UV Disinfection Systems for Drinking Water - Planning and Design

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3. Planning Analyses for UV Facilities

This chapter provides information on the elements that should be addressed during the UV disinfection planning or preliminary design phase.

Chapter 3 covers:

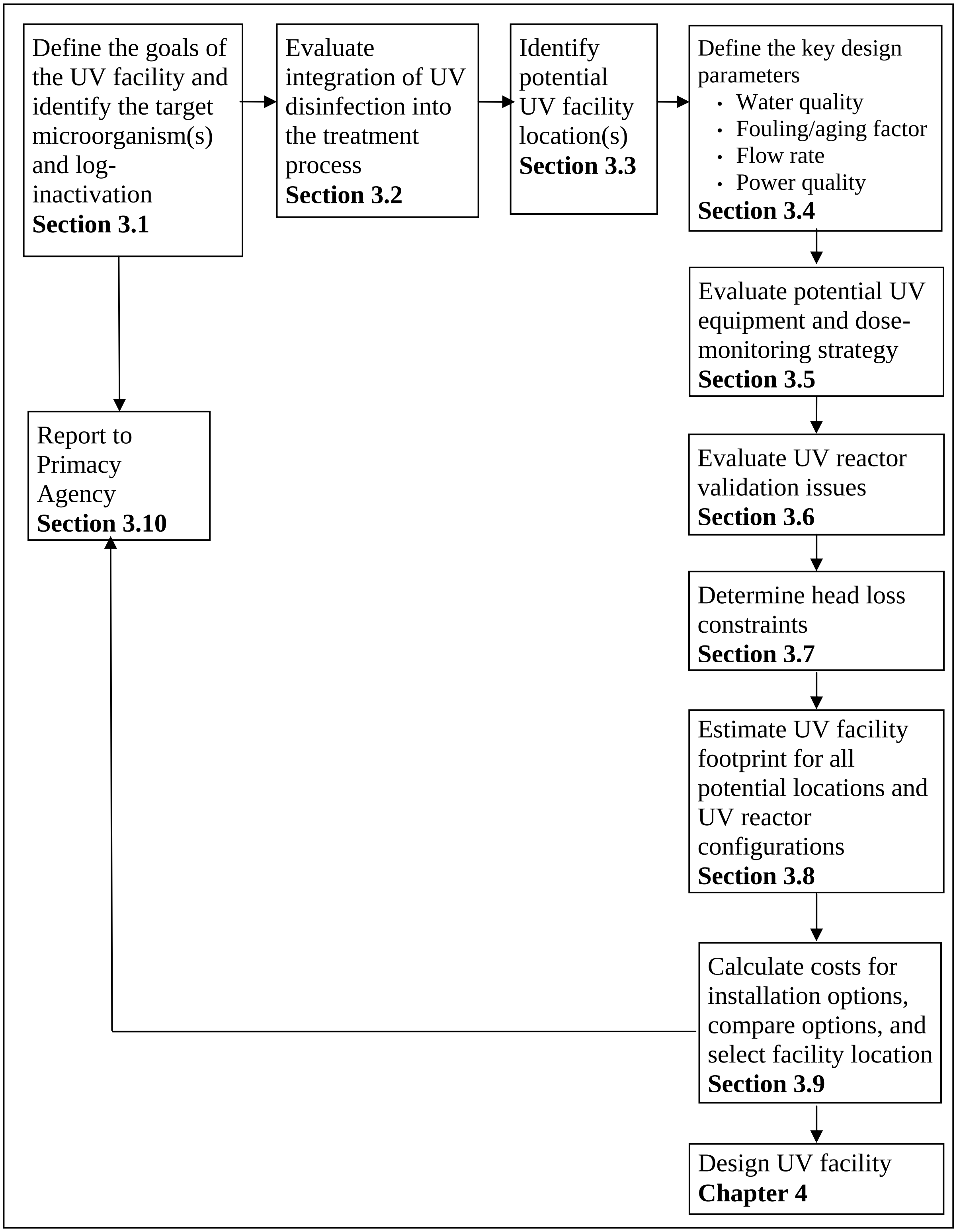
The planning for any UV facility is site-specific. Given the wide range of possible treatment scenarios, a guidance document such as this one cannot address or anticipate all possible treatment conditions. The information presented here should be used within the context of sound engineering judgment and applied appropriately on a case-by-case basis. Appendix F presents case studies that illustrate how various public water systems (PWSs) have implemented UV disinfection in their water systems. Additionally, this manual was written with the understanding that UV technology will continue to expand and evolve, so the information presented is current only as of the publication date. Furthermore, unless otherwise stated, throughout Chapter 3 the water to be disinfected is assumed to be from ***surface water systems*** [(i.e., filtered water, an unfiltered source water, or groundwater under the direct influence (GWUDI)], meeting applicable regulatory requirements that pre-date the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR).

The process of planning and designing a UV facility is presented in Figure 3.1. Once the design parameters are defined and the implementation issues are identified, they are incorporated into the detailed design phase, which is discussed in Chapter 4.

3.1 UV Disinfection Goals

The first step in planning a UV disinfection facility is to define the goals for the facility as part of a comprehensive disinfection strategy for the entire treatment process. Additionally, the target pathogen(s), target log-inactivation, and corresponding required UV dose should be identified.

Figure 3.1. Example Flowchart for Planning UV Facilities



- **Comprehensive Disinfection Strategy:** A comprehensive disinfection strategy provides multiple barriers to reduce microbial risk, while minimizing disinfectant byproduct (DBP) formation. UV disinfection is a tool that can contribute to a comprehensive disinfection strategy by providing a cost-effective method of inactivating pathogens that are more resistant to traditional disinfection methods. Also, UV disinfection can replace chemicals for primary disinfection of chlorine-resistant pathogens (e.g., *Cryptosporidium* and *Giardia*), thereby reducing DBP formation. Note that PWSs that plan to significantly change their disinfection process, including adding UV disinfection, must prepare a disinfection benchmark[1] (40 CFR 141.708) and consult with the state before making any changes. Further, PWSs must continue to provide 2-log *Cryptosporidium* removal by meeting filtered water turbidity requirements (40 CFR 141.173 for PWSs serving at least 10,000 people and 40 CFR 141.551 for PWSs serving fewer than 10,000 people) unless they meet the filtration avoidance criteria.

- **Target Pathogen and Log Inactivation:** The required UV doses for *Cryptosporidium* and *Giardia* inactivation are lower than those needed to inactivate viruses. (See Table 1.4.) Accordingly, the capital and operational costs for inactivating *Cryptosporidium* and *Giardia* should be lower than for viruses. One study estimated capital costs for *Cryptosporidium* and *Giardia* inactivation by UV disinfection on a log removal basis to be about half the cost associated with the UV inactivation of viruses (Cotton et al. 2002). Additionally, most viruses can be easily inactivated with chlorine so UV disinfection for virus inactivation may not be necessary. The target log inactivation also should be considered because higher target inactivation requires higher UV doses that will affect the design and cost of the UV facility. Therefore, the target microorganism(s) and their log-inactivation level should be determined early in the planning process.

3.2 Evaluating Integration of UV Disinfection into the Treatment Process

When installed, UV disinfection will typically be one of several treatment processes to help meet water quality goals. Accordingly, UV disinfection should be evaluated in the context of the complete treatment process, and the impacts on UV disinfection on other treatment processes should be considered. These issues are summarized in this section.

3.2.1 UV Disinfection Effects on Treatment

Typically, UV disinfection cannot entirely replace chemical disinfectants used in the treatment process. Some of the reasons are listed below.

- Surface water systems must maintain a disinfectant residual in the distribution system (40 CFR 141.72).

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[1] More information on completing a disinfection benchmark can be found in *Disinfection Profiling and Benchmarking Guidance Manual* (EPA 1999).

- UV disinfection is not as efficient in inactivating viruses as more traditional, chlorine-based disinfection processes.

- Chemical disinfectants may also be needed to oxidize other constituents present in the water (e.g., iron, manganese, or taste- and odor-causing compounds).

- Some water systems apply chlorine to reduce algal growth in sedimentation basins.

Consequently, some level of chlorine-based disinfectant (chlorine or chloramines) usually will be needed even when UV disinfection is implemented. Therefore, any reduction in chlorine-based disinfectants should be evaluated in the context of other water quality and treatment goals.

When UV disinfection is applied to water having a chlorine residual, some chlorine residual reduction may occur, depending on the UV dose, chlorine species, UV light source, and water quality characteristics (Brodkorb and Richards 2004, Örmeci et al. 2005, Venkatesan et al. 2003). Brodkorb and Richards (2004) reported chlorine residual reduction between 0.1 and 0.7 milligrams per liter (mg/L) at a wide range of UV doses (described in Section 2.5.2). Significant chlorine reduction could occur inadvertently if the UV equipment cannot provide enough power modulation capacity and actually operates at much higher doses than designed. Two options are available to avoid chlorine reduction by UV disinfection:

1. Consider moving the chlorine addition point to after the UV facility if possible, especially when targeting viruses (because their required UV doses are higher).

2. Procure the UV equipment that has adequate power modulation to prevent overdosing and subsequent chlorine reduction.

In addition, UV disinfection of water having a chlorine residual, which results in a higher oxidation-reduction potential (ORP), could result in sleeve fouling (Section 2.5.1.4) if iron or manganese are present even at low levels and a proper cleaning system is not in place (Malley et al. 2001). Several studies have shown that fouling occurs at iron levels below the secondary maximum contaminant level (SMCL) when the water has a high oxidation-reduction potential (ORP) (Collins and Malley 2005, Derrick 2005, Wait et al. 2005). Again, moving the point of chlorination to after the UV facility can possibly reduce sleeve fouling (Section 3.4.4.2). Alternatively, oxidation and removal of iron and manganese (e.g., by adding potassium permanganate upstream of the sedimentation basin) reduces the fouling potential.

3.2.2 Upstream Treatment Process Effect on UV Disinfection

Water treatment processes upstream of the UV reactors can be operated to maximize the ultraviolet transmittance (UVT), thereby optimizing the design and costs of the UV equipment (Section 3.4.4.1). For example, coagulation, flocculation, and sedimentation remove soluble and particulate material, and optimizing coagulation for organics removal will increase the UVT, which could reduce the UV facility costs. Also, upstream chemicals may affect UV disinfection performance as described in Sections 2.5.1.3 and 3.4.4.1.

3.3 Identifying Potential Locations for UV Facilities

The UV dose tables (see Table 1.4) in the LT2ESWTR apply to post-filter applications of UV disinfection in filtration plants and to unfiltered systems that meet filtration avoidance criteria. In general, installing UV disinfection prior to filtration in conventional water treatment plants (WTPs) is not recommended because of the potential particle interference in raw and settled waters. As such, only post-filter locations are discussed for filtered systems in this section.

After the potential locations are identified, design criteria, hydraulics, validation issues, and footprint estimations should be evaluated at each location to identify which location is most feasible for the UV facility. These evaluations are described in subsequent sections.

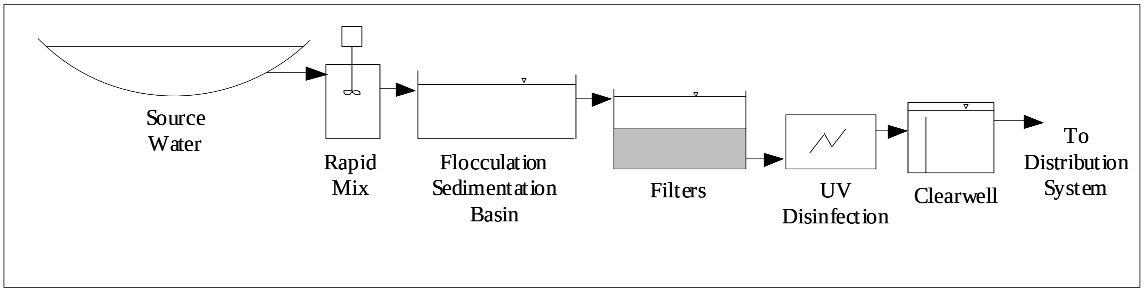
3.3.1 Installation Locations for Filtered Systems

In conventional WTPs, the three most common installation locations are downstream of the combined filter effluent (upstream of the clearwell), on the individual filter effluent piping (upstream of the clearwell), and downstream of the clearwell.

3.3.1.1 Combined Filter Effluent Installation (Upstream of the Clearwell)

A combined filter effluent installation is defined as the application of UV disinfection to the filtered effluent after the effluent from individual filters has been combined (as opposed to applying UV disinfection to the individual filter effluents) and ahead of the clearwell, as shown in Figure 3.2. For retrofits on existing WTPs, these installations are usually housed in a separate building.

Figure 3.2. Schematic for UV Facility Upstream of the Clearwell



This type of design and installation has several advantages:

- The UV reactor operation is largely independent of the operation of individual filters, which provides flexibility for design and operation.

- If the entire UV facility failed, a WTP can continue to disinfect by adding a chemical disinfectant to the clearwell. (Note that backup chemical disinfection will likely not provide *Cryptosporidium* inactivation.)

- Surge and pressure fluctuations typically are not a concern for this installation location unless membrane filtration, pressure filters, or intermediate booster pumps are used.

- Because this type of UV facility is typically constructed in a new building, there may be greater flexibility to maintain the recommended inlet and outlet hydraulic conditions for the UV reactors (Section 3.6.2).

The primary disadvantages of this type of installation are:

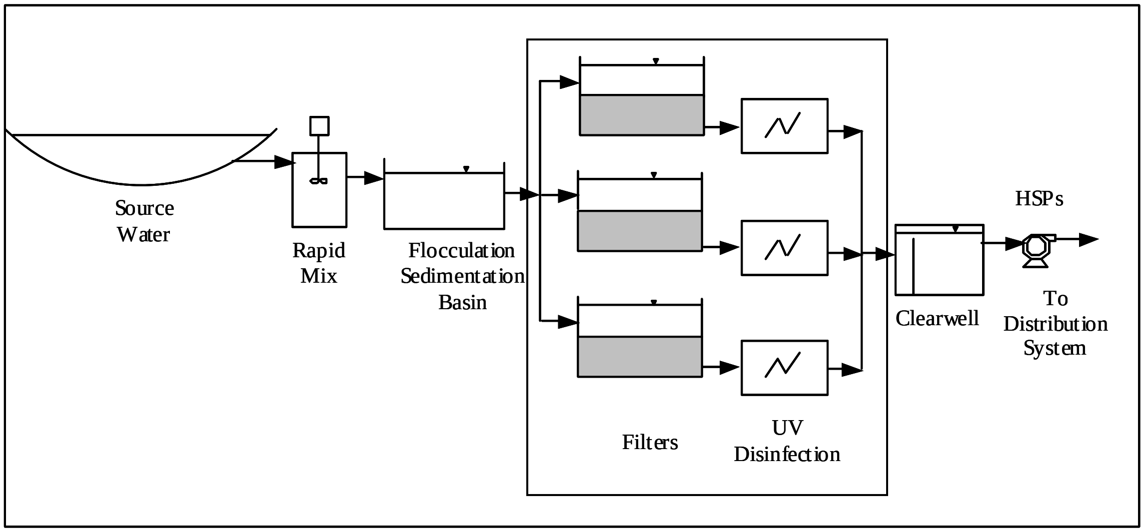
- An additional building and space may be necessary.

- The piping and fittings may result in greater head loss than alternative configurations, which may result in the need for intermediate booster pumps.

3.3.1.2 Individual Filter Effluent Piping Installation

Individual filter effluent piping installations are defined as UV reactors installed on each filter effluent pipe (Figure 3.3). This type of installation is typically located within an existing filter gallery.

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



The primary advantages of this type of installation are:

- A new building is not necessary, which will decrease construction costs.
- The hydraulic effect of the UV facility is less because the only additional head loss is from the UV reactors (most necessary valves and appurtenances are already present in the filter gallery).
- If the UV reactors fail, a WTP can continue to disinfect by adding a chemical disinfectant to the clearwell. (Note that backup chemical disinfection likely will not provide *Cryptosporidium* inactivation.)

This installation location, however, has several disadvantages:

- Many filter galleries have insufficient space within existing effluent piping to accommodate the UV reactors.
- Sufficient space is needed in the filter gallery or nearby for the control panels and electrical equipment.
- Access to existing equipment may be impeded by the UV reactor, and access to UV reactor components for maintenance may be more restricted than for a combined filter effluent installation.
- 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. This situation would necessitate improvements to the heating, ventilating, and air conditioning (HVAC) system.
- The existing piping may constrain how the UV reactor is validated because of the unique inlet and outlet conditions that may be present (Section 3.6.2).
- Surge and pressure fluctuations would need to be investigated if UV reactors are installed directly downstream of pressure filters or membrane filtration because water hammer can damage lamp sleeves.

Additionally, the individual filter effluent installation may also complicate treatment plant operations and limit operational flexibility, as described below:

- In general, this option increases the number of UV reactors required compared to a combined filter installation because the number of filters dictates the number of UV reactors. More reactors may increase operation and maintenance costs.
- The head loss of the UV reactors may affect the operation of the filters and the clearwell.
- The operations of the UV reactor and the filter are closely related. If one reactor or one filter is off-line, the other process may not be operable.

- When a UV reactor goes off-line, the corresponding filter also should be taken off-line to minimize off-specification operation.

- The filter backwash cycle can complicate UV reactor operation.

