields, the plasma within a MP lamp can be displaced off center within the lamp. The diameter of a plasma centered within the lamp envelope should have a small impact on the UV intensity field and dose delivery (Bolton 2000). However, displacement of the plasma off-center within the envelope could impact the intensity field and dose delivery. The reactor should be re-validated if design changes to the lamp diameter significantly impact the intensity field.

The UVT of the lamp envelope will impact the UV output of both LP and MP lamps. With LP lamps, envelope material can be selected to allow or prevent LP lamps from emitting UV light at 185 nm. While UV light at 185 nm has a negligible impact on dose delivery and UV intensity sensor measurements because of the high UV absorbance of water at this wavelength, 185 nm light may promote the formation of ozone within the lamp sleeve. Ozone will absorb UV light at 254 nm and lower the output from the lamp. Ozone could degrade components within the lamp assembly leading to internal sleeve fouling. Typically, LP lamps are selected with envelopes that prevent output at 185 nm.

With MP lamps, the envelope material has a significant impact on the intensity of UV light emitted below 260 nm. Lamp envelope material can be selected to eliminate or maximize UV output at lower wavelengths. Since envelope transmittance decreases with increased temperature, the UVT of the envelope of a MP lamp should be assessed at the operating temperature of the lamp. Dose delivery and UV intensity sensor modeling can be used to assess the impacts of changing lamp material and justify the need for re-validation.

LP lamps typically operate near 40ºC with a relatively low mercury vapor pressure that promotes UV output at 254 nm. Because the amount of mercury added to the lamp is well in excess of the amount that enters the vapor state during lamp operation, the UV output of a LP lamp is independent of the mercury dose added to the lamp during lamp manufacture. On the other hand, MP lamps operate at a high temperature, near 600ºC, with all of the added mercury in the vapor phase. As such, the mercury vapor pressure is dependent on the mercury dose and the lamp operating temperature. The vapor pressure influences the fraction of mercury that is ionized or excited to higher energy states, and hence the spectral output of the MP lamp. Table F.6 presents the calculated impact of mercury dose on the germicidal output and measured intensity from a MP lamp operating with an electrical input of 70 W/cm. The results suggest that

a change in mercury dose has no impact on the relationship between dose delivery and monitoring with germicidal sensors and a small impact on the relationship with SiC sensors.

Table F.6 Impact of the Mercury Dose on the Relationship Between Germicidal Output and Measured Output of a MP Lamp[1]

Mercury Dose (mg/cm)	UV Output (W/cm) Weighted by			Ratios	
	MS2 Action	SiC Sensor	Filtered SiC Sensor	SiC:MS2	Filtered SiC:MS2
4.8	6.88	11.4	6.82	1.65	0.990
8	6.53	10.3	6.46	1.58	0.989
10.1	7.10	10.8	7.06	1.52	0.993

[1] Adapted from lamp output data from 248 to 400 nm provided by Phillips (1983).

F.6.2 Ballasts

Modifications to lamp ballasts include changing the operating voltage, current, frequency, and waveform. With LP lamps, modifications will impact the amount of UV generated by the lamp, but will not impact the relationship between dose delivery and UV intensity measurements. With MP lamps and some LPHO lamps, changes in lamp operating temperature and mercury pressure caused by changes in ballast power will impact the spectral distribution of emitted light. Table F.7 presents the impact of changing the input power from 48 to 92 W/cm on the germicidal output and measured intensity from a MP lamp dosed with 4.8 mg/cm of mercury. The results suggest a change in lamp operating power has no impact on the relationship between dose delivery and monitoring with germicidal sensors and a small impact with SiC sensors.

Table F.7 Impact of Operating Power on the Relationship Between Germicidal Output and Measured Output of a MP Lamp[1]

Lamp Input Power (W/cm)	UV Output (W/cm) Weighted by			Ratios	
	MS2 Action	SiC Sensor	Filtered SiC Sensor	SiC:MS2	Filtered SiC:MS2
48	4.13	7.01	4.08	1.70	0.99
70	6.86	11.3	6.78	1.66	0.99
92	9.29	15.2	9.14	1.65	0.98

[1] Adapted from lamp output data from 248 to 400 nm provided by Phillips (1983) for a MP lamp dosed with 4.8 mg/cm Hg.

F.6.3 Lamp Sleeves

Design changes to the lamp sleeves include changing the sleeve diameter, thickness, and material. Changing the sleeve diameter may impact the hydraulics through the reactor, the measurement of UV intensity, and the optimal placement of UV intensity sensors relative to the lamp. Changing the thickness and material of the lamp sleeve will impact the spectral UVT, thereby impacting both dose delivery and UV intensity measurements.

Dose delivery and UV intensity sensor modeling may be used to assess the impact of lamp sleeve design changes. Figure F.19 provides the ratio of dose delivered with a standard sleeve to dose delivered with an "ozone-free" sleeve for a given sensor reading as a function of water UVT, sensor-to-lamp distance, and sensor spectral response. Dose and UV intensity values were predicted using Equations F.14 and F.15 applied to the annular reactor described in section F.4.2. Sleeve UVT is provided in Figure F.20. The results show that a design change from a regular sleeve to an ozone-free sleeve described in Figure F.20 would have a small impact on the relationship between dose delivery and UV intensity sensor readings with a SiC sensor and a negligible impact with a germicidal sensor. Modeling can also be used to show that the dose delivery at a given lamp output, water UVT, and flowrate would be approximately 10 percent greater with the standard sleeve than with the ozone-free sleeve. If models indicate the sleeve design change causes a significant impact on dose delivery and monitoring, the UV reactor should be re-validated.

Figure F.19 Ratios of Dose Delivered with Standard Sleeve to Dose Delivered with "Ozone-Free" Sleeves by an Annular Reactor

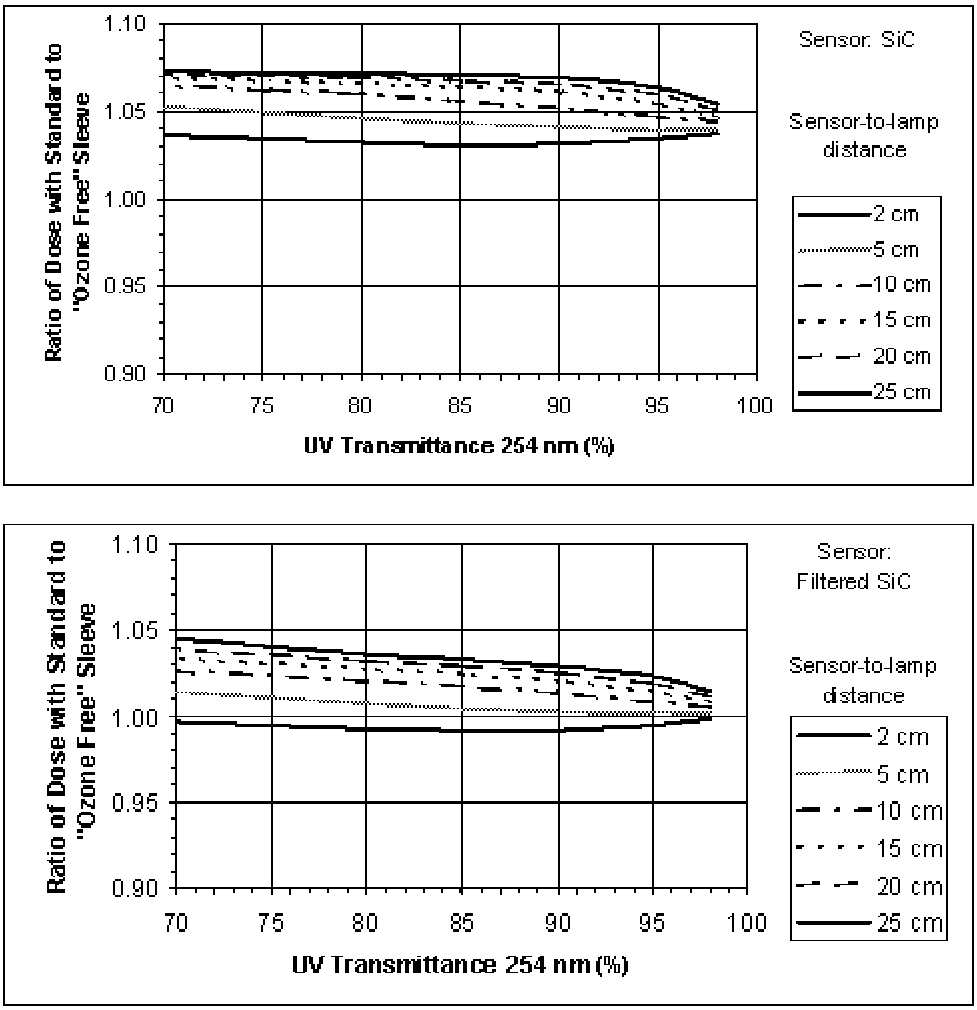
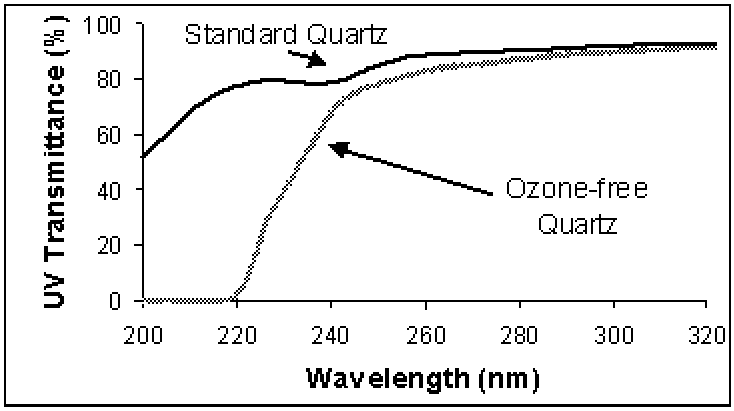


Figure F.20 UVT of Standard and "Ozone-Free" Quartz Assuming Air-Quartz and Quartz-Water Interfaces



F.6.4 Reactor and Component Dimensions

Modifications to the wetted dimensions and positioning of the components within the reactor will impact the reactor hydraulics and dose delivery. Modifications could also impact the intensity field within the reactor and the measurement of UV intensity. Modifications include changes to the dimensions of the reactor, inlet piping, exit piping, baffles, lamp sleeves, wipers, and UV intensity sensors. The impact of such modifications on dose delivery and UV intensity measurements can be insignificant or large. Addition of a baffle plate will likely have a large impact on dose delivery and a small impact on measured UV intensity, while changing the position of a UV intensity sensor will likely have a small impact on dose and a large impact on measured UV intensity. Dose delivery and UV intensity modeling may be used to assess the impacts of these modifications. If the impacts are significant, the reactor should be re-validated.

F.6.5 UV Intensity Sensors

Modifications to the UV intensity sensors include changes made by the sensor manufacturer to the sensor, changes by the UV manufacturer to the sensor housing and associated optical components, and changes by the UV manufacturer to the number and positioning of the sensors within the reactor.

Changes to the semi-conductor and optical components within the UV intensity sensor could impact the sensor's spectral response, linearity, angular response, and temperature stability. Changes to those properties could impact the sensor's measurement uncertainty. If the new measurement uncertainty is quantified, it should be used to define a new safety factor for the UV reactor. If the angular response or spectral response of the sensor changes, measurements supported by calculations should be used to evaluate the impact of the change on dose delivery monitoring.

Changes to the measuring window of the UV intensity sensor include dimensional and material changes. Changes may impact the UVT of the window and the detection angle. Measurements supported by calculations should be used to evaluate the impact of the change on dose delivery monitoring.

Modifications to the positioning of the UV intensity sensor within the reactor could disturb the flowrate and impact dose delivery. If the impact on dose delivery is negligible, measurements supported by calculations may be used to compare measured UV intensity at the two positions and modify the dose monitoring approach without the need for re-validation.

Addition of UV intensity sensors to the reactor could disturb the flowrate through the UV reactor and impact dose delivery. If sensors are added, they should be positioned relative to the lamps in a similar manner as the other sensors. For example, if one sensor is positioned to view two lamps through a 5-cm water layer, then all added sensor should view two lamps through a 5 cm water layer.

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Appendix G. Issues for Unfiltered Systems

Unfiltered systems are utilities that use surface water sources and meet the filtration avoidance criteria of the Surface Water Treatment Rule (SWTR) (40 CFR 141.71). The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) requires unfiltered systems to meet overall disinfection requirements (i.e., *Cryptosporidium*, *Giardia*, and virus inactivation) using a minimum of two disinfectants (40 CFR 141.721(d)). The information presented in this manual is focused on post-filtration applications of UV disinfection; however, the information is also relevant to UV disinfection of unfiltered supplies. In addition, the UV dose requirements presented in section 1.3.1.3 are applicable to both filtered water and water supplies that meet the regulatory requirements for filtration avoidance (40 CFR 141.729(d)). This appendix identifies issues that are specific to unfiltered applications of UV disinfection. The following issues are of particular interest to unfiltered supplies because they make applying UV disinfection different from post-filter locations:

- Water quality (especially particle content)
- Debris
- Ozone residual (when ozone is applied prior to UV disinfection)
- Off-specification requirements recommendations

G.1 Water Quality

Differences in the quantity and nature of particles in unfiltered surface water supplies are the most pertinent distinction between post-filtration and unfiltered supply water qualities. Typically, the turbidity in unfiltered surface waters is less than 1 nephelometric turbidity units (NTU). However, the SWTR allows turbidity up to 5 NTU immediately prior to the first point of disinfection application (40 CFR 141.71). Several studies have examined the effects of turbidity up to 10 NTU on UV disinfection, including changes in UV absorbance measurements made with a spectrophotometer and inactivation of microorganisms.

Particles in water absorb and scatter UV light to varying degrees based on size and composition. Particles impact the disinfection process in two distinct manners:

1. Particles can decrease the UV transmittance (UVT) of water and thereby impact UV dose delivery (section A.4.1.2).
2. Particle association can shield microorganisms from UV light, thereby changing the characteristics of the UV dose-response curve (section A.2.6.5).

Christensen and Linden (2001) concluded that the light scattering and changes in absorbance caused by turbidity up to 10 NTU can be accounted for when calculating UV dose in collimated beam testing provided that the ultraviolet absorbance at 254 nanometers (A_{254}) of the sample is measured according to a modified version of Standard Method 5910B (i.e., without

0.45 μm filtration). Direct reading spectrophotometers, the most common type of spectrophotometer, may overestimate the A_{254} of water with turbidity greater than 3 NTU, resulting in an overly conservative UV dose calculation (Christensen and Linden 2002). To reduce this overestimation, an integrating sphere can be installed in a direct-reading spectrophotometer that will provide accurate A_{254} measurements. Regardless of the type of spectrophotometer used, the effects of increased absorbance due to particles can be accounted for in the A_{254} measurement, which can then be used to determine the design UVT. If an appropriate design UVT is used, the UV reactor will be able to respond to changes in UVT that arise due to particles.

Particles and microorganisms in a water sample are either dispersed or aggregated together. Studies have demonstrated that dispersed coliform bacteria in wastewater are easier to disinfect than aggregated bacteria (Parker and Darby 1995). To date, research examining the effects of particles in drinking water on UV disinfection has been performed with seeded organisms and particles. It is unknown at this time how well these studies represent naturally occurring microorganism and particle interactions. However, since the concentration of microorganisms in unfiltered sources is typically below detectable limits, methods to examine this phenomenon directly (without seeding) do not currently exist. Consequently, seeded drinking water studies can only suggest the impact of turbidity on dose-response as it relates to the impact of UV light scattering by particles rather than particle-association or clumping of microorganisms.

Recent research has shown that particles present in supplies meeting regulatory requirements for unfiltered drinking water do not impact the UV inactivation of seeded microorganisms. Passantino and Malley (2001) reported that for unfiltered surface waters, turbidity up to 7 NTU does not affect the inactivation of seeded male specific-2 bacteriophage (MS2) in bench-scale, batch, collimated beam testing. In this study, turbidity was increased by adding natural sediment to waters collected from unfiltered water supplies. Therefore, naturally occurring interactions between particles and microorganisms could not be evaluated. In another study, batch (bench-scale) and continuous-flow (pilot-scale) studies showed that turbidity ranging from 0.65 to 7 NTU does not affect the UV dose necessary per log inactivation of seeded MS2, G*iardia muris*, or *Cryptosporidium parvum* in unfiltered waters (Oppenheimer et al. 2002). Womba et al. (2002) evaluated the impact of turbidity on UV inactivation of MS2 at the bench- and pilot-scale. They found that on the bench-scale, when the impact of turbidity was accounted for in the UV dose determination, the inactivation of MS2 was not affected by turbidity. However, in this study on the pilot-scale, because the lamp intensity and flowrate (and therefore residence time in the reactor) remained constant, the effects of turbidity were not accounted for in the reactor control strategy. Therefore, the reduction equivalent dose (RED) observed decreased as turbidity increased.

Unfiltered supplies are also susceptible to algal blooms. Womba et al. (2002) monitored algae levels in an unfiltered supply reservoir for over one year and found that algal counts were typically below 30,000 cells/mL; however one algae event had a higher level of nearly 300,000 cells/mL. Although not regulated, the presence of algae may interfere with the UV disinfection process. Womba et al. (2002) and Passantino and Malley (2001) examined the effects of algae on UV disinfection of MS2 at the bench-scale in batch, collimated beam testing. Both studies found that up to algal counts up to 70,000 cells/mL and 42,000 cells/mL, respectively, do not affect the inactivation of MS2.

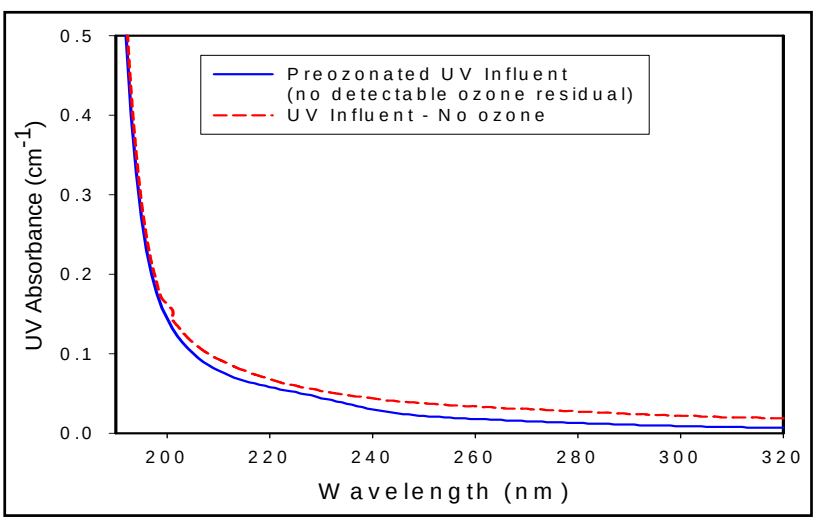
G.2 Debris

Relative to post-filter applications of UV disinfection, there may be greater opportunity for debris to be present in the influent to UV reactors in unfiltered applications. Debris entering the UV reactor with sufficient momentum could cause lamp sleeve and lamp breakage. The mass and size of an object that might cause damage is installation-specific and depends on UV reactor configuration (e.g., horizontal versus vertical reactor orientation) and water velocity through the reactor. As such, designs should incorporate features that prevent potentially damaging objects from entering the system; the optimal approach is site-specific. Such features could include screens, baffles, or low velocity collection areas. Another option is to install the UV reactors vertically with the inlet closest to the ground, following a low velocity zone. This arrangement will decrease the momentum of larger debris and reduce the risk of lamp breakage. The effects of lamp breakage and methods of minimizing it are discussed in Appendix N.

G.3 Ozone Impacts on Absorbance

Some utilities using an unfiltered source may consider applying ozone in addition to UV disinfection. There are a number of benefits associated with this process combination, including addressing multi-barrier disinfection requirements. Additionally, if ozone is added prior to UV disinfection, the A_{254} of the water can be reduced as shown in Figure G.1, thereby improving the efficiency of UV disinfection.

Figure G.1 Impact Of Pre-Ozonation On A_{254} (Malley 2002).

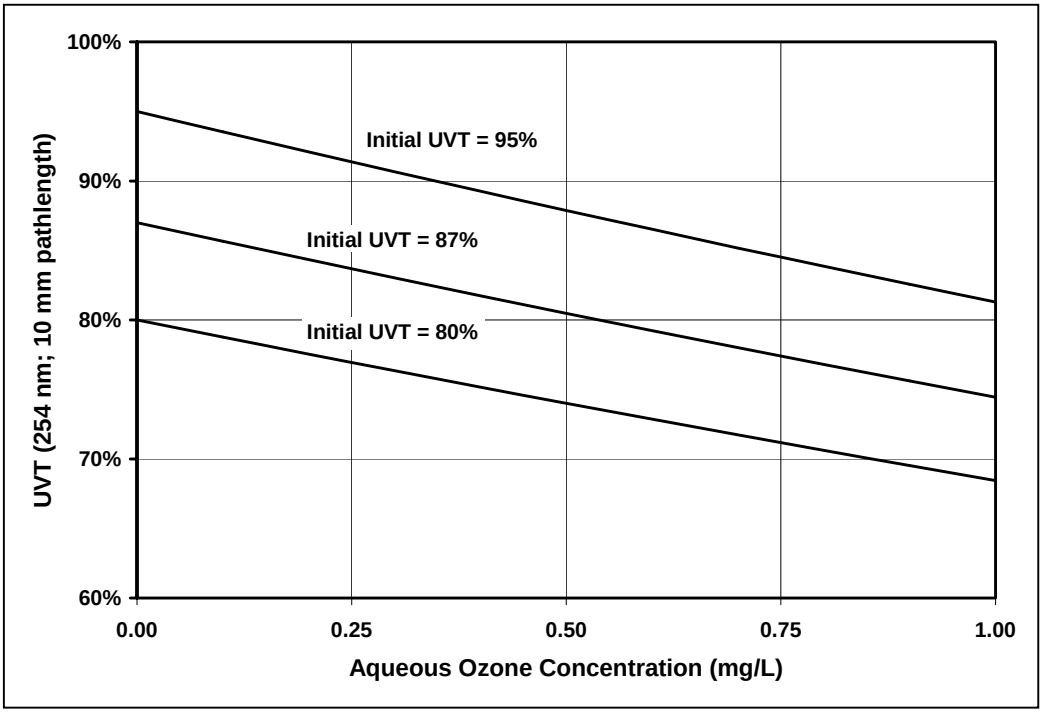


It should be noted, however, that ozone is a strong UV absorber with a molar absorbance value of 0.0677 L/mg/cm at 254 nm. Figure G.2 illustrates the impact of ozone concentration on UVT[1] for three baseline transmittance values. If ozone is applied prior to UV reactors and residual ozone enters the UV reactor, the increase in UV absorbance due to ozone residual can be

[1] $UVT(\%) = 100 * 10^{A_{254}}$

significant and should be considered when determining the design UVT. To address this issue, utilities can monitor the ozone residual and add an ozone-reducing chemical to maintain the ozone residual below a specified setpoint value (e.g., 0.1 mg/L). There are several chemicals that can be used to quench ozone; however, some chemicals (such as sodium thiosulfate) have a high molar absorbance value (as shown in Table A.5, section A.4.1.3), and thus have the potential to decrease the UVT. Such chemicals should not be used prior to UV disinfection. Sulfite has a lower molar absorbance value and is therefore an acceptable chemical to quench ozone residual. The impact of water treatment chemicals on UV absorbance can be assessed by preparing solutions of various concentration and measuring their UV absorbance using a standard spectrophotometer (Bolton et al. 2001).