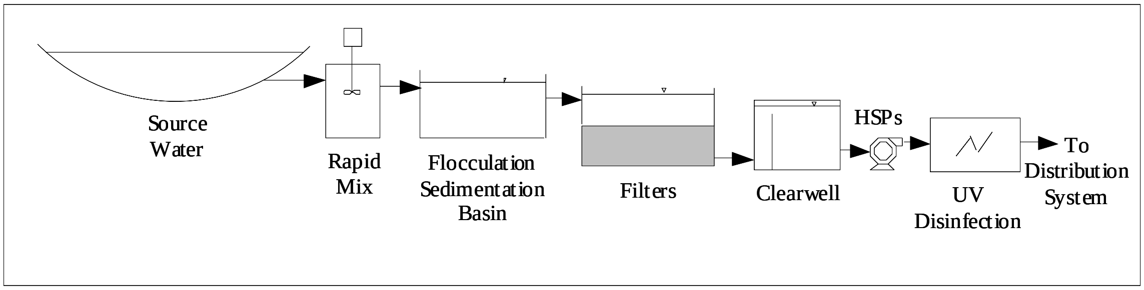
  - Lamps that remain energized during a backwash may require cooling water because some lamps should not be energized in stagnant water. ***The designer should consult the UV manufacturer to determine whether the UV reactor requires cooling water during start-up.***

  - If a UV reactor is off-line during a backwash, the UV reactor may be operating outside of its validated limits (i.e., off-specification—discussed in Section 3.4.1) if water is being treated during lamp warm-up. If the piping configuration permits, energizing the UV reactors during the filter-to-waste period and having the filter-to-waste water pass through the reactors during the warm-up period would cool the lamps and reduce the volume of the off-specification water.

3.3.1.3 UV Disinfection Downstream of the Clearwell

A WTP may be able to locate the UV facility downstream of the clearwell, either upstream or downstream of the high-service pumps (HSPs), as shown in Figure 3.4. In many WTPs, the HSPs pump water directly from the clearwell, which limits space and the availability of suitable piping for installing the UV facility upstream of the HSPs. Installation downstream of the HSPs may provide greater space and flexibility in locating the UV facility.

Figure 3.4. UV Disinfection Downstream of High Service Pumps



The primary advantage of this type of installation is that UV reactor installation is possible even if the space or available head is insufficient to allow installation of the UV equipment between the filters and the clearwell. However, these options have significant disadvantages:

- UV facilities located downstream of the clearwell may experience greater fluctuations in flow rate because the flow rate is more closely related to demand changes.

Accommodating flow rate fluctuations may necessitate increasing the UV reactor size or number of UV reactors.

- Post-clearwell installation locations are more prone to water hammer because of their proximity to the HSPs and subsequent high pressures, and water hammer could damage lamp sleeves and the lamps. Hydropneumatic tanks or pressure-relief valves may be needed to avoid water hammer.

- In the event of a lamp break, post-clearwell installations may have less ability to contain mercury and quartz resulting from the break in a low-velocity collection area (depending on the distribution system configuration).

- In post-HSP installations, the water is at distribution system pressure. The UV reactor housing may need reinforcement to accommodate high pressure, which would increase the cost of the UV reactors.

- A UV facility located after the HSPs will reduce the discharge pressure to the distribution system, and a UV facility 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 affected at these two locations unless the HSPs are upgraded to account for the UV facility hydraulic needs.

- When UV disinfection is applied to water with a free or total chlorine residual, some reduction of the residual may occur, which may necessitate increasing the chlorine dose in the clearwell or moving the chlorination point to downstream of the UV facility.

3.3.2 Unfiltered System Installation Locations

In an unfiltered system, UV facilities can be located either before or after a storage reservoir. If the storage is covered, UV disinfection facilities can be installed in either location. If the storage reservoir is uncovered, however, the PWS is subject to the uncovered reservoir requirements of the LT2ESWTR and as such should install UV disinfection on the discharge side of the reservoir to provide the necessary treatment. Most unfiltered systems flow to the distribution system by gravity; however, water hammer may still be a concern if the facility is located near HSPs (if applicable). This installation location is similar to installations downstream of the clearwell, and as such, the items described in Section 3.3.1.3 also apply to this location.

More debris may be present in the influent to UV reactors in unfiltered applications than in post-filter applications. Debris entering the UV reactor with sufficient momentum can cause the lamp and sleeve to break. The mass and size of an object that might cause damage are installation-specific and depend on UV reactor configuration (e.g., horizontal versus vertical reactor orientation) and water velocity through the reactor. Methods of addressing debris are described in Section 4.5.1, and additional information on lamp breakage is presented in Appendix E.

3.3.3 Groundwater System Installation Locations

For groundwater applications of UV disinfection, UV facilities may be installed either at each well in a production system or at a centralized facility. If installed at or near well pumps, the hydraulic and water hammer considerations described in Section 3.3.1.3 will also apply. An engineering cost analysis can be conducted to compare centralized versus wellhead UV disinfection treatment, as well as any other treatment needs, such as removing iron, manganese, or sulfides.

3.3.4 Uncovered Reservoir Installation Locations

The LT2ESWTR requires PWSs with uncovered finished water storage facilities to either cover the storage facility or treat the discharge of the storage facility that is distributed to consumers to achieve inactivation and/or removal of 4-log virus, 3-log *Giardia*, and 2-log *Cryptosporidium* [40 CFR 141.714(c)]. When applying UV disinfection to uncovered reservoirs, the UV facility should be on the outlet of the uncovered reservoir. In some cases, the inlet and outlet to the uncovered reservoir is the same pipe, and the UV facility should be designed so it operates when the water flows from the uncovered reservoir to the customer. Water from most uncovered reservoirs flows by gravity to the distribution system; however, water hammer may still be a concern if the UV reactors are located close to HSPs. As such, the items described in Section 3.3.1.3 also apply to this location.

3.4 Defining Key Design Parameters

Off-specification requirements (see Section 3.4.1 below), target pathogen inactivation, flow, water quality, the fouling/aging factor, and power quality affect the sizing of the UV reactors and associated support facilities. Specifically, UV manufacturers use the design flow, design UVT, the range of UVT expected, and the fouling/aging factor to determine the appropriate number of UV reactors to achieve the required UV dose.

Pilot- and demonstration-scale testing for UV disinfection systems can be helpful in determining key design parameters but typically are unnecessary. For example, pilot- or demonstration-scale testing may be warranted when bench-scale analysis cannot determine the design criteria (e.g., prediction of fouling/aging factor in waters with high inorganic constituents). This section also describes some pilot- or demonstration-scale testing that can be used to determine key design criteria if deemed necessary by the PWS or design engineer.

3.4.1 Off-specification Requirements

The LT2ESWTR requires validation of UV reactors to demonstrate that they achieve the required UV dose [40 CFR 141.720(d)]. Validation testing establishes the conditions under which the UV reactors must be operated to ensure the required UV dose delivery [40 CFR 141.720(d)].

Receiving log inactivation credit to meet the treatment requirement of the LT2ESWTR requires 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 141.720(d)(3)]. In other words, the UV reactors cannot be operated outside of their validated limits for more than 5 percent of the volume of water that is treated each month. Operating outside of the validated limits is defined in this manual as off-specification operation.

Determining the appropriate design criteria related to flow, water quality (UVT and fouling), the fouling/aging factor, and power quality is important to comply with LT2ESWTR off-specification requirements. These design criteria also define the conditions under which the UV reactors must be validated and then operated. If the design parameters are not sufficiently conservative, the UV reactors may often operate off-specification and be out of compliance.

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

- The flow rate is higher than the validated range.
- The UVT is lower than the validated range [if the Calculated Dose Approach is used (see Section 3.5.2)].
- The UV intensity is below the validated setpoint [if the UV Intensity Setpoint Approach is used (see Section 3.5.2)].
- The validated dose [2] is less than the required UV dose at a given flow rate [if the Calculated Dose Approach is used (see Section 3.5.2)].
- One or more lamps are not energized unless the UV reactor was validated with these lamps off.
- All UV lamps are off because of a power interruption or power quality problem, and water is flowing through the reactors.
- One or more UV sensors are not within calibration criteria, and the remedial actions are not taken. (See Section 6.4.1.1).
- A UVT analyzer is needed for the dose-monitoring strategy; the UVT analyzer is out of calibration; and a corrective action was not taken. (See Section 6.4.1.2.)
- The UV equipment includes installed or replaced components (or both) that are ***not*** equal to or better than the components used during validation testing unless the UV equipment was re-validated. (See Section 5.13.)

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[2] For the purposes of this manual, the “Validated Dose” is the UV dose in units of mJ/cm^2 delivered by the UV reactor as determined through validation testing. The validated dose is compared to the required dose to determine log inactivation credit. For the Calculated Dose Approach, the validated dose equals the calculated dose from the dose-monitoring equation, divided by the Validation Factor. The Validation Factor accounts for key uncertainties and biases resulting from validation testing.

3.4.2 Target Pathogen Inactivation and Required UV Dose

As described in Section 3.1, the UV facility design criteria should include the target pathogen, log inactivation level, and corresponding required UV dose. The required UV dose (D_{Req}) for the various pathogens and inactivation are shown in Table 1.4; however, the PWS may consider increasing the required dose beyond those listed in Table 1.4 by 10 to 20 percent to provide flexibility and conservatism. Similar approaches are commonly used by many PWSs with chlorine disinfection where they provide higher chlorine residuals and contact times (CT) than required.

3.4.3 Design Flow Rate

The UV facility design criteria should identify the average, maximum, and minimum flow rates that the UV reactors will experience. Methods for determining the design flow rate for the installation locations described previously are listed in Table 3.1.

Table 3.1. Potential Method to Determine Design Flow

Installation Location	Design Flow Basis
Combined Filter Effluent	Combined rated capacity of all duty filters[1]
Individual Filter Effluent	Rated design flow for individual filter
Downstream of the Clearwell	Rated capacity of the HSP station
Unfiltered Application	Rated capacity of the treatment facility
Groundwater Application	Rated capacity of the well pump or well field
Uncovered Reservoir Application	Maximum reservoir outflow

[1] Does not include redundant filters

3.4.4 Water Quality

As highlighted in Chapter 2, the following water quality parameters and issues affect UV dose delivery and should be considered in UV facility planning:

- UVT at 254 nanometers (nm)
- UV transmittance scan from 200 – 300 nm (i.e., germicidal range)
- Sleeve and UV sensor window fouling, including
  - Calcium
  - Alkalinity
  - Hardness
  - Iron
  - Manganese
  - pH

  - Lamp temperature
  - ORP

- Particle content and algae (unfiltered and uncovered reservoir applications)

Water quality data should be collected from locations that are representative of the potential UV facility location(s). The duration of sampling, numbers of samples collected, and data analyses used to evaluate water quality for UV disinfection are similar to the approaches used for other water treatment technologies. The data collection should capture typical water quality and any water quality variation due to storm events, reservoir turnover, seasonal changes, source water blends, and variations in upstream treatment. The data collection frequency should be based on flow rate 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 to be collected and the data analysis should be left to the discretion of the PWS and the design engineer based on experience and professional judgment.

Water quality information should be communicated to the UV manufacturers, so they can determine the applicable UV reactors for the target pathogen inactivation. This section provides more details on the data collection and analysis recommendations.

3.4.4.1 UVT and UVT Scans

The most important water quality characteristic affecting UV facility design is UVT[3,4] because the UVT of the water directly influences UV dose delivery, as discussed in Chapter 2. Overly conservative design UVT values (i.e., low UVT) can result in over-design and increased capital costs. Conversely, inappropriately high design UVT values can result in frequent UV reactor off-specification operation, which could violate LT2ESWTR requirements.

Quantifying both a design UVT and the full range of UVT expected during operation is essential. Understanding the full range of UVT is critical because the UV reactor should be validated for the range of UVT and flow combinations expected at the WTP to avoid off-specification operation. Specifying a matrix of flow and UVT conditions for the UV reactors to meet the required UV dose may be appropriate. Also, the UV manufacturers may use the UVT range at the WTP to help determine the turndown (i.e., power modulation) needs of the UV reactors.

This section discusses the issues with using existing UVT data and describes the data collection, UVT measurement, and data analysis that can be used to determine design UVT and UVT range. Table 3.2 summarizes the recommendations for collecting and analyzing UVT data.

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[3] UVT in this section implies UVT measurement specifically at 254 nm and 1 cm pathlength unless otherwise noted.

[4] $A_{254} = -\log\left(\frac{UVT(\%)}{100}\right)$

Table 3.2. Summary of UVT Data Collection and Analysis[1]

Issue	Recommendation
Water Quality Events to Capture in Data Collection	• Typical/average water quality conditions • Rainfall effects on source water • Reservoir turnover • Seasonal variations • Possible water quality blends if multiple source waters are used • Variation in upstream water treatment
Water Quality Sampling Locations	Locations that are representative of potential UV facility location(s)
Sample Type for Various Installation Options[2]	• Composite samples from operating filters or grab samples from the combined filtered water header should be collected for combined filter effluent installations • Grab samples from representative filter(s) for individual filter piping effluent installations • Grab samples from any locations downstream of clearwell under consideration
Collection Frequency and Period	• Weekly for 1 – 2 months if water quality is stable • Weekly[3] for 6 – 12 months (or more) if water quality changes seasonally
Existing Data for Potential Use	A_{254} is often collected in filtered waters to determine the specific UV absorbance (SUVA), and these measurements could be used in the data analysis. However, ultraviolet light absorbance at 254 nm (A_{254}) is typically filtered for the SUVA calculation, which would bias the A_{254} low (high UVT). Therefore, such data should only be used with this understanding.
Recommended Data Analysis	• Cumulative frequency analysis • UVT occurrence with flows
Recommended Data to Provide to UV Manufacturer	• Matrix of flows with corresponding UVTs • Target pathogen(s) and log inactivation • Design UVT[4] (corresponding to design flow) • Range of operating UVTs

[1] Existing A_{254} or UVT data may be available, which would reduce the sampling and analysis needed.
[2] The potential installation locations are described in detail in Section 3.3.1.
[3] More frequent samples may be needed to capture a water quality event (e.g., storm events).
[4] The design UVT is the UVT that will typically occur at the location of the facility.

Availability of Existing UVT Measurements

UVT data collection may not be necessary if sufficient filtered water UVT data are available to perform the recommended data analysis described subsequently. Additionally, filtered water A_{254} is often collected to determine the SUVA, and these measurements could be used in the data analysis. However, the water sample is typically passed through a 0.45-micrometer (μm) filter for the A_{254} measurement needed for the SUVA calculation, which may bias the A_{254} low (high UVT). If the only available A_{254} measurements are on water that has been passed through a 0.45- μm) filter, they can still provide input to the planning process, but additional UVT data collection may be necessary to understand the magnitude of the bias.

Data Collection

UVT measurements should be collected from locations that are representative of the potential facility location(s). UVT data can be collected using grab or composite samples, and the type of sample collected depends on the potential UV facility locations under consideration. For example, composite samples from operating filters or a grab sample from a combined filter effluent header should be collected for combined filter effluent UV facilities. For individual filter effluent pipe installations, grab samples from representative filters at the beginning and the end of filter runs are recommended. Grab samples from any location(s) downstream of the clearwell under consideration should be collected.

As with most engineering designs, the larger the data set, the more refined the design UVT can be. If UVT data are not available, weekly UVT measurement is recommended, but the duration of the sampling period depends on the source water quality. For example, a PWS with very stable UVT measurements may need only one or two months of data. A PWS that experiences seasonal changes, however, would benefit from more frequent data collection during seasonal events and over a longer period (6 to 12 months or more). If seasonal UVT decreases occur regularly, increased sampling frequency (e.g., daily) during these periods will better capture the magnitude and duration of the decreases. The possible effect of upstream processes on UVT should be assessed by collecting UVT data during the various operating conditions (e.g., a range of alum doses). If different sources or combinations of sources are used during the year, the UVT of the potential source water blends should be characterized to properly identify the representative water quality conditions.

UVT Measurement

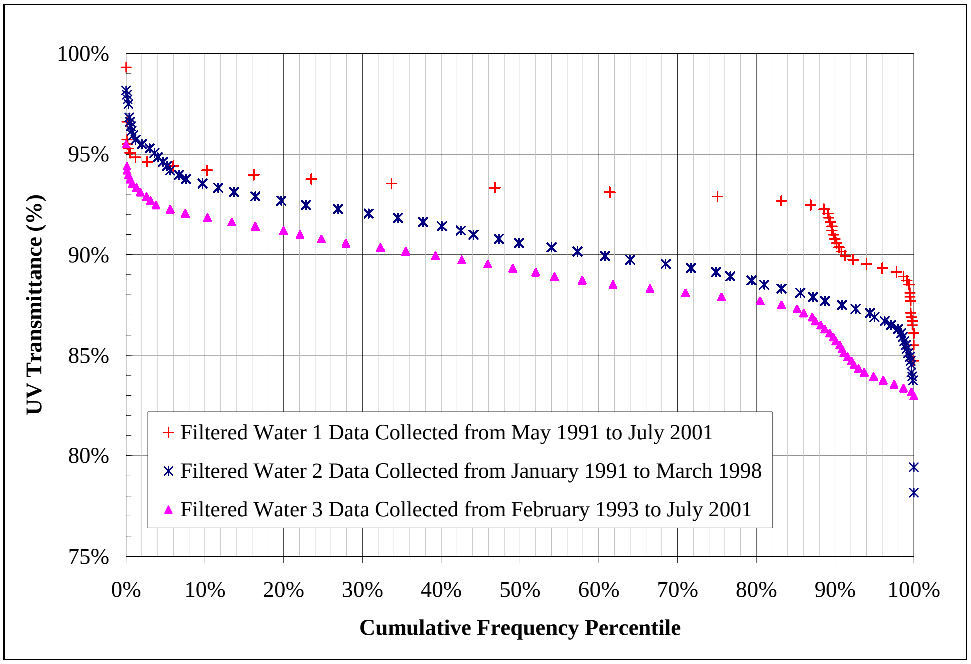
UVT can be measured with a bench-top spectrophotometer or can be continuously measured by an on-line UVT analyzer. During planning, UVT is typically measured using a spectrophotometer and is typically reported as a percent. The wavelength of the spectrophotometer should be set to 254 nm, and the pathlength of the quartz cuvette used to measure UVT is usually 1 centimeter (cm). If the UVT is high, however, longer pathlengths can be used to improve measurement resolution. When longer pathlengths are used, the A_{254} measured on the spectrophotometer should be normalized by the specific pathlength to calculate the A_{254} on a per cm basis, and then the UVT should be calculated based on the A_{254} with the converted 1-cm pathlength. Because particles can affect the absorbance of UV light, samples for UVT should ***not*** be passed through a 0.45-μm filter before analysis. The sample pH also should not be adjusted.