Figure G.2. Impact of Ozone Residual on UVT (adapted from Cushing et al. 2001)



In at least some cases, the increase in UVT resulting from ozone addition will improve overall UV disinfection effectiveness provided that any remaining ozone residual is adequately controlled. Each utility should explore the sequence of disinfectants that best fits their site-specific objectives and constraints.

G.4 Off-specification Requirements

Off-specification is when the UV reactor is operating outside of its validated limits. UV installations should be designed with process monitoring and control components (e.g., alarms, shut-off valves) to prevent water from entering the distribution system when a UV reactor is operating outside of validated conditions. Unfiltered systems that use UV disinfection to meet the *Cryptosporidium* treatment requirement of the LT2ESWTR must demonstrate that at least 95

percent of the water delivered to the public during each month is treated by UV reactors operating within validated limits (i.e., operating conditions that have been validated to achieve the necessary log inactivation) (40 CFR 141.721(c)). Failure to demonstrate this will result in a treatment technique violation.

The UV reactors are off-specification when any of the following conditions occur (40 CFR 141.729(d)):

- The flow, UV intensity, or lamp status is outside of the validated range.
- The UVT or UV intensity is outside of the validated range (if the UV intensity and UVT setpoint approach is used (section 3.1.5))
- The calculated dose is outside of the validated range at a given flow (if the calculated dose approach is used (section 3.1.5))
- All UV lamps in all UV reactors are off because of a power interruption or power quality problem (as discussed in section 3.1.3.3), and water is flowing through the reactors.

More information on off-specification is in section 3.1.3, and compliance information is in section 5.4.1.

G.5 References

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Appendix H. Issues for Ground Water Systems

The UV installation design, operation, and maintenance principles presented in Chapters 3 and 5 of this manual are focused on the use of UV reactors to disinfect filtered surface water. Most of the information presented in those chapters is also applicable to ground water systems. Additional ground water-specific regulatory requirements and recommendations, site issues, hydraulic issues, and water quality issues that affect design and operation are discussed in this appendix.

H.1 Ground Water Systems Background

Regulations should be reviewed to determine the goals and requirements for disinfection. Existing treatment processes and distribution system parameters should also be analyzed before selecting a strategy for integrating UV disinfection into the system.

H.1.1 Regulatory Background

Currently, federal regulations do not require ground water systems to provide primary or secondary disinfection unless the water is a ground water source under the direct influence of surface water (GWUDI). However, some States require ground water systems to maintain a residual disinfectant in the distribution system. In addition, ground water systems are required to meet the requirements of the Total Coliform Rule (TCR) (54 FR 27544) and the Stage 1 Disinfection and Disinfection Byproducts Rule (DBPR) (63 FR 69390) and are expected to be affected by the upcoming Stage 2 DBPR.

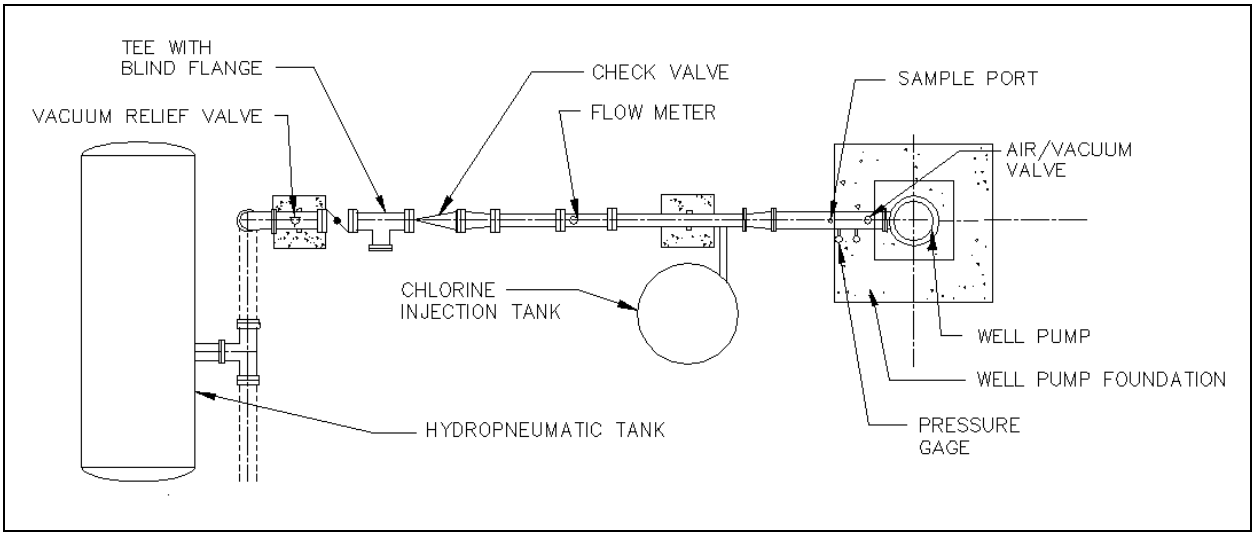
The upcoming Ground Water Rule, as proposed, would require some ground water systems to provide 4-log removal or inactivation of viruses. Systems with significant deficiencies, as determined by States during sanitary surveys, and systems that detect fecal indicators in their source water will be affected. These systems will be required to correct any deficiencies, provide water from an alternative source, or install treatment that provides 4-log removal or inactivation of viruses.

Ground water supplies that are designated as GWUDI, as defined in the Surface Water Treatment Rule (SWTR), 40 CFR Part 141.2, are classified as Subpart H Systems and must meet the same regulatory requirements as surface water systems. GWUDI systems often use many of the same treatment strategies as surface water systems, including filtration. The issues involved with implementing UV disinfection at filtered water utilities (including GWUDI) are discussed in detail in Chapters 1 through 5 of this manual. GWUDI systems are subject to the Stage 1 DBPR and would be subject to the upcoming Stage 2 DBPR and the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). Both of these regulations are summarized in section 1.3.

H.1.2 Typical Ground Water System Design

Most ground water systems operate by cycling ground water pumps on and off in response to demand or storage capacity. Because significant treatment is not usually necessary beyond secondary disinfection, ground water systems typically do not have a single, centralized treatment system. Many ground water systems pump to storage (e.g., hydropneumatic tank, elevated storage tank), but some may discharge directly to the distribution system. A production well typically consists of a well pump, and may contain a chlorinator (for secondary disinfection) and corrosion control equipment (for Lead and Copper Rule compliance), air release valves, vacuum relief valves, and other ancillary equipment necessary for well operation (Figure H.1).

Figure H.1. Typical Ground Water Well Site Layout



UV reactors may be installed at each well in a production system. If multiple wells are located in the same area, centralizing the flow through a common header minimizes the number of UV reactors needed and possibly reduces the project cost. In addition, treatment for other aesthetic issues (e.g., removal of iron and manganese or stripping of sulfides) may be more effectively accomplished with centralized treatment. An engineering cost analysis should be conducted to compare centralized treatment with the installation of individual reactors at each well.

H.2 Water Quality Issues

Although ground water typically exhibits small variations in water quality, specific parameters need to be analyzed when planning for a ground water system. As with surface water systems, UV absorbance at 254 nm (A_{254}) and the corresponding UV transmittance (UVT) is the most important parameter when designing a UV installation because it affects the UV reactor size. In addition, many naturally occurring constituents present in ground water (e.g., calcium, iron, manganese, aluminum, chloride, carbonate, sulfide, and phosphate) are capable of fouling the lamp sleeves in UV reactors, and these constituents should be monitored. The potential for

fouling is greater with medium pressure (MP) reactors than low pressure (LP) and low pressure high output (LPHO) reactors because MP lamps operate at higher temperatures (section 2.4.2). Mechanical wipers are often effective at removing fouling on the lamp sleeves. In situations where the ground water has detectable levels of iron and manganese, chlorination prior to the UV reactors may cause increased fouling or staining, necessitating chemical cleaning (Malley et al. 2001). A complete discussion of the relevant water quality parameters and the determination of their design values is presented in section 3.1.3.1.

With ground water systems, it is common for one or more wells to be taken out of service for an extended period due to fluctuations in water demand, ground water quality, operational problems, or other planned and unplanned circumstances. Toivanen (2000) reported that the lamp sleeves and internal surfaces of the UV reactors became fouled when the UV reactors were out-of-service and full of water. The amount of time it takes to foul the UV reactor while off-line is site-specific and depends on the water quality. At a minimum, it is recommended that the reactors be drained if the UV reactor is off-line for more than one week; however, the appropriate period for this could be shorter or longer depending on the water quality. If the UV reactor will be off-line for an extended period of time (longer than 30 days), it is recommended that the reactor be cleaned prior to re-starting the UV reactor. Routine shutdown and start-up procedures are discussed in section 5.2.3.

H.3 Off-Specification Issues

UV reactors must be validated as discussed in Chapter 4 and operated within the conditions determined during validation. When a utility is operating outside of the validated limits, the utility is operating “off-specification."

LT2ESWTR includes requirements limiting off-specification for compliance with the LT2ESWTR for unfiltered supplies (40 CFR 141.721(c)(2)); however, the rule does not state an off-specification requirement for filtered systems or ground water systems. States may develop statewide or site-specific requirements off-specification requirements for ground water systems.

There are two ways that a ground water system could be operating off-specification. First, off-specification can occur when the flow, UVT, or UV intensity is outside of the validated conditions. Second, UV lamps can lose arc if a voltage fluctuation, power quality anomaly, or a power interruption occurs. LP lamps generally can return to full operating status within 15 seconds after power is restored. However, LPHO and MP UV lamps exhibit restart times between 4 and 10 minutes if power is interrupted (Cotton et al. 2002). During these restart times, the water being distributed is inadequately disinfected and is considered off-specification.

H.3.1 Power Quality Assessment

A power quality assessment at each well site should be performed to determine if power quality might cause off-specification operation. In addition, the reliability of commercial power at remote sites may be less than that of more populated areas. Backup power or an uninterruptible power supply (UPS) may be needed, depending on the findings of the power

quality assessment. If backup power is already available for the well pumps, then the backup power supply should be assessed to determine if sufficient output is available for the UV reactor. However, UPS may also be needed if there are frequent power quality problems. For systems that have storage following UV disinfection, it may be possible to isolate the UV reactor and rely on stored water to meet demand during periods of power failure. Power quality assessments are discussed in more detail in section 3.1.3.3.

H.3.2 Well Pump Cycling

Well pumps may regularly cycle on and off in response to changes in distribution system pressure, causing the UV reactor to also be cycled. Frequent lamp cycling reduces lamp life. Manufacturers recommend that whenever possible lamps remain energized for a minimum of 6 hours (Dinkloh 2001). In addition, the warm-up time when the UV reactor is coming on-line is considered off-specification until the UV intensity sensor reading reaches the validated value if water is flowing to the distribution system.

Depending on its current operation and direction from the State, the utility may need to consider changing the well pump cycling strategy or incorporate UV reactor controls to reduce off-specification time and to meet the needs of the distribution system. The utility should discuss its proposed operating strategy with the UV manufacturer to ensure it is appropriate for the selected UV reactors. While there may be any number of operating strategies that a utility could use, two operational strategies that could be incorporated to sequence the well pumping with the operation of the UV reactor are presented below.

The first strategy is to incorporate a delay that prevents the well pump from starting until the UV reactor reaches its validated UV intensity sensor setpoint (i.e., no flow through the UV reactor). Under this control strategy there will be a period when the UV reactor will be “on” but no flow will be passing through it. This control strategy is only effective when LP or LPHO reactors are used because their lamps can operate for up to 1 hour under no-flow conditions (Dinkloh 2001) without overheating. However, MP UV reactors may heat the water above the safe operating temperature of 50 degrees Celsius in 1 to 15 minutes, causing the reactor’s internal safety devices to shut the reactor off (Miller 2001). As such, this control strategy may be infeasible for MP reactors unless they incorporate a low flow waste line that allows water to circulate through the reactor in order for MP lamps to reach the validated UV intensity sensor setpoint without overheating. The UV manufacturer should be contacted to confirm that this operational strategy is feasible with or without the waste line.

The second strategy is to provide a system of automated valves that diverts the UV reactor discharge away from the distribution system until the reactor reaches its validated UV intensity sensor setpoint. Then the automated valves are repositioned to direct the water from the UV reactor to the distribution system. This strategy delivers the off-specification water to “waste” until the validated UV intensity sensor setpoint is reached. This ensures that sufficient cooling water will flow through MP reactors to prevent overheating and reactor shutdown. For this strategy, the utility needs to develop an approach for managing the water that is wasted during reactor warm-up. The water may be wasted to a sanitary sewer, storm sewer, on-site disposal or drainage system, or temporary storage tank. The utility should coordinate the discharge location with the State and other involved parties.

Both operational strategies introduce a lag between the time when the pump is initiated and the time when water is introduced into the distribution system. Because of this, existing controls may need to be adjusted to avoid insufficient system pressure or storage during periods of UV reactor warm-up. This will be particularly important for those ground water systems that have frequent on-off cycles or limited storage.

H.4 Well Location Issues

Ground water production wells are sited in a variety of locations, ranging from urban areas to remote installations. The well location will affect the design and operation of the UV installation, especially if there is limited space.

H.4.1 Design Considerations

As discussed in section 3.3.5.2, the UV reactor should be installed within a building or underground vault if possible to facilitate maintenance and protect sensitive equipment. The need for enclosure of the UV installation will ultimately be based on the manufacturer's recommendations, local regulatory and code requirements, environmental conditions, and site-specific constraints. Site security should be appropriate to prevent tampering with the equipment and water supply and to protect people from injury (e.g., electrocution).

Well sites, particularly in urban areas, may be spatially constrained by adjacent development. As a result, the amount of exposed pipe and available area for locating equipment may be limited. In these cases, it may be necessary to modify the pump discharge piping to accommodate a UV reactor. When constructing a UV installation in an extremely confined location, the designer must consider the area necessary for operation and maintenance and the area needed for installation (e.g., staging areas, personnel, and equipment access). In addition, the inlet and outlet piping should meet the criteria listed in section 3.3.1.1 as compared to the validated inlet and outlet piping.

UV reactors are susceptible to damage by suspended sand particles or other debris that may be present in a ground water supply and pass through the well screens. Therefore, it is important to determine if sand, grit, or fines are present in a well supply and if it is necessary to install a sand/debris trap or removal equipment prior to UV disinfection. Particles flowing through the UV reactor may scratch the lamp sleeves, cause the sleeve wiping mechanisms to jam, or shield pathogens from UV light, thereby decreasing the UV disinfection effectiveness. In addition, larger particles could break the lamp sleeves and lamps (see Appendix N for lamp breakage issues).

H.4.2 Operational Issues

Because most well sites are not continuously staffed, UV installations may need sufficient automation to allow remote monitoring and operation. Controls and alarms should be designed to ensure that real-time operational and monitoring data are communicated to the

operators. These factors also emphasize the importance of a power quality assessment and the design of alarms, monitoring capabilities, and backup power facilities.

Disposal of the chemicals used to clean the UV reactors may be an issue if an on-line chemical cleaning (OCC) system is used (section 2.4.5). If sewer connections or other standard means of disposal are not available, then chemical waste will need to be transported off-site for disposal or handled on-site. Utilities should consult with chemical suppliers and the State when developing disposal strategies.

H.5 Hydraulic Issues

The hydraulic issues associated with ground water systems include high operating pressures, piping configuration, air entrainment, and the potential of water hammer and surge events.

Many well pumps discharge directly to the distribution system or to elevated or pressurized storage; therefore, the discharge will often be at system pressure. The UV reactor design may need to be modified to accommodate these higher distribution system pressures.

The actual inlet and outlet hydraulics of the UV reactor should be designed to match the validated hydraulics as discussed in section 3.3.1. Space is often limited with ground water installations so valves, flow meters, or other appurtenances may be directly upstream or downstream of the UV reactor. Consequently, these site constraints may need to be considered in determining how the UV reactor should be validated. Detailed discussions of UV installation layout and validation are given in section 3.3.5 and Chapter 4, respectively.

UV reactors should be flooded at all times because air binding can interfere with the UV disinfection process or cause the lamps to overheat. UV reactors should be located downstream of any existing or planned air removal equipment (if necessary). Otherwise, the UV installation design should include a means for automatically releasing air prior to the UV reactor. The UV reactor may have integral air release valves or valve ports, or air release valves can be installed in the inlet and outlet piping.

Pressure surge events (water hammer) near the UV reactor may be more likely with ground water systems than surface water systems because of the UV reactor's proximity to the well pumps. Surge events can cause positive or negative pressure transients in the well discharge piping. Negative pressures as small as -1.5 psi may cause the lamp sleeves to break (Dinkloh 2001). A surge analysis is recommended to determine if surge protection is necessary. Many well sites and distribution systems are already equipped with surge control tanks to dampen surge effects. These tanks may provide sufficient protection for the UV reactors, depending on their location relative to the UV reactors.

Other surge control devices, such as air/vacuum release valves, may rely on the introduction of air into the system to mitigate surge. As discussed previously, the presence of air can negatively affect the performance of the UV reactors. Air/vacuum valves should only be used if surge tanks are not an option and the design can eliminate the air prior to the UV reactor (e.g., install the valve in a section of pipe at a higher elevation than the UV reactor).

H.6 References

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Appendix I. Issues for Small Systems

The objectives of this appendix are to highlight the issues that small systems face when considering UV disinfection and to reference the more detailed discussion of these issues in this manual.

To be classified as a public water system, a utility must provide water to a minimum of 15 service connections or serve at least 25 people for at least 60 days per year (40 CFR 141.2). For the purpose of this appendix, the term small system includes those utilities serving fewer than 10,000 people or having a daily production rate of less than approximately 1.0 mgd. Most of the information regarding UV disinfection in Chapters 2, 3, 4, and 5 is valid for both small and large systems.

I.1 Is UV Disinfection Applicable to Small Systems?

UV disinfection is applicable to small systems and may be attractive for the following reasons:

- It is a relatively low cost technology for the inactivation of *Cryptosporidium* (Cotton et al. 2001).
- Chemical use is little to none.
- Operation is relatively simple and maintenance is low.
- Space needs are small.

Two types of UV reactors can potentially be used by small systems, conventional and point-of-entry (POE) devices. Conventional UV reactors are manufactured for a wide range of flows (e.g., from 20 gallons per minute (gpm) up to 40 mgd) and are described in section 2.4. POE units are small UV reactors that are installed at the service connection of the customer. POE units contain the same components as conventional low-pressure (LP) installations but are more compact. They are primarily intended for use at individual properties and may be more suitable for utilities with a limited number of service connections. POE units are required to be owned, controlled, and maintained by the utility or by a person under contract with the utility to facilitate proper operation and maintenance and compliance with the treatment requirements (Safe Drinking Water Act (SDWA) Section 1412(b)(4)(E)). The use of POE units may result in higher total costs when compared to a centralized, conventional UV installation for all but the smallest water utilities.

I.2 What Information is Necessary to Assess the Feasibility of UV Disinfection?

Small systems generally need the same information to assess UV disinfection as larger systems. Chapter 3 describes the planning and design process for a UV installation in a

conventional plant and discusses each of the elements that should be considered. In general, the utility should answer the following questions when assessing the suitability of UV disinfection:

- What are the disinfection goals and can UV disinfection be used to meet these goals? (section 3.1.1)

- What are the minimum, average, and maximum flowrates that the UV reactors will need to treat? (section 3.1.3.2)

- What is the design UV absorbance at 254 nm (A_{254}) and corresponding design UV transmittance (UVT)? What is the fouling potential of the water supply? What is the potential for process upset or variability in water quality? Do any of the existing processes have the potential to interfere with the performance of the UV reactors? (section 3.1.3.1)

- Can the UV reactors be incorporated into the existing hydraulic profile? If not, can the existing operations be modified to accommodate the UV reactors, or does intermediate pumping need to be installed? (section 3.1.6.1)

- Can the UV installation be incorporated into the existing facility layout? Does a building need to be constructed to house the UV reactors? (section 3.1.6.2)

- Is the quality and reliability of the electrical power supply adequate? Does a backup power supply or other supplemental electrical equipment need to be installed? (sections 3.1.3.3 and 3.3.4)

- How should the UV reactors be controlled? What level of automation and operational complexity is appropriate? Does the potential for power savings justify using a more complex operating strategy? Is the existing operations staff sufficient? (section 3.3.3)

- Is the number of UV reactors installed appropriate to efficiently respond to the anticipated range of flowrates? Does the UV installation have the capability to be expanded to meet future increases in demand? Is there sufficient redundancy to allow operating flexibility and to meet the disinfection goals under the operating scenarios? (section 3.1.3.2)

- How should the UV reactors be procured? (section 3.2)

- Do the characteristics of the proposed UV application (e.g., flowrate, UVT, UV intensity) differ from those under which a selected UV reactor was validated? If so, should the selected equipment be validated on-site or off-site under characteristics that match those of the intended installation? (Chapter 4 and section 3.1.4.2)

- What is the capital cost of the UV installation? What are the operating costs associated with a UV installation? (section 3.1.7)

- What is the cost of the UV installation as compared to other disinfection alternatives?

- Is there a cost benefit to using POE units as opposed to a centralized UV installation? If so, how should the utility administer the POE units? Is some form of access agreement or water use ordinance necessary to allow administration of the POE units?

I.3 Do the UV Reactors Need to be Housed in a Building?

If possible, the UV reactors should be constructed within a building to facilitate maintenance and protect the UV reactors. Nonetheless, the need for enclosing the UV reactors will ultimately be based on manufacturers' recommendations, State requirements, and environmental conditions. Although some current UV installations do not have a building (e.g., Hanovia facility in Australia), local building and electrical codes may necessitate a building or other protection for the electrical equipment. Regardless of whether the UV reactors are enclosed, site security is important to prevent tampering with the equipment and water supply and to protect people from injury (e.g., electrocution). Section 3.3.4 discusses the electrical equipment issues that should be considered during the planning and design of a UV installation.

I.4 Do the Components of a Small System Differ from Larger UV Reactors?

The main components of a UV reactor (including the necessary instrumentation and controls) do not differ between large and small systems. Components of the UV reactor may include the UV lamps, lamp sleeves, UV intensity sensors, ballasts, and cleaning mechanisms, which are described in section 2.4.

Full-scale drinking water applications generally use LP, low-pressure high-output (LPHO), or medium-pressure (MP) lamps. Small systems may find reactors that use LP or LPHO lamps more economical because they convert power into germicidal wavelengths of UV light more efficiently than MP lamps. Additionally, LP lamps typically have a longer useful life than either MP or LPHO lamps. For small systems, UV reactors with LP lamps are likely to represent the most cost-effective disinfection solution. For systems that serve near 10,000 people or treat near 1 mgd, more consideration should be given to LPHO or MP lamps. An additional discussion of the different lamp types is given in section 2.4.2.

I.5 What are the Power Needs?

The power needs depend on the manufacturer. Common manufacturers' power needs are as follows:

- POE UV units – 120V/60Hz/1 phase
- Conventional LP reactors – 120/208V/60Hz/3 phase
- Conventional LPHO reactors – 480V/60Hz/3 phase
- Conventional MP reactors – 480V/60Hz/3 phase

Backup power may be necessary, depending on the type of installation that is selected, the power quality at the installation site, and the regulatory requirements for the installation. However, backup power for small systems may not be necessary as some small systems can accommodate a shutdown for longer periods because there is sufficient storage to meet demand. Additional detail on the need for backup power and the factors that should be considered when assessing the power supply are discussed in section 3.1.3.3.

I.6 Do Small UV Reactors Need to be Validated?

All UV reactors, including POE units, are required to be validated (40 CFR 141.729(d)). Small systems will probably purchase UV reactors that have been validated by the manufacturer. UV intensity sensor operating setpoints (and potentially UVT setpoints) are established at specific flowrates during validation testing. These are the setpoints that the systems are required to operate within to receive inactivation credit. For many small UV reactors and nearly all POE units, UV reactor control will be limited to “on” and “off” with UV reactor shutdown under specific critical alarm conditions. Chapter 4 discusses the UV reactor validation requirements, and Chapter 5 describes operating requirements.

I.7 How are UV Reactors Monitored?

Monitoring UV reactors (conventional and POE) is required to ensure that the UV reactors are operating within the validated range (40 CFR 141.729(d)). Parameters that must be monitored include flowrate, UV intensity sensor readings, and UVT (if it is part of the control strategy) (40 CFR 141.729(d)). POE units should be equipped with mechanical warnings to ensure that customers are automatically notified of operational problems. Additional detail on monitoring requirements is provided in section 5.4.1.

I.8 Can the UV Reactors be Operated Remotely?

UV reactors can be operated remotely if the monitoring components provide a 4-20 mA analog output signal and are integrated into a control strategy. Even though UV reactors can be operated remotely, routine inspections and on-site maintenance will be necessary to confirm that the UV reactor is operating properly. Provisions for hydraulic and electrical lockout should be provided to enable local isolation and lockout for maintenance. Section 3.3.3 provides additional detail on control strategies for centralized UV installations, and section 5.3 discusses operations and maintenance needs.

If the utility uses POE units, it may be beneficial to telemeter all alarm conditions to a central location to facilitate administration and maintenance of the POE units. However, incorporating this remote capability will likely increase the cost of the UV installation.

I.9 How Much Maintenance is Needed?

Maintenance is generally limited but will vary depending on the manufacturer and the specific application. Maintenance may include the following activities:

- Periodic calibration verification of UV intensity sensors, UVT meters, or flowmeters
- Periodic replacement of UV intensity sensors, UVT meters, or flowmeters (if applicable), depending on calibration or age of the equipment
- Lamp sleeve and reactor cleaning
- Replacement of UV lamps and other components
- Maintenance of other operating components and the electrical systems

Operators should be trained by the UV manufacturer on the proper operation and maintenance of the UV reactors. The utility should consider contracting trained service personnel to maintain the UV reactors if this is not possible. Additional detail on operations and maintenance is given in section 5.3.

I.10 References

Cotton, C.A., D.M. Owen, G.C. Cline, and T.P. Brodeur. 2001. UV disinfection costs for inactivating *Cryptosporidium*. *Journal of the American Water Works Association* 93, no. 2: 67-74.

Appendix J. Pilot-Scale and Demonstration-Scale Testing

In some cases, pilot- or demonstration-scale testing may be warranted to aid in selection of design criteria. For example, long-term UV unit performance will be impacted by lamp aging and sleeve fouling. With increased use, lamp output decreases due to deposition of inorganic material on the outside and inside of the sleeve (i.e., "fouling"). Fouling reduces the transmittance of the lamp energy to the water. Over time, these phenomena will contribute to a reduction in UV dose. The effect of these parameters should be incorporated into the UV reactor design. A "lamp aging factor" and a "fouling factor" are usually specified by the design engineer. Pilot testing can provide useful information for the development of these factors.

This appendix discusses when pilot or demonstration tests may be needed and the types of tests that may be performed on UV disinfection systems. The purpose(s) of pilot and demonstration testing is to establish or confirm system design factors, test system reliability, and evaluate operation and maintenance (O&M) needs. The tests described herein may be performed individually or in parallel. Validation of reactor microbial inactivation performance is addressed separately in Appendix C (Validation Protocol).

J.1 When Is Pilot or Demonstration Testing Needed?

Pilot and demonstration tests can be used to meet the following three goals:

1. Assess the impact of unusual water quality conditions (e.g., high calcium or iron concentrations).

2. Improve estimation of safety factors for large water systems for which such an investment can yield a high return in reduced life cycle costs.

3. Gain first-hand experience with operating and maintaining a UV installation.

A UV disinfection system should be designed with some knowledge of the likely fouling potential of the water and lamp-aging characteristics to ensure the system operates as intended. If the design and the operation protocol do not properly account for the effects of lamp aging and sleeve fouling, the system may go into alarm frequently (indicating under dosing).

While pilot or demonstration testing may be warranted in some cases, it is becoming less necessary as more performance and fouling information is developed. The need for pilot or demonstration testing should be carefully considered in light of the pre-existing data available on both system performance and water quality effects on sleeve fouling. Pilot or demonstration testing may be used to gain operational experience or primacy agency acceptance, as discussed in the following sections.

Microbiological challenge tests are not recommended during pilot studies because inactivation efficiency in a pilot system may not be indicative of full-scale performance. However, UV reactor validation bioassays could be conducted as part of a full-scale

demonstration test if on-site testing is planned. Appendix C presents a detailed discussion of UV reactor performance validation.

Because UV disinfection is a relatively new drinking water treatment technology in the United States, State regulatory agency acceptance may depend in part on the confidence in the technology gained through pilot- and demonstration-scale studies. Identifying previous studies of similar scope that provide background and precedents may also be helpful in gaining acceptance of its planned use (see, for example, et al. Mackey 2001).

If a utility chooses to or is required to conduct pilot or demonstration tests, the primacy agency should understand the objective(s) of the test(s) and the methodologies used. It is recommended that the primacy agency be contacted before testing and involved throughout the pilot and/or demonstration testing. Identifying and resolving State regulatory agency concerns when planning testing can help produce a more useful dataset. Additionally, it may be helpful to include the State in interim briefings on progress and results, and to give them a final report after completing the testing.

J.1.1 Water Quality Impacts

Extensive data have been generated from pilot-scale testing on waters of low to moderate hardness and iron content (Mackey et al. 2001, Mackey and Cushing 2003). At total hardness and calcium levels below 140 mg/L and low iron (less than 0.1 mg/L), standard cleaning protocols and wiper frequencies (one sweep every 15 minutes to an hour) were more than adequate to deal with the impact of sleeve fouling at all sites tested. At sites with hardness or iron in the feed water that exceed these levels, it may be advantageous to evaluate fouling rates on a site-specific or worst case basis via pilot or demonstration testing to identify how best to keep the sleeves clean.

J.1.2 Lamp Fouling Factors for Large Systems

In UV reactor design, a lamp aging factor of 0.7 is commonly used, as discussed in section 3.1.3.1 of the Manual. For larger systems, it may be economical to pilot or demonstration test lamp aging to provide data for selecting lamp aging and low-dose-alarm design factors that will best balance operational costs (how many hours one wants to be able to operate a lamp before replacing it) with capital costs (the size of the system needed based on end-of-lamp-life). Lamp aging factors may also be obtained from a certified lamp age testing program performed by equipment or lamp manufacturers. A lower lamp aging factor means the utility will have less frequent lamp replacements, but may require a larger system to ensure compliance at all times.

J.1.3 Gaining Operational Experience

Due to the small number of U.S. drinking water UV installations, very few United States operators have experience with UV disinfection systems. It may be beneficial for a facility's

staff to obtain operational experience with UV disinfection systems prior to selecting and implementing UV disinfection. If a utility staff becomes familiar with the operational aspects of UV disinfection, that staff will be able to provide feedback input on the UV installation design. In addition, operational experience can help facility managers to determine the staffing/training needs and help maintenance staff understand and plan for the maintenance needs of the system (e.g., time to change lamps and calibrate UV intensity sensors and perform manual cleaning).

On-site testing is site-specific depends on the needs and preferences of the utility. Methods by which facility staff can gain operational experience (besides on-site testing) include: site visits and partnerships with systems already using UV disinfection; conversations and visits with manufacturers and attendance of seminars; and on-site training programs (a detailed discussion of training programs is provided in section 5.7.2).

J.2 Pilot- Versus Demonstration-Scale Testing

Table J.1 presents a comparison of the advantages and disadvantages associated with pilot-scale and demonstration-scale testing. Pilot-scale testing involves operating a smaller version of a full-sized UV disinfection reactor. It may or may not include all the components of the full-sized system. Demonstration-scale testing is essentially pilot testing of a full-scale UV disinfection reactor.

Table J.1 Comparison of Pilot and Demonstration Testing

Testing Method	Advantages	Disadvantages
Pilot-scale	• Smaller footprint needed for UV reactors • Less-expensive installation and operation • Operators gain O&M experience • High flexibility in placement of equipment • Lesser volumes of water to dispose	• Design conditions for UV disinfection systems may not scale-up to full-scale systems • In rare cases it may be advisable to use pilot-scale treatment process equipment (filters, clarifiers, etc.) to simulate operational conditions (e.g., upstream ozone process)
Demonstration-Scale	• Confidence in long-term operation of the UV unit due to the representative scale at which results are obtained • Scale-up factors need not be developed • Operators gain operations and maintenance experience on a full-scale system.	• Approval from the primacy agency may be required to conduct a demonstration study • Demonstration setups are not as flexible as pilot studies for operational experimentation • Installation and operation more expensive than pilot scale • Greater volumes of water to dispose.

J.3 Documenting the Test Reactor

For a given test, should the properties of the components that may influence the final outcome of the test should be identified and recorded. That record may later be used to confirm that key components of installed UV reactors match those of the systems tested. Table J.2 lists the components of a UV disinfection system that should be documented and compared between testing and the final design.

Table J.2 Key Components Associated with UV Reactor Pilot-Scale and Demonstration Scale Testing

Test	Components to Document
Operational Experience	Controls, alarms, cleaning mechanisms, operation, maintenance.
Fouling Assessment	Lamps, sleeves, ballasts, power settings, UV intensity sensor windows, flow velocity.
Head loss Assessment (demonstration-scale only)	Reactor and wetted components, inlet/outlet conditions.
Ballast Performance	Lamps, sleeves, ballast, power settings, operation.
Cleaning Mechanism Performance	Lamps, sleeves, ballasts, power settings, ballast operation, UV intensity sensor windows (if wiper used), cleaning mechanism, cleaning solutions, wiper maintenance and operation.
Lamp Aging/Failure	Lamps, sleeves, ballasts, power settings, ballast operation, cleaning mechanism, cleaning solutions, wiper maintenance and operation.
Sleeve Breakage	Sleeves, cleaning mechanisms, flow velocity, water hammer.
Controls/Alarms	Lamps, sleeves, ballasts, UV intensity sensors, cleaning mechanisms, controls, operation.

J.4 Testing Objectives

Pilot/demonstration testing may be used to gain information on a specific UV reactor, a specific water treatment plant (WTP) site, or a combination of the two. Common test objectives include the following topics:

- The long-term performance and failure modes of the lamps
- The efficacy of cleaning mechanisms for lamp sleeves and UV intensity sensor windows
- The stability of UV intensity and UVT monitors

- The reliability of controls and alarm systems
- The ease of lamp and UV intensity sensor replacement, the use of reference sensors, and the maintenance of cleaning devices and solutions
- The rate of fouling on lamp sleeves and UV intensity sensor windows
- The most appropriate cleaning method
- The head loss across the reactor at various flow rates (demonstration-scale only)
- The impact on other unit operations at the WTP

The information obtained during pilot and demonstration testing should be applicable to the final UV disinfection system installed at the WTP. Accordingly, the equipment tested should be representative of the UV disinfection system that will be installed. Specific elements of a pilot/demo-scale system that should be identical include the UV intensity sensors, lamp and sleeve type, power system, cleaning system, cleaning frequency, and water quality. For example, lamp-aging data on a 3 kW 25 cm medium pressure (MP) lamp driven by an electromagnetic ballast cannot be used to predict the aging expected with a 10 kW 50 cm MP lamp driven by a transformer.

J.5 Testing Protocols

This section describes the major elements and benefits of a range of pilot and demonstration testing protocols to investigate sleeve fouling and cleaning, lamp aging, head loss and alarms and controls.

J.5.1 Assessing Fouling

A fouling assessment can be conducted to answer the following questions:

- How fast do the lamps foul?
- How does water quality affect fouling?
- What lamp fouling factor should be specified?
- What lamp cleaning interval is required?
- What sleeve replacement interval is required?
- How do lamp/reactor configurations affect fouling?
- Is fouling of the UV intensity sensor window(s) significant and how should it be addressed?

Fouling may occur on the inner and outer surfaces of the lamp sleeves, the internal surfaces of the reactor, and UV intensity sensor windows. Lamp sleeve fouling may have an impact on dose delivery and cleaning requirements. Sensor window fouling may have an important impact on assessing dose delivery (e.g., the sensor will not be able to accurately measure lamp intensity). Fouling on the wetted surfaces of a UV reactor has been attributed to precipitation of compounds whose solubility decreases as temperature increases, precipitation of compounds with low solubility, and deposition of particles by gravity settling and turbulence-induced impaction (Lin et al. 1999a). More detailed discussion on fouling is provided in sections 3.1.3.1 and A.4.1.4.

In one method for assessing sleeve fouling similar to that employed by Lin et al. (1999b), a new lamp can be placed inside the fouled sleeve and ignited. Ultraviolet absorbance at 254 nanometers (A_{254}) is measured by a calibrated radiometer and compared to a similar measurement made using a new, clean sleeve. The ratio of these two measurements (UV light passing through the fouled sleeve to that passing through the new sleeve) is the lamp sleeve-fouling factor.

Manual, chemical cleaning should restore the sleeve A_{254} to very near that of a new, clean sleeve. If not, manually clean the inside of the sleeve and measure A_{254}. If it is still low, the sleeve material has likely degraded. If A_{254} cannot be recovered, further testing may be used to identify a proper sleeve replacement interval. The lamp sleeve-fouling factor can be plotted as a function of time. Worst-case results can be analyzed to determine cleaning requirements and fouling factors for design purposes.

When assessing lamp sleeve fouling, care should be taken to ensure that the results scale-up to full-scale applications. Some differences in system geometry may lead to erroneous conclusions based on pilot data alone. For instance, in parallel flow reactors, fouling has been found to be uneven along the length of the lamps (Lin et al. 1999a). If the lamp and lamp sleeve geometry (e.g., length or diameter) of the pilot unit is very different from the full-scale system, the fouling that will occur in the full-scale plant may be markedly different from expectations based on pilot-scale data. The lamp lengths will be very different and end-effects may be more pronounced (i.e., the blackened lamp ends of an aged lamp will comprise a greater percentage of the total length of the lamp).

To assess fouling on the UV intensity sensor windows, clean the sensor monitoring windows with phosphoric or citric acid at varying time intervals and record the change in sensor readings. It is expected that the rate of fouling on the lamps will be greater than the rate of fouling on the sensor windows due to elevated lamp temperature.

J.5.2 Evaluating Cleaning Systems

An evaluation of system cleaning methods can be performed to answer the following questions:

- Does a particular cleaning protocol work for the UV reactor application?

- What is the long term effectiveness of the cleaning method?
- What cleaning frequency is required for each method considered?

Various cleaning methods can be used to periodically remove the foulants that accumulate on the lamp sleeves and UV intensity sensor windows. Lamp sleeve cleaning methods include off-line chemical cleaning (OCC) (off-line manual or mechanized cleaning), on-line mechanical cleaning (OMC) (e.g., brushes or rings), and on-line physicochemical wipers (acid solution in a wiper collar). Sensor window cleaning methods also include manual cleaning and mechanical wipers.

J.5.2.1 Assessing Lamp Sleeve Cleaning Protocols

A sleeve cleaning assessment should be performed on at least four lamp sleeves, and the results be used to identify a sleeve fouling design factor for sizing the UV reactor based on the lowest individual sleeve-fouling factor observed. This will help ensure proper dose delivery for the entire life of the sleeve. One method for assessing lamp sleeve cleaning needs is detailed below:

Pass water through the reactor at the minimum flow rate and operate the lamps at maximum power. With systems using mechanical or physicochemical wipers, an unwiped sleeve can be used as a control to verify that fouling is occurring. The manufacturer's recommendations regarding the maintenance of the cleaning device should be followed.

Record the UV intensity sensor readings before and after the cleaning cycle and use this data to optimize the cleaning frequency. Sensor windows should be manually cleaned before measurements to ensure only lamp sleeve fouling is affecting the sensor values. If possible, check all UV intensity sensor readings with a reference sensor.

At regular time intervals and immediately prior to the scheduled sleeve cleaning cycle, remove the lamp sleeves and assess the sleeve A_{254} for low pressure (LP) lamps and absorbance from 200 - 400 nm for MP. The non-destructive method of Lin et al. (1999b) may be used as discussed in section J.5.1.

After 6 months, or when manual, chemical cleaning is recommended, remove the sleeves and measure the sleeve A_{254} before and after cleaning the outer surfaces. If the new sleeve transmittance is not restored by the cleaning, it is likely that the sleeve material has fouled internally or permanently degraded. Further monitoring and testing may be necessary to identify the proper sleeve replacement interval.

J.5.2.2 Assessing UV Intensity Sensor Window Cleaning Protocols

To assess fouling of the UV intensity sensor window, one alternative is to operate the reactor under the conditions suggested in section J.5.2.1 (i.e., minimum water flow rate, maximum lamp power). After 6 months, or a time interval suggested by the manufacturer, a chemical cleaning of the monitoring sensor window could be performed. Alternatively, cleaning

could be performed when the sensor reading falls to a minimum value suggested by the manufacturer. The A_{254} of the window should be measured before and after cleaning. A sensor window cleaning frequency can then be estimated as discussed in section 3.1.3.1.

J.5.3 Assessing Head Loss

Head loss assessments should be performed for demonstration-scale (full-scale) systems to verify that head loss constraints at the final install station will not be exceeded. Head loss data from pilot scale units should not be used to estimate head loss in a full-scale system.

The head loss, ΔH, through a UV reactor may be calculated according to Equation J.1:

$$\Delta H = \frac{Kv^2}{2g} \qquad \text{Equation J.1}$$

where

K	=	Head loss coefficient (unitless) for the UV reactor
v	=	Water velocity (m/s) through the reactor
g	=	Gravitational constant (9.8 m/s^2)

To assess head loss through a UV reactor, the UV unit can be installed with instrumentation to measure pressure loss across the reactor (including baffles and specialized inlet/outlet piping). Since the head loss coefficient will be higher at lower temperatures due to decreased water viscosity, it may be desirable, if feasible, to measure head loss at the lowest water temperature expected at the UV reactor installation to assess the worst-case condition.

If head loss is measured at various flow rates through the reactor, including the minimum and maximum flow rates, these measured head loss values can be plotted as a function of the square of the calculated water velocity through the reactor to determine a head loss coefficient.

J.5.4 Lamp Aging and Failure

A lamp aging evaluation can be conducted to answer the following questions:

- What is the actual operating lamp life?
- How does lamp output degrade over time?
- What lamp aging factor should be specified?

The service life of a UV lamp extends for thousands of hours. The germicidal output of the lamp will decline during this period (Phillips 1983). In MP systems, UV lamp aging can also result in a change in the spectral output over time. With polychromatic (MP) UV lamps, lower wavelengths will likely decline at a faster rate than will higher wavelengths. The rate and manner in which a lamp ages is lamp- and operation-specific. A detailed discussion of lamp

aging is presented in section A.3.1.6. Lamp output will decrease over time as a function of the lamp hours in operation, the number of on/off cycles, and the power applied per unit (lamp) length.

Lamp aging tests should be designed to assess the reduction and variance in lamp germicidal output over time under defined worst-case operating conditions. Lamp age testing may use either a pilot/demonstration-scale UV reactor installed at a WTP or a test bed designed to emulate the reactor (i.e., identical power supply). It is strongly recommended that all tests be done with the lamps housed in the sleeves and powered by the ballasts that will be used in the final application. It is best if the lamp sleeves are maintained free of external foulant during aging tests, in a manner similar to that of the final application.

Factors to consider in designing the test(s) include lamp batch, lamp assembly, electrical characteristics of the ballasts, heat transfer from the lamps to the water, and operation of the lamps. Since lamps will be manufactured in batches, it is recommended that lamps from several different lots be evaluated. During demonstration and pilot scale testing, the lamps should be operated in a manner and in an environment that reflects conditions expected when the UV disinfection system is installed at a WTP.

Parameters to monitor over time include electrical power delivered to the ballast, electrical power delivered to the lamp, and water temperature. If UV intensity sensors alone monitor lamp output, it is recommended that the A_{254} of the water also be measured.

During testing, it is recommended that the following analyses be considered:

- Visually inspect the lamps at regular intervals to document any visible degradation of the lamp assembly, including electrodes and seals, and any darkening of the lamp envelope;

- Document any fouling on the internal surfaces of the lamp sleeves;

- Measure the germicidal output of the lamp under fixed conditions of ballast operation (e.g., power setting), heat transfer (e.g., lamp sleeves), and environment (water temperature and transmission).
  - One measurement should be made with the lamps aged 100 hours (“new”).
  - The germicidal output may be measured using one of the following: a radiometer equipped with a germicidal filter; a reference UV intensity sensor or radiometer from 200 to 400 nm; or by bioassay.
  - The output from various positions along the lamp may be measured based on visual inspection (i.e., the pattern of darkening on the lamp).
  - If lamp power is variable, lamp output as a function of lamp power setting may be measured.
- Assess the output from lamps of different lots.

Pilot/demo-scale test data and visual inspections can be used to identify operational issues and provide operational guidance. The output of the lamps measured under fixed operating conditions can be plotted over time and fit to provide mean expected performance and prediction intervals (e.g., 90th, 95th, and 99th percentiles) to estimate the range of performance in

lamp intensity at different lamp ages. In a robust system, all the lamps will age in a similar manner. If lamps age differently than expected, the results will affect dose delivery and UV intensity sensor measurements. This data can be used to assess a proper end-of-lamp-life.

J.5.5 Evaluating Controls and Alarms

An evaluation of the UV reactor controls and alarms should be conducted to verify their performance and to gain familiarity with alarm/control response procedures. A test plan is typically organized prior to testing, describing the control function to be tested, the test procedure, and the expected response. Faults may be induced or simulated. Low-dose conditions may be simulated by reducing lamp power, increasing the A_{254} of the water, reducing or increasing flow beyond the validation limits of the reactor, turning off lamps or ballasts, or disconnecting sensors. Valve failure, high temperature, and ground fault interrupts may be induced or simulated. Simulating faults may require disconnecting components of the UV disinfection system or using modified electronics. Accordingly, qualified personnel as identified by the manufacturer of the UV disinfection system should undertake these simulations. All operational functions can be verified, including startup and shutdown sequences and cleaning cycles. Dose pacing if used, may be verified by monitoring lamp power settings and dose compliance as flow rate, A_{254}, and lamp output are varied.