Data Analysis

A cumulative frequency diagram of the UVT data can help the PWS determine its design UVT value and will also illustrate the UVT range. Cumulative frequency diagrams can be prepared by ranking UVT results from lowest to highest and then calculating the percentile for each value. Figure 3.5 presents an example cumulative frequency diagram for three filtered waters; the cumulative frequency percentile (x-axis) shows the percentage of the dataset that is less than a given value of UVT over the data collection period. For example, if the 90th percentile UVT is 91 percent, then 90 percent of the measurements are greater than 91 percent, and 10 percent of the UVT measurements are less than 91 percent.

In Figure 3.5, the UVT data for Filtered Waters 1, 2, and 3 display different characteristics. Filtered Water 1 has a relatively stable UVT, while Filtered Waters 2 and 3 have gradually increasing cumulative frequency slopes that indicate greater variability. Selection of an appropriate UVT design value for these waters should consider the variability in UVT and flow values and the maximum allowable volume of off-specification finished water at different UVT design levels. The water supply's preferred level of conservatism should also be taken into account in this comparison.

Figure 3.5. Example Cumulative Frequency Diagram for Three Filtered Waters

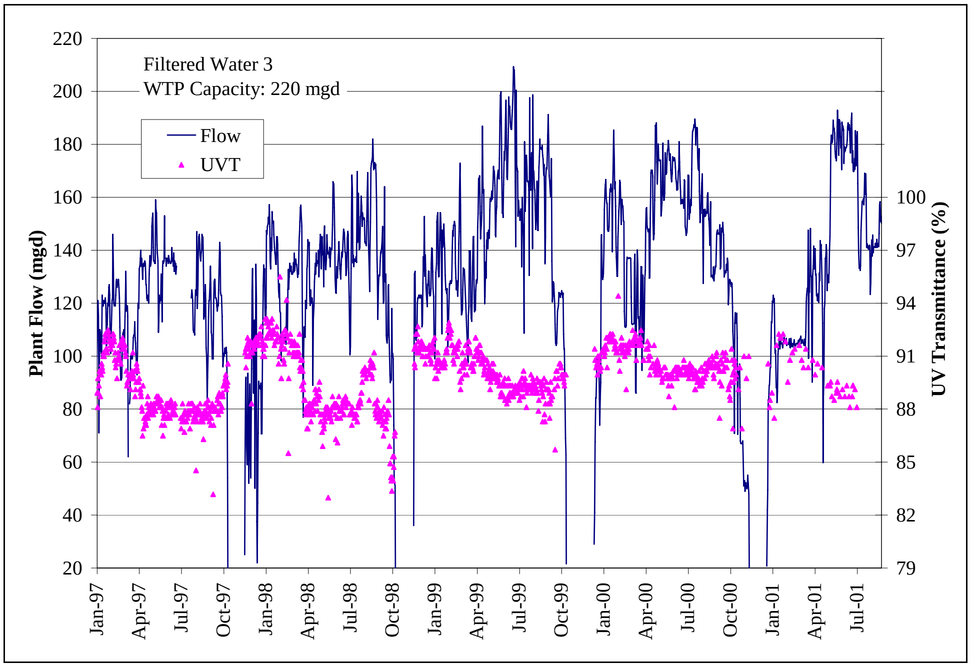


Additionally, the minimum operating UVT may not correspond to the period with the highest flow rates. The relationship between seasonal flow rates and UVT data should be considered when selecting a design UVT value and the matrix of UVT and flow conditions to be defined for the UV manufacturer. Figure 3.6 presents flow rate and UVT variations and seasonal patterns for Filtered Water 3. For this example WTP, the low UVT typically occurs in September and October and not during the high flow rate period in the summer. In this example, the following conditions for UVT and flow could be communicated to the UV manufacturers, so they can determine the applicable UV reactors for the required UV dose:

A 90th-percentile design UVT value of 86 percent at the design 220-million gallons per day (mgd) capacity

Minimum UVT of 83 percent coupled with a flow of 140 mgd

Figure 3.6. Example Flow Rate and UVT (at 254 nm) Data



Upstream Treatment Chemicals Effect on UVT

As described in Section 2.5.1.3 and Bolton et al. (2001), the following chemicals alone will not significantly affect UVT under typical filtered water conditions: alum, aluminum, ammonia, ammonium, zinc, phosphate, calcium, hydroxide, ferrous iron (Fe^{+2}), hypochlorite (ClO^-), ferric iron (Fe^{+3}), and permanganate. However, ozone residual affects UVT, as described below. If other chemicals of concern are present, the effect of water treatment chemicals on UV absorbance can be assessed by preparing solutions of various concentrations and measuring their UV absorbance using a standard spectrophotometer.

If ozone is added before UV disinfection, the UVT of the water can be increased measurably, thereby improving the efficiency of UV disinfection. Ozone also absorbs UV light, however, so if residual ozone enters the UV reactor, the resulting decrease in UVT can be significant and should be considered when determining the design UVT. To address this issue, PWSs can monitor the ozone residual and add an ozone-reducing chemical prior to the UV reactor to maintain the ozone residual below a specified setpoint value. Several chemicals can quench ozone, but some (such as sodium thiosulfate) also have a high UV absorbance value and can decrease UVT. Such chemicals should not be used prior to UV disinfection unless their application causes no residual concentration. Sodium bisulfite is an alternative to sodium thiosulfate that does not significantly affect UVT.

UVT Scans

If MP lamps are being considered, measuring the UVT at the wavelengths in the germicidal range (in addition to 254 nm) may also be important. A UVT scan is used to determine the UVT of the water over 200 – 300 nm (i.e., germicidal range). In a UVT scan, the absorbance at each wavelength is measured and converted to UVT using Equation 2.2 ($\%UVT = 100 \times 10^{-A}$). The UV absorbance of water typically decreases with increasing wavelength over the germicidal range. Thus, the UV light attenuation in a UV reactor and the corresponding disinfection performance depend on the absorbance at each emitted wavelength. Some UV manufacturers use site-specific UVT scans in their UV dose monitoring and control systems. UVT scans can also vary seasonally; therefore, UVT scans could be measured at different times during the year to account for this variation. Also, the UVT scans can be used to determine the appropriate UV-absorbing chemical for validating the UV reactors that will be installed.

3.4.4.2 Water Quality Parameters That Affect Fouling

Water quality can affect the amount and type of lamp sleeve fouling that occurs in UV reactors. The factors that affect fouling pertain to all UV equipment.

Fouling is typically caused by precipitation of compounds on the lamp sleeve, as described in Section 2.5.1.4. The rate of fouling and the consequent frequency of sleeve cleaning depend on ORP, hardness, alkalinity, lamp temperature, pH, and the presence of certain inorganic constituents (e.g., iron and calcium). If significant seasonal shifts in any of the parameters or coagulant doses are expected, the duration of the monitoring period should be sufficiently long to capture the variations.

Although fouling should not be a significant problem for most PWSs, the water quality parameters listed below should be monitored before the UV facility is designed, unless adequate water quality data are available. A summary of the data collection and analysis related to fouling parameters is provided in Table 3.3. Providing these data to UV manufacturers is recommended to help them qualitatively assess the fouling potential for their UV reactors and to assist designers in determining whether a particular cleaning system should be specified. These data will also help determine the fouling/aging factor, which is discussed in Section 3.4.5. (Note that ORP can be challenging to measure, so the data collected may have limited value.)

- Calcium
- Alkalinity
- Hardness
- Iron
- Manganese
- pH
- ORP

Table 3.3. Summary of Fouling Data Collection and Analysis

Issue	Fouling Parameters[1]
Collection Location	Locations that are representative of potential UV facility location(s)
Collection Frequency[2] and Period	• Monthly for 1 – 2 months if water quality is stable • Monthly for 6 – 12 months (or more) if water quality changes seasonally
Recommended Data Analysis	Based on design engineer's and PWS' best professional judgment
Recommended Data to Provide to UV Manufacturer	Median and maximum values

[1] Fouling parameters include calcium, alkalinity, hardness, iron, manganese, pH, and ORP.
[2] More frequent samples may be necessary to capture a water quality event (e.g., storm events).

Pilot tests of waters with total hardness levels less than 140 mg/L and iron less than 0.1 mg/L found that standard cleaning protocols and wiper frequencies (one sweep every 15 – 60 minutes) addressed the effect of sleeve fouling at the sites tested (Mackey et al. 2001, Mackey et al. 2004). Recent research has shown, however, that the addition of a chemical oxidant directly upstream of UV reactors (i.e., downstream of filters) will increase the ORP and potential for fouling (Derrick 2005, Wait et al. 2005). Therefore, moving the chemical oxidation point from immediately upstream of the UV reactors to downstream of the UV reactors should be considered to reduce the potential for fouling. It should be noted that if oxidation and filtration occur prior to UV disinfection, the iron and manganese are typically oxidized and then filtered out prior to the UV reactor, and fouling will be minimal (Derrick 2005, Wait et al. 2005, Jeffcoat 2005).

If the ORP, pH, and inorganic constituent concentrations are low, fouling is not likely to be an issue, and a cleaning system may not be necessary. However, a cleaning system should be considered if iron and manganese are present. Also, if the chemical oxidation point cannot be moved from immediately upstream of the UV equipment and iron and manganese are present, pilot testing (Section 3.4.5.1) may be necessary to determine the fouling rate and effectiveness of sleeve cleaning.

3.4.4.3 Additional Water Quality Considerations for Unfiltered Supplies and Treatment of Uncovered Reservoir Water

Water supplies are susceptible to variable water quality, turbidity spikes, reservoir turnover, and seasonal algal blooms. Typically, water treatment processes at filtered WTPs dampen the effects of such variations on UV disinfection. Unfiltered supplies, however, generally do not have upstream treatment that mitigates these variations. Specifically, the presence of particles and algae may affect UV dose delivery, and water quality and UVT may fluctuate more in unfiltered supplies and thus should be a consideration in the water quality data analysis.

Uncovered reservoirs have similar water quality issues as unfiltered supplies. In most cases, however, the problems are less severe because the water has been treated before it enters the uncovered reservoir and the operation of uncovered reservoirs is more controlled (e.g., smaller volumes, storm water control, concrete lining, and bird control). One exception is that algal blooms may be more prevalent in uncovered reservoirs than in unfiltered supplies if phosphate-based corrosion inhibitors are added at the WTP. Phosphates can promote algal growth.

Issues that should be considered in the water quality data analysis for unfiltered supplies and uncovered reservoirs are described in this section and summarized in Table 3.4.

Table 3.4. Summary of Particle and Algal Data Collection and Analysis

Issue	Particles and Algae
Collection Location	Locations that are representative of potential UV facility location(s)
Collection Frequency[1] and Period	• Monthly for 1 – 2 months for an Unfiltered PWS • Bi-weekly for the summer months[2] for Uncovered Reservoirs
Recommended Data Analysis	Based on design engineer’s and PWS’ best professional judgment
Recommended Data to Provide to UV Manufacturer	Median and maximum values

[1] More frequent samples may be needed to capture a water quality event (e.g., storm events).
[2] Algal blooms often occur in summer months in uncovered reservoir supplies.

Water Quality Fluctuations from Reservoir Turnover

Reservoir turnover in unfiltered supplies and uncovered reservoirs may cause water quality changes that affect UV disinfection. The UVT and parameters that affect fouling should be monitored over a complete reservoir cycle to account for these issues in the design criteria. For example, reservoir turnover can cause increased iron levels, which is a factor that should be considered when assessing fouling potential. If the potential for increased iron levels is not assessed, the appropriate sleeve cleaning technology may not be installed, and UV dose delivery may be affected.

Particle Content and UVT Variability

For unfiltered systems, the Surface Water Treatment Rule (SWTR) allows turbidity up to 5 nephelometric turbidity units (NTU) immediately prior to the first point of disinfection application (40 CFR 141.71). Storm-related turbidity spikes are more prevalent in unfiltered supplies than in filtered supplies because no upstream treatment is available to remove the particles. Particles in water absorb and scatter UV light to varying degrees based on their size and composition. Particles affect the disinfection process in two ways:

1. Particles can decrease the UVT of water and thereby affect UV dose delivery.

2. Microorganisms can associate with particles and be shielded from UV light, thereby changing the characteristics of the UV dose-response curve that is obtained using collimated beam studies.

Several studies have found that the effects of turbidity up to 10 NTU on UV disinfection can be accounted for in the UVT measurements (Passantino et al. 2004, Christensen and Linden 2002). However, the most commonly used spectrophotometer (bench-top direct reading) may underestimate the UVT of water with turbidity greater than 3 NTU (Christensen and Linden 2002). To reduce this underestimation, all unfiltered systems and uncovered reservoir applications should use a bench-top UV spectrophotometer with an integrating sphere to provide more accurate UVT measurements for planning purposes.

For unfiltered waters susceptible to turbidity fluctuations, the UVT sampling should occur during these events and be accounted for in the design UVT and UVT range. If the design UVT is appropriate, the UV reactor will be able to respond to changes in UVT that arise due to particles.

As described previously, particle content and UVT variability will probably be less prevalent in uncovered reservoirs compared to unfiltered supplies. The UVT sampling, however, should be conducted during a period sufficient to include seasonal events (e.g., rainstorms and runoff) that will affect the design UVT and the UVT range.

Algae

Previous research with male-specific-2 bacteriophage (MS2) has shown that algal counts up to 70,000 cells/mL do not affect disinfection performance (Wobma et al. 2004). Whether algal counts greater than 70,000 cells/mL affect the UV disinfection process is unknown. Therefore, for both unfiltered supplies and uncovered reservoirs, UVT sampling should be conducted during algal blooms to enable their effects on UVT to be assessed. At high algal concentrations, bench-, pilot-, or demonstration-scale testing may be warranted to determine if UV disinfection is significantly affected.

3.4.5 Fouling/Aging Factor

Sleeve fouling, sleeve aging, lamp aging, and UV sensor window fouling (if applicable) affect long-term UV reactor performance, as described in Sections 2.4.2 and 2.4.4. The fouling/aging factor accounts for these issues.

An acceptable fouling/aging factor and guaranteed lamp life should be determined based on experience and professional judgment. Alternatively, pilot- or demonstration-scale testing can be used to estimate the fouling factor and aging factor if deemed necessary by the PWS, as described in Sections 3.4.5.1 and 3.4.5.2, respectively.

The lamp-fouling portion of the factor (i.e., fouling factor) is the estimated fraction of UV light passing through a fouled sleeve as compared to a new sleeve. A lamp sleeve can become fouled when inorganics (e.g. iron) precipitate onto a lamp sleeve and reduce the UV transmittance of the sleeve. Water quality parameters that affect fouling are described in Section 3.4.4.2.

The lamp aging portion of the factor (i.e., aging factor) is the fraction of UV light emitted from aged sleeves and lamps compared to new sleeves and lamps and can be estimated by the lamp and sleeve aging characteristics obtained from the UV manufacturer. The lamp aging factor is important because as UV lamps age, the output of the lamps decrease.

The fouling/aging factor is calculated by multiplying the fouling factor by the aging factor and typically ranges from 0.4 (NWRI 2003) to 0.9. The fouling/aging factor is typically used in validation testing to ensure the UV equipment can meet the required dose in a fouled and/or aged condition. (See Equation 3.1.)

$$UV\ Dose\ with\ Clean\ Lamps * Fouling\ \ Factor * Aging\ \ Factor \geq Required\ UV\ Dose \quad \text{Equation 3.1}$$

When purchasing a pre-validated reactor, the PWS should determine if validation testing was conducted under conditions of reduced lamp output (e.g., 70 percent) that is equal to or less than reduced lamp output expected for fouled/aged conditions at its water treatment plant (e.g., 0.75, or 75 percent). If the site-specific fouling/aging factor is lower (e.g., 0.5, or 50 percent) than considered during validation testing, adjustments in validation test results or additional testing should be considered.

Selection of a fouling/aging factor coupled with a guaranteed lamp life is a trade-off between maintenance costs (the frequency of lamp replacement or chemical cleanings necessary) and capital costs (the size of the UV reactors). Both a fouling/aging factor and a guaranteed lamp life should be selected because doing so will guarantee that the fouling/aging factor will not be exceeded within the guaranteed lamp life. Lamps for a UV reactor with a lower fouling/aging factor will require less frequent replacement because the UV reactors are designed with more or higher powered lamps to achieve the necessary UV output at the guaranteed lamp life. This strategy, however, may necessitate an increase in the size of the UV reactor and facility. Conversely, the use of an insufficiently conservative factor may underestimate the reduction in the lamp output and potentially result in off-specification operation or more frequent lamp replacement.