J.6 References

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Appendix K. Preliminary Engineering Report

Critical design and implementation issues need to be resolved early in the planning phase of a UV disinfection facility. The purpose of a preliminary engineering report is 1) to provide conceptual level layouts and preliminary cost estimates for implementation of UV disinfection at the water treatment plant (WTP), and 2) to recommend an implementation plan for UV installation design and construction. Specific components of the preliminary engineering analysis are listed below:

- Identification of UV reactor design criteria and implementation issues
- Evaluation of UV reactor alternatives and potential locations for the proposed installations in the plant treatment train
- Determination of the hydraulic characteristics of the UV reactor and incorporate it into the hydraulic model of the plant
- Development of estimates for capital, operational, and life-cycle costs for each alternative
- Comparison of feasible alternatives and development of implementation recommendations

This appendix presents an example of a preliminary engineering report (PER) for retrofitting a UV disinfection facility into an existing WTP. The basic elements involved in the planning phase of the UV installation are discussed in this report. The format and content of a site-specific PER should be coordinated with the State. This example report is based largely on a predesign report prepared for North Shore Water Commission, Wisconsin (Carollo Engineers 2001).

Chapter 3 of the Guidance Manual presents a detailed discussion of UV installation planning and design principles. A flowchart depicting the planning and design process is included in Figure 3.1. Table K.1 presents a correlation between the flowchart elements discussed in Chapter 3 and respective sections in this appendix.

Table K.1 Elements of the Planning and Design Process (Ref. Figure 3.1)

Element	Chapter 3 Section	Appendix K Section(s)
Define UV disinfection goals	3.1.1	K.1, K.2
Identify potential retrofit locations	3.1.2	K.5
Determine design parameters	3.1.3	K.2.2
Evaluate potential UV reactors	3.1.4	K.3
Evaluate operational and control strategies	3.1.5	K.4
Evaluate hydraulic profile and site layouts	3.1.6	K.5
Compare retrofit options and costs; select retrofit locations	3.1.7	K.6, K.7, K.8

K.1 Background of Example WTP

A 20 million gallon per day (mgd) surface WTP is used as an example in this appendix. The water treatment processes employed are coagulation and sedimentation pretreatment, granular media (anthracite and sand) filtration followed by chlorine disinfection. Since the plant was put into service in the 1960s, water quality regulations have become more stringent. In addition, there are growing concerns over chlorine-resistant pathogens (e.g., *Cryptosporidium*) and production of chlorinated disinfection byproducts (e.g., trihalomethanes, haloacetic acids). In order to upgrade the facility to meet current and future regulations and health concerns, several research studies have been performed involving the use of ozone, membranes, and UV disinfection. From the results of those studies, it was concluded that the most feasible and cost effective solution to achieve disinfection of chlorine-resistant pathogens was to add UV disinfection to the current treatment train.

The following are the general performance goals of the UV installation for the example WTP:

- Provide 2-log *Cryptosporidium* inactivation.
- Provide an additional disinfection barrier for other chlorine-resistant pathogens.

K.2 UV Disinfection Criteria

This section includes general information regarding the optimal application point for UV disinfection at the WTP and design considerations for implementation.

K.2.1 Application Point and UV Transmittance

One of the important parameters controlling UV installation design is the UV transmittance (UVT) of the water to be treated (section 3.1.3.1). The lower the UVT, the greater the UV intensity is needed to provide a given UV dose at a given flowrate. UVT typically varies with source water, seasonally, and through the treatment processes. Consequently, a thorough UVT analysis was completed during development of design criteria.

K.2.1.1 Point of Application for UV Disinfection

In keeping with the content of this guidance manual, the UV disinfection alternatives assessed for the WTP were limited to applications after filtration. Based on statistical results of the filtered water ultraviolet absorbance at 254 nanometers (A_{254}) data, the UV reactors are sized based on a 0.032/cm A_{254} (93 percent UVT; 10 mm path length; light at 254 nm), which is the 99th percentile minimum of the available A_{254} data.

K.2.1.2 Treatment Chemical Impact on Absorbance

Some chemicals used in water treatment absorb UV light and hence, can influence the design absorbance value, as discussed in Chapter 3.1.2 of the manual. Ferric iron and permanganate are two of these, and are used at the example WTP. Ferric iron strongly absorbs UV light; however, post-filtration iron levels are generally low. Permanganate absorbs UV light, but at permanganate levels of less than 1 mg/L, which is typically the case post-filtration, the impact is not significant. Therefore, for the PER, chemical A_{254} is not considered to influence the UV design criteria.

K.2.1.3 Power Quality Impact on Absorbance

As stated in section 3.1.3.3, the sensitivity of UV reactors to power fluctuations make electrical power supply a critical component of the UV installation planning and design. Preliminary pilot testing of UV reactors over the course of a year at this site did not indicate any problems with existing water utility power quality for the UV reactor's operational continuity. Therefore, for this PER, power quality is not considered to negatively impact the UV installation design.

K.2.2 Inactivation Goals and UV Dose

The goal of UV disinfection at the example WTP is to provide inactivation of chlorine-resistant pathogens. By using UV disinfection, the general goal of improving public health protection will be met and compliance with the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) *Cryptosporidium* inactivation requirements may be achieved, if needed (40 CFR 141.702). (Source water sampling for "Bin" determination has not yet been completed at this example WTP, so the level of additional credit needed in the future is unknown.) UV disinfection credit will also be available for *Giardia* and virus inactivation. This additional UV disinfection credit will most likely reduce chlorine disinfection requirements, and hence, reduce disinfection by-product formation.

The desired UV dose (or validated reduction equivalent dose [RED]) depends on the disinfection strategy of the individual UV installation. The State, utility, and designer must decide the log inactivation requirements for a target pathogen. Once this information is known, the UV dose can be established (section 3.1.1). For this PER example, a UV dose of 40 mJ/cm^2 is recommended to achieve 2-log *Cryptosporidium* inactivation and is used for UV disinfection pre-design purposes.

A 12-month pilot study was conducted to assess the long-term disinfection efficiency and operation and maintenance (O&M) issues. The study results indicated that lamp fouling and power quality issues should not be a concern for the facility (Mackey et al. 2001).

K.3 UV Installation Equipment

General information on UV reactors and the types of reactor configurations used for water treatment is provided in this section.

K.3.1 UV Lamp Types

For the flowrates associated with the WTP applications in this example, the number of lamps needed for a low-pressure (LP) reactor would be excessive, so consideration is limited to low pressure high output (LPHO) and medium pressure (MP) lamps. The general relative characteristics of each of these lamp types are listed in Table K.2. The ratio of number of lamps needed to achieve equivalent RED for LPHO lamps as compared to MP lamps is on the order of 6:1.

Table K.2 Relative Characteristics of LPHO and MP Lamps

	LPHO	MP
Lamp Power Output	Low	High
Power Efficiency	High	Low
Number of Lamps Needed	High	Low
Operating Temperature (°C)	130 – 200	600 - 900
Typical Lamp Life (hours)	8,000 - 12,000	3,000 - 8,000

K.3.2 UV Reactor Configuration

UV installations can be designed around open-channel or closed-vessel configurations. In keeping with the content of this guidance manual and the general trend of the drinking water industry, the conceptual designs developed herein are limited to MP and LPHO closed-vessel reactors.

K.4 UV Reactor Description

This section contains information on the UV reactor design criteria for disinfection at the WTP.

K.4.1 General UV Reactor Description

Each UV reactor for the WTP should include appropriate control and electrical cabinets and an off-line chemical cleaning (OCC) system or an on-line mechanical cleaning (OMC) system for the lamps. The cleaning systems should allow for the removal of organic and inorganic foulants that have accumulated on the surfaces of the lamp sleeves.

K.4.2 Process Control

For disinfection of drinking water, the ability of the UV reactor to deliver the design RED of 40 mJ/cm^2 depends on the flowrate, feed water UVT, and UV intensity. UV intensity is subject to lamp aging, lamp sleeve cleanliness, and water quality (mainly water UVT). The UV reactor should be designed to deliver the appropriate dose of UV light to the process flow based on predetermined maximum flowrate and minimum water quality parameter setpoints with an appropriate factor of safety (see Chapter 3).

UV intensity sensors in each UV reactor should provide continuous performance verification of the reactor during operation. In case of lamp failure, the UV reactor programmable logic controller (PLC) should be programmed to either replace one row of lamps with another row that was off, or turn the reactor off after replacing it with a stand-by reactor. (Note that Alternative 1, described in section K.5.1, involves placing a UV reactor on each filter effluent pipe, therefore stand-by reactors for individual filter installations are not provided). The failed lamp can then be replaced with minimal interruption of UV reactor operation.

In case of incorrect operation of lamps or low level of UV intensity, the PLC should display a warning to indicate to the operator that cleaning of the reactor should be performed. The operator initiates the cleaning of any reactor through the local human machine interface (HMI). After selection, the UV reactor PLC turns on the stand-by reactor. Then, the PLC closes the inlet and outlet valves and isolates the reactor to be cleaned.

K.4.3 Expected UV Reactor Maintenance

Although maintenance methods are installation and site-specific, some general maintenance tasks have been developed and are briefly described in this section. As the UV reactor represents a critical disinfection process, preventative maintenance should be carried out on a routine basis to ensure that UV reactors reliably provide the specified dose (40 mJ/cm^2). Inadequate cleaning is a common cause of underdosing in UV reactors. The lamp sleeves should be cleaned regularly by OMC or periodic OCC, and manually cleaned periodically to supplement automatic cleaning. The cleaning frequency is dependent on the water quality. Chemical cleaning is most commonly done with dilute citric or phosphoric acid.

The effective life of the UV lamps depends on the minimum UV dose. The UV lamps should be replaced either at the end of their expected lifetime or following failure. Generally, UV lamps are replaced when the intensity has dropped to 70 percent of the original new-lamp intensity (following cleaning of the chamber). This typically occurs after about 8,000 to 12,000 hours (approximately 300 to 500 days) of operation for LPHO lamps and about 3,000 to 8,000 hours (approximately 100 to 300 days) for MP lamps. The front panel of the enclosures indicates the cumulative hours each lamp has operated. The lamp run time display will facilitate monitoring of lamp replacement needs.

K.4.4 Power Needs

UV reactor power needs to vary depending on the type of equipment that is installed and UVT of the water being disinfected. The LPHO reactors used for this pre-design have power requirements of approximately 20 kW for treating 20 mgd. The MP UV reactors require about 130 kW for treating 20 mgd. As indicated in Table K.3 through K.5, additional power would be necessary to allow for future expansion of the UV facilities.

K.5 Site Plans and Facility Layouts

The preferred process location for a UV installation at a WTP is downstream of the filters and upstream of the high-service pumps (section 3.1.2). At the example WTP, there are three viable alternatives for the UV installation downstream of the filters:

- Alternative 1 – Filter Gallery
- Alternative 2 – Existing Chemical Room
- Alternative 3 – New Building

There are eight granular media filters at the WTP. Alternative 1 involves placing one UV reactor on the effluent pipe of each filter in the filter gallery between the filters and clearwell. Alternative 2 is to construct the UV installation in a chemical room in the WTP between the low service pumps and the reservoir. Alternative 3 involves constructing a new building between the low service pumps and the reservoir to house the UV reactors. Figure K.1 presents a portion of the plants hydraulic profile and indicates the vertical locations of the three viable alternatives.

The construction requirements and preliminary drawings for each alternative are illustrated and described in the following section, along with preliminary design criteria. Costs for the three alternatives are also compared. The preliminary site-specific design criteria are provided for example purposes only. Application-specific design criteria should be provided by the UV manufacturer for each individual UV disinfection implementation project on a case-by-case basis.

K.5.1 Alternative 1 - Filter Gallery

In Alternative 1, one 3 mgd UV reactor is installed on the discharge pipe of each of the eight filters, as shown in Figure K.2. The UV reactors would be installed below the hydraulic grade-line (HGL) of the existing clearwell to ensure constant submergence (section 3.1.6.1). Flow through the UV reactors is by gravity from the filters into the clearwell. During filter backwashing and filter-to-waste cycles, valves located at the influent of each UV reactor can be closed to keep the reactor flooded while it is taken off-line.

Compared to the other alternatives, construction of Alternative 1 is the simplest. Construction would include lowering the level in the clearwell to below the filter discharge

pipes, then taking each filter off-line individually to install the new piping, valves, and UV reactor. This would preclude significant disruption of plant operation during construction.

Figure K.1 Portion of the WTP Hydraulic Profile and Alternative Locations for UV Implementation (Carollo Engineers 2001)

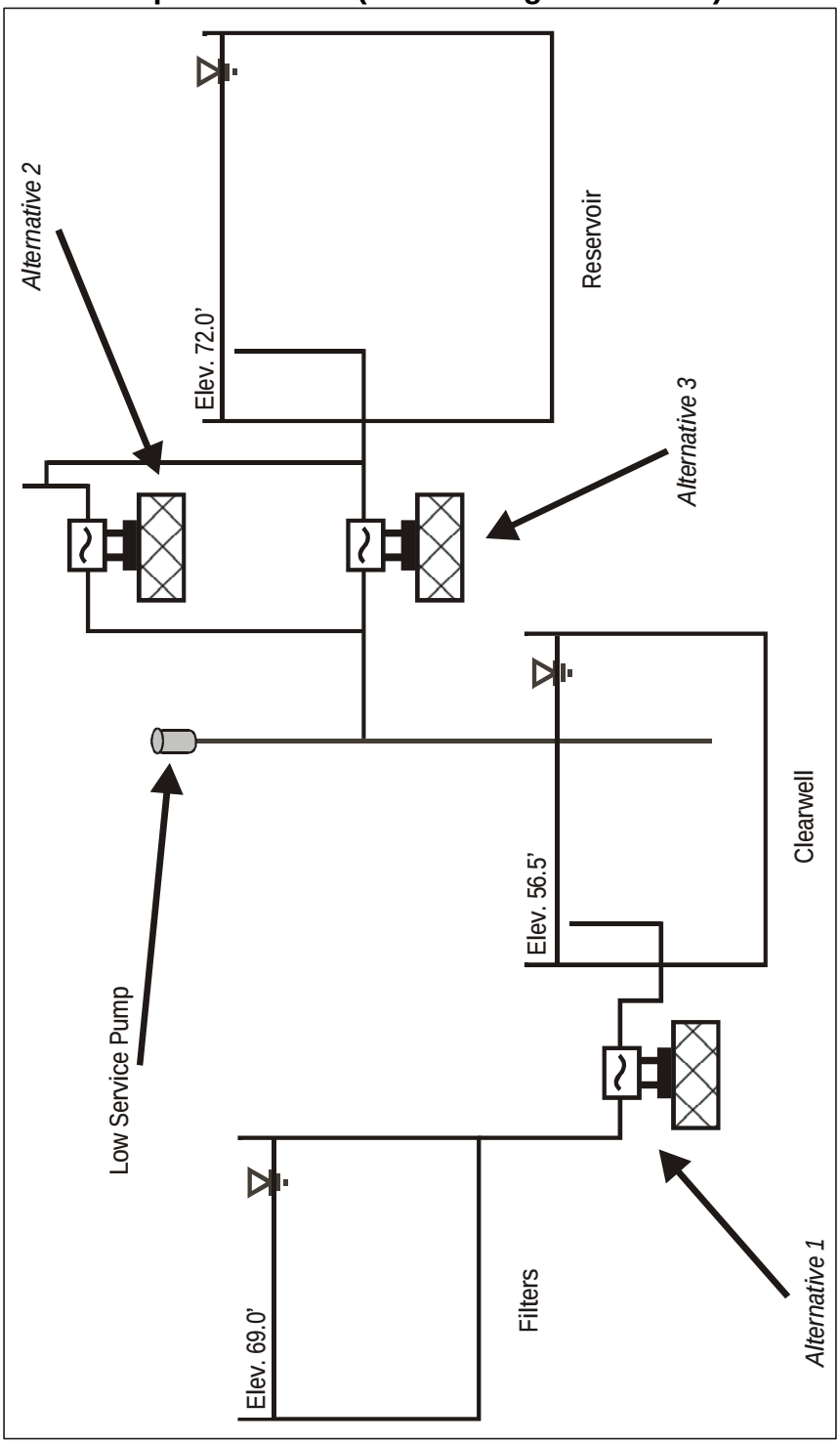
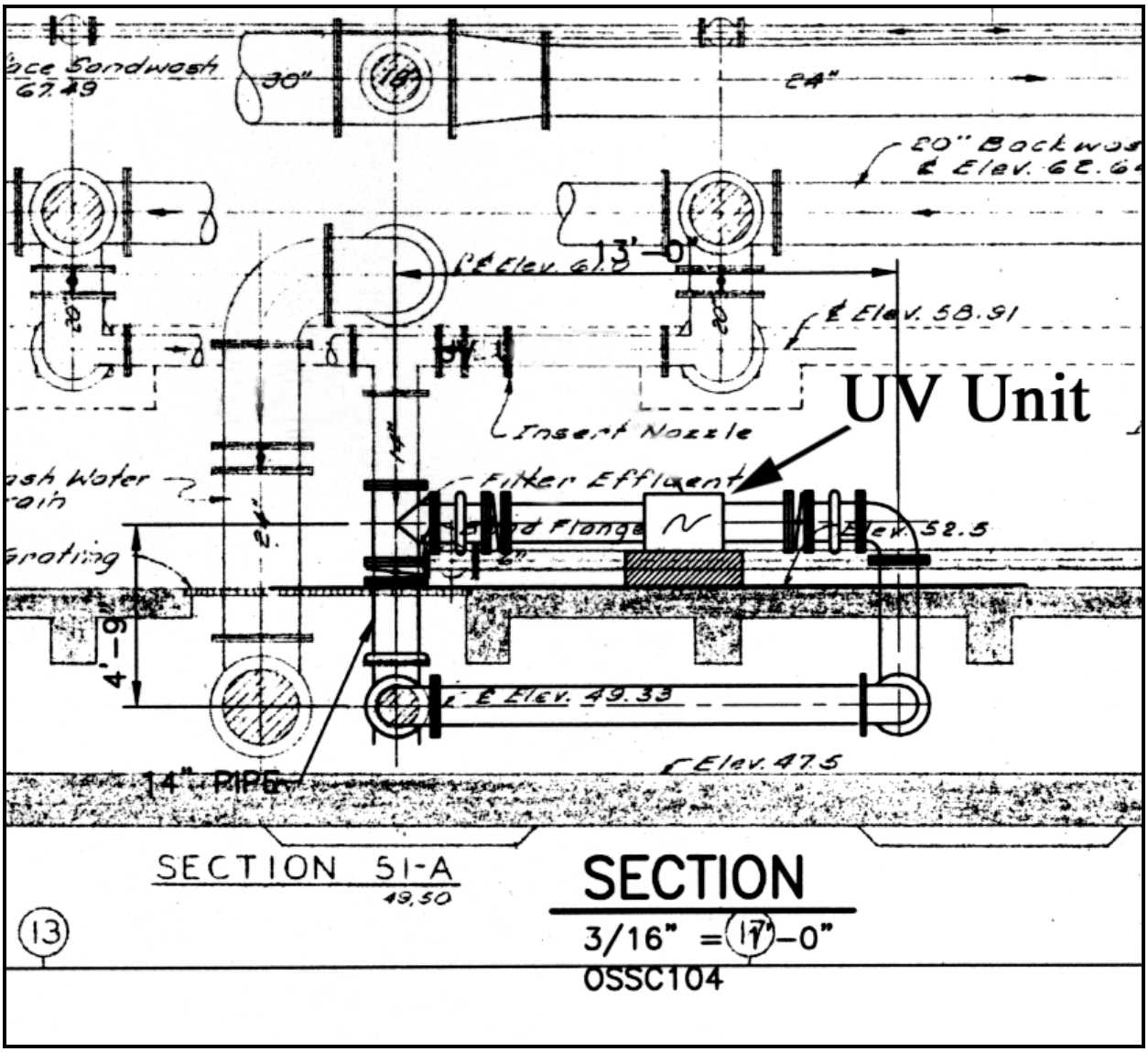


Figure K.2 Alternative 1 - Filter Gallery (Carollo Engineers 2001)



Note: UV reactor is installed on discharge pipe of each filter. Valve on UV reactor influent is closed to maintain water in the UV reactor during filter backwashing.

Some concerns associated with installing UV reactors in the filter gallery are space constraints, climate control, and impact on filtration. In the design, care would need to be taken to allow enough space for maintenance and construction of the UV installation. Although the UV installation in this example will fit into the existing filter gallery of the WTP, generally there is little room to work in these locations. In addition, depending on the location of the WTP, humidity and pipe sweating in this space might be a concern. However, there are protective climate controlled enclosures available for these conditions, though they add to cost and maintenance needs. A detailed hydraulic analysis of the filters would need to be completed prior to designing a UV installation on the filter effluent piping. There must be adequate head available from the filters to the clearwell to allow for the addition of a UV reactor that will not

adversely affect the filter performance. Furthermore, in the event of a UV reactor shutdown, the filter associated with that UV reactor shutdown would also need to be removed from service.

The preliminary design criteria for Alternative 1 are provided in Table K.3. Due to the large size of the LPHO reactors, they will not fit into the filter gallery. Therefore, only the MP reactors are considered for Alternative 1.

Table K.3 Preliminary Design Criteria – Alternative 1 – MP UV Reactors

Description	Unit	Criteria	
		Current	Future
Treatment plant capacities			
Flowrate	mgd	20	40
Water quality			
UVT In a 10mm quartz cell @ 254 nm	% UVT	93	93
Ultraviolet reactors			
Type of reactors: medium-pressure			
Number of reactors	No	8	16
Number of banks per reactor	No.	2	2
Number of lamps per bank	No.	4	4
Total number of lamps per reactor	No.	8	8
Input power per lamp	W	2000	2000
Total operating electric load	kW	128	256
Total installed electric load	kW	128	256
Headloss through reactor (at current and future flowrates)	Inches	12	36
Approximate dimensions of each UV reactor			
Length	Inches	22	50
Width	Inches	36	36
Height	Inches	26	26
Flanges diameter	Inches	12	12

As stated previously, the eight UV reactors listed in Table K.3 are designed for a maximum capacity of 3 mgd each. This design is based on the assumption that one UV reactor would be taken off-line periodically during a filter backwash cycle. The WTP must be able to treat 20 mgd with one filter out of service, so the remaining seven UV reactors would need to be able to disinfect the maximum plant flow. This arrangement also provides reactor redundancy. If one UV reactor were taken out of service, the associated filter would also be taken out of service.