3.4.5.1 Testing to Determine the Fouling Factor

The specific fouling rate and optimal cleaning protocol for any given application cannot be predicted with existing empirically-proven, mathematical equations. A proper cleaning protocol and sleeve-fouling factor, however, can be adequately estimated for most water sources without pilot- or demonstration-scale testing and then adjusted during normal operation.

Alternatively, fouling rates can be evaluated on a site-specific basis through pilot- or demonstration-scale testing or during UV reactor start-up. Testing could consist of the following test elements:

- **Test setup:** The UV sensors, lamp and sleeve type, power system, and cleaning system tested in a pilot- or demonstration-scale system should be identical to the full-scale reactor. Differences in lamp and lamp sleeve geometry can lead to erroneous conclusions based on pilot data alone.

- **Flow and UV equipment conditions:** Water should flow through the reactor at the minimum flow rate, and the lamps should be operated at maximum power.

- **Establishment of cleaning settings:** UV equipment with on-line chemical cleaning (OCC) systems should be operated for a prescribed length of time (e.g., 2 weeks) without a chemical cleaning to evaluate fouling. With water systems using on-line mechanical cleaning (OMC) and on-line mechanical-chemical cleaning (OMCC), the cleaning systems should be operated at the manufacturer's recommended frequency to assess fouling. One sleeve should be unwiped, however, for the entire testing period to serve as a control to verify that fouling is occurring.

- **Assessment of fouling factor:** Fouling is assessed by placing a new lamp inside a fouled sleeve, igniting it, and measuring the UV intensity. The UV intensity should be 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 fouling factor.

- **Evaluation of sleeve cleaning efficiency:** A sleeve cleaning assessment can also be performed to determine if more frequent cleaning could reduce the fouling factor.

- **Sensor window fouling (if applicable):** To assess fouling on the UV sensor windows, the windows should be cleaned with phosphoric or citric acid at varying time intervals, and the change in UV sensor readings recorded. The fouling rate of the lamp sleeves is likely to be greater than the fouling rate of the sensor windows because the sleeves are hotter than the windows, and higher temperatures accelerate fouling.

- **Quality assurance:** The fouled sleeve should be manually cleaned, which should restore the sleeve UV intensity value to very near that of a new, clean sleeve after the fouling factor has been determined. If not, the inside of the sleeve should be manually cleaned and the UV intensity measured again. If the UV intensity is still low, the sleeve material has likely degraded, and the test should be performed with a new sleeve to ensure that the test results indicate fouling only and not sleeve degradation.

The fouling factor data can be analyzed to determine the water system's preferred fouling factor under the observed sleeve cleaning efficiencies.

3.4.5.2 Testing to Determine the Aging Factor

The aging factor is the fraction of UV light emitted from aged sleeves and lamps compared to the fraction emitted from new sleeves and lamps. The lamp aging factor is typically between 0.5 and 0.8. In most cases, the aging factor can be determined from manufacturer data with existing empirically proven, mathematical equations. The PWS, however, may desire testing to better understand lamp aging characteristics. Lamp aging tests assess the reduction and variance in lamp germicidal output over time under defined worst-case operating conditions. 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 lamp operation. Because lamps are manufactured in batches, lamps from several different lots should be evaluated to ensure that collected data are representative.

Lamp age can be tested with either a pilot- or demonstration-scale UV reactor or a test stand designed to simulate the UV lamp aging in full-scale operation. For either setup, lamps should be operated in an environment that reflects conditions expected when the UV equipment is installed at a WTP (e.g., use lamp sleeves, ballasts, and cleaning systems that will be used in the final application).

During testing, the following activities should be considered:

- Monitor the UV intensity, UVT, electrical power delivered to the ballast, electrical power delivered to the lamp, and water temperature over the lamp life.

- Visually inspect the lamp sleeves at regular intervals to document any 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.

- Using either a radiometer equipped with a germicidal filter or a reference UV sensor, 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). The following procedure should be used:

    - Take one measurement with lamps that have been aged 100 hours (“new”).

    - Measure the output from various positions along the lamp based on visual inspection (i.e., the pattern of darkening on the lamp).

    - Measure lamp output as a function of lamp power setting if lamp power is variable.

    - Assess the output from lamps of different lots.

The lamp output measured under fixed operating conditions can be plotted over time and fit to estimate the mean expected performance for various lamp ages. To determine the aging factor, measure the output of a new lamp and the output at the end-of-lamp life. The aging factor is the ratio of the output at the guaranteed lamp life to new lamp output and is expressed as a fraction.

Although it does not impact reactor design, studies have shown that non-uniform lamp aging can occur. Non-uniform lamp aging should be considered during validation testing. (See Section 5.4.6)

3.4.6 Power Quality Evaluations

UV lamps can turn off if a voltage fluctuation, power quality anomaly, or a power interruption occurs. Power quality tolerances depend on the UV equipment design and vary significantly among UV manufacturers (Table 3.5). The UV manufacturer should be contacted to determine the power quality tolerance and the length of time for the equipment to reach full power after a power quality event. (See Section 2.4.2.3.)

Table 3.5. Power Quality Triggers for UV Reactors[1]

Power Quality Event		LPHO Manufacturer #1	LPHO Manufacturer #2	MP Manufacturer #1	MP Manufacturer #2
Voltage Sag/Swell Tolerance	Voltage[2]	± 20%	± 10%	± 30%	± 20%
	Duration[3]	2 seconds (s)	> 0.03 s	> 0.02 s	2 s
Power Interruption Tolerances[4]	Duration[3]	> 0.05 s	> 0.03 s	> 0.009 s	> 0.05 s

[1] Information shown in the table is compiled from Calgon Carbon Corporation, Trojan Technologies, and WEDECO.

[2] Percent of line voltage. For example, a 10-percent voltage loss is when the voltage is at 90% of the line voltage.

[3] 1 cycle is 0.017 s.

[4] Power interruption assumes total voltage loss.

Source: Cotton et al. (2005)

Studies have shown that the typical industrial power user experiences an average of eight power quality events per month (Grebe et al. 1996). Accordingly, power quality problems alone likely will not cause UV reactors to exceed the maximum off-specification requirements even though UV reactors are sensitive to power quality (Cotton et al. 2005). Therefore, a power quality assessment is probably necessary only when the installation site is (1) known to have power quality problems (e.g., 30 power interruptions and/or brownouts per month); or (2) located in a remote area and the power quality is unknown.

If power quality may be a problem at the intended installation location, a power quality assessment can be performed to quantify and understand the potential for off-specification operation, which consists of the following five steps:

1. Estimate the power quality at the potential location(s) of the UV facility. Local power suppliers often can provide data on power quality and reliability and should be the first source of information. Other sources of information are operating records of power quality incidents (if available), power interruptions, or Supervisory Control and Data Acquisition (SCADA) information for the existing plant.

2. Understand the power quality tolerance of the UV equipment under consideration by contacting the UV manufacturer or consulting published data.

3. Contact the UV manufacturer to determine how long it will take their equipment to be functioning at full power after a power quality event.

4. Estimate the off-specification time for the potential UV equipment-based information gathered in Steps 1 through 3. Examples of how to estimate off-specification based on this information are presented in Cotton et al. (2005).

5. Determine if backup power or power conditioning equipment is needed to reduce off-specification time or to improve UV equipment reliability.

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. More advanced assessments can include the installation of power quality monitors or the retention of an outside consultant to conduct a detailed power quality assessment.

3.5 Evaluating UV Reactors, Dose Monitoring Strategy, and Operational Approach

Selecting the appropriate UV reactor depends on the installation locations under consideration and the design parameters discussed in Section 3.4. The UV reactor manufacturer is a valuable resource for such evaluations and can determine what UV reactors are most appropriate for the installation locations under consideration. Evaluating the available UV reactors in the planning process is important because each manufacturer’s UV reactors are unique and proprietary, and installation needs (e.g., power requirements) differ. UV reactors can generally be characterized based on lamp type with low-pressure high-output (LPHO) lamps and medium-pressure (MP) lamps applicable to most WTPs. This section discusses the general characteristics of LPHO and MP reactors and describes the various control strategies. UV manufacturers should be contacted directly to gain a better understanding of the available and appropriate UV reactors.

3.5.1 Characteristics of LPHO and MP Reactors

The fundamental difference between LPHO and MP reactors is the lamp intensity output (which influences the UV reactor configuration and size), lamp life and replacement, power use, power modulation capabilities, and sleeve cleaning.

- **UV reactor configuration and size:** Several UV reactor configurations are available. Reactors can be in-line (i.e., shaped like a pipe), 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 required UV dose. MP reactor footprints will also vary, depending on lamp orientation (e.g., parallel versus perpendicular to flow).

- **Lamp life and replacement:** Lamp life also varies between LPHO and MP reactors. Most manufacturers provide warranties of 8,000 – 12,000 hours for LPHO lamps and 4,000 – 8,000 hours for MP lamps. Although the lamp life for LPHO reactors is greater than that for MP reactors, more lamps are needed for an LPHO reactor. The actual number of lamps replaced during a given period, therefore, may be less for MP reactors.

- **Power use:** Even though LPHO reactors typically have more lamps, they require less power input than similarly sized MP reactors because LPHO lamps are more efficient in converting the power to germicidal UV light for disinfection. This decreased energy efficiency results in higher power needs and increases in overall power consumption for MP reactors compared to LPHO reactors.

- **Power modulation capabilities:** The ability of the UV equipment to adjust lamp power or number of UV lamps energized will affect the energy use. Unlike the other issues described, power modulation capabilities depend on the UV equipment design and not the lamp type.

- **Sleeve Cleaning:** The lamp sleeve cleaning systems for LPHO and MP reactors can also differ. LPHO reactors typically have OCC systems, and MP reactors typically have OMC systems. Although OCC systems tend to be more labor intensive than OMC systems, OMC systems typically have more parts to replace. The extent of fouling will determine the amount of maintenance (labor and parts) that is needed on a routine basis and will affect the overall maintenance costs.

As described, the PWS should evaluate the differences between LPHO and MP reactors and determine any preferences based on the different characteristics and site-specific constraints. If one technology is precluded, it should not be evaluated further in the planning analyses.

3.5.2 Dose-monitoring Strategy and Operational Approach

The dose-monitoring strategy establishes the operating parameters used to confirm UV dose delivery. It affects how a reactor is validated, how instrumentation and controls are designed, and how the reactor is operated. In the planning phase, the water system should evaluate the various dose-monitoring strategies to determine whether a particular approach is preferable based on the ease of integration into their existing operation and control system. If a particular dose-monitoring strategy is preferred, the water system should select a UV equipment that has been validated for that strategy. The effect of the dose-monitoring strategy on the instrumentation and controls design is described in Section 4.3.

UV manufacturers commonly design their reactors to operate using either:

- The UV Intensity Setpoint Approach or
- The Calculated Dose Approach

This guidance manual focuses on the design, validation, and operation of UV reactors that use one of these two approaches. Another existing dose-monitoring strategy or a new strategy developed after this manual is published, however, may also be suitable for reactor operations as long as they meet minimum regulatory requirements.[5] Alternative strategies should be considered on a case-by-case basis.

Table 3.6 summarizes key characteristics of the two dose-monitoring approaches discussed in this manual. The next two sections provide an overview of how the approaches operate. Advantages and disadvantages of each are discussed in Section 3.5.2.3, and Section 6.4 provides additional guidance on monitoring frequency and reporting requirements for these control strategies.

Table 3.6. Dose-monitoring Approaches – Key Characteristics

Dose-monitoring Strategy	Parameter Used as the Operational Setpoint	Parameters Monitored During Operations to Confirm Dose Delivery
UV Intensity Setpoint Approach	UV Intensity	Flow rate Lamp status UV intensity
Calculated Dose Approach	Calculated or Validated dose [1]	Flow rate Lamp status UV intensity UVT

[1] As noted in Section 3.4.1, the calculated dose is estimated using a dose-monitoring equation. For the Calculated Dose Approach, the validated dose is equal to the calculated dose divided by a Validation Factor, which accounts for biases and experimental uncertainty.

3.5.2.1 UV Intensity Setpoint Approach

As indicated by its name, the UV Intensity Setpoint Approach relies upon one or more “setpoints” for UV intensity that are established during validation testing. During operations, the UV intensity, as measured by UV sensors, must meet or exceed the setpoint(s) to ensure delivery of the validated dose. Importantly, reactors must also be operated within the validated range of flow rates and lamp statuses (i.e., the “validated operating conditions”) [40 CFR 141.720(d)(2)].

One key characteristic of the UV Intensity Setpoint Approach is that water systems ***need not monitor UVT*** during operations to confirm dose delivery. Instead, the approach relies on UV intensity readings by UV sensors to account for changes in UVT. In order for UV sensors to efficiently monitor dose delivery, they should be as close as possible to the “ideal” location. This means that they should be positioned so that the UV intensity is proportional to the UV dose, irrespective of changes in UVT and lamp output. If the sensor is too close to the lamp, changes in lamp output will disproportionately impact the measured UV intensity. If the sensor is too far from the lamp, changes in UVT of the water will disproportionately impact the measured UV

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[5] Systems must monitor flow rate, lamp status, and UV intensity, plus any other parameters required by the state at a minimum to show that a reactor is operating within validated conditions [40 CFR 141.720(d)(3)(i)].

intensity. Water systems can check if sensors are in the ideal location by reviewing validation test data. (See Chapter 5.)

The recommended validation protocol in Chapter 5 will produce conservatively high UV intensity setpoint(s) under many water quality and lamp output conditions if the sensor is not in the ideal location, resulting in overdosing during operations. In some cases, UV manufacturers have developed modifications to the UV Intensity Setpoint Approach to account for non-ideal sensor placement.

Water systems can use one of the following operating strategies for the UV Intensity Setpoint Approach: single-setpoint operation or variable-setpoint operations. Table 3.7 describes these operating strategies and summarizes the advantages and disadvantages of each.

Table 3.7. Advantages and Disadvantages of Single-setpoint and Variable-setpoint Operations for the UV Intensity Setpoint Approach

Operating Strategy	Description	Advantages	Disadvantages
Single-setpoint	One UV intensity setpoint is used for all flow rates that were validated	Simplest to operate and control	When flow rate is variable, not energy efficient under most conditions because reactor is overdosing at low flow rates
Variable-setpoint [1]	The UV intensity setpoint is determined using a lookup table or equation for a range of flow rates	Lamp output can be reduced at low flow conditions to reduce energy costs	More validation data are needed. More complex operation compared to single-setpoint approach. Necessitates more advanced UV reactor monitoring and control.

[1] For the purposes of this guidance manual, variable-setpoint operations refers to variations based on flow rate only, as this is the most common application. In theory, multiple setpoints could also be established for different lamp statuses and UVT ranges.

3.5.2.2 Calculated Dose Approach

The Calculated Dose Approach uses a ***dose-monitoring equation*** to estimate the UV dose based the parameters measured during reactor operations. The most common operational parameters in dose-monitoring equation are:

- Flow rate,
- UV intensity, and
- UVT

Some manufacturers also consider lamp status as a variable in the dose-monitoring equation.

UV manufacturers may develop a theoretical dose-monitoring equation using numerical models (e.g., computational fluid dynamics [CFD]). Although the theoretical equations can be used as a starting point, EPA strongly recommends that water systems use an empirical dose-monitoring equation developed through ***validation testing***. To generate the empirical dose-monitoring equation, validation tests are performed over a wide range of flow rates, UVT values, and lamp power combinations. Regression analysis is used to fit the observed validation data to an equation. Chapter 5 of this manual provides detailed guidance on how to derive an empirical dose-monitoring equation through validation testing.

During reactor operations, the UV reactor control system (i.e., the internal reactor electronics) typically inputs the measured parameters into the dose-monitoring equation to produce a calculated dose. The system operator divides the calculated dose by a Validation Factor that accounts for uncertainties and biases to determine the validated dose.[6] The operator compares the validated dose to the required dose for the target pathogen and log inactivation level.

3.5.2.3 Advantages and Disadvantages

The principal operating advantage of the UV Intensity Setpoint Approach compared to the Calculated Dose Approach is that UVT monitoring is not needed to confirm dose delivery. Another important advantage is that the UV Intensity Setpoint Approach, single-setpoint operation is straightforward and simple to control with one operational setpoint and one maximum value for flow rate. For these reasons, EPA believes this option is good for small water systems. Other advantages are that the UV Intensity Setpoint requires fewer validation tests than the Calculated Dose Approach and data analyses are relatively straightforward. Data analyses to develop the dose-monitoring equation for the Calculated Dose Approach can be complex.

Water systems may favor the Calculated Dose Approach over the UV Intensity Setpoint Approach because it offers significant flexibility to reduce operating costs by manipulating lamp power (e.g., turning off banks of lamps or powering down lamps when the UVT increases and/or the flow rate decreases). This process is also called “dose pacing.” Another potential advantage is that operations are more intuitive because the calculated dose, adjusted for uncertainties and biases, can be directly compared to the required dose for the target pathogen and log inactivation.

Manufacturers may favor the Calculated Dose Approach because they have more flexibility in UV sensor positioning (i.e., because internal analyzers monitor UVT during operations instead of relying on sensors to respond to changes in UVT, positioning sensors as close as possible to the “ideal” location offers no advantages). As noted in Section 3.5.2.1, UV Intensity Setpoint Approach operations will be more efficient if the UV sensors are at or near the ideal location.

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[6] In some cases, the UV reactor control system will perform this step as well, outputting the validated dose automatically.

3.6 Assessing UV Equipment Validation Issues

For disinfection credit, the LT2ESWTR requires UV reactors to be validated [40 CFR 141.720(d)]. A water system's approach to UV reactor validation and to UV facility design is interrelated. The issues to consider are whether equipment will be validated on-site or off-site and the hydraulic conditions of the UV reactor validation and installation. This section describes how these issues affect the design and the relationship between the validation and hydraulic installation approaches. Chapter 5 details the UV reactor validation guidelines.

3.6.1 Off-site Versus On-site Validation

UV reactors can be validated either off-site or on-site. With off-site validation, the UV reactors are validated before installation (i.e., pre-validated), typically at a third-party validation test center or a UV manufacturer facility. With on-site validation, the UV reactors are validated at the PWS after they have been installed. Many PWSs will use off-site validation to meet the LT2ESWTR requirements. In some cases, however, on-site validation may be appropriate (e.g., when the full UVT range was not tested in off-site validation). The advantages and disadvantages of off-site and on-site validation are presented in Table 3.8.

Table 3.8. Advantages and Disadvantages of Off-site and On-site Validation

	Advantages	Disadvantages
Off-site	• Broader ranges of flow and water quality are tested so a reactor can be validated for more than one application • Installation hydraulics are general, allowing for installation at most WTPs • Process is simpler for utilities because testing is conducted at a remote location • Cost is usually lower • Reactor performance is known before facility is designed and constructed	• Re-validation or additional on-site validation testing may be necessary if site-specific hydraulics and water quality are not within the tested ranges • Water quality and hydraulics may not match the installation location, potentially resulting in less efficient operation
On-site	• Exact hydraulics of the installation are used • Water quality tested is specific to the installation • Having provisions for on-site testing (e.g., feed and sample ports and static mixers) enables flexibility for future testing to optimize performance	• Facility may be designed and constructed before reactor performance is verified • Water quality is limited to the highest UVT at the facility during the testing period • Testing logistics can be complex, including isolation of the test reactor, assessment of additive mixing, and challenge microorganism stability • Cost may be higher • Disposal of test water may require special permits

The PWS should determine whether off-site or on-site validation will be used to meet the LT2ESWTR requirements. If on-site validation is preferred, the UV facility design should be adapted to enable testing. The UV reactor design should incorporate feed and sample ports, static mixers, space for tanks near the UV facility for adding the challenge microorganism and UV absorbing chemical, and a method to discharge the validation test water. If off-site validation is preferred, the UV facility need not incorporate provisions for on-site validation testing.

If pre-validated reactors that were validated off-site are chosen, the PWS should confirm that the validation hydraulic recommendations in Section 3.6.2 can be met without additional on-site validation or PWS-specific off-site validation.

3.6.2 Validation and Installation Hydraulics Recommendations

The inlet and outlet piping to the UV reactor in the UV facility should result in a UV dose delivery that is equal to or greater than the UV dose delivered when the UV reactor was validated. If off-site validation is used, the three preferred options for meeting this condition are presented below.

1. **Minimum five pipe diameters of straight pipe upstream of UV reactor:** The length of straight pipe upstream of each UV reactor at the UV facility is the length of straight pipe used in the validation testing plus a minimum of five (5) pipe diameters. During validation testing, the inlet piping to the reactor consists of either a single 90-degree bend, a “T” bend, or an “S” bend, followed by a length of straight pipe if necessary. See Figure 3.7 for validation and installation configuration options.

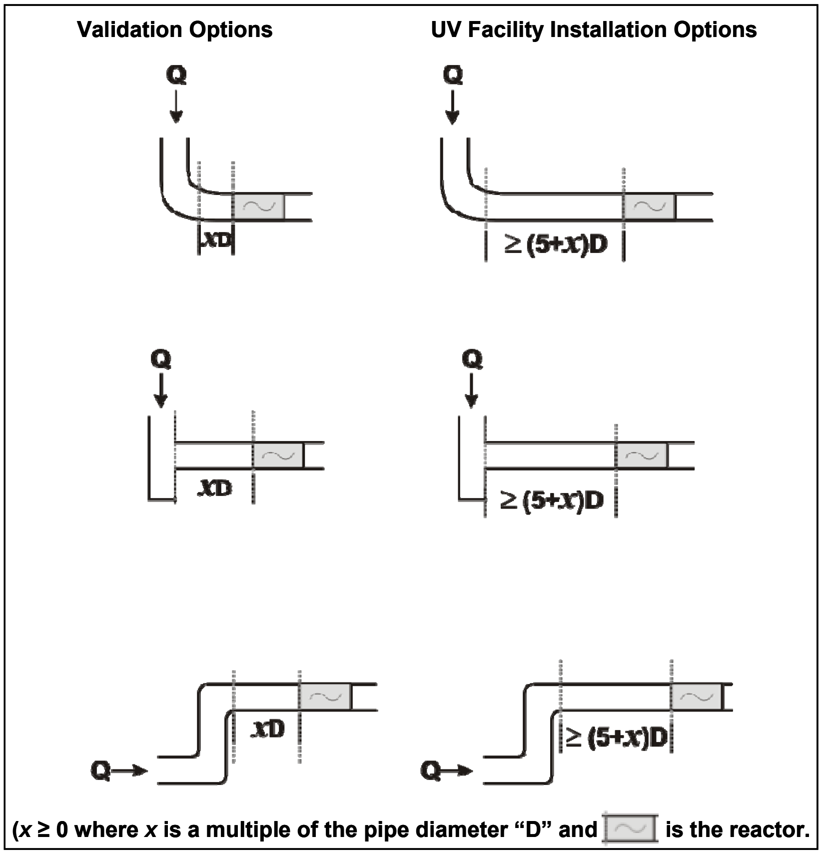
2. **Identical inlet and outlet conditions:** Inlet and outlet conditions used during validation match those used at the WTP for at least ten (10) pipe diameters upstream and five (5) pipe diameters downstream of the UV reactor.

3. **Velocity profile measurement:** 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 WTP installation (NWRI 2003). The theoretical velocity is defined as the flow rate divided by the cross-sectional area.

Jetting and swirling flow will impact the assumptions for Options 1 and 3. To avoid jetting flow, the inlet piping should have no expansions for at least ten (10) pipe diameters upstream of the reactor. Also, any valves located in that length of straight pipe should always be fully open during UV reactor operation. To avoid swirling flow, the validation piping should not include two out-of-plane 90°-bends in series.

The most suitable validation option depends on the site-specific layout and piping constraints and on the validation data. Option 1 is more generally 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 2 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 2 may be the only validation option for an individual filter effluent location, which likely will not have 5 diameters of straight pipe before the UV reactors (Option 1) because of existing site constraints. Option 3 also provides flexibility but may have the practical limitation of measuring the velocity through a cross-section at the installation.

Figure 3.7. Schematic of Hydraulic Option #1 (90°-Bend, T-Bend, S-Bend Inlet Piping Scenarios)



(x ≥ 0 where x is a multiple of the pipe diameter “D” and ▭ is the reactor.

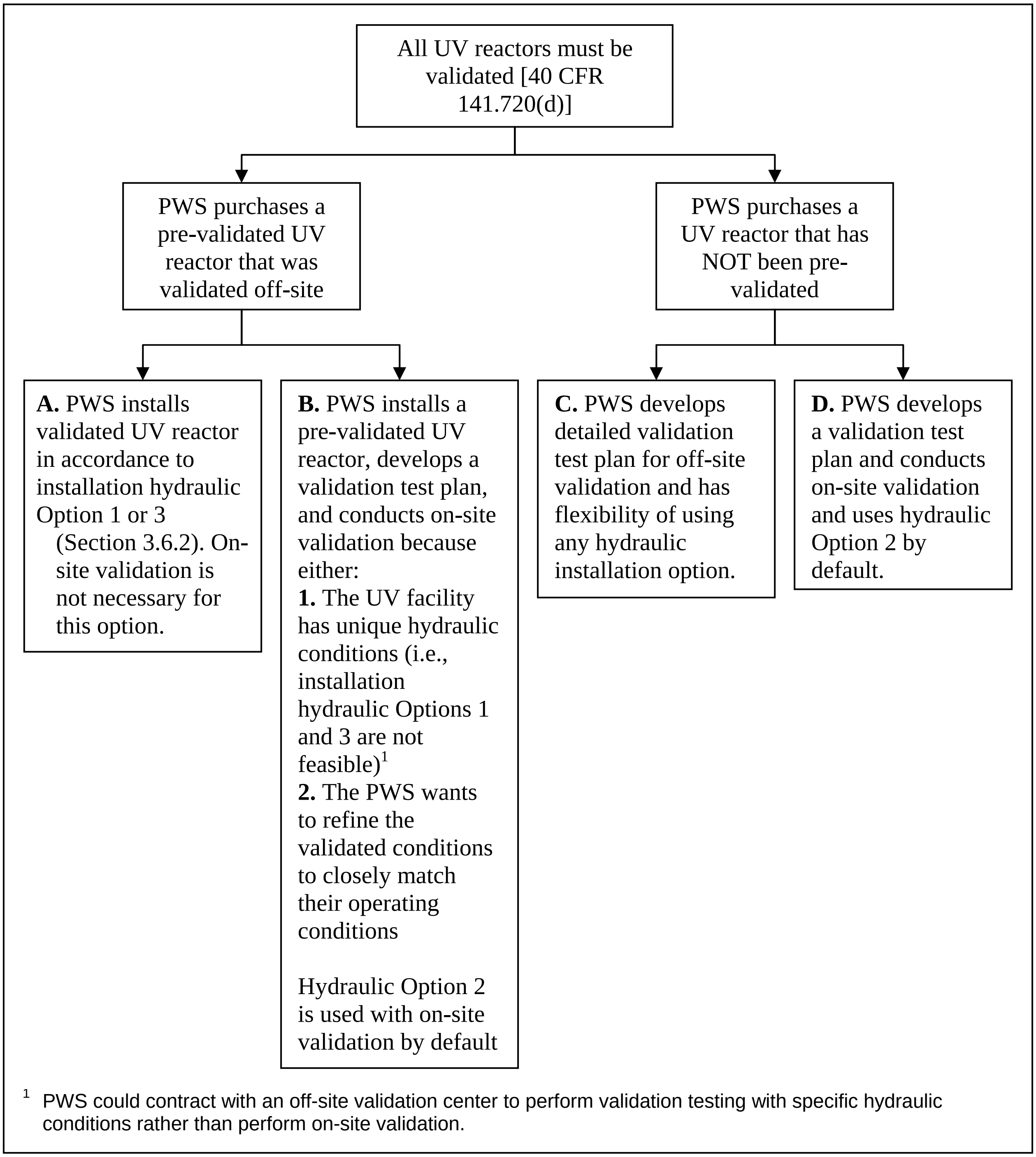
If available, the validation report for pre-validated UV equipment under consideration should be reviewed to determine what the inlet/outlet conditions were during validation, which will help determine if Option 1 is feasible. The method for meeting these recommended inlet/outlet constraints should be determined in the planning stage and considered when developing the UV facility layout (Section 3.8.2).

CFD modeling and CFD-based UV dose modeling of inlet and outlet conditions may be used to assess whether UV dose delivery at the WTP installation is better than UV dose delivery achieved during validation for given conditions of flow rate, UVT, and lamp output. The state should approve such models and their reliability should be properly evaluated before their results are accepted. Appendix D provides guidance on evaluating CFD models.

3.6.3 Selection of Validation and Hydraulic Approach

Whether or not the UV reactor was pre-validated off-site affects the inlet/outlet piping options for the UV facility. Completing on-site validation provides more inlet/outlet piping flexibility, but on-site validation means additional design considerations and testing at the water treatment plant. If the selected UV equipment is not pre-validated, the PWS can choose either off-site or on-site validation based on their site-constraints and preferences. These options are described in Figure 3.8.

Figure 3.8. UV Reactor Validation Options and How They Affect Installation Hydraulics



All UV reactors must be validated [40 CFR 141.720(d)]

PWS purchases a pre-validated UV reactor that was validated off-site

PWS purchases a UV reactor that has NOT been pre-validated

A. PWS installs validated UV reactor in accordance to installation hydraulic Option 1 or 3 (Section 3.6.2). On-site validation is not necessary for this option.

B. PWS installs a pre-validated UV reactor, develops a validation test plan, and conducts on-site validation because either:
1. The UV facility has unique hydraulic conditions (i.e., installation hydraulic Options 1 and 3 are not feasible)[1]
2. The PWS wants to refine the validated conditions to closely match their operating conditions

Hydraulic Option 2 is used with on-site validation by default

C. PWS develops detailed validation test plan for off-site validation and has flexibility of using any hydraulic installation option.

D. PWS develops a validation test plan and conducts on-site validation and uses hydraulic Option 2 by default.

[1] PWS could contract with an off-site validation center to perform validation testing with specific hydraulic conditions rather than perform on-site validation.

3.7 Assessing Head Loss Constraints

When selecting a feasible location for UV reactors, the hydraulic requirements should be met. Head loss through a UV reactor is specific to the equipment and flow rate and generally varies from 0.5 – 3 feet (UV reactor only). Characteristic head loss data should be obtained from the UV manufacturer(s) for all candidate UV reactors. In addition to the head loss associated with the UV reactor itself, the head loss associated with piping, valves, flow meters, and flow distribution devices (e.g., baffles) should be considered when assessing the feasibility and location of the installation. When selecting a reactor that has been validated off-site (Options A of Figure 3.8), the UV reactor inlet/outlet piping used to estimate the head loss through the facility should be consistent with the validation recommendations described in Section 3.6.2. The head loss through the entire UV facility (i.e., piping, valves, joints, and UV reactors) can be between 1 and 8 feet.

If the head loss through the UV facility is greater than the available head, the plant design or operation, or both, may require modification. Some potential modifications, alone or in combination, that may be considered to address hydraulic limitations are listed below, and details for each are provided in the sections that follow:

- Eliminating existing hydraulic inefficiencies within the facility to improve head conditions (e.g., replacing undersized or deteriorated piping and valves)
- Modifying the operation of the clearwell
- Modifying the operation of the filters
- Installing intermediate booster pumps
- Modifying the operation of the HSPs

3.7.1 Eliminating Existing Hydraulic Inefficiencies

Replacing undersized piping and valves with larger diameter piping and valves may increase the available head for the proposed UV facility. Older piping can also produce excessive head loss if the inner pipe surface is pitted or scaled or if the pipe material has a high coefficient of friction. Slip-lining the interior of existing pipe with material having a lower coefficient of friction (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 head loss.

3.7.2 Modifying Clearwell Operation

A PWS may increase head available to a UV facility by lowering the surface water level of the clearwell. This strategy, however, decreases the storage volume available to meet peak demands, reduces the contact time available in the clearwell for chemical disinfectants, and may affect the pump discharge head and distribution system pressure. Evaluating any potential reduction in disinfection credit is important if contact time in the clearwell is used for calculating chlorine disinfectant requirements (i.e., CT). The UV facility, however, may reduce the *Giardia* CT requirements sufficiently to offset the reduction in CT.

3.7.3 Modifying Filter Operation

A treatment facility can alter the operation of its filters (e.g., increase the water elevation above the filters) to increase the head available for the UV facility. This approach, however, can reduce filter run times and reduce unit filter run volumes, resulting in a need for 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 above the filters to help minimize the reduction in head as the water is filtered.

3.7.4 Installing Intermediate Booster Pumps

When modifications to the existing facility or operations do not provide adequate head for the UV reactors, intermediate booster pumps can be installed. Booster pumping increases flexibility in locating the UV reactors. Installing booster pumps, however, increases facility operation and maintenance costs and space requirements. The reliability of the pumps should also be considered in the evaluation because they become a critical operating component. More information on intermediate booster pumps is presented in Section 4.1.6.

3.7.5 Modifying Operation of HSPs

When UV disinfection is installed close to the HSPs (e.g., after the clearwell in a filtration plant or after an unfiltered reservoir), one option to increase the head available for the UV facility is to modify the pumping operation of the HSPs. Modifications may not be practical, however, if they change the distribution system pressure.

3.8 Estimating UV Facility Footprint

The process footprint should be estimated in the planning phase to help determine feasible UV facility locations. The critical components for estimating the UV facility footprint are UV equipment constraints and UV facility layout.

3.8.1 UV Equipment Constraints

The UV equipment constraints that affect the footprint estimation are the number of UV reactors needed to meet the design criteria, the UV reactor orientation, and the control panel location constraints.

- **Number of UV reactors:** The number of UV reactors depends on the redundancy chosen and the power modulation capabilities of the UV reactor. UV reactor redundancy should be determined using sound engineering approaches similar to those used for other major equipment (e.g., capacity to provide full treatment with the largest UV reactor out-of-service). The ability of the UV equipment to modulate lamp power or change the number of lamps energized also should be considered, so that energy efficient operation is possible at the operating range of flows and UVTs expected for the UV reactors. The UV manufacturer should be contacted to determine a particular UV reactor's power modulation capabilities.

- **UV reactor orientation:** UV reactors can be oriented either parallel or perpendicular to the ground. Two advantages of vertical orientation (i.e., flow perpendicular to the ground) are that (1) the footprint will be smaller and (2) the potential for lamp breaks due to debris may be reduced (as described in Appendix E).