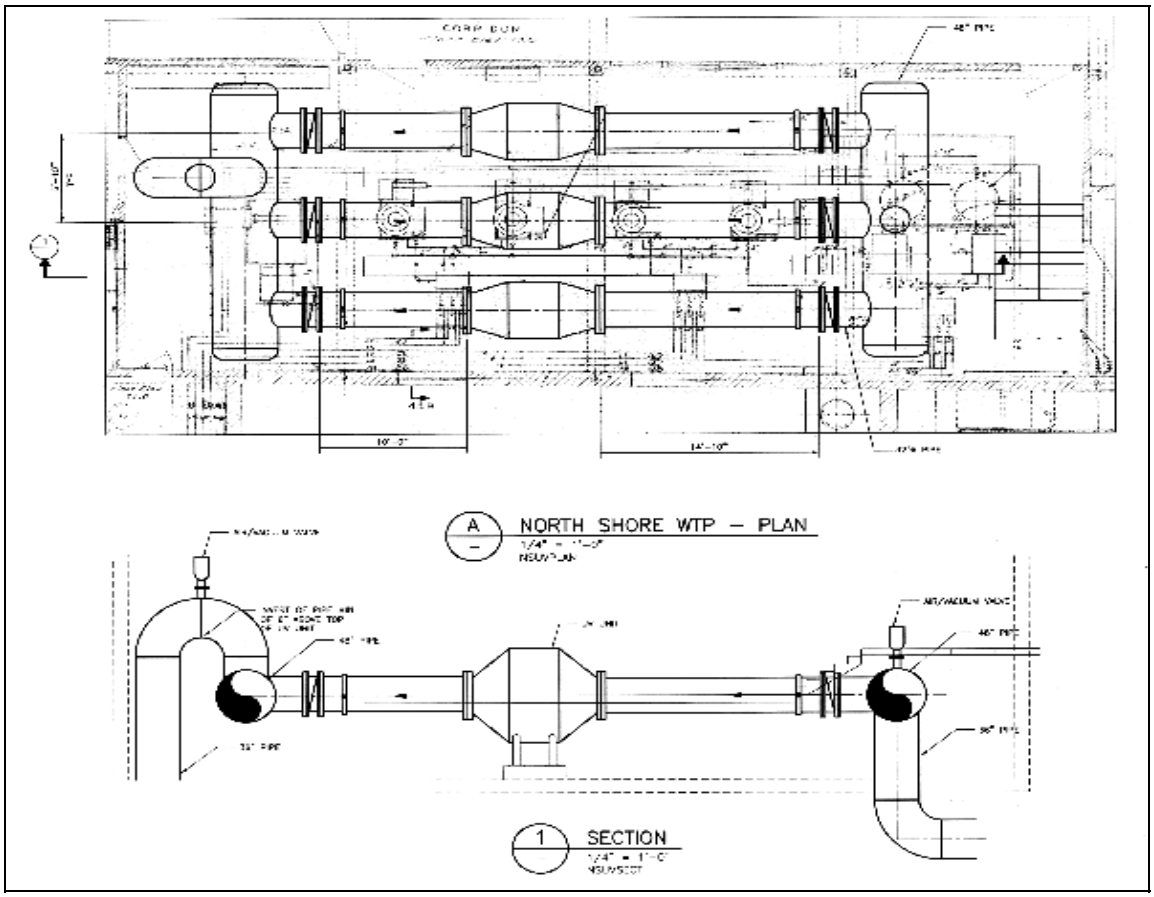
In this example, future plant expansions needed to be taken into account. For the present analysis, provisions are made so that future expansion of the UV installation to an ultimate flow of 40 mgd will be possible. If the filter capacities can be expanded to 40 mgd, the UV installation expansion will necessitate placing two UV reactors (16 total) in series along each filter effluent pipe. During the construction of the initial design for 20 mgd, adequate space and

mechanical layouts would be provided for the addition of a second UV reactor. For example, a section of pipe located at the outlet of the UV reactor for the 20 mgd design could be designed for easy removal and installation of a second UV reactor.

K.5.2 Alternative 2 - Existing Chemical Room

Alternative 2 consists of installing three 10 mgd reactors (2 operational + 1 stand-by) in an existing chemical room in the WTP, as shown in Figure K.3. This alternative necessitates placing the UV reactors above the existing HGL of the plant. The low-lift clearwell pumps provide the head through the UV reactors. (It is generally more advantageous to place the UV reactors below the HGL. However, due to the space constraints at the example WTP, and to provide an example of issues that may arise during design, this option is discussed.)

Figure K.3 Alternative 2 - Existing Chemical Room with UV Reactors (Carollo Engineers 2001)



In theory, an outlet weir structure would be a viable option to raise the HGL of the plant to ensure constant submergence of the UV reactors (section 3.1.6.1). In this case, there is not enough space for such a structure. To ensure constant submergence of the UV reactors, a vertical pipe at the outlet header would maintain the water level at an elevation above the top of

the UV reactors. Air vacuum valves would be installed on the inlet and the effluent vertical pipe to counteract siphon effects on the UV reactors. The discharge from the effluent header would then flow by gravity to the reservoirs. The hydraulic design of the inlet and outlet channels provides a continuous equal flow split between the reactors (section 3.3.1.2).

The construction needs of Alternative 2 are more difficult than Alternative 1. A 36-inch finished water pipe from the low head pumps would need to be taken out-of-service long enough to cut the pipe and tie-in a new section with fittings and valves for connection of the new UV reactors. The existing equipment would need to be moved to alternate locations to accommodate the new large piping and UV reactors, and the floor would need to be cut to provide clearance for the piping to and from the lower floor.

Other issues with Alternative 2 are that space constraints in the chemical room, possible structural upgrades of the building, and raising the HGL of the plant. To allow for adequate space for maintenance, piping, and instrumentation, the existing chemical equipment in the room would need to be removed and reinstalled elsewhere in the plant. Since this is a second level room, a detailed structural analysis would need to be completed to ensure the floor is able to withstand the load of the UV installation. If structural upgrades are needed, they could prove to be expensive and difficult to design and construct. Installing the UV reactors in the second level room above the HGL would significantly increase the total dynamic head (TDH) placed on the low-lift clearwell pumps. Therefore, pump upgrades would be necessary to overcome the additional headloss of the UV installation.

K.5.3 Alternative 3 - New Building

Alternative 3 includes constructing a new building to house three 10 mgd UV reactors (2 operational for 20 mgd + 1 standby) and related equipment. The building layout and UV design for Alternative 3 is presented in Figures K.4 and K.5. The 36-inch finished water line from the low-service clearwell pumps would be modified to provide flow to the UV reactors in the new building. The new facility would include a two-level structure to house mechanical and electrical equipment and large diameter piping to convey the filtered water through the UV reactors. The UV reactors would be installed in the basement of the new building below the HGL of the plant to ensure constant submergence. The hydraulic design of the inlet and outlet channels would provide an equal flow split between the reactors, and the discharge would flow under pressure to the reservoirs.

The UV building design and mechanical piping shown in Figures K.4 and K.5 are for preliminary design and cost estimates only. If this option were selected, the building size and configuration for this alternative would need to be evaluated in more detail during the design phase and adjusted as necessary, depending on the final UV reactors selected to be used.

Construction for Alternative 3 would be the most involved of the three options because it would include excavation and construction of a new building. Besides the building construction, the project would involve tying into the existing 36-inch finished water pipe in two locations below grade, and modifying site amenities such as pavement and landscaping. In addition, the new building would also need new power, control, and security systems as well as plumbing, HVAC, etc.

Figure K.4 Alternative 3 - New Building with UV Reactors – Plan View (Carollo Engineers 2001)

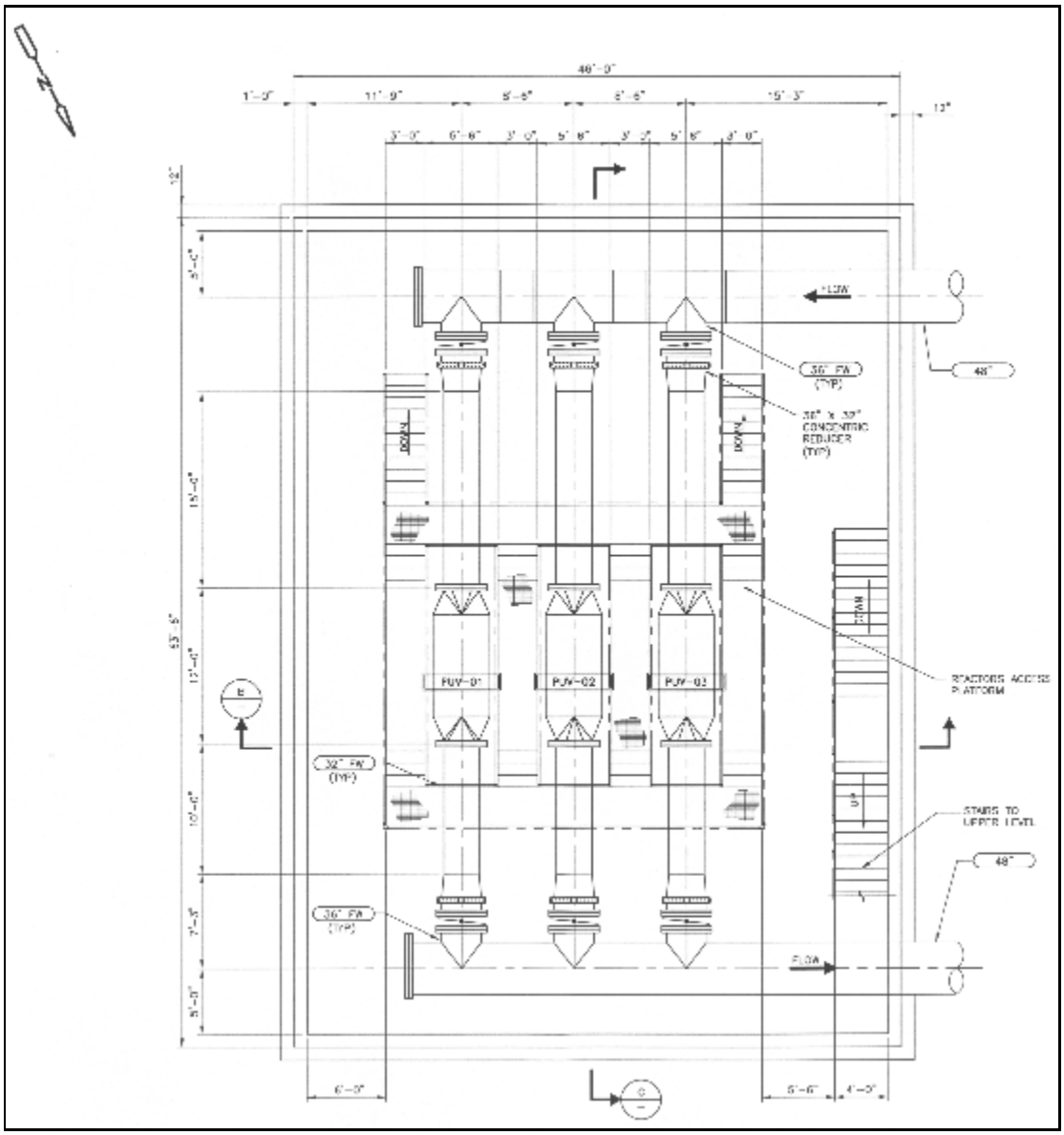
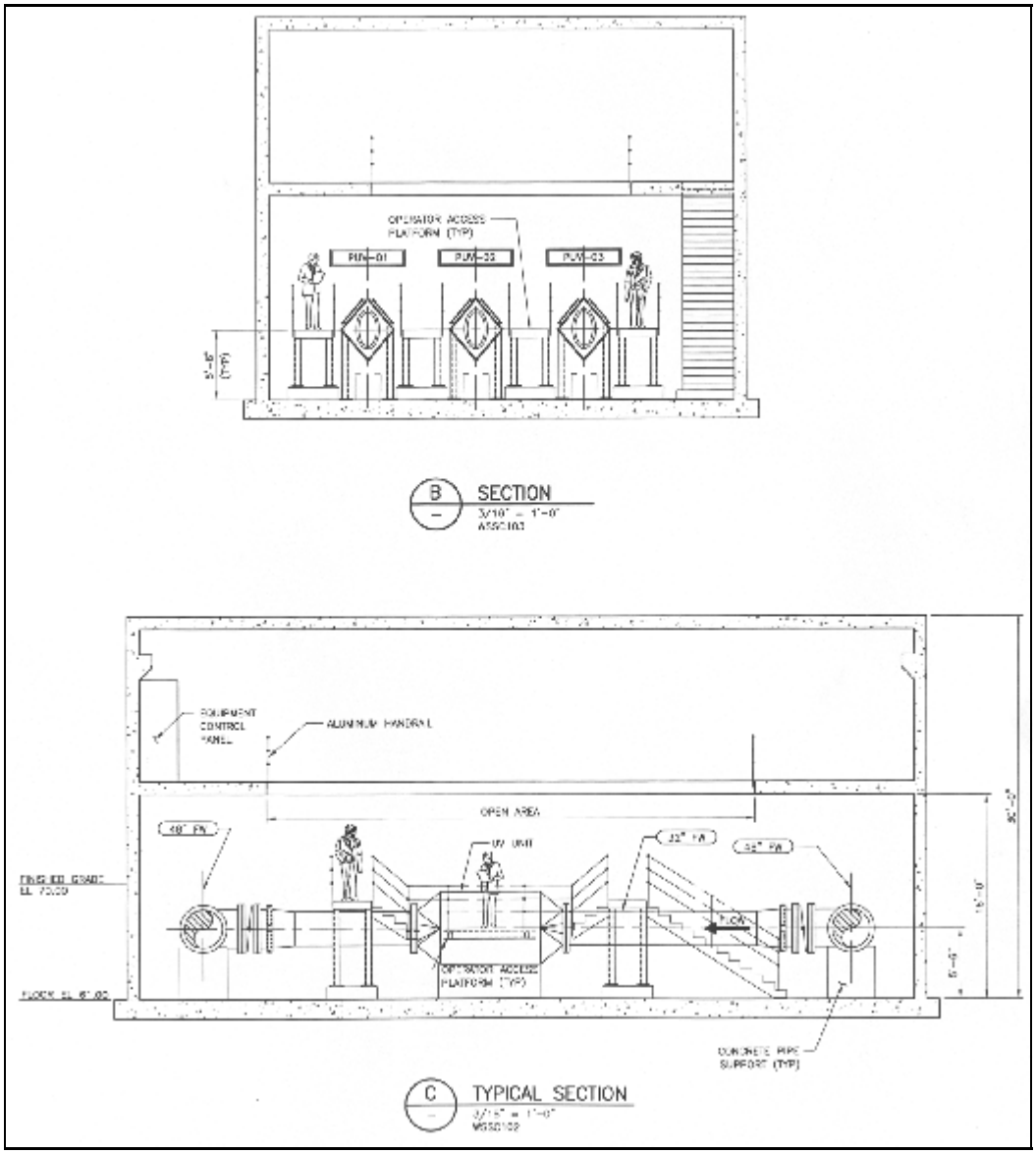


Figure K.5 Alternative 3 - New Building with UV Reactors – Section View (Carollo Engineers 2001)



The preliminary design criteria for Alternatives 2 and 3 using the MP UV reactors are presented in Table K.4.

Table K.4 Preliminary Design Criteria – Alternatives 2 and 3 – MP UV Reactors

Description	Unit	Criteria	
		Current	Future
Treatment plant capacities			
Flowrate	mgd	20	40
Water quality			
UVT in a 10mm quartz cell at 254 nm	% UVT	93	93
Ultraviolet reactors			
Type of reactors: medium-pressure			
Number of reactors	No. (Duty + Standby)	2+1	2 + 1
Number of banks per reactor	No.	2	2
Number of lamps per bank	No.	8	8
Total number of lamps per reactor	No.	16	16
Input power per lamp	W	4000	4500
Total operating electric load	kW	128	144
Total installed electric load	kW	192	216
Headloss through reactor (at current & future flows)	Inches	10	48
Approximate dimensions of each UV reactor			
Length	Inches	48	48
Width	Inches	49	49
Height	Inches	41	41
Flanges diameter	Inches	30	30

The three MP UV reactors selected have design capacities of 10 mgd each. Three 10 mgd UV reactors for the 20 mgd design provide one stand-by reactor in the event of a malfunction, cleaning, or maintenance of one UV reactor.

Note that for expansion of the UV installation using the MP reactors given in Table K.4, the size and number of UV reactors remains constant. In order to provide extra lamp intensity to meet dose requirements at the ultimate flow, 4000 W lamps would replaced with 4500 W lamps. (Note that re-validation of the reactors with the 4500 W lamps would be required (40 CFR141.729 (d)).

The preliminary design criteria using the LPHO reactors for Alternatives 2 and 3 is provided in Table K.5.

Table K.5 Preliminary Design Criteria – Alternatives 2 and 3 – LPHO UV Reactors

Description	Unit	Criteria	
		Current	Future
Treatment plant design capacities			
Plant flowrate	mgd	20	40
Water quality			
UVT in a 10mm quartz cell at 254 nm	% UVT	93	93
Ultraviolet reactors			
Type of reactors: Low-Pressure High-Output			
Number of reactors	No (Duty + Standby)	2+1	2+1
Number of rows per reactor[(1)]	No.	5	9
Number of rows with lamps installed	No.	4	8
Number of lamps per row	No.	12	12
Total number of lamps per reactor	No.	48	96
Input power per lamp	W	200	200
Total operating electric load	kW	19.2	38.4
Total installed electric load	kW	28.8	57.6
Headloss through reactor (at current & future flows)	Inches	24	35
Approximate dimensions of each UV reactor			
Length[(2)]	Inches	110	144
Width	Inches	51	51
Height	Inches	100	100
Flanges diameter	Inches	32	32

[1] Preliminary design assumes one spare row in addition to current flow demand requirements for installation of lamps in the future.
[2] Length varies depending on the number of rows installed.

The expansion from 20 mgd to 40 mgd using the LPHO UV reactors would be accomplished by adding additional rows of lamps to the reactor. The UV manufacturers would oversize the reactor and additional rows of lamps could be inserted as needed for increasing flow capacities. However, UV reactor validation would need to be done both with and without the additional rows for the maximum and ultimate flow conditions.

Alternatively, the UV installation could be sized to allow additional UV reactors to be installed for expansion. Initially, three 10 mgd reactors would be installed for a capacity of 20 mgd (2 operational and 1 standby). Space would be provided to install two additional reactors in the future for a capacity of 40 mgd (4 operational and 1 standby).

These examples of UV installation expansion alternatives provide various options to the designer. To confidently design for future UV installation expansions, it will be critical to have an accurate flow projection and adequate space for the UV installation expansion. In addition to the UV reactors needed for an expansion, mechanical piping, controls, instrumentation, and wiring would need to be considered during the preliminary engineering phase. Furthermore, the designer should work closely with the UV manufacturer to decide on an expansion plan that has been proven to work effectively and efficiently for the specific UV installation design.

K.6 Preliminary Capital and O&M Cost Estimates

The preliminary capital, operational, and maintenance costs for each alternative are summarized in this section. Estimated costs presented for Alternative 1 are based solely on the MP design. The LPHO UV reactors used for comparison here would not fit into the filter gallery and so was not considered for that alternative.

K.6.1 Capital Cost Estimate Summary

The estimated capital improvement costs for each alternative are summarized in Table K.6. Total project cost includes UV reactors, construction cost, engineering services, and a 20 percent estimating contingency.

The cost estimates presented for Alternative 1 in Table K.6 are based on using eight MP UV reactors. The costs presented for Alternatives 2 and 3 were developed around using three MP and LPHO UV reactors. The equipment cost for installing the MP UV reactors for all three Alternatives is higher than installing LPHO UV reactors for Alternatives 2 and 3. However, due to the relatively simple construction details associated with Alternative 1, the total project cost is considerably lower than Alternatives 2 and 3, which require significant construction provisions. A comparison of these alternatives is provided in section K.7.

Table K.6 Preliminary Capital Cost Estimates

	UV Reactor Cost	Total Project Cost	Annualized Capital Cost[1]
Alternative 1- Filter Gallery (MP)	$531,000	$1,900,000	$166,000
Alternative 2- Chemical Room (MP)	$556,000	$2,400,000	$209,000
Alternative 2- Chemical Room (LPHO)	$450,000	$2,300,000	$201,000
Alternative 3- New Building (MP)	$556,000	$2,800,000	$244,000
Alternative 3- New Building (LPHO)	$450,000	$2,700,000	$235,000

[1] Annualized costs calculated at 6 percent interest for 20 years.

K.6.2 Preliminary Operating and Maintenance Costs

Table K.7 presents a summary of the estimated O&M costs and total annualized costs for each alternative (four MP reactors in service for Alternative 1, two MP and LPHO UV reactors are in service for Alternatives 2 and 3). Detailed O&M costs for an average flow of 10 mgd are provided for each alternative and UV reactors in Tables K.8 and K.9.

Table K.7 Estimated UV Disinfection Costs

	Annul O&M Cost[1]	Annualized Capital Cost[2]	Total Annual Cost	Annual Difference[3]
Alternative 1	$72,000	$166,000	$238,000	$1,000
Alternative 2 (MP)	$111,000	$209,000	$320,000	$83,000
Alternative 2 (LPHO)	$36,000	$201,000	$237,000	-0-
Alternative 3 (MP)	111,000	$244,000	$355,000	$118,000
Alternative 3 (LPHO)	$36,000	$235,000	$271,000	$34,000

1. Costs for UV intensity sensor calibrations, lamp sleeve, ballast and sensor replacement are not included.
2. Annualized costs calculated at 6 percent interest for 20 years.
3. Relative to the least expensive alternative (Alternative 2-LPHO).

Table K.8 MP UV Installation O&M Cost Estimates for Alternatives 1, 2 and 3

					O&M Costs Alt. 1	Alts. 2 & 3
		Average Plant Flow		10 mgd		
1 - Power Consumption						
Annual power consumption of lamps in kWh					530,155	883,592[1]
Price of electricity ($/kWh)					0.10	0.10
Annual Expenses ($)					53,015	88,359
2 - Consumables						
Lamp replacement	# operating	32	$/Lamp	500 (#1) 600(#2&3)	17,500	21,000
	# replaced / yr	35				
Annual Expenses ($)					17,500	21,000
3 - Labor						
Lamps	# replaced / yr 15 min / lamp	35	Time (hr)	8.8		
Cleaning	1 clngs / yr / reactor 3 hrs / cleaning	3	Time (hr)	9.0		
Total			Time (hr)	17.8	$/hr 65	65
Annual Expenses ($)					1,153	1,153
TOTAL COSTS						
1 - Power Consumption					53,015	88,359
2 - Consumables					17,500	21,000
3 - Labor					1,153	1,153
4 - Chemicals					100	100
Total Annual Costs					71,770	110,610
COSTS PER MG TREATED						
Costs per MG Treated				$/MG	20.00	30.00

[1] Alternative 1 utilizes eight smaller UV reactors while Alternatives 2 and 3 utilize 2 large reactors. At an average flow of 10 mgd, the large UV reactors operate at the lowest possible setting, which is higher than required at 10mgd.

Table K.9 LPHO UV Installation O&M Cost Estimates for Alternatives 2 and 3

						O&M Costs
			Average Plant Flow		10 mgd	
1 - Power Consumption						
Annual power consumption of lamps in kWh						168,303
Price of electricity ($/kWh)						0.10
Annual Expenses ($)						16,830
2 - Consumables						
Lamp replacement	# operating		96	$/Lamp	150	12,600
	# replaced / yr		84			
Annual Expenses ($)						12,600
3 - Labor						
Lamps	# replaced / yr	84	Time (hr)	21.0		
	15 min / lamp					
Cleaning	1 clngs / yr / reactor	24	Time (hr)	72.0		
	3 hrs / cleaning					
Total			Time (hr)	93.0	$/hr	65
Annual Expenses ($)						6,045
TOTAL COSTS						
1 - Power Consumption						16,830
2 - Consumables						12,600
3 - Labor						6,045
4 - Chemicals						600
Total Annual Costs						36,070
COSTS PER MG TREATED					$/MG	10.00

Power consumption represents the majority of the operational cost. The power cost used for calculation of the annual O&M costs was $0.10/kWh. As expected, the MP reactors have considerably higher power costs associated with their operation than the LPHO reactors (Tables K.8 and K.9).

Lamp replacement costs are also significant. Cost of lamp replacement is based on an estimated lamp life of 10,000 hours and $150/lamp equipment cost for the LPHO reactors. The MP estimated lamp life is 8,000 hours with a lamp replacement cost of $500/lamp for Alternative 1 and a lamp cost of $600/lamp for Alternatives 2 and 3.

Estimated labor needs range from 18 hours for the MP UV installation to 93 hours per year for the LPHO UV installation. Labor estimates are based on lamp replacement at four lamps per hour and three hours per cleaning.

K.7 Summary of Alternatives and their Advantages and Disadvantages

A comparison of the three alternatives is presented in this section. The alternative comparisons are based on cost, feasibility of construction, and ease of maintenance. The advantages and disadvantages of each alternative are summarized in Table K.10.

Table K.10 Advantages and Disadvantages of Each Alternative

Alternative 1 – Filter Gallery	
• New building not necessary • Below existing hydraulic grade line (HGL) • Relatively simple construction • Likely no plant down-time for construction • Lowest capital cost	• Damp during periods of the year • Needs protective cabinet for each UV reactor • Tight quarters for construction and maintenance • Less manufacturer flexibility • Must take a filter off-line for UV reactor maintenance • Does not accommodate expansion easily • No redundancy at maximum flow
Alternative 2 – Chemical Building	
• New building not necessary • Main floor access	• UV reactors above the plant HGL • Difficult construction constraints • Uncertainty associated with structural upgrades • Very limited space for relocation of existing • Chemical equipment to other parts of the plant • Low lift pump upgrades necessary
Alternative 3 – New Building	
• Ample space for UV reactors and controls • UV reactors placed below the plant HGL • Room for future expansion • Flexibility in UV installation design options • Custom designed space for UV reactors	• Highest capital and total project cost • Necessitates a new building • Longer construction schedule

K.8 Conclusions and Recommendations

Alternative 1, which involves the installation of the UV reactors in the filter gallery, is the least expensive option. However, there are concerns about the moisture associated with the location that may adversely affect the performance of the UV reactors and cause maintenance problems. Servicing and maintaining the UV reactors in the filter gallery and installing the necessary control panels might be problematic based on space constraints. In addition, to expand the capacity of the UV installation to accommodate the ultimate flow (40 mgd), the size of the pipes connecting the UV reactors to the filter effluent pipes would have to be increased and an additional UV reactor would have to be installed. Furthermore, Alternative 1 does not provide adequate redundancy at the ultimate flow.

Alternative 2, retrofitting the existing chemical feed room has the advantage of not requiring a new building. However the disadvantages of this option include the space limitations, associated pump upgrade needs and the need to find a new location for the chemical feed equipment currently housed in that room.

Alternative 3, constructing a building addition to the WTP, is the most expensive alternative, but this option has some important advantages over Alternatives 1 and 2. The new building would offer flexibility in design options. The design would not be limited to using the MP or LPHO reactors; any UV reactors could be accommodated. There would be room for future expansion of the UV installation, if necessary, and ample space would be provided for mechanical and instrument layouts. The UV reactors would be installed below the existing hydraulic grade line of the plant to ensure submergence of the reactors.

Although Alternative 3 has some distinct advantages over Alternatives 1 and 2, the capital cost is significantly higher, due to the cost of the new building and appurtenances. Alternative 1 is the most economical alternative, but does not accommodate expansion easily and provides no redundancy at maximum flow. The disadvantages of Alternative 2, including lack of space for the existing chemical equipment, make this alternative the least desirable.

Given the above discussion, and based on both economical and non-economical criteria for comparison in this example, including anticipated future expansion needs, the ranking of the alternatives from most desirable to least desirable is as follows:

- Most desirable – Alternative 3, New Building
- Next best option – Alternative 1, Filter Gallery
- Least desirable – Alternative 2, Existing Chemical Room

K.9 References

Carollo Engineers. 2001. *Weber basin water treatment plant No. 3 expansion*. Layton, Utah.

Mackey, E.D., R.S. Cushing, and G.F. Crozes. 2001. *Practical Aspects of UV Disinfection*. Denver, Colo.: AWWA Research Foundation.

Appendix L. Regulatory Timeline

The purpose of this appendix is to provide utilities with a timeline (Figure L.1) to assist in planning and implementation of tasks to achieve compliance with the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). The timelines present the important tasks that utilities are likely to complete; however, the tasks and their duration will change based on utility-specific priorities and constraints.

Tasks have been divided into two general categories: regulatory and engineering. Compliance dates and resulting planning activities are based on utility size (i.e., systems serving fewer than 10,000 persons or systems serving 10,000 or more persons).

L.1 Regulatory Tasks

Regulatory tasks and milestones include key dates in the regulatory schedule such as monitoring requirements and compliance dates.

L.1.1 *Cryptosporidium* Monitoring

One of the key provisions of the LT2ESWTR is the requirement to conduct monitoring to determine *Cryptosporidium* removal/inactivation requirements (40 CFR 141.702). Monitoring results will be used to determine a "bin classification," which prescribes the *Cryptosporidium* inactivation/removal required. More information regarding the monitoring requirements is available in the Source Water Monitoring Guidance Manual for Public Water Systems for the LT2ESWTR.

L.1.2 Compliance Deadlines for *Cryptosporidium* Treatment

For utilities required to provide additional treatment for *Cryptosporidium*, the compliance deadline is the date when a utility must have implemented the selected treatment techniques (40 CFR 141.701). Table L.1 summarizes the *Cryptosporidium* treatment compliance deadlines for the LT2ESWTR.

Table L.1 LT2ESWTR Compliance Schedule Summary[1]

System Size	Compliance Deadline for Systems Making No Capital Improvements for Compliance[2]
Serving 10,000 or more people	6 years after LT2ESWTR promulgation
Serving fewer than 10,000 people	8 ½ years after LT2ESWTR promulgation

1 (40 CFR 141.701)
2 State may grant an additional two years for systems making capital improvements.

L.2 Engineering Tasks and Milestones

Engineering tasks and milestones include tasks that should be completed by a utility to develop and implement an LT2ESWTR compliance strategy.

L.2.1 Process Evaluation and Planning

Compliance with the LT2ESWTR *Cryptosporidium* treatment requirements will necessitate varied levels of process evaluation and planning. After compliance strategy options have been reviewed (see section 3.1.5) and a decision has been made to implement UV disinfection, planning may include one or more of the following activities:

- Engaging the State during planning to ensure the installation of UV disinfection is approved
- Conducting disinfection benchmarking and profiling if distribution system total trihalomethane (TTHM) and five haloacetic acids (HAA5) concentrations are at least 80 percent of the Stage 1 DBPR maximum contaminant levels for TTHM and HAA5 (40 CFR 141.711-713)
- Developing a capital improvement program that includes the necessary modifications for LT2ESWTR compliance (i.e., UV disinfection)
- Evaluating and implementing funding alternatives

Utilities are encouraged to seek approval of their LT2ESWTR compliance plan from the State before implementation of a compliance strategy. This may take several months and can have a significant impact on the implementation schedule, particularly when the State requires modifications. Because UV disinfection is a relatively new technology, the State may take longer to approve UV disinfection or require more significant involvement in the compliance strategy development.

L.2.2 UV Installation Design

The duration of the facility design phase will be contingent on a number of utility-specific factors, including scope of design (i.e., new facility or retrofit), scale of design (size of facility), available in-house resources, procurement methods, and validation testing requirements (discussed in detail in chapters 3 and 4). The design will likely include one or more of the following tasks:

- Evaluation of equipment and contractor procurement methods
- UV reactor procurement
- UV installation design

- UV reactor validation strategy determination

Many States require final approval of process improvements. As such, utilities should review the UV installation design and validation strategy with the State. If the State is not consulted during these phases, additional time may be necessary to receive final approval.

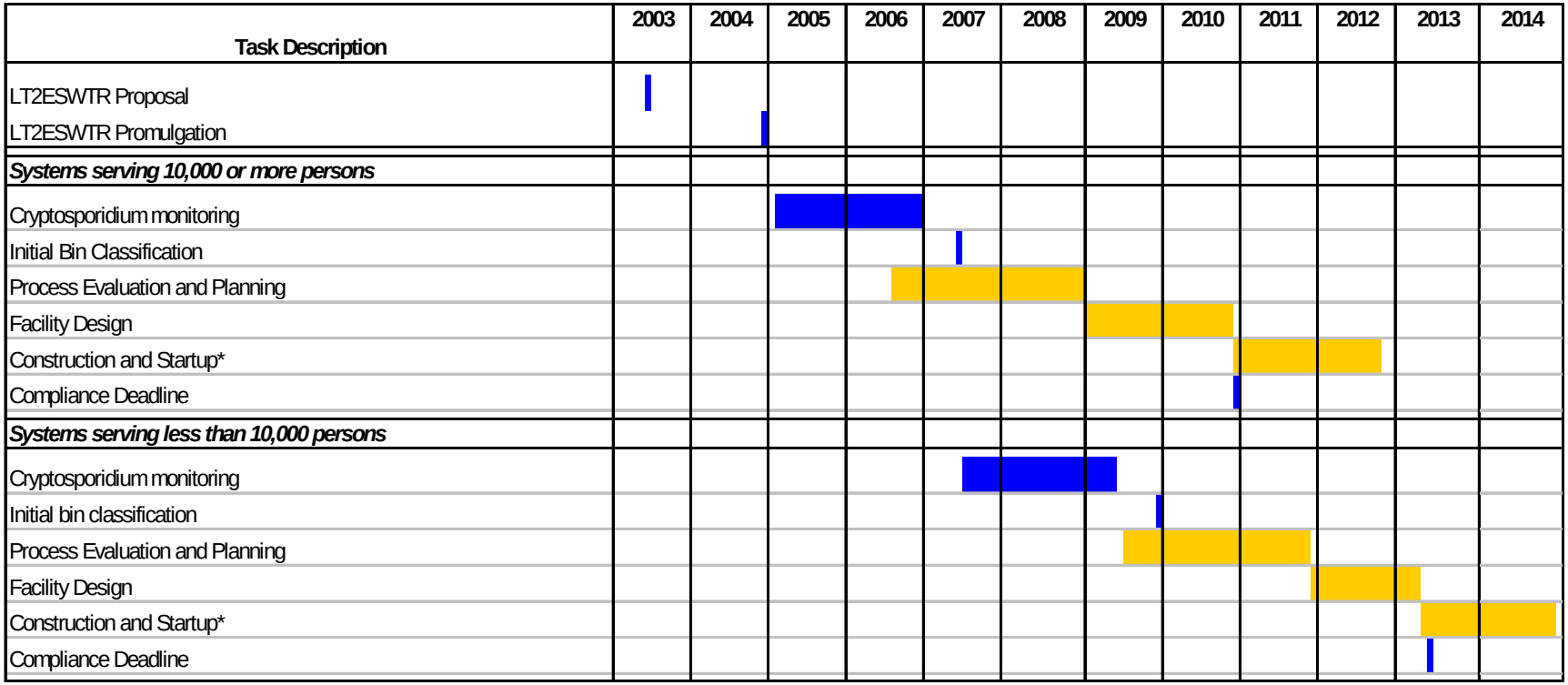
L.2.3 Construction and Startup

The timeline in Figure L.1 reflects a construction period of two years for both large and small utilities. However, the actual duration of construction and startup can vary significantly, depending on the scope of the project, the significance of the changes to the existing treatment plant, and other utility specific factors. Utilities should consider these factors during planning phases and adjust accordingly to ensure regulatory milestones are achieved by the necessary dates.

L.3 Example Timeline

Figure L.1 presents example timelines that encompass the regulatory and engineering tasks discussed in the previous sections. Utilities may have site-specific constraints that may shorten or extend the duration of the engineering tasks listed; however, regulatory milestones are not flexible.

Figure L.1 Example LT2ESWTR Compliance Timeline



* State may grant an additional 2 years for system making capital improvements

Regulatory Tasks/Milestones
Engineering Tasks/Milestones

Appendix M. Compliance Forms

This appendix is intended to supplement the monitoring information provided in section 5.4 with examples of monthly compliance report and monitoring log forms that utilities might use for reporting to the State. (Note, these are only examples; the States may develop their own compliance forms and require additional monitoring.) The specific monitoring and reporting requirements for each utility should be confirmed with the State, and the forms should be modified accordingly. For those utilities with advanced control systems (e.g., Supervisory Control and Data Acquisition (SCADA)), it may be possible to automatically generate these reports and compliance forms.

To receive disinfection credit, the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) requires validation testing of UV reactors to demonstrate a set of operating conditions where the UV reactor will deliver the required dose (40 CFR 141.729 (d)). These operating conditions must include flowrate, UV intensity, and UV lamp status, and the utility must monitor these parameters during routine operation to ensure dose delivery. (40 CFR 141.729 (d)). States may specify additional monitoring or reporting requirements. The example forms presented in this appendix list both required and recommended monitoring parameters (required parameters are identified with the applicable rule citation).

Table M.1 summarizes the recommended minimum level of monitoring and record keeping for utilities utilizing UV disinfection. For many of the UV reactor components, the required or recommended performance level is based on the measurement uncertainty of the specific equipment that was used when the UV reactor was validated. This uncertainty is used to determine the validation safety factor and recommended reduction equivalent dose (i.e., operational UV dose), as described in section 4.2.

Table M.1. Summary of Compliance Monitoring and Reporting Activities[1, 2]

Item	Description	Measured Parameter	Recommended Monitoring Frequency	Reporting Frequency
Off-specification/ Validated Parameters for UV Dose	Monitor reactor to ensure operation within conditions validated for required UV dose (40 CFR 141, Subpart W, Appendix D).	Flowrate, UV intensity, lamp status, and other parameters (e.g., UVT) used to monitor dose.	Continuously. Record at least once every four hours (daily for very small systems).	Required monthly report of off-specification operation as a percent of distributed flow or operating time (40 CFR 141.730).[3]
Calibration of UV Intensity Sensors	Calibration checks compare the duty sensor to the reference sensor and are recommended at the power setting utilized during normal operation.	Percent difference between duty and reference sensors relative to the level of uncertainty used in determining the RED. (see section C.4.7)	Monthly. If a sensor fails for three consecutive months, then the sensor should be checked weekly and the manufacturer contacted.	Requirements in a State approved protocol.
Calibration of UV Transmittance (UVT) Monitor	It is recommended that grab samples be collected to confirm performance.	Percent difference relative to the manufacturer's guaranteed uncertainty.	Weekly initially. Reduced frequency following one-year of supporting data.	NR.

[1] Section 5.4.2 presents all recommended monitoring activities, including the compliance monitoring shown in this table.
[2] Unless noted in the table with an LT2ESWTR citation, the monitoring is recommended and not required.
[3] The reported off-specification value is the percentage of water entering the distribution that was not treated with UV reactors operating within validated conditions. This is required by the LT2ESWTR (40 CFR 141.730).
NR – No requirement

The LT2ESWTR requires utilities to submit monthly reports to the State (40 CFR 141.730). At a minimum, the reports must detail operating performance during the reporting period and, specifically, the percent of total distributed volume treated during periods when the UV reactor(s) was off-specification. An example monthly monitoring form is shown in Table M.2. Tables M.3 through M.6 present a format that the utility can use to log operating data for development of the monthly reports. With minor modification, the example forms are applicable for any of the three control strategies discussed in section 4.3.2.2: UV intensity setpoint, UV intensity and UV transmittance (UVT) setpoint, and calculated dose.

For those utilities utilizing multiple reactors, the operation of each reactor must be monitored, recorded, and reported. Requirements for compliance monitoring beyond those established by the LT2ESWTR and the specific content of the monthly report will be established by the State and coordinated with all other reporting requirements. Additional information on UV reactor monitoring and maintenance is provided in Chapter 5.

Greater detail on each of the example forms is provided below:

- Form M.2 is an example of a summary report that would be completed by the utility and submitted to the State on a monthly basis.

- Forms M.3A, M.3B, and M.3C are example reference forms for each of the three control strategies discussed in section 4.3.2.2. These forms would be completed by the utility based on validation results and then referenced throughout the operation of the UV installation to confirm compliance.

- Form M.4 is an example operating log that would be completed on a daily basis. The form would be used to record the operating status of the UV installation and to estimate the volume of water that was discharged during off-specification operation.

- Form M.5 is an example sensor calibration log. This log would be completed whenever sensor calibration checks are performed. The log would be used to record the results of the calibration testing as well to track any sensor recalibration or repair work that was completed.

- Form M.6 is an example on-line UVT monitor calibration log. This log would only be completed by those utilities that have included on-line UVT monitors as part of their design. The log would be completed whenever UVT monitor calibration checks are performed. The log would be used to record the results of the calibration testing as well to track any recalibration or repair work that was completed.

Table M.2 Example Monthly Report to State

Reporting Period: _____
System/Treatment Plant: _____
PWSID: _____

Monthly Reactor Operating Report

Operating Data			Off-Specification[1]			
Unit No.	**Operating Time (Hours)**	**Volume Treated (Gallons)**	**No. of Events**	**Volume (Gallons)**	**Time (Hours)**	**Percent of Volume Treated**
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
_____	_____	_____	_____	_____	_____	_____ %
TOTALS: _____		_____	_____	_____	_____	

Compliance Certification:

By volume the total percent of off-specification operation during the reporting period = _____ %

Of the _____ sensors within those reactors that operated during this reporting period, _____ have been checked for calibration and were within the acceptable range of tolerance.

Signature of Principal Executive Officer or Authorized Agent: _____ **Date:** _____

[1] From Table M.4

Table M.3A UV Intensity Setpoint Control Strategy[1]

Validated Operating Requirements to Achieve Disinfection Credit for _____*(Target Pathogen)*_____
(Reference Document - See Instructions Below)

Validated Operating Conditions

Flow Rate	UV Intensity	Log Inactivation[2]

[1] *This form is for use with a UV Intensity setpoint operating strategy. If a different operating strategy is employed by the utility, then one of the other sample reference forms should be used or a form summarizing the specific validation criteria necessary to confirm compliance using the selected operating strategy should be developed.*

[2] *For those utilities that do not employ variable power settings or that have a single target log inactivation, this column may not be necessary.*

Instructions:

This form should be completed based on the validation testing results and used as a reference document.

This form should be referenced to determine if the UV system is operating within its validated conditions and meeting the performance requirements for inactivation credit for the target pathogen.

Table M.3B UV Intensity and UVT Setpoint Control Strategy[1]

Validated Operating Requirements to Achieve Disinfection Credit for _____*(Target Pathogen)*_____
(Reference Document - See Instructions Below)

Validated Operating Conditions

Flow Rate	UV Intensity	UVT	Log Inactivation[2]

[1] *This form is for use with a UV Intensity/UVT setpoint operating strategy. If a different operating strategy is employed by the utility, then one of the other sample reference forms should be used or a form summarizing the specific validation criteria necessary to confirm compliance using the selected operating strategy should be developed.*

[2] *For those utilities that do not employ variable power settings or that have a single target log inactivation, this column may not be necessary.*

Instructions:

This form should be completed based on the validation testing results and used as a reference document.

This form should be referenced to determine if the UV system is operating within its validated conditions and meeting the performance requirements for inactivation credit for the target pathogen.

Table M.3C Calculated Dose Control Strategy[1]

Validated Operating Requirements to Achieve Disinfection Credit for *(Target Pathogen)*
(Reference Document - See Instructions Below)

Validated Operating Conditions

Flow Rate	UV Intensity	UVT	Calculated Dose	Log Inactivation[2]

[1] *This form is for use with a calculated dose operating strategy. If a different operating strategy is employed by the utility, then one of the other sample reference forms should be used or a form summarizing the specific validation criteria necessary to confirm compliance using the selected operating strategy should be developed.*

[2] *For those utilities that do not employ variable power settings or that have a single target log inactivation, this column may not be necessary.*

Instructions:

This form should be completed based on the validation testing results and used as a reference document.

This form should be referenced to determine if the UV system is operating within its validated conditions and meeting the performance requirements for inactivation credit for the target pathogen.

Table M.4 Daily UV Intensity Sensor and UVT Monitoring and Compliance Log[1]

Date: _____
System/Treatment Plant: _____
PWSID: _____
Unit Number: _____

Unit Did Not Operate During This Monitoring Interval: ☐

Operator Signature: _____

UV Transmittance Monitor: Grab Sample Collected: Y/N _____ If yes, complete Calibration Log Sheet.
Calibration Check Performed: Y/N _____

UV Intensity Sensors: Calibration Check Performed: Y/N _____ If yes, complete Calibration Log Sheet.

No.	Time	Flow Rate (gpd)	Cumulative Volume (gals)	UV Intensity Sensors									UVT Monitor [b]	
				Reading		Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading
1														
2														
3														
4														
5														
6														

	Time	Flow Rate	UVT Acceptable (Y/N)	UV Intensity Acceptable (Y/N) [2]	Calculated Dose [2]	Volume [3]	Operating Time	Off-Spec (Y/N)	Volume Off-Spec [4]
Reading No.1									
Reading No.2									
Reading No.3									
Reading No.4									
Reading No.5									
Reading No.6									
				Daily Total:					
						A			B

Percent Off-Specification by Volume: _____ %
(B/A x 100)

>5% (Y/N) [5] _____

Notes:

[1] *As presented, this form is most applicable to a calculated dose control strategy, but can be modified to suit all control strategies.*

[2] *Only if applicable to selected control strategy.*

[3] *Volume treated since last reading.*

[4] *For systems that rely solely on manual readings, the volume off-specification shall be calculated as the total volume discharged since the last recording interval during which operation within validated conditions was observed. If continuous monitoring is provided, then the volume off-specification shall be only that portion of the volume distributed during the recording interval that was outside of the validated conditions.*

[5] *LT2ESWTR requires that off-specification be less than 5 percent by volume on a monthly basis for unfiltered systems (§141.721). For filtered systems, it is that off-specification operation be less than 5 percent by volume on a monthly basis. The specific requirements for allowable off-specification for filtered systems will be established by the state.*

Instructions:

This form should be completed daily for each operating unit. If a unit did not operate during the 24-hour monitoring interval, please note as such in the box at the top of the log.

This form is intended for periodic manual monitoring of system operating conditions at the recommended interval of once every four hours. If automated or more frequent monitoring is performed, then this form should be modified by the utility.