- **Control panel location constraints:** Maximum allowable separation distance between the UV reactors and electrical controls should be considered in the UV facility layout and footprint estimation. This information is unique to each UV reactor and should be obtained from the UV manufacturer.

- **Validation hydraulic restrictions:** Section 3.6.2 describes how the validation piping configuration can dictate the possible UV facility piping configurations.

3.8.2 Develop UV Facility Layout

The UV facility layout is dictated by site constraints and the UV equipment constraints described in the previous section. The following items should be considered when developing the UV reactor and piping configuration and estimating the UV facility footprint in the planning phase:

- Number, capacity, dimensions, and configuration of the UV reactors (including redundancy and connective piping)

- Vertical or horizontal orientation of the UV reactor

- Maximum allowable separation distance between the UV reactors and electrical controls if distance limitations apply

- Adequate distance between adjacent reactors to afford access for maintenance tasks (e.g., lamp replacement)

- Configuration of the connection piping and the inlet/outlet piping necessary before and after each UV reactor, based on validated hydraulic conditions (see Section 3.6.2) and UV manufacturer recommendations

- Space and piping for booster pumps and wetwells (if necessary)

- Space for electrical equipment, including control panels, transformers, ballasts, backup generators, and possible uninterruptible power supplies

- Room for storing spare parts and chemicals (if needed)
- Lifting capability for heavy equipment
- Provisions for on-site validation (if applicable)

The dimensions of UV reactors and associated electrical equipment vary depending on the UV manufacturer. Installation footprint and layout should therefore be estimated for all UV manufacturers being considered. Once the UV facility footprint is estimated, feasible site locations can be determined based on the available land and buildings.

3.9 Preparing Preliminary Costs and Selecting the UV Facility Option

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

Preliminary life-cycle cost estimates should include capital costs and operation and maintenance (O&M) costs. Capital costs include the cost of the UV reactors; building (if necessary); piping; pumping (if necessary); electrical and instrumentation provisions; site work; contractor overhead and profit; pilot-testing (if necessary); validation costs; and engineering, legal, and administrative costs. The O&M costs should include the estimated labor, energy, and equipment replacement costs. The LPHO equipment and MP equipment have different O&M needs (Section 3.5.1) that should be considered in the O&M costs.

Selection of the best option should be based on the disinfection and design objectives and consideration of the following and other PWS-specific criteria:

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

3.10 Reporting to the State

Interaction with the state throughout the planning and design phases is recommended to ensure that the objectives of both the PWS and the state are met. This interaction may require several months and can have a significant effect on the implementation schedule, particularly when the state requires modifications. Given the relatively limited use of UV disinfection in the

United States to date, drinking water treatment, and the unique technical characteristics of this technology, state agencies may not have developed approval requirements specifically for UV disinfection. As such, PWSs are urged to consult with their state early in their UV disinfection planning process to understand the approvals and documentation that will be required for the use of UV disinfection.

The state may require that a preliminary design report be submitted that summarizes the decision logic used to identify, evaluate, and select UV disinfection. The following items may be addressed in the preliminary 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
- Design criteria
- Validation Test Plan (if performing on-site or off-site validation- See Section 5.11 for guidance on developing a Validation Test Plan)

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4. Design Considerations for UV Facilities

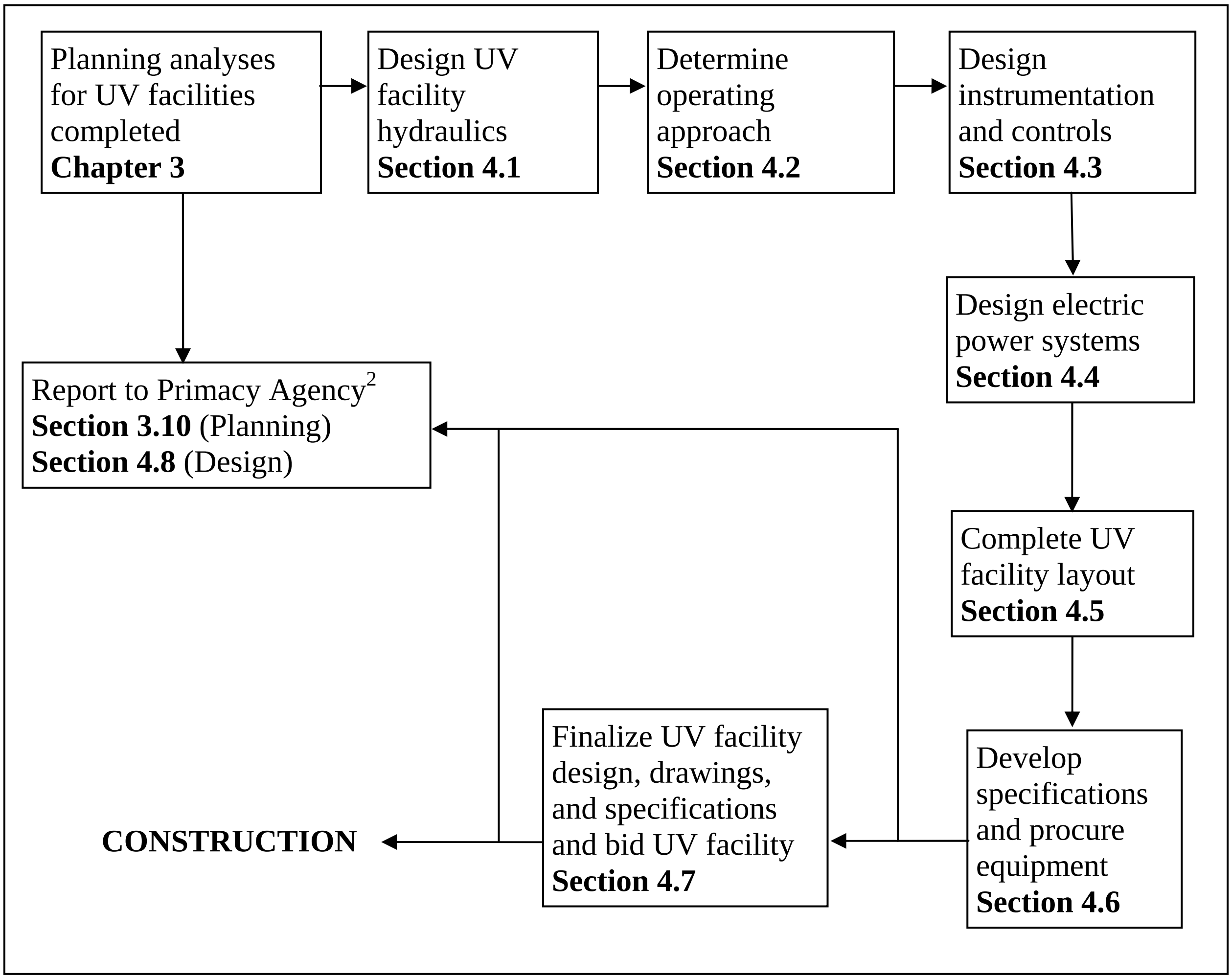
This chapter presents the key factors that should be considered during the detailed design phase and is written under the premise that the necessary planning and evaluation work discussed in Chapter 3 has been completed. This chapter focuses primarily on the design of UV disinfection applications for filtered surface water. Most of the information presented, however, also applies to unfiltered systems, groundwater under the direct influence (GWUDI), and uncovered finished water reservoirs. Additional design issues specifically associated with unfiltered, GWUDI, and uncovered finished water reservoir systems are also described.

Chapter 4 covers:

In the United States, most public water systems (PWSs) purchase or select the UV equipment before the UV facility design is complete. Pre-purchase or pre-selection of the UV equipment enables the designer and the UV manufacturer to coordinate during the detailed, final design phase to consider manufacturer-specific design recommendations. Sometimes the equipment is pre-selected and the UV equipment manufacturer is included in the construction contract. Other procurement methods (e.g., base-bid and contractor selection of equipment) are also used, but these methods are less common.

The process for designing a UV facility is presented as a flowchart in Figure 4.1. The illustrated process is based on pre-purchasing or pre-selecting the UV equipment using a traditional design-bid-build approach. Any of the equipment procurement and contractor selection approaches currently available within the industry, however, can be used to build UV facilities. The PWS and the engineer are responsible for selecting the most appropriate approach for their specific project. The order of the steps for other procurement approaches may differ from that shown in Figure 4.1, but the analyses completed are likely to be very similar. The steps described in this chapter follow the order presented in Figure 4.1. Some states may have design and plan review requirements that could impact the timing or sequence of steps shown in Figure 4.1. The appropriate state regulatory agency should be contacted early in the design process to discuss specific design requirements, plan review fees, and review scheduling.

Figure 4.1. Flowchart for Planning, Design, and Construction of UV Facilities[1]



[1] Flowchart is based on pre-purchase of UV reactors that have undergone validation testing and equipment installation using a traditional design-bid-build approach.

[2] Additional state coordination may be necessary.

4.1 UV Facility Hydraulics

After the facility location and UV equipment are selected during the planning phase, a more detailed evaluation of system hydraulics for the UV facility layout developed in Section 3.8 should be conducted. In most cases, the UV facility will be designed with multiple, parallel UV reactor trains of the same capacity. Each train consists of the lateral piping, UV reactor, valves, and flow meter (if applicable) and is joined to the other trains by the distribution and recombination channel or manifold. The hydraulic evaluation should include upstream and downstream processes for free water surfaces, the inlet/outlet piping configuration, flow control and distribution, flow rate measurement, level control, air and pressure controls, valving, and, where applicable, intermediate booster pumps.

4.1.1 Inlet and Outlet Piping Configuration

The recommended inlet and outlet conditions for validation and for the UV facility are described in detail in Section 3.6.2. If validation is conducted at an off-site testing facility, the designer should refer to the validation report to determine the validated inlet and outlet conditions, and then use the recommendations in Section 3.6.2 to determine the recommended inlet and outlet piping for the UV facility. If on-site validation or custom off-site validation is planned, the inlet and outlet hydraulics should be designed according to manufacturer recommendations and to accommodate any site-specific constraints. In addition, to avoid jetting flow, the inlet piping should have no expansions for at least ten (10) pipe diameters upstream of the reactor.

4.1.2 Flow Distribution, Control, and Measurement

Regulations specify flow rate, UV intensity, and lamp status as the minimum operating conditions that a PWS must routinely monitor [40 CFR 141.720(d)(3)]. Accordingly, proper flow distribution and measurement are essential for compliance monitoring of the UV reactors. This section discusses various methods for designing proper flow distribution and measurement through the UV reactors.

4.1.2.1 Flow Distribution and Control

The lateral piping for each UV reactor train should be sized and configured to provide approximately equal head loss through each UV reactor train over the range of flow rates. Importantly, flow rate through each reactor must conform to the validated operating conditions, [40 CFR 141.729(d)] as described in the validation report.

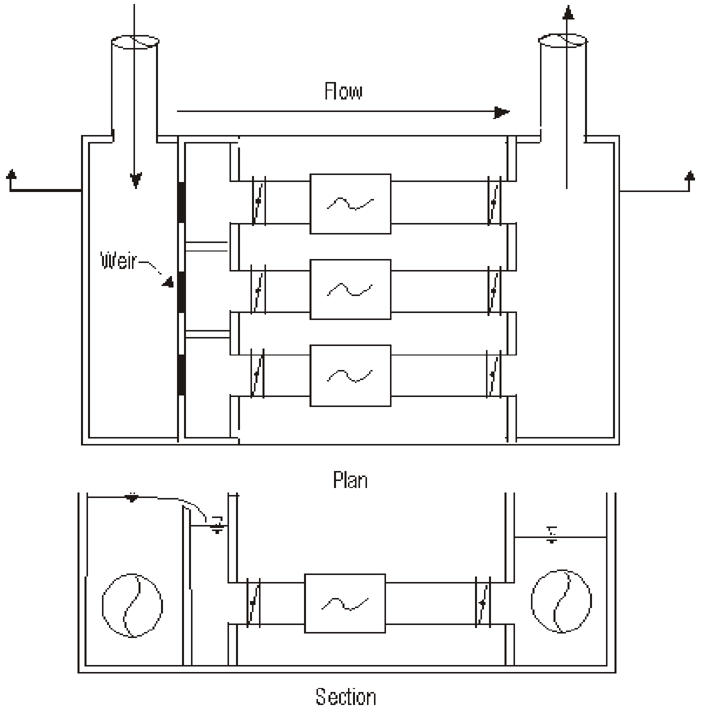
Two approaches for flow distribution and control are generally used. The first is active flow control and distribution, in which a dedicated flow meter and modulating control valve are installed for each UV reactor. Active flow control provides the greatest hydraulic control in applications with widely varying flow rates. The second method is passive flow distribution. For the passive approach, equal flow split is monitored with flow meters.

For PWSs that use distribution and recombination channels (instead of influent and effluent manifolds), designers typically have two basic choices to achieve passive flow distribution (Figure 4.2): (1) a series of individual weirs set at the same elevation or (2) a series of orifices submerged in the individual UV reactor laterals.

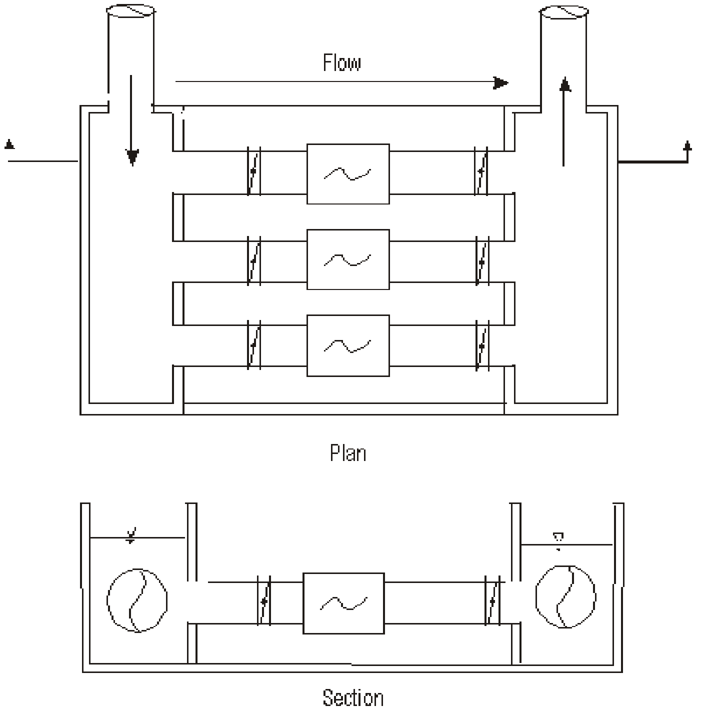
4.1.2.2 Flow Rate Measurement

The method of flow rate measurement selected should be based on the variability in plant flow rate, the type of flow split used, and any state requirements. Selection of the flow rate measurement method should be at the discretion of the PWS and the design engineer based on experience and professional judgment. Generally, each UV reactor should have a dedicated flow meter (as described in Table 4.1) to confirm that the reactor is operating within the validated flow rate. The state, however, may approve other methods (e.g., one flow meter coupled with pressure differential measurements).

Figure 4.2. Open-channel Flow Distribution Options



A. Flow Splitting Weirs



B. Submerged Orifices

Table 4.1. Comparison of Techniques for UV Facility Flow Rate Measurement for Combined Filter Effluent and Post-clearwell UV Facilities [1]

Flow Rate Measurement Method	Flow Control Method	Advantages	Disadvantages
Individual UV Reactor Flow Rate Measurement	Passive flow control such as a weir or an orifice	• Measures individual UV reactor flow rates accurately	• May have unequal flow distribution • Cannot control the UV reactor flow rate
Individual UV Reactor Flow Rate Measurement and Control	Individual flow control (valve) for each UV reactor	• Measures individual UV reactor flow rates accurately • Does not rely on passive flow distribution	• Increases capital cost • May increase facility footprint due to hydraulics of UV reactor, meter, and valves

[1] For individual filter effluent installations, the flow rate from the filters can be used to determine the flow rate through the UV reactors.

When selecting a flow meter, the flow meter's effect on the inlet/outlet hydraulics of the UV reactor should be considered. Magnetic or other types of flow meters (such as Doppler) that do not protrude into the flow path exert the least effect on the velocity profile, which minimizes the potential effect on reactor inlet or outlet hydraulics.

4.1.3 Water Level Control

The UV lamps in the UV reactor should be submerged at all times to prevent overheating and UV equipment damage. This is accomplished by installing the UV reactors at an elevation below the hydraulic grade line elevation. Two common methods for keeping the UV lamps submerged are to:

1. Install a flow control structure (e.g., weir or orifice) immediately downstream of the UV reactor or at another location that ensures full pipe conditions through the UV reactors.

2. Use flow control valves to monitor and maintain the hydraulic grade line.

Damage to UV lamps caused by operation in air is specific to each lamp type and size. Low-pressure (LP) lamps can typically operate in air for up to 24 hours with minimal damage. Low-pressure high-output (LPHO) lamps will begin experiencing damage as a result of dislodged amalgam or mercury adsorption to the inner surface of the lamps in 6 – 12 hours (Lawal 2006). Medium-pressure (MP) lamps can experience advanced aging or solarization in fewer than 6 hours and can break (see Appendix E).