Table M.5 Daily UV Intensity Sensor and UVT Monitoring and Compliance Log[1]

Reporting Period: _____
System/Treatment Plant: _____
PWSID: _____

Duty UV Intensity Sensor Uncertainty (%): _____
Reference Intensity Sensor Uncertainty (%): _____
Total Uncertainty Criteria (%): _____

Total Uncertainty Criteria = $\left(\frac{I_{Duty}}{I_{Ref}} - 1\right) * 100 \leq \left(\sigma_{Ref}^2 + \sigma_{Duty}^2\right)^{1/2}$

where,
I is measured intensity
σ is measurement uncertainty

UVT Intensity Sensor Calibration Report (Make Additional Copies of Form as Necessary)

Reactor/Duty Sensor No.	Reference Sensor ID	Duty Sensor ID	Date	Time	Duty Sensor Reading (A)	Reference Sensor Reading (B)	Error [(A-B)/Bx100]	Acceptable (Y/N)

Certification:

Of the _____ sensors within those reactors that operated during this reporting period, _____ have been checked for calibration. ☐

One or more of the sensors within those reactors that operated during this reporting period were outside the acceptable range of tolerance. ☐

____ UV Intensity Sensor(s) sent to manufacturer to be recalibrated as documented below. ☐

UV intensity sensors sent to manufacturer for calibration:

Sensor ID	Unit No.	Date Sent	Date Received

Operator Signature: _____ **Date:** _____

Appendix N. UV Lamp Breakage Issues

Lamps used in UV reactors typically contain mercury or an amalgam composed of mercury and another element, such as indium or gallium. Other elements, such as xenon, cadmium, zinc, and magnesium, are also capable of generating UV light; however, the temperatures required to volatilize these elements are much higher than to volatilize mercury. In contrast, mercury has a sufficient vapor pressure at ambient temperatures to provide the optimum pressure for efficient production of resonance radiation. Moreover, mercury has a low ionization energy to facilitate starting a lamp (Phillips 1983). In order to provide a cost-efficient lamp while addressing perceived risks and disposal issues associated with mercury, lamp manufacturers are continuing to develop ways to reduce the mercury content of lamps without impacting their efficiency (USEPA 1997b; Walitsky 2001).

The mercury contained within a UV lamp is isolated from exposure to water by a lamp envelope and surrounding lamp sleeve. In order for mercury to be released into the water, both the lamp and lamp sleeve must break. For the purposes of this appendix, lamp breakage is defined as fracture of the lamp sleeve and the lamp envelope. This is further divided into off-line and on-line breaks. Off-line breaks occur during handling or maintenance functions when the lamps are not installed in the reactor. On-line lamp breaks occur while UV reactors are in operation.

Due to the general public health concern with mercury, this appendix discusses the issues associated with UV lamps used for drinking water disinfection by addressing potential causes of lamp breakage, preventive measures, disposal issues, the fate of mercury after release, and regulatory issues.

N.1 Off-Line Lamp Breaks

Off-line breaks occur when a lamp breaks during shipping, handling, or storage. These releases do not pose a hazard to the water consumer but are a concern for operators or employees in the vicinity of the break.

N.1.1 Potential Causes of Off-Line Lamp Breaks and Corresponding Prevention Measures

Mercury is sealed in a UV lamp within the lamp envelope; therefore, there is no risk of mercury exposure from handling an unbroken UV lamp. The UV manufacturer should train operators in proper handling and maintenance of UV lamps to avoid mishandling and potential off-line breaks. In addition, proper storage procedures will also reduce the potential for lamp breakage. Lamps should be stored horizontally in individual packaging. Lamps should not be stacked unpackaged on one another or vertically propped in corners (Dinkloh 2001a).

N.1.2 Off-Line Mercury Release Cleanup Procedures

Off-line lamp breaks resulting in a release of mercury can occur; therefore, Standard Operating Procedures (SOPs) should be developed that describe the procedures for containing and cleaning the off-line spills. The local poison control center, fire department, or public health board can assist in the development of SOPs.

Small spills, defined as less than about 0.6 to 2.25 grams (USEPA 1992) or the amount in a broken thermometer (USEPA 1997a), can be contained and collected with commercially available mercury spill kits. Mercury and materials used during the cleanup procedure are regulated as hazardous wastes and should be disposed of properly as described in section N.3.3. The USEPA Office of Emergency and Remedial Response recommends that "[i]n the event of a large mercury spill (more than a broken thermometer's worth), immediately evacuate everyone from the area, seal off the area as well as possible, and call your local authorities for assistance" (USEPA 1997a). Local authorities can help determine the appropriate response for various spill sizes to be included in SOPs. Given that the mercury content in a single UV lamp typically ranges from 0.005 to 0.4 grams (as discussed in section N.4.3), large mercury spill actions would not be warranted for a single lamp break or multiple lamp breaks that result in release of less than roughly two grams.

Superfund Amendments and Reauthorization Act (SARA) Title III regulations address emergency release, inventory, and release reporting requirements for hazardous materials. The reportable quantity for mercury spills is one pound (454 grams) as mercury. Based on typical mercury levels in UV lamps (discussed in section N.4.3), this would necessitate the breakage of approximately 1,100 medium pressure (MP) lamps and up to 90,000 low pressure (LP) lamps; as such, spilling more than one pound of mercury is highly unlikely.

N.2 On-Line Lamp Breaks

A recent survey of domestic water and wastewater municipalities, UV lamp manufacturers, and UV reactor manufacturers identified relatively few instances of on-line lamp breaks and mercury release (Malley 2001). This section discusses potential causes of lamp breakage and corresponding prevention measures, followed by a summary of documented incidents of on-line lamp breaks.

N.2.1 Potential Causes of On-Line Lamp Breaks and Corresponding Prevention Measures

Lamp breaks can potentially be caused by debris in the water, temperature variations, exceeding positive or negative pressure limits (water hammer), electrical surges, or improper maintenance. Lamps may also break as a result of inherent mechanical or physical limitations of the lamp and improper material selection.

N.2.1.1 Debris

Debris in the water can potentially break the lamp sleeves and lamps. Although the majority of UV reactors will be installed after the filters in the treatment train, it is possible that equipment failure upstream may release parts or fragments, such as nuts or bolts. In addition, if UV disinfection is applied prior to the filters the probability of having debris in the water might be higher compared to post-filter UV installation. Ground water systems have reported stones or gravel from wells entering UV reactors and breaking lamps (Malley 2001; Roberts 2000).

Placement of screens, baffles, or low velocity collection areas upstream of UV reactors or vertical installation of UV reactors (when applicable) may reduce the risk of debris in the water from entering the reactor (Cairns 2000; Malley 2001, McClean 2001b). The extent of containment provided by these safety measures is unknown. Utilities and designers should determine the applicability of these isolation techniques on a site-specific basis.

N.2.1.2 Loss of Water Flow and Temperature Considerations

UV lamps are designed to operate within a specific temperature range to maximize the UV light output of the lamp. Without flowing water to cool the lamp, the lamp temperature can rise to dangerous levels and may break (Dinkloh 2001a; Malley 2001; Srikanth 2001a; Srikanth 2001b). This overheating is more likely to occur with MP than LP lamps (due to lamp operating temperatures) and occurs much faster in air than stagnant water. Even if upper temperature levels are not exceeded, after restoration of water flow, the lower temperature water entering the reactor may cause the lamp sleeve and the lamp to break due to temperature differentials (Dinkloh 2001a; Malley 2001). In order to prevent lamp breaks, operating procedures should ensure that the following conditions are met:

- Water is flowing through the UV reactor if the UV lamps are energized.
- The lamps are not energized while the reactor is not flowing full (i.e., no air in the reactor).

Temperature sensors should be, and typically are, incorporated into the reactor design and will shut down the reactor before critical temperatures are exceeded (Cairns 2000; Dinkloh 2001a; Malley 2001; Srikanth 2001b). Proper hydraulic design is also necessary to ensure that lamps are submerged at all times during reactor operation. Reactor designs should incorporate low flow alarms, air relief valves, or other devices to ensure that lamps are operating only when the reactor is completely flooded and water is flowing. These sensors should be linked to an alarm and automatic shutoff system (Cairns 2000; Dinkloh 2001a; Srikanth 2001b). Lamp overheating and temperature differentials could break all the lamps within the affected reactor.

N.2.1.3 Pressure-Related Issues

Hydraulic pressures within the reactor that are not within UV installation operating limits may also break the lamp sleeve. Although breaking the lamp sleeve does not automatically break the lamp envelope, the lamp is more vulnerable when its lamp sleeve has been

compromised, potentially allowing the lamp envelope to come into direct contact with the surrounding water.

Most lamp sleeves are designed to withstand continuous positive pressures of at least 120 pounds per square inch gauge (psig) (Roberts 2000; Aquafine 2001; Dinkloh 2001c; Srikanth 2001a; Srikanth 2001b). However, negative gauge pressures below -1.5 psig have been shown to adversely affect lamp sleeve integrity (Dinkloh 2001c). The tolerance level of the lamp sleeve depends on the quality of the quartz and the thickness and length of the lamp sleeve; therefore, pressure thresholds vary between lamp sleeves. Positive and negative pressures, such as those associated with water hammer, that exceed these levels may compromise the integrity of the lamp sleeve. Manufacturers should provide lamp sleeves with the appropriate material, thickness, geometry, and seals for the specified pressure and flow ranges of a given UV installation. Water hammer can affect all UV reactors and break all lamps; therefore, utilities should perform a surge analysis to determine if water hammer is a potential problem.

N.2.1.4 Procedural Errors

Operation and maintenance training can help prevent lamp breaks during on-line operations because a lamp damaged by off-line handling or improper maintenance operations may potentially break under on-line pressure or temperature stresses. For example, a common procedural error that can occur during lamp replacement is over-tightening compression nuts when securing the lamp sleeve (Aquafine 2001; Dinkloh 2001a; Srikanth 2001a; Srikanth 2001b; Swaim 2002). Over-tightening can cause a fracture of the lamp sleeve or a leak around the sleeve or compression nut cavity that may not become apparent until after start-up and operation of the UV reactor.

N.2.1.5 UV Reactor Design

The UV reactor manufacturer should design the UV reactor to reduce the possibility of lamp sleeve and lamp breaks. This subsection describes design problems that may cause lamp sleeve and/or lamp breakage if not properly addressed.

Electrical Considerations

If the UV installation electrical support system is improperly designed (e.g., inadequate circuit breakers and ground fault indicator circuits), electrical surges can cause short-circuiting and lamp socket damage (Srikanth 2001a; Srikanth 2001b). In addition, system electronics that can provide voltages that exceed lamp ratings (overdriving lamps) may also result in breaking the lamp (Malley 2001).

Cleaning Mechanism Considerations

The cleaning mechanism may break the lamp sleeve and lamp envelope if it is not aligned properly. Although the cleaning mechanism closely surrounds the lamp sleeve for cleaning, manufacturers should ensure that the mechanism is flexible and able to adjust to minor misalignment of the lamp sleeves.

At high lamp temperatures, the cleaning mechanism in some UV reactors may fuse to the lamp sleeve when not in use. As a result, during the next cleaning event, the lamp sleeve may crack when the cleaning mechanism is activated or when the cleaning mechanism passes back over the residual left on the lamp sleeve (Dinkloh 2001a). Routine inspection according to manufacturers' recommendations will help detect problems with the cleaning mechanism before damage occurs. In some UV reactors, wipers rest away from the lamp sleeve when not in use and an alarm sounds when the wiper stops along the lamp sleeve.

Thermal Expansion and Contraction

Other potential causes of lamp breaks include improper matching of lamp materials with respect to thermal expansion characteristics. Compatible materials within the lamp should be used by the manufacturer to avoid stress and damage that can be caused by thermal expansion and contraction differences between materials under various operating, shipping, or handling conditions (Cairns 2000). In addition, improper seal design or lamp envelope swelling may cause water leaks around the seals that may result in electrical shorts and cracking of lamps (Cairns 2000).

N.2.1.6 Summary of Potential Causes and Methods of Prevention of On-Line UV Lamp Breaks

Table N.1 summarizes the potential causes of on-line lamp breaks and provides a brief description of the preventive measures that UV installation designers and operators can implement to reduce each risk. There are few documented cases where lamps have been broken during on-line operations, which are discussed in section N.2.2.

Table N.1 Summary of Potential Causes and Methods of Prevention of On-Line UV Lamp Breaks

Potential Cause	Description	Preventive Measure
Debris	• Physical impact of debris on lamp sleeves may cause lamp breaks.	• Installation of screens, baffles, or low velocity collection areas upstream of UV reactors or vertical installation of UV reactors will help prevent debris from entering the reactor.
Loss of Water Flow and Temperature Considerations	• Lamps may overheat and break. • The temperature differential between stagnant water or air and flowing water may cause lamp breaks.	• Reactors should always be completely flooded. Temperature and flow sensors that are linked to an alarm and automatic shutoff system can be used to indicate irregular temperature or flow conditions.
Pressure-Related Considerations	• Excessive positive or negative pressures may exceed lamp sleeve tolerances and break the lamp sleeve.	• A surge analysis should be completed to determine the occurrence of water hammer. • Pressure relief valves or other measures can be used to reduce pressure surges. • Applicable pressure ranges should be specified for lamp sleeves.
Procedural Errors	• Improper handling or maintenance may compromise the integrity of the lamp sleeve and/or lamp.	• Operators and maintenance staff should be trained by the manufacturer.
UV Reactor Design	• Electrical surges can cause short-circuiting and lamp socket damage. • Applying power that exceeds design rating of lamps can cause lamps to burst from within.	• Adequate circuit breakers/ground fault indicators should be specified to prevent damage to the reactor. • Replacement lamps should be electrically compatible with reactor design.
	• Misaligned or heat-fused cleaning mechanism may break or damage the lamp sleeve and lamp envelope.	• Operators and maintenance staff should perform routine inspection and maintenance according to manufacturers' recommendations.
	• Thermally incompatible materials do not allow for expansion and contraction of lamp components under required temperature range.	• Designers should specify temperature ranges likely to be encountered during shipping, storage, and operation of lamps to aid the manufacturer in the selection of thermally compatible materials.

N.2.2 Frequency of On-Line Lamp Breaks

There have been relatively few documented incidents of on-line lamp breaks. As part of a survey of domestic water and wastewater municipalities, UV lamp manufacturers, and UV reactor manufacturers, Malley (2001) identified nine cases of on-line lamp breaks. Both the lamp sleeve and lamp envelope were damaged in all nine cases, resulting in mercury release (Table N.2). No cases of on-line failures using LP or low pressure high output (LPHO) lamps were identified. However, LPHO lamps are relatively new to the UV disinfection market and all LPHO lamp installations have been operating for 5 years or fewer (Malley 2001). All nine cases involved MP lamps. Four of the nine lamp breaks were caused by impacts from stones on lamps

oriented perpendicular to flow. In one of the nine lamp breaks, the applied power exceeded design rating of lamp (30kW) causing the lamp to burst from within. Differential sleeve heating resulted in two of the nine documented lamp breaks. The lamps were mounted vertically in the UV reactor allowing heat to accumulate at the top of the lamp, eventually cracking the sleeve. In two of the nine instances, operating lamps reached extremely high temperatures (>600 °C) in air because the reactors lost water flow. When water flow resumed, the cooler water (20 °C) broke the lamps. Most of these documented cases of lamp failure were the result of design issues that have been addressed in modern reactor designs. As mentioned previously, temperature and flow alarms should shut the UV reactor down when the potential for overheating or differential heating exist.

Another documented instance of MP lamp breakage occurred in a UV-peroxide reactor designed for well-head treatment of tetrachloroethene-contaminated ground water (Moss 2002a). The UV reactor was positioned between the ground water extraction pump and distribution system booster pumps. The 7-foot long MP lamp sleeve sagged and came into contact with the lamp envelope. The lamp envelope and lamp sleeve broke, releasing mercury to the water in the reactor. The lamp failure triggered an alarm, shutting down both the ground water extraction and distribution system booster pumps. Mercury liquid was found settled in the bottom of the reactor. Water sampling at a nearby fire hydrant detected mercury concentrations below the maximum contaminant level (MCL) of 2 micrograms per liter (µg/L) (Moss 2002a; Moss 2002b).

European drinking water utilities have an extensive history with UV technologies. Unfortunately, no written documentation of lamp failures was identified; however, two instances of lamp breakage during UV disinfection of drinking water were noted by European manufacturers (Roberts 2000; Table N.2). In one instance, a ground water well pump discharged gravel or stones into the reactor, resulting in a lamp break. A strainer was placed in-line prior to the reactor to prevent any future instances. The other documented case of a lamp breaking was due to operator error. A forklift was driven into an operating reactor and physically damaged the UV reactor. The event activated an alarm and pneumatic valve closure, which contained the contamination (Roberts 2000). In addition, there was an incident in which equipment debris (a bolt from the filter underdrain) impacted a lamp sleeve. Although the lamp sleeve was broken, the lamp envelope remained intact and mercury was not released because of the immediate UV installation shutdown and prompt operator response (McClean 2001a). Table N.2 summarizes the documented lamp breakages discussed in this section.

Table N.2 Mercury Release Incidents Involving UV Lamp Breaks

Identified Cause	Number of Incidents	Description of Incident
Debris	5	(4)[1] Stones entered the reactors and impacted and broke the lamps. (1)[2] Gravel entered reactor through the booster pump and impacted and broke the lamp.
Loss of Water Flow and Temperature Considerations	2	(2)[1] Lamps were left on and allowed to reach high temperatures (600 ^{o}C) in empty non-operating reactors. Restoration of flow resulted in cooler water (20 ^{o}C) breaking the lamps.
Operator Error	1	(1)[3] Forklift collided with on-line reactor resulting in lamp breakage.
Manufacturer Design	4	(1)[1] Applied power exceeded design rating of lamp (30kW) causing the lamp to burst from within. (2)[1] Vertical orientation of lamps resulted in differential heating and eventual cracking of lamp sleeve as surrounding water cooled the submerged portion of lamp and the exposed portion of the lamp accumulated heat. (1)[4] High operating temperatures resulted in deformation of the lamp sleeve. The lamp sleeve sagged and on contact with the lamp envelope, both envelope and lamp sleeve broke.

[1] Survey of domestic water, wastewater, and hazardous waste treatment utilities (Malley 2001)
[2] European drinking water facilities (Roberts 2000)
[3] European brewery (Roberts 2000)
[4] UV-peroxide ground water remediation reactor (Moss 2002a)

N.2.3 On-Line Mercury Release Response Plan

On-line lamp breaks are rare occurrences that are preventable with appropriate design and operation of UV reactors. However, utilities may consider developing a mercury release response plan for an on-line UV lamp break. The plan may include the following components:

- Site-specific containment measures
- Mercury sampling and compliance monitoring guidelines
- Clean-up procedures
- Reporting requirements

In the event of an on-line lamp failure alarm, the UV reactor should be immediately shut down and operators should attempt to determine the cause of the alarm. Unfortunately, lamp failure alarms or sensors cannot typically determine the cause of the alarm, whether it is partial or complete breakage of the lamp sleeve or lamp envelope (Kolch 2001) or another problem unrelated to the lamps. Thus, it is recommended that the reactor be taken off-line when investigating the cause of a lamp failure alarm (Kolch 2001).

In the event of an on-line lamp break and mercury release, operators should attempt to isolate the mercury in the reactor or downstream. Utilities may install spring-return actuated valves with a short closure time on the reactor inlet and outlet piping (McClean 2001b) to isolate the mercury. Given the short residence time of many MP reactors, the outlet-side valve may need to be located quite a distance downstream so that the valve has time to close and isolate the mercury upstream. UV installation designers should evaluate valve closure times with respect to creating water hammer.

Condensed mercury may collect in areas of low water velocity such as the bottom of a shutdown reactor, sump areas, or a clearwell. In addition, a strainer positioned on the reactor outlet piping may prevent lamp fragments from entering the water supply system (McClean 2001b; Srikanth 2001a; Srikanth 2001b). The headloss associated with such measures should be considered in the hydraulic profile. Designers may also consider installation of drains, vacuum relief valves, and piping to allow disposal of potentially contaminated water in the reactor to a waste container or truck.

The extent of containment provided by these safety measures is unknown. Utilities and designers should determine the applicability of these isolation techniques on a site-specific basis.

Utilities should coordinate with their State primacy agency when developing the following action items:

- **Mercury sampling plan** – Sampling procedures may outline sample locations, sampling frequencies, and analysis methods. Sample locations should be chosen with consideration of where mercury may settle and to assess the mercury concentrations potentially reaching the consumer. Sampling frequencies should consider flowrate, detention time, and travel time to the first potential consumer.

- **Site-specific cleanup procedures** – Site-specific cleanup procedures should be incorporated into a utility process hazard analysis (PHA). Issues to consider are detection and disposal of isolated or condensed mercury, potential disposal or treatment of contaminated water, and cleanup responsibilities (by utility staff or contracted hazardous materials team).

- **Reporting to State** – Reporting may include a description of the release, estimated quantity of release, shutdown or containment procedures, cleanup or disposal methods, sampling procedures (including sampling locations, frequencies, and results).

- **Public notification requirements, if applicable** – Revised public notification requirements (40 CFR 141.203) outline three tiers of public notification, depending on the severity of the violation or situation. Exceeding the mercury MCL of 2 µg/L is classified as a Tier 2 notice, where public notification is required within 30 days, unless extended to 90 days by the State primacy agency. Public notification requirements do not specifically address mercury releases due to UV lamp breakage where the MCL is not exceeded.

N.3 Regulatory Review

This section presents a review of regulations that may apply to the use or breakage of UV lamps containing mercury in water treatment plants (WTPs).

N.3.1 Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) established a primary MCL of 2 µg/L for inorganic mercury (40 CFR 141.62(b)). The required monitoring frequency depends on the water source and the frequency of detections. Utilities using ground water sources are required to sample once every 3 years. WTPs using surface water sources are required to sample annually. If mercury is detected above the MCL in any ground water or surface water utility, the utility must sample quarterly.

These regulations are independent of the use of UV disinfection at a facility. As discussed in section N.2.3, utilities should consult with their primacy agencies when developing a sampling plan for responding to an on-line UV lamp break.

N.3.2 Operator Health and Safety - Exposure Limits

The Mercury Study Report to Congress (USEPA 1997c) provides detailed information on health effects associated with exposure to elemental mercury and mercury compounds. Mercury exposure to employees in WTPs falls under the regulatory authority of the Occupational Safety and Health Administration (OSHA). The exposure limits set by OSHA focus on exposure by inhalation.

OSHA regulations have established permissible exposure limits (PELs) for mercury compounds and organo alkyls containing mercury. A PEL is a time weighted average concentration for an 8-hour workday during a 40-hour work week that is not to be exceeded. When a PEL is designated as a ceiling level (cPEL), the concentration cannot be exceeded during any part of the workday. PELs and cPELs are enforceable standards. The National Institute for Occupational Safety and Health (NIOSH) also publishes Immediately Dangerous to Life or Health (IDLH) concentrations for a variety of compounds. IDLH concentrations represent the maximum concentrations that one could escape within 30 minutes without symptoms of impairment or irreversible health effects. These values are not enforceable, but can be used as guidance for safety procedures. Table N.3 outlines the PELs, cPELs, and IDLHs for mercury compounds and organo alkyls containing mercury.

Table N.3 Health and Safety Standards for Mercury Compounds in Air

Compound	PEL (mg-Hg/m^3)	cPEL (mg-Hg/m^3)	IDLH (mg-Hg/m^3)
Mercury compounds	NR	0.1	10
Organo alkyls containing mercury	0.01	0.04	2

NR - not reported.

In the event of a spill, the volatilization and the resultant concentration of mercury in air depends on the vapor pressure (0.002 mm Hg; Table N.4), air currents, temperature, surface area/dispersion of mercury droplets, and time. Calculations using the ideal gas law (PV=nRT) indicate that these levels may be exceeded if cleanup of the mercury spills does not occur; however, prompt response and proper cleanup procedures should prevent exposure levels over these standards.

N.3.3 UV Lamp Disposal Regulations

Lamp manufacturers are required to determine whether their products exhibit the toxicity characteristic for mercury using a test called the Toxic Characteristic Leaching Procedure (TCLP, 40 CFR 261). If the TCLP level of a lamp is above the regulatory limit of 0.2 mg/L, the lamp is regulated as a universal hazardous waste (Universal Waste Rule, 40 CFR 273) under Subtitle C of the Resource Conservation and Recovery Act (RCRA). As such, these lamps should be sent to a mercury recycling facility where the mercury is recovered and lamp components are recycled. Although some mercury lamps do not exceed the TCLP regulatory level, utilities are encouraged to recycle these lamps to reduce mercury loading to the environment. Some UV reactor and lamp manufacturers will accept spent or broken lamps for recycling or proper disposal (Dinkloh 2001a; Lienberger 2002; Gump 2002). Alternatively, utilities should contact their primacy agency for a list of local recycling facilities.

N.4 Additional Factors Affecting Risk

This section provides further information that may be helpful in evaluating risk associated with on-line lamp breakage. The ultimate fate of mercury after a lamp is broken is currently unknown but is expected to depend on the following conditions:

- Physical and chemical properties of mercury species in air and water
- Mercury behavior in operating UV lamps
- Quantity of mercury released (type, age, and number of broken lamps)
- Potential mercury reactions in water treatment plants and the distribution system

N.4.1 Physical and Chemical Properties of Mercury

Mercury can exist in three oxidation states: elemental (Hg^0), mercurous (Hg^{+1}), and mercuric (Hg^{+2}). Mercury cycles between oxidation states as a function of the redox conditions of the surrounding environment and the availability of other reactive compounds.

Elemental mercury is a liquid at ambient temperature and pressure; however, given its high vapor pressure (Table N.4), elemental mercury is easily vaporized at ambient temperatures. Other physical and chemical properties of elemental mercury that affect its fate and transport are outlined in Table N.4.

Table N.4 Physical and Chemical Properties of Elemental Mercury (Merck & Co., Inc. 1983)

Property	Value
Melting point (^oC)	-38.87
Boiling point (^oC)	356.72
Density (g/mL at 25 ^oC)	13.534
Solubility (g/L at 25 ^oC)	0.06[1]
Vapor pressure (mm Hg at 25 ^oC)	0.002

[1] Further information regarding mercury solubility in water can be found in Glew et al. 1971

N.4.2 Mercury Behavior in UV Lamps

It is important to characterize the quantity and form of mercury in an operating lamp because they represent the starting point for mercury dispersion, speciation, and reaction chemistry in the water system following a lamp break. However, the quantity and form of mercury placed in UV lamps typically is considered proprietary information by manufacturers because these parameters affect the efficiency, operation, and life of the lamp. In general, the form of mercury contained in a UV lamp is elemental mercury (LP and MP) or a mercury amalgam (LPHO). An amalgam is an alloy of elemental mercury with another metal (typically indium in lamp applications) that can be either solid or liquid at room temperature, depending on the relative proportions of the two metals. In operating lamps, elemental mercury (from pure or amalgamated mercury) is vaporized in the presence of an inert gas. Vapor phase mercury is excited and then ionized by the energy transfer from the excited inert gas and the supply of electrons generated from the applied voltage (Phillips 1983). It is the transition of mercury electrons from excited state back to ground state that releases energy in the wavelength range of the UV spectrum.

The concentration of mercury in the vapor phase in LP and LPHO lamps is controlled predominantly by temperature. Manufacturers of these lamps use different methods to control or maintain the temperature of the liquid mercury or mercury amalgam to establish the desired vapor phase mercury concentrations. Methods of controlling the temperature of mercury and, consequently, the vapor pressure in LP and LPHO include using either a mercury amalgam attached to the lamp envelope (LPHO only), a cold spot on the lamp wall, or a mercury condensation chamber located behind each electrode. At typical LP and LPHO lamp operating temperatures, mercury remains predominantly in the liquid or solid amalgam phase with a small proportion in the vapor phase.

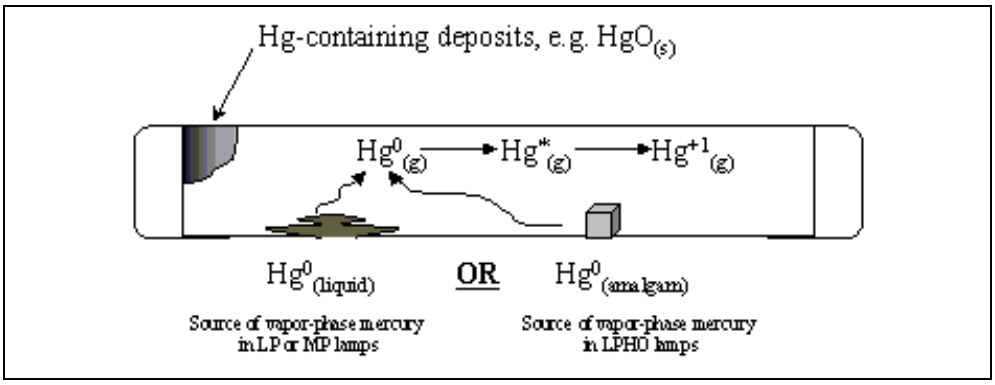
MP lamps are dosed with elemental mercury liquid. In operating MP lamps, mercury is primarily present in the vapor phase due to high operating temperatures (600 to 900 ^oC; Table 2.1) that cause all liquid elemental mercury to volatilize (Phillips 1983). In order to control the concentration of vapor phase mercury, manufacturers strictly control the amount of mercury dosed or added to the lamp during production. This is different from the LP and LPHO lamps where an excess of mercury is placed in the lamp and only a portion of the elemental mercury enters the vapor phase. Once elemental mercury enters the vapor phase, mercury ionization in a MP lamp occurs the same way as in LP or LPHO lamps.

The relative proportion of mercury in the liquid/amalgam phase and the vapor phase becomes important when an operating lamp breaks in water. Vapor phase elemental or ionized mercury may be released as very fine particles. These particles may more readily dissolve in water as opposed to condensed liquid or amalgamated mercury that settles in low velocity areas.

In addition to these functional mercury interactions, Altena (2001) reported reactions of vapor phase mercury with fluorescent lamp components, such as the glass bulb, glass stems, coatings, and the emission material (electrodes). This process results in the embedding of mercury in lamp components and the accumulation of mercury-containing deposits, such as mercury oxide, on the internal lamp envelope surface. Altena (2001) theorized that mercury reactions with UV lamp components would be comparable to fluorescent lamps. These deposits represent approximately 2 to 15 percent of the total mercury present in a lamp as calculated from Altena (2001). After breakage, these deposits are available to dissolve in water; however, mercury oxide has a low solubility in water (Merck & Co. 1983).

Figure N.1 outlines the expected forms of mercury in an operating lamp. Note that all liquid elemental mercury will volatilize in an operating MP lamp, leaving no mercury in the liquid phase. Also, amalgams are only used in LPHO lamps.

Figure N.1 Mercury Speciation In Operating UV Lamps



N.4.3 Quantity of Mercury in Lamps

The amount of mercury in a UV reactor is a function of the type of lamp, the number of lamps in a reactor, and the number of reactors. Mercury content within lamps depends on type (LP, LPHO, or MP), length, and power rating. Although mercury content data are specific to manufacturer and lamp, lamps with higher pressures, power ratings, and lengths typically contain more mercury. Table N.5 summarizes the quantities of elemental mercury dosed into lamps during manufacturing according to a confidential manufacturer survey and published literature values.

Table N.5 Elemental Mercury Content in UV Lamps

Lamp Type	Electrical Power Rating (W)	Mercury Content (mg per lamp)		
		Phillips (1983)	Clear et al. (1994)	Manufacturer Survey
LP	15-70	"a single drop"[1]	20[2]	5-50
LPHO	120-260	NR	26[3], 36[4]	150
	400	NR	75.5	NR
MP	1000	NR	250	NR
	1-25 kW	1.4 - 14.5 mg/cm[5]	NR	200-400, 0.3 - 7 mg/cm length, 7.9 mg/cm length

[1] Phillips 1983
[2] 75 W mercury vapor lamp
[3] 175 W mercury vapor lamp
[4] 250 W mercury vapor lamp
[5] mg per cm of lamp length, reported lamp lengths are 6-300 cm (Primarc Limited 2001)
NR - Not Reported

N.4.4 Quantification of Mercury in Example UV Installations

This section illustrates example calculations of the amount of mercury contained in hypothetical UV installations. Two UV reactor manufacturers established design parameters for three treatment flowrates (0.18, 3.5, and 210 million gallons per day (mgd)) with a specified water quality and design dose (Table N.6). Design parameters included the number of lamps needed to obtain a dose of 40 mJ/cm^2 and the total number of reactors for each of the three design flows. Calculations assume 50, 150, and 400 mg of mercury per LP, LPHO, and MP lamp, respectively. Utilities should use site-specific UV installation information to determine quantities because mercury content varies with lamp type and manufacturer.

Table N.6 Mercury Quantity in Example UV Installations[1,2]

Design Flow (mgd)	Average Flow (mgd)	Lamp Type	Average Number of Reactors	Average Number of Lamps (per reactor)	Total Hg in UV Installation[3] (g)
0.18	0.054	LP	1	2	0.1
		LPHO	1	1	0.2
		MP	1	1	0.4
3.5	1.4	LPHO	1	30	4.5
		MP	1	4	1.6
210	120	LPHO	6	72	64.8
		MP	6	7	16.8

1 UV Dose = 40 mJ/cm^2
2 Water quality criteria: UVT = 89% (A_{254} = 0.05 cm^{-1}), Turbidity = 0.1 NTU, Alkalinity = 60 mg/L as $CaCO_3$, Hardness = 100 mg/L as $CaCO_3$
3 Values given represent the amount of elemental mercury dosed in lamps during manufacturing.

N.4.5 Fate of Mercury After Release

The previous sections define the quantity and form of mercury in an operating lamp and thus define the starting point for the investigation of the fate of mercury in the water system. Unfortunately, little documentation exists on the fate of mercury in WTPs or distribution systems. The few case studies that do exist are mainly in the wastewater industry and focus primarily on removal of influent mercury by the following wastewater treatment processes:

- Primary sedimentation (Lester 1983; Firk 1986; Balogh and Liang 1995; Goldstone et al. 1990; Oliver and Cosgrove 1974)
- Activated sludge (Gilmour and Bloom 1995; Lester 1983; Chen et al. 1974; and Wu and Hilger 1985)
- Conventional treatment process (Mugan 1996; Balogh and Liang 1995; Bodaly et al. 1998)

Much of the knowledge about mercury and its potential fate in water systems is derived from studies performed in natural environments. It is expected that this knowledge of mercury cycling within the natural environment can be applied to mercury dynamics within a WTP and distribution system where environmental conditions are largely controlled and remain fairly stable. However, WTPs employ a number of chemicals that are not typically found in natural environments. No studies were identified on influence and reaction of mercury with coagulants, polymers, corrosion inhibitors, ammonia, strong oxidants, and other disinfectants (e.g., chlorine and ozone). This subsection projects mercury reactions within a WTP and distribution system based on documented mercury reactions in the natural environment.

N.4.5.1 Potential Mercury Reactions in Water Treatment Plants and Distribution System

Liquid phase elemental mercury is considerably denser than water (specific gravity = 13.6; Table N.4) and does not readily dissolve in water. Therefore, liquid elemental mercury and mercury amalgams may settle in areas of low water velocity, thereby providing an option for early containment and removal. For example, in cases where mercury was released from other water treatment equipment (such as manometers, flow instrumentation, or pump seals), mercury was found to have condensed and settled in the clearwell. However, the amount of mercury recovered relative to the amount of mercury released is unknown (Cotton 2002). Kolch (2001) monitored the mercury concentrations in a 50-liter batch reactor following the destruction of one LPHO lamp (approximately 150 mg-Hg). Mercury concentrations reached approximately 2.5 µg/L in water. Amalgamated mercury was found settled on the bottom at the reactor (Dinkloh 2001b). However, it was not reported whether all the 150 mg of mercury present in the operating lamp was recovered with the amalgam or accounted for in the aqueous phase.

Also, Kolch (2001) did not determine whether the source of aqueous phase mercury was dissolved mercury from the amalgam or vapor phase mercury present in the lamp prior to when it was broken. This issue may become important when considering the aqueous behavior of mercury following a MP lamp break. Mercury in a MP lamp is predominantly in the vapor phase during operation. It is unknown how the vapor phase mercury will react with the water. Vapor phase elemental and ionized mercury may become very fine particles when contacting the water as opposed to liquid or amalgamated mercury that settles in low velocity areas.

Depending on the age of the lamp, mercury-containing deposits, such as mercury oxide, may accumulate on the inner surface of the lamp envelope in all lamp types. Dissolution of the deposits would result in additional ionized mercury entering the water. Prompt response to a lamp break would include removal of lamp fragments; therefore, the compounds on the lamp fragments should not have the opportunity to enter the WTP.

Once in the water, aqueous (dissolved) elemental and ionized mercury are expected to cycle between phases and oxidation states as determined by temperature, pH, organic carbon concentration, minerals and inorganic species, and dissolved oxygen level. The mercurous ion (Hg_2^{+2}) is formed by the oxidation of elemental mercury or the reduction of the mercuric ion (Hg^{+2}). The mercurous ion is capable of bonding with inorganic constituents; however, it does not bind with organic compounds. Hg_2^{+2} is rarely stable under typical environmental conditions and is readily reduced to Hg^0 or oxidized to Hg^{+2}.

Inorganic reactions involving the mercuric ion (Hg^{+2}) include binding with inorganic ligands such as chloride, hydroxide, and sulfide. Considering sulfide is present in anoxic environments, mercury sulfide (HgS) is not expected to form in a water treatment environment. Reactions of Hg^{+2} with chloride and hydroxide resulting in mercuric chloride and mercuric hydroxide compounds depend on the pH and chloride concentrations (Beckvar et al. 1996).

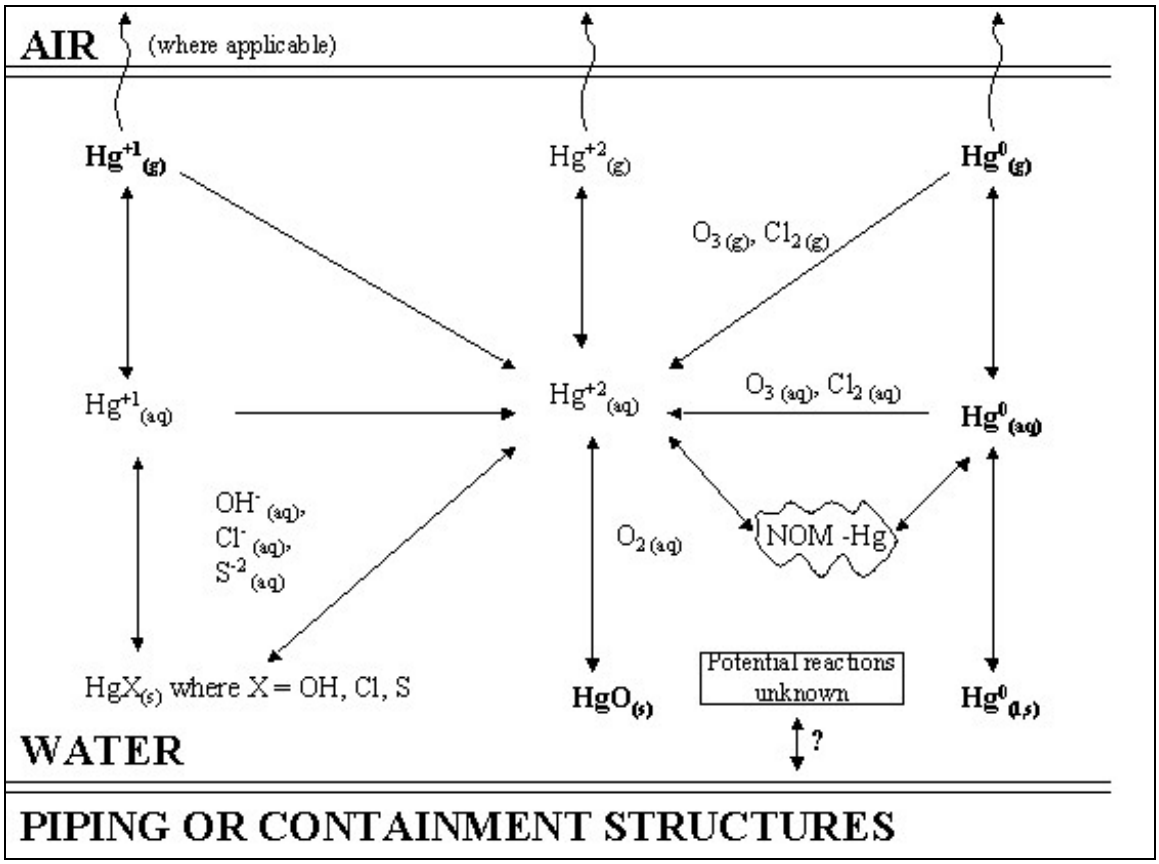
Additional discrepancies arise in the comparison of mercury reactions and fate in a drinking water environment versus the natural environment when organic carbon concentrations and existing microbial populations are considered. The mercuric ion (Hg^{+2}) is the only oxidation state of mercury capable of association with organic compounds such as phenyl and methyl

groups. The resultant organic compounds, commonly known as methylated mercury, have different chemical, physical, and toxicological properties than inorganic mercury and offer more cause for concern due to toxicity and bioaccumulation properties (Beckvar et al. 1996). Methylation of mercury to form methyl and dimethyl mercury is primarily a biological process involving sulfate-reducing bacteria although it can also occur abiotically. The extent to which methylation occurs depends on the availability of Hg^{+2} and the presence of an appropriate microbial population. Methylation rates are higher under anoxic conditions, low pH, elevated temperatures, and high organic matter concentrations (USEPA 1997c). Therefore, even though Hg^{+2} may be present in the water column, all of the above factors oppose the occurrence of methylation in a drinking water environment.

Another divergence of a water treatment environment from the natural environment is the presence of treatment chemicals such as coagulants, strong oxidants, polymers, corrosion inhibitors, and ammonia. Seigneur (1994) researched the reaction chemistry of mercury with inorganic species and strong oxidants such as chlorine and ozone in the aqueous and gas phases that are present in the atmosphere. Ionized mercury can form inorganic compounds with chloride and hydroxide ions. Depending on reactant concentrations, these compounds may be present in the aqueous phase and as solid precipitate. Also, based on reduction oxidation potentials, it is possible that the oxidation of elemental mercury would occur in the presence of chlorine and ozone, forming mercury ions and thereby increasing the solubility of elemental mercury.

Further research and investigation is necessary to determine the mechanisms of any potential mercury reactions. Figure N.2 outlines this preliminary assessment of mercury speciation and reaction in a drinking water environment.

Figure N.2 Potential Reactions of Mercury in a Drinking Water Environment (Compounds released from a broken lamp are in boldface type.)



Mercury (methylated and ionic) sorption to dissolved and particulate organic matter is commonly found in natural environments (Beckvar et al. 1996; USEPA 1997c). This observation was also made in water and wastewater treatment plant studies, where mercury became incorporated into coagulant flocs and activated sludge waste, respectively (Logsdon 1973; Gilmour and Bloom 1995; Lester 1983; Chen et al. 1974; Wu and Hilger 1985).

If UV disinfection of raw water is used and a UV lamp breaks, the mercury could potentially be removed within the WTP. Logsdon (1973) investigated the efficiency of mercury removal in conventional WTPs. Bench-scale laboratory tests indicated that inorganic mercury was removed via coagulation, softening, adsorption on turbidity, powdered activated carbon (PAC) adsorption, and granular activated carbon (GAC) column adsorption.

N.5 Summary and Conclusions

The risk associated with a mercury release to the water system depends on many factors. More research is needed to close the knowledge gap that exists regarding the fate of mercury in a drinking water environment following a UV lamp break. The influence of treatment chemicals such as oxidants, disinfectants, and coagulants is largely unstudied. Likewise, dispersion and transport of mercury through a WTP and distribution system has yet to be evaluated. Although

these issues are, at present time, largely unknown, there are procedures and actions that can be taken to reduce or mitigate mercury release caused by UV lamp breakage.

For the purposes of this appendix, lamp breakage was defined as fracture of the lamp sleeve and the lamp envelope. This was further divided into off-line and on-line breaks. Off-line lamp breaks typically occur during storage or handling and cause small spills (< 2g). Small spills should be contained, cleaned up, and disposed of properly.

On-line lamp breaks occur while the UV reactor is in operation. There have been reported incidents of on-line UV lamp breaks associated with impact from debris, loss of water flow, temperature differentials, faulty electrical equipment and design, and procedural errors. However, on-line lamp breaks are a rare occurrence and are largely preventable with appropriate design, operation, maintenance, and operator care. The following engineering and administrative methods have been proposed that may help prevent UV lamp breakage:

- Screens, baffles, or low velocity collection areas prior to the reactor influent to prevent entrance of debris
- Temperature and flow sensors and alarms to detect critical conditions and shut the UV reactors down
- Surge analysis to determine if water hammer may be a potential problem
- Comprehensive training and maintenance program

In the event of a mercury release, the following engineering controls are additional precautions that may aid in the containment and collection of mercury:

- Strainers and low velocity collection areas downstream of the reactor
- Isolation valves activated by an alarm to attempt to isolate potentially contaminated water

The extent of containment and prevention provided by these measures is unknown. Utilities and designers should consider the applicability of these isolation techniques on a site-specific basis. Utilities should consult with their State primacy agency in the development of standard operating procedures, clean-up procedures, and reporting requirements in preparation for a potential UV lamp break and mercury release. It is recommended that a utility prepare a mercury release response plan to address these issues. This plan should address compliance with the SDWA, OSHA health and safety standards, and RCRA universal waste rules. Utilities are encouraged to recycle or return all mercury-containing lamps to mercury re-generating facilities or the lamp manufacturer.

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Appendix O. Case Studies

This appendix will be included in the final draft when more information is available.

Appendix P. Validation Protocol Calculator Tool

The validation protocol described in Chapter 4 and Appendix C of this guidance manual involves several calculations to determine the log inactivation credit achieved during validation of a UV reactor. For this protocol, a safety factor calculated from uncertainties and known variability associated with UV reactors, monitoring, and validation methods is used to relate the reduction equivalent dose (RED) demonstrated during validation to the UV dose required to achieve a specified log inactivation credit (Table 1.4). EPA developed a spreadsheet that enables a user to input information associated with the uncertainty of validation and monitoring and calculate the safety factor and resulting target RED. The calculator was used to develop Tier 1 RED targets and can be used to apply the Tier 2 approach. (See section C.4.10.2 for a description of the Tier 2 approach, including the safety factor calculation.)

The Microsoft Excel® spreadsheet contains the following five worksheets:

- Instructions – provides step-by-step instructions for entering data into the "RED Bias", "Polychromatic Bias", and "Safety Factor" worksheets and executing macros to calculate safety factor and resulting target RED.
- RED Bias – calculates RED bias from input of Chapter 1 UV dose requirements and inactivation and RED measured during validation.
- Polychromatic Bias – calculates the polychromatic bias for medium-pressure UV systems using spectral data on the lamp output, sleeve UV transmittance, water UV transmittance, and sensor response.
- Safety Factor – calculates safety factor from RED bias, polychromatic bias, and expanded uncertainty associated with reactor validation and monitoring.
- Default Data – contains assumed data for calculating the polychromatic bias; alternatively, the user can provide validation testing data as specified in the instruction worksheet.