4.1.4 Air Relief and Pressure Control Valves

UV reactors should be kept free of air to prevent lamp overheating. Negative gauge pressures or surge effects within the UV reactors should also be prevented to avoid damage to the lamps and lamp sleeves. Quartz sleeves are designed to accommodate continuous positive pressures of at least 120 pounds per square inch gauge (psig) but have been shown to break at negative pressures of 1.5 (Roberts 2000, Aquafine 2001, Dinkloh 2001). Negative pressures can result from line breaks or accidental dewatering of the reactor. The use of air release valves, air/vacuum valves, or combination air valves may be necessary to prevent air pockets and negative gauge pressure conditions. The UV manufacturer should be contacted to determine any equipment-specific air release and pressure control valve needs. The valve locations will be dictated by the specific configuration of the facility and should be determined during design.

4.1.5 Flow Control and Isolation Valves

Each UV reactor should be capable of being isolated and removed from service. Isolating or shutting down a UV reactor will require valves, gates, or similar devices upstream and downstream of the UV reactor. Valves are recommended because they provide a tighter seal. During design, the inlet and outlet valve configuration should be discussed with the UV manufacturer to ensure that UV reactor performance will not be adversely affected and that the required inlet conditions used during validation are met, as discussed in Section 3.6.

If the isolation valves are also used for flow control, the flow control valve should be located downstream of the UV reactor to limit the disturbance of the flow entering the UV reactor. Valves downstream of the UV reactor can be equipped with an actuator to open or close automatically on a critical alarm occurrence and to enable start-up sequencing.

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 and chemicals that may be used for reactor cleaning. Resistant materials will help avoid valve degradation.

4.1.6 Installation of Intermediate Booster Pumps

A detailed evaluation and design of a booster pumping system is recommended if head constraints indicate a pumping system is necessary. 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 needed for intermediate pumping applications and are generally not appropriate. Mixed- or axial-flow pumps with high-flow and low-head operating characteristics are usually better choices for intermediate pumping applications because typically only 1 – 8 feet of additional hydraulic head is needed to overcome the head loss through the UV facility.

Pumps can be installed before or after the UV reactors, allowing more flexibility in the UV facility’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.

Booster pump operation may be controlled by the water level within the upstream wetwell. The use of variable frequency drives or a rate-of-flow controller with a modulating valve to dampen flow rate peaks is recommended, especially 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 rate through the water treatment plant (WTP).

4.1.7 Evaluating Existing Pumps and Potential Water Hammer Issues

In some WTPs, the most feasible location for installing the UV reactors may be immediately upstream or downstream of existing high-service pumps (HSPs) (Section 3.3.1.3). The HSP discharge curves should be analyzed to determine the effect of the increased head loss through the UV reactors and whether HSP modifications are necessary.

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 defined, including procedures for 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 should be taken into account with the sequencing of the pump operation.

4.1.8 Groundwater System Hydraulic Issues

Common hydraulic issues associated with groundwater systems include high operating pressures, air entrainment, and the potential for water hammer events.

Lamp sleeves are designed to resist high external operating pressures. Before selecting equipment, however, the designer should determine the maximum expected operating pressure, which may occur during a failure event (e.g., downstream valve closes), and confirm that the proposed equipment can withstand that pressure.

Pressure surge events (water hammer) near the UV reactor may be more likely with groundwater 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 and potentially break the sleeves and lamps. 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.

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 facility design should include a means for automatically releasing air prior to the UV reactor. The UV reactor may have air release valves or valve ports, or air release valves can be installed in the inlet piping.

4.1.9 Uncovered Finished Water Reservoir Hydraulic Issues

Many uncovered finished water reservoirs serve as distribution storage and are directly affected by the water system demand. Others may be used solely as an emergency supply or may function as both distribution storage and emergency supply. The specific hydraulic considerations that a PWS and designer should consider will vary depending on the function of the uncovered finished water reservoir. Regardless of reservoir function, however, specific hydraulic issues that should be considered when designing UV facilities at uncovered finished water reservoirs include widely varying flow rates, bi-directional flow (under certain piping configurations), and the effect a UV facility will have on system pressure.

- **Variable flow rate:** The methodology described in Section 3.4 should be followed to determine the flow rate and UVT that are used to design the UV facility. Most UV facilities at uncovered finished water reservoirs should be designed to handle the peak instantaneous demand that must be met by the reservoir. The instrumentation and control (I&C) design must consider how the PWS will sequence the UV reactors with highly variable flow conditions, especially warm-up times for UV lamps (Section 2.4.2.3).

- **Bi-directional flow:** In some cases, the inlet and outlet to the uncovered finished water reservoir is the same pipe, and the UV facility should be designed so that disinfection continues when the water is flowing from the uncovered finished water reservoir. The PWS may also consider operating the UV reactors at a minimum level as the water flows into the reservoir so that the UV lamps are energized and ready for UV disinfection if the flow direction changes suddenly. The necessity for this latter approach depends on the number of directional changes per day in the context of meeting off-specification requirements.

- **UV facility effect on system pressure:** As discussed in Section 3.7, head loss through a UV reactor generally varies from 0.5 to 3 feet, with the overall head loss through a UV facility typically about 1 to 8 feet. This head loss could affect the distribution system pressure. As discussed in Chapter 3, a hydraulic assessment should be completed to determine if head loss constraints occur for the UV facility or if booster pumping is needed.

4.2 Operating Approach Selection

The operating approach is the method of operating a UV reactor based on the **dose-monitoring strategy (Section 3.5.2) and validation report data** and should be determined before the I&C design is complete. The operating conditions for each UV reactor must be based on validation testing results [40 CFR 141.720(d)(3)].

As described in Section 3.5.2, this guidance manual focuses on two dose-monitoring strategies: UV Intensity Setpoint Approach and Calculated Dose Approach. The UV Intensity Setpoint Approach can be used with a single or variable setpoint operation; variable setpoint operation allows for some energy savings. The Calculated Dose Approach typically uses a single setpoint (e.g., the required dose), and the UV equipment automatically compensates based on the UVT, UV sensor measurements, and flow rate, which increases energy savings.

When considering the dose-monitoring strategy and operating approach, the operational complexity should be compared to the potential for energy savings. The UV manufacturer should be contacted to determine the potential energy savings with the available dose-monitoring strategies and operating approaches. For small water systems, the UV Intensity Setpoint Approach with a single setpoint may be the best option because the energy savings with a more complex operating approach may not be worth the additional operational needs. Detailed examples of how to determine the operational setpoints from validation reports for these operating strategies are described in Section 6.1.4.

4.3 Instrumentation and Control

The necessary level of I&C depends on the selected techniques for flow control and distribution, flow rate measurement, and the operating approach. For example, passive flow distribution with the UV Intensity Setpoint Approach that uses a single setpoint is simple and demands limited I&C but may result in reduced operating flexibility and energy efficiency. More complex control strategies, such as the use of dedicated flow meters and flow control valves with the Calculated Dose Approach, necessitate a higher level of I&C, but improve operating flexibility and enable optimization of disinfection performance. The control system complexity and operating flexibility should be balanced to meet the needs of the PWS.

Most of the manufacturers’ equipment has similar I&C attributes and alarm conditions incorporated in the UV reactor designs. The designer should identify the

- Elements that are preprogrammed in the UV reactor control panel
- Necessary supplemental controls to coordinate the operations of the UV reactor trains
- Actions necessary for each alarm condition.

At a minimum, UV lamp intensity, flow rate, and lamp status must be monitored (40 CFR 141.720(d)(3)). The final I&C design can be modified as needed after UV equipment is selected. The following sections describe the elements that should be considered in I&C design.

4.3.1 UV Reactor Start-up and Sequencing

This section describes the typical UV reactor start-up protocol, strategies for sequencing the start-up of multiple UV reactors, and considerations for groundwater UV facility start-up.

4.3.1.1 UV Reactor Start-up

The UV reactor start-up sequence depends on whether the UV reactor requires cooling water while the UV lamps warm up. Some reactors require cooling water (Leinberger 2005, Larner 2005) and some do not (Larner 2005, Bircher 2005). Without water flow, some UV lamps may heat the water above the safe operating temperatures of 30 – 49 °C in 2.5 – 15 minutes, causing the reactor's internal safety devices to shut the reactor off (Leinberger 2005, Bircher 2005). LP and LPHO reactors typically do not and some MP reactors do not need cooling water as the UV lamps are warming up (Haubner 2005). UV lamp breaks (discussed in detail in Appendix E) can occur if the lamps become overheated because of no flow or minimal cooling water flow. **The designer should consult the UV manufacturer to determine whether the UV reactor requires cooling water during start-up.**

The potential start-up sequences for UV reactors that do and do not need cooling water and are starting cold (i.e., previously off as opposed to shut down for a very short period) are summarized below:

- **UV reactors that do not require cooling water:** The potential control sequence will ignite the lamps, get the UV reactor to its validated conditions, and open the isolation valves. With this strategy, the UV reactor will be "on" for some time when no water is flowing through it. Flow should be established in the UV reactor within an hour to prevent fouling of the quartz sleeves.

- **UV reactors that do require cooling water:** The potential control sequence will open the isolation valves to allow the minimal cooling water flow, ignite the lamps, get the UV reactor to its validated conditions, and then fully open the isolation valves to allow the full flow through the UV reactor. The I&C should be designed to reduce the amount of off-specification water by providing the minimal flow necessary to keep the lamps cool during start-up. If the amount of off-specification water should be limited, methods are available to design the UV facility piping to minimize off-specification water (e.g., cooling water being diverted to waste).

For facilities that do not operate continuously, the designer should discuss the specific operating schedule with the manufacturer to identify any special provisions that should be included in the design or the operating procedures (e.g., automatic cleaning before each start-up, draining for extended periods of downtime).

4.3.1.2 UV Reactor Sequencing

UV facilities with multiple UV reactors should develop two types of UV reactor start-up sequences in I&C loop descriptions:

- **Routine operation:** The UV reactor sequencing should be developed based on the validated conditions and the operational approach.

- **Start-up after a power quality event:** The control system should monitor the power input to the UV reactors and the UV reactor status. LPHO and MP reactors have different start-up characteristics after a power quality event (Section 2.4.2.3) and should have different start-up sequences to minimize warm-up and corresponding off-specification time.

- **LPHO reactors –** UV reactors that were on-line (i.e., operating) before the power quality event and shut-down should be restarted first after normal power is restored.
- **MP reactors –** UV reactors that were off-line before a power quality event that shuts down UV rectors should be started first when normal power is restored.

4.3.1.3 Groundwater Pump Cycling Effects on UV Reactor Start-up

Groundwater well cycling can adversely affect UV reactor performance, causing an increase in off-specification water. An analysis should be performed to estimate off-specification volume based on the current well cycling frequency. The well cycling approach may need to be changed if off-specification requirements cannot be met under current well cycling frequency. Two approaches that can minimize the effects of well cycling, depending on whether the UV reactors require cooling water, are discussed below.

- **UV reactors that do not require cooling water:** A time delay can be incorporated in the I&C loops that prevents the well pump from starting until the UV reactor reaches its validated conditions. As described in Section 4.3.1.1, the UV reactor will be "on" for some time when no water is flowing through it.
- **UV reactors that do require cooling water:** The I&C programming would supply the minimum water flow through the UV reactor until the reactor reaches validated conditions. Then, the groundwater flow can be increased to meet system demand. If desired, the cooling water can be discharged to waste if site conditions permit.

4.3.2 UV Equipment Automation

UV equipment operation can range from manual to fully automatic, depending on the reactor's size and complexity. Manual operation includes manually initiating lamp start-up and shut-down, and activating the appropriate valves. Various levels and types of automation are typically part of the internal UV equipment controls and 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 include starting UV reactors, activating rows of lamps, or making lamp intensity adjustments based on UV intensity, UVT, or flow rate. Automatic UV reactor shut-down under critical alarm conditions (e.g., high temperature, lamp or sleeve failure, loss of flow) is essential for all operating approaches, including manual operation.

4.3.3 Alarms and Control Systems Interlocks

Many UV reactor signals and alarms are specific to the UV facility and the level of automation used. Alarms may be designated as minor, major, or critical, depending on the severity of the condition being indicated.

- A **minor alarm** generally indicates that a UV reactor requires maintenance but that the UV reactor is operating in compliance. Minor alarms also can be set for conditions just short of failure conditions so that major alarm conditions are not reached. For example, a minor alarm would occur when the UVT is within 1 percent UVT of the minimum allowed UVT or when the end-of-lamp-life based on hours of operation is reached, indicating the possible need for lamp replacement.

- A **major alarm** indicates that the UV reactor requires immediate maintenance (e.g., the UV sensor value has dropped below the validated setpoint) and that the unit may be operating off-specification. Based on the water system'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 critical alarm is the UV reactor's temperature exceeding a pre-determined maximum value, resulting in automatic shut-down to prevent overheating and equipment damage.

The same alarm condition may represent a different level of severity depending on the validated conditions, the type of UV reactor, the operating approach, and the disinfection objectives of the PWS. For example, if a UV reactor was validated with one lamp out of service, a single lamp failure alarm may trigger a minor alarm. Had the reactor been validated with all lamps in operation, a single lamp failure may trigger a major alarm. Table 4.2 summarizes typical UV reactor monitoring and alarms that would likely be integral to the UV reactor control panel.

4.3.4 UV Reactor Control Signals

The designer should coordinate with the UV manufacturer to determine what elements of the control system are integral to the UV reactor and what elements should be addressed with supplemental controls and equipment (i.e., supervisory control and data acquisition or SCADA). For installations with multiple UV reactors, a common, master control panel may be necessary to optimize UV reactor operations. Typically, each UV reactor has a dedicated control panel, and the plant's SCADA system receives control signals from each control panel to control the entire UV facility. The SCADA system also monitors and records the process parameters. Recommended monitoring and recording frequencies are provided in Chapter 6, and the designer should coordinate with the state to determine if expected frequencies differ. This section describes the control signals that could be transferred from each reactor's control panel to the SCADA system.

4.3.4.1 UV Intensity

Signals from UV sensors should be displayed locally on the UV reactor control panel and in the plant's SCADA system screen (if applicable).

Table 4.2. Typical Alarm Conditions for UV Reactors [1]

Sensor	Alarm Type	Purpose/Description
Lamp Age	Minor alarm	Run-time for lamp indicates end of defined operational lamp life.
Calibration Check of UV sensor	Minor alarm	UV sensor requires calibration check based on operating time.
Low UV Validated Dose	Major alarm	Indicated validated UV dose (based on UV reactor parameters, i.e., flow rate, UV intensity, and UVT) falls below required UV dose.
Low UV Intensity	Major alarm	Intensity falls below validated conditions.
Low UV Transmittance	Major alarm	UVT falls below validated conditions.
High Flow Rate (Not Integral to UV Reactor—Relies on Flow Meters)	Major alarm[2]	Flow rate falls outside of validated range.
Mechanical Wiper Function Failure (If Applicable)	Major alarm	Wipe function fails.
Lamp/Ballast Failure	Major alarm	Single lamp/ballast failure identified.[3]
	Critical alarm	Multiple lamp/ballast failures identified.
Low Liquid Level	Critical alarm	Liquid level within the UV reactor drops and potential for overheating increases.
High Temperature	Critical alarm	Temperature within the UV reactor or ballast exceeds a setpoint.

[1] Alarm conditions and relative severity shown above may vary depending on the specific validated conditions, type of UV reactor, manufacturer, dose-monitoring strategy, and disinfection objectives of the PWS.

[2] Based on measurement from dedicated flow meters or calculated based on total flow rate divided by number of UV reactors operating.

[3] Coordinate with UV manufacturer to determine if a lamp/ballast failure could indicate a sleeve and lamp break, which should be classified as a critical alarm.

4.3.4.2 UV Transmittance

If the Calculated Dose Approach is used, the UVT must be known to ensure that it is within the validated range. An on-line UVT analyzer or a bench-top spectrophotometer may be used to monitor UVT. Output from an on-line UVT analyzer can be input directly into a control loop for most UV reactors, a SCADA system, or both. Results from a bench-top spectrophotometer can be manually input into a SCADA system or UV reactor control panel(s).

4.3.4.3 Flow Rate Measurement

To maintain regulatory compliance, the flow rate through a UV reactor must be known to ensure that it is within the validated range [40 CFR 141.720 (d)(2)]. Section 4.1.2 discusses flow rate measurement and control options. The flow rate signal should be displayed locally or be input directly into a control loop for the UV reactor, a SCADA system, or both.

4.3.4.4 Calculated and Validated UV Dose (If Applicable)

If the Calculated Dose Approach is used, the calculated and validated doses should be displayed locally and transmitted to the SCADA system. The validated dose is equal to the calculated dose divided by the Validation Factor (See Section 5.10 for details).

4.3.4.5 Operational Setpoints

The operational setpoints should be displayed locally and remotely in the SCADA system. These setpoints will depend on the specific dose-monitoring strategy, operating approach (Section 4.2), and the validation data, and may include UV intensity, UVT, flow rate, calculated dose, and validated dose.

4.3.4.6 Lamp Age

The operating time of each lamp should be monitored, displayed locally, and transmitted to the SCADA system to facilitate O&M and lamp replacement, as discussed in Section 6.3.2.6.

4.3.4.7 Lamp Power, Lamp Status, and Reactor Status

Water systems must monitor lamp status to verify that UV reactors are operating within validated conditions [40 CFR 141.720(d)(3)]. Lamp status refers to whether the lamp is “on” or “off.” The operating power level should also be monitored and displayed at the control panel and remotely in the SCADA system. Each reactor’s on-line or off-line status should also be monitored and indicated locally and remotely, which can be accomplished by monitoring power and valve status.

4.3.4.8 UV Reactor Sleeve Cleaning

Sleeve cleaning information should be displayed locally and communicated between the local control panels and the SCADA system. This information should include the date and time of the last cleaning for off-line chemical cleaning (OCC) systems and the wiping frequency for on-line mechanical cleaning (OMC) or on-line mechanical-chemical cleaning (OMCC) systems.

4.3.4.9 Alarms

At a minimum, alarm conditions should be displayed locally. The use of visual or audible alarms is also recommended. If the UV facility will frequently be unstaffed or a SCADA system is already in place, provisions should also be included in the design to allow remote monitoring and display through the SCADA system.

4.4 Electrical Power Configuration and Back-up Power

The electrical power configuration should take into account the power requirements of the selected equipment, the disinfection objectives, and power quality issues, if applicable. (See Section 3.4.6.)

4.4.1 Considerations for Electrical Power

The proper supply voltage and total load requirements should be coordinated with the UV manufacturer, considering the available power supply. In addition, the power needs for each UV reactor component may differ. For example, the UV reactor may require 3-phase, 480-volt service, while the on-line UVT analyzer may need single-phase, 110-volt service. Excluding high service pumping, the electrical load from UV reactors will typically be among 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 cause electrical system problems, including overheating of some power supply components and can affect other critical systems, such as variable frequency drives (VFDs), programmable logic controllers (PLCs), and computers. Selection of the UV reactors should be based on a thorough analysis of the potential for the equipment to induce harmonic distortion. Additionally, the UV facility design and UV equipment should meet the Institute of Electrical and Electronic Engineers (IEEE) 519 Standard that addresses harmonics.

One method for controlling harmonics is to use a transformer with Delta Wye connections to isolate the UV reactor from the remainder of the WTP power system. The Delta-connected primary feed can 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 can be added to the UV reactor power supply to control distortion.

4.4.2 Back-up Power Supply and Power Conditioning

The continuous operation of the UV reactor is highly dependent on the power supply and its quality (Section 3.4.6). If the power reliability requirements and, consequently, the disinfection objectives cannot be met by relying solely on the commercial power supply, the use of back-up power, power conditioning equipment, or both may be necessary.

4.4.2.1 Back-up Power Supply

A simple backup power supply (e.g., generator) may be sufficient if power quality issues are infrequent. If an existing backup power supply is in place, its load capacity should be assessed to determine whether it can accept the additional load associated with the UV facility. The time necessary for switching from the primary power supply to a backup power supply and how that time affects compliance with the allowable off-specification operation should be determined.

4.4.2.2 Power Conditioning Equipment

Power conditioning equipment may be necessary if the power quality analysis reveals frequent events (Section 3.4.6) that cause the UV facility not to meet disinfection objectives. A site-specific analysis should be completed to determine the most appropriate power conditioning approach (Cotton et al. 2005). Consideration should include off-specification compliance, quality of the power supply, the cost of power conditioning equipment, and site constraints (e.g., land availability).

- **Uninterruptible Power Supply (UPS)** systems provide continuous power in the event of voltage sag or power interruption. The battery capacity is large enough to supply power to all connected equipment until a generator starts. UPS systems can either be on-line or off-line:

  On-line UPS: The unit and batteries are installed in series between the incoming power feed and all critical equipment. The incoming power feed charges the UPS batteries, and the batteries supply the electrical load. In this situation, the power feed is completely separated from the electrical load. This alternative is the most costly and has the largest footprint.

  Off-line UPS: The unit is installed in parallel with the connection from the incoming power feed to the critical equipment. During normal operations, the electrical load receives power directly from the power feed. When the off-line UPS senses a voltage fluctuation greater than or less than 10 percent of the nominal voltage, the load transfers to the UPS until the electrical feed stabilizes or the generator starts. Off-line UPS systems are less costly and have a smaller footprint than on-line UPS systems.

- **Active Series Compensators** protect electrical equipment against momentary voltage sags and interruptions. These devices boost the voltage by injecting a voltage in series with the remaining voltage during a sag condition. The corrected response time is a fraction of a cycle, preventing the equipment from experiencing a voltage sag. Active series compensators are well suited for instantaneous sags and interruptions; however, they cannot correct sustained sags or interruptions. Active series compensators are the lowest cost and smallest power conditioning option.

4.4.3 Ground Fault Interrupt and Electrical Lockout

Proper grounding and insulation of electrical components are critical for protecting operators from electrical shock and protecting the equipment. When combined with effective lockout/tagout procedures, the risk of electrical shock is further minimized. Ground fault interrupt (GFI) is another 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 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.

4.5 UV Facility Layout

Site layout for a UV facility is generally similar to the layout for any treatment process. Access for construction, operation, and maintenance should be considered. Typically, a preliminary layout is developed during project planning (Section 3.8.2). This preliminary layout may be modified to address space constraints or special installation conditions that result from the final equipment selection or based on more extensive site information gathered during detailed design. In addition to those items identified in Section 3.8.2, this section describes the items to be considered in the more detailed layout developed in the design phase.

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 should be enclosed. In some installations, UV reactors and control panels are uncovered. Before designing an uncovered facility, however, the state and UV manufacturer should be consulted. 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 piping, valve, and flow meter design developed in the hydraulic evaluation (Section 4.1) should be considered in the UV facility configuration. For example, the length of straight-run piping before and after each flow meter to achieve the proper hydraulic conditions for accurate and repeatable flow rate measurement should be considered in the piping layout, depending on the flow control and measurement technique used (Section 4.1.2).

The location of the power and control panels associated with UV reactors should allow adequate space for panel doors to be opened without interference, and to allow unhindered access to the UV reactors when the doors are 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 power quality is a concern, room for power conditioning equipment should be provided. Such equipment may be located adjacent to the UV reactors or in a separate control room.

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. If applicable, sufficient space should be maintained around the UV reactors to provide access for the OCC procedure. Also, 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 in the lateral pipe are recommended upstream and downstream of each UV reactor. The sample taps may be used for collecting water quality samples or 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 oversight entity to comply with the recommendations of the selected validation protocol. Additional details on the locations of sample taps and other validation-related appurtenances are provided in Section 5.4.

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 facility to enable the UV reactor and entire lateral to be fully drained for maintenance activities. These drains should be large enough to drain the reactor and adjacent piping in a reasonable amount of time.

Additionally, the UVT analyzer installation (if necessary) should be considered in the layout. The specific size and operating characteristics of the UVT analyzer will vary depending on the UV manufacturer. If an on-line UVT analyzer is included in the design, adequate space and access to an electrical supply for monitor installation should be provided and appropriate sample taps and drains for withdrawing and discharging sample water should be included in the design. The sample line should be equipped with a valve to isolate the UVT analyzer. A sample pump (e.g., peristaltic) should be installed if insufficient pressure is available in the system. The UVT analyzer should be in a location that minimizes the likelihood of air bubbles (which can cause erroneous readings) passing through the monitor.

4.5.1 Additional Considerations for Unfiltered and Uncovered Reservoir UV Facility Layouts

Site issues that should be considered with unfiltered systems are generally consistent with those for filtered surface water systems. The most significant difference is the increased opportunity for debris to be present in the inflow to UV reactors in unfiltered applications. To address the increased potential for debris, UV facility designs for unfiltered applications should incorporate features that prevent potentially damaging objects from entering the UV reactor. 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 for minimizing it are discussed in Appendix E.

4.5.2 Additional Considerations for Groundwater UV Facility Layouts

Site issues that should be considered with groundwater systems are generally consistent with those for post-filtration surface water systems; the most significant difference is access of the site and potential sand particles affecting the UV reactor. Because well sites can be located in remote areas and may be more accessible to the general public or unauthorized individuals, the UV reactor should be installed within a building to protect sensitive equipment. The need to enclose the UV facility will ultimately be based on the manufacturer’s recommendations, local regulatory and code requirements, state 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).

In addition, sand or debris flowing through the UV reactor may scratch the lamp sleeves or cause the sleeve wiping mechanisms to jam. Larger sand and debris could break the lamp sleeves and lamps. (See Appendix E for lamp breakage issues.) Intermittently used wells may accumulate sand or other particles; this initial concentration of particles should be discharged before operation and should bypass the UV reactor to avoid scratching the quartz sleeves. A sand/debris trap or other removal equipment prior to UV disinfection may be necessary if evidence suggests that the well pump will pull any sand or particles through the screen during normal well operation.

4.6 Elements of UV Equipment Specifications

When procuring the UV reactors, the UV facility layout and UV reactor specification are typically provided to the UV manufacturer. This section describes the potential elements included in a UV reactor specification and outlines the information that could be requested from the UV manufacturer.

4.6.1 UV Equipment Specification Components

Table 4.3 summarizes the factors that should be considered when developing equipment specifications for the UV equipment. The information included in Table 4.3 is not exhaustive and should be modified to meet the specific needs of the PWS and the requirements for the UV facility.

Table 4.3. Possible Content for UV Equipment Specifications (Table Spans Pages 4-20 – 4-22)

Item	Specification Content
Flow rate	Maximum, minimum, and average flow rates should be clearly identified. The maximum flow rate must be within the validated range documented in the validation report [40 CFR 141.720 (d)(3)]. The minimum flow rate may be important to avoid overheating with MP reactors. One method for determining the maximum flow rate is described in Section 3.4.3.
Target Pathogen(s) and Log Inactivation	The log inactivation for the target pathogen(s)
Required UV Dose	The required UV dose for the target microorganism and log inactivation that must be verified by the validation process. Additional detail is provided in Chapter 5.
Water Quality and Environment	The following water quality criteria should be included: - Influent temperature - Turbidity - UV transmittance at 254 nm - UVT scan from 200 – 300 nm (MP reactors only) - Total hardness - pH - Iron - Calcium - Manganese - ORP For some parameters, a design range may be most appropriate.
Operating Flow and UVT Matrix	Appropriate matrix of paired flow and UVT values based on flow and UVT data (Section 3.4.4.1).
Operating Pressure	The expected operating pressures, including the maximum and minimum operating pressure to be withstood by the lamp sleeves and UV reactor housing.
UV Sensors	A germicidal spectral response should be specified (Section 5.4.8). A minimum of one UV sensor should be specified per UV reactor. The actual number should be identical to the UV reactor that was, or will be, validated. The uncertainty of the UV sensors used during **validation** should meet the criteria described in Section 5.5.4. The uncertainty of the duty UV sensors during **operation** should meet the criteria described in Section 6.4.1.1. Reference UV sensors should be calibrated against a traceable standard. For example, the following standards are currently being used by UV manufacturers: - National Physical Laboratory (NPL) - National Institute of Standards and Technology (NIST) - Deutsche Vereinigung des Gas- und Wasserfaches (DVGW) - Österreichisches Normungsinstitut (ONORM)
Redundancy	The reactor redundancy determined in Section 3.8.1.
Hydraulics	The following hydraulic information should be specified: - Maximum system pressure at the UV reactor - Maximum allowable head loss 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).

Table 4.3. Possible Content for UV Equipment Specifications (Table Spans Pages 4-20 – 4-22)

Item	Specification Content
Size/Location Constraints	Any size constraints or restrictions on the location of the UV reactor or control panels (e.g., space constraints with individual filter effluent installation).
Validation	The range of operating conditions (e.g., flow, UVT) that must be included in the validation testing, and submittal of a validation report (40 CFR 141.720) should be required. The validation testing should be completed in accordance to the procedures and data analysis described in detail in Chapter 5.
Dose-Monitoring Strategy	A description of the preferred dose-monitoring strategy for the UV reactors.
Operating Approach	A description of the intended operating approach for the UV reactors, as described in Section 4.2.
Economic and Non-Economic Factors	The necessary information to thoroughly evaluate the UV equipment based on the PWS's specific goals. As appropriate, this information may include both economic (e.g., energy use, chemical use) and non-economic (e.g., future expansion, manufacturer experience) factors.
Lamp Sleeves	Lamp sleeves should be annealed to minimize internal stress.
Safeguards	At a minimum, the following UV reactor alarms should be specified: - Lamp or ballast failure - Low UV intensity or low validated UV dose (depending on dose-monitoring strategy used) - High temperature - Operating conditions outside of validated range - Wiper failure (as applicable) - Other alarms discussed in Section 4.3.3, as appropriate.
Instrumentation and Control	At a minimum the following signals and indications should be specified: - UV lamp status - UV reactor status - UV intensity - Lamp cleaning cycle and history - Accumulated run time for individual lamps or banks of lamps - Influent flow rate. At a minimum the following UV reactor controls (**as applicable**) should be specified: - UV dose setpoints, UV intensity setpoints, or UVT setpoints (depending on dose-monitoring strategy used) - UV lamps on/off - 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.

Table 4.3. Possible Content for UV Equipment Specifications (Table Spans Pages 4-20 – 4-22)

Item	Specification Content
Performance Guarantee	The equipment provided should meet the performance requirements stated in the specification for an identified period or during on-site performance testing (Section 6.1.5). The following specific performance criteria may be included: - Allowable head loss at each design flow rate - Estimated power consumption under the design operating conditions - Disinfection capacity of each reactor under the design water quality conditions - Sensitivity of equipment to variations in voltage or current - Reference UV sensor, duty UV sensor, and UVT analyzer (if provided) performance compared to specification
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 PWS and engineer. Significant variation from common commercial standards should be discussed with the manufacturer. Lamps should be warranted to provide the lamp intensity under the design conditions for the fouling/aging factor and a minimum number of operating hours. To limit the UV manufacturer's liability, the guarantee could be prorated after a specified number of operating hours.
UVT Analyzer	During operation, the difference between the UVT analyzer measurement and the UVT measured by a calibrated spectrophotometer should be less than or equal to 2 % UVT.

4.6.2 Information Provided by Manufacturer in UV Reactor Bid

The UV manufacturers should 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 4.4.

Table 4.4. Suggested Information to Be Provided by UV Manufacturer

Item	Description of Information
Design Parameters	Demonstration of an understanding of the design parameters for the UV equipment. All UV equipment design parameters from the contract documents should be repeated in the proposed UV equipment submittal information.
Summary of Design	A summary of the equipment proposed (number of UV reactors, lamp type) and specified equipment redundancies.
Reactor Technical Specifications	Ability of proposed UV reactors to meet technical specifications and an explanation of any exceptions taken.
UV Equipment Documentation and Specifications	Documentation that identifies and describes the UV equipment components that were validated, as described in Section 5.11.1.[1]
UV Manufacturer's Experience	Information on project experience, including previous facilities and references.
UV Lamps	Detailed description of the lamp dimensions and electrical requirements.

Table 4.4. Suggested Information to Be Provided by UV Manufacturer

Item	Description of Information
UV Sensor	Information on the UV sensor(s), including spectral response, acceptance angle, external dimensions, working range in mW/cm^2, measurement uncertainty, environmental requirements, linearity, and temperature stability. Data and calculations should be provided showing how the total measurement uncertainty of the UV sensor used during **validation** meets the criteria established in Section 5.5.4. Data that demonstrate duty UV sensors will meet the criteria described in Section 6.4.1.1 will be met during **operation**.
Lamp Sleeves	Calculations showing the maximum allowable pressure for the lamp sleeves and the maximum bending stress the lamp sleeves may experience under the maximum specified flow rate conditions.
UVT Analyzer (if applicable)	Data that prove the UVT analyzer used during validation meets the criterion in Section 6.4.1.2 during operation.
Validation Report	UV reactor validation should be provided that includes the elements described in Section 5.11.3. If on-site validation is proposed, validation data for the UV reactors from off-site validation (if completed) should be included to provide a baseline comparison to the proposed 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. If pre-validated equipment is specified, a description of the hydraulic configuration used during validation testing should be provided.
Power Requirements	The power needs of each UV reactor and which elements, including electrical cable and wiring, are included as part of the equipment.
Power Quality Tolerance	The power quality tolerance of the UV equipment for voltage sags, surges, and interruptions.
Cleaning Strategy	The strategy that will be used for cleaning the UV lamps in the UV reactor.
Dose-monitoring Strategy	The proposed UV reactor dose-monitoring 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 list 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, UV lamps, lamp sleeves, fouling/aging factor, and the system performance guarantee. Any exceptions should be indicated and explained.

[1] Key elements of this documentation are also listed in this table.

4.7 Final UV Facility Design

The UV reactors can be selected after all bids have been carefully reviewed. Once the UV reactors are selected, the designer can coordinate with the selected UV manufacturer to develop the final facility design based on the selected UV equipment. The hydraulic design, I&C design, electrical design, and facility layout should be modified based on the selected UV equipment.

Particular emphasis should be given to the integration of the overall dose-monitoring strategy with the alarms, signals, and interlocks that are integral to the UV reactor design. That the final design be coordinated with the validation testing results is critical. The validation results must be sufficient to implement the proposed operations approach and should meet the water supply's disinfection objectives under the specified operating conditions.

4.8 Reporting to the State during Design

Interaction with the state throughout the design phases is recommended and increases the likelihood that the objectives of both the PWS and the state are met. Currently many states have limited experience in the use of this technology; therefore, the appropriate level of state involvement during design should be greater than that for more traditional designs. Early agreement on the specific objectives and requirements of the project can significantly reduce the potential for conflict or costly design changes later in the project. The level of state involvement during design, as well as the specific submittal requirements, will vary by state and may vary by project. PWSs are urged to consult with their state early in their UV disinfection design process to understand what approvals and documentation will be required.