DESIGN OF UV DISINFECTION SYSTEMS FOR DRINKING WATER

In EPA's economic analyses for the proposed LT2ESWTR, EPA estimated that 500 to 1000 filtration plants will choose UV disinfection as part of their treatment process (USEPA, 2003). EPA also assumed that 100% of small unfiltered systems will adopt UV disinfection, and that for most systems, UV disinfection will be part of the least cost method for achieving *Cryptosporidium* inactivation requirements. It is important to remember that UV disinfection is just one component of a system of multiple barriers to achieve good disinfection and that chlorine or chloramines are still needed in most systems to maintain a residual in the distribution system.

UV disinfection will not be used solely by systems to meet the requirements of LT2ESWTR. According to Malley et al. (2002), many water systems, including small systems using ground water not under the influence of surface water, will decide that UV disinfection is an attractive alternative. Examples of such systems include:

- systems where no residual is required for the distribution system,
- a small number of systems where achieving an adequate CT with chlorine would be too costly, but chlorine or chloramines could be used to provide a residual in the distribution system; this includes systems with wells in multiple locations,
- systems with current or potential problems with DBPs either because of chlorination or ozonation by-products; such systems could use UV disinfection as the primary disinfectant and chloramines for residual in distribution system.

The design information below is taken mostly from the USEPA's draft *Ultraviolet Disinfection Guidance Manual* (USEPA, 2003), which was developed in order to help overcome the lack of design experience in the U.S. Results from Cotton et al. (2001) are also used herein as well as *Ultraviolet Disinfection: Guidelines for Drinking Water and Water Reuse* (NWRI 2003). Both of these sources are generally consistent with EPA's draft *Ultraviolet Disinfection Guidance Manual* except where noted.

Steps in the design process. The draft *Ultraviolet Disinfection Guidance Manual* (USEPA, 2003) recommends the following steps in the design:

Planning:

- define the goals of the UV disinfection installation and identify the target microorganism(s), which should then be discussed with the primacy agency,
- determine design parameters (water quality, flowrate, power quality),
- evaluate potential UV disinfection equipment,
- evaluate equipment validation options (Note: the timing of UV reactor validation testing depends on whether it has been validated off-site or if on-site validation is necessary.),
- evaluate operational and control strategies,
- identify alternative UV facility locations by evaluating hydraulic constraints and requirements, footprint, and existing infrastructure,
- compare options and costs and select UV facility location,

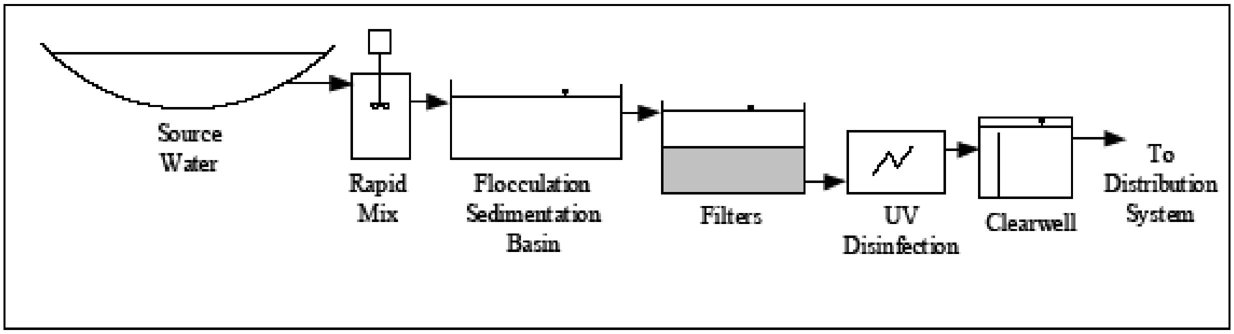
- report planning results to primacy agency,
- evaluate and select procurement options,

Design
- design system hydraulics,
- determine operating and control strategy,
- design instrumentation and controls,
- design electric power systems,
- complete facility layout,
- develop plans and specifications, i.e., a procurement document and procure equipment,
- finalize designs of
  - hydraulic systems,
  - design layout,
  - power, instrumentation and controls, and electrical,
- develop final UV facility drawings and specifications based on specific equipment procured,
- report to the primacy agency.

UV reactor location. The design approach discussed herein assumes that the UV reactors will be located after filtration. A post-filter location has the advantages of 1) probable lower UV light absorption compared to upstream and 2) less potential shielding of microorganisms by particulates and flocs. Indeed, the LT2ESWTR has only developed criteria for a post-filter location.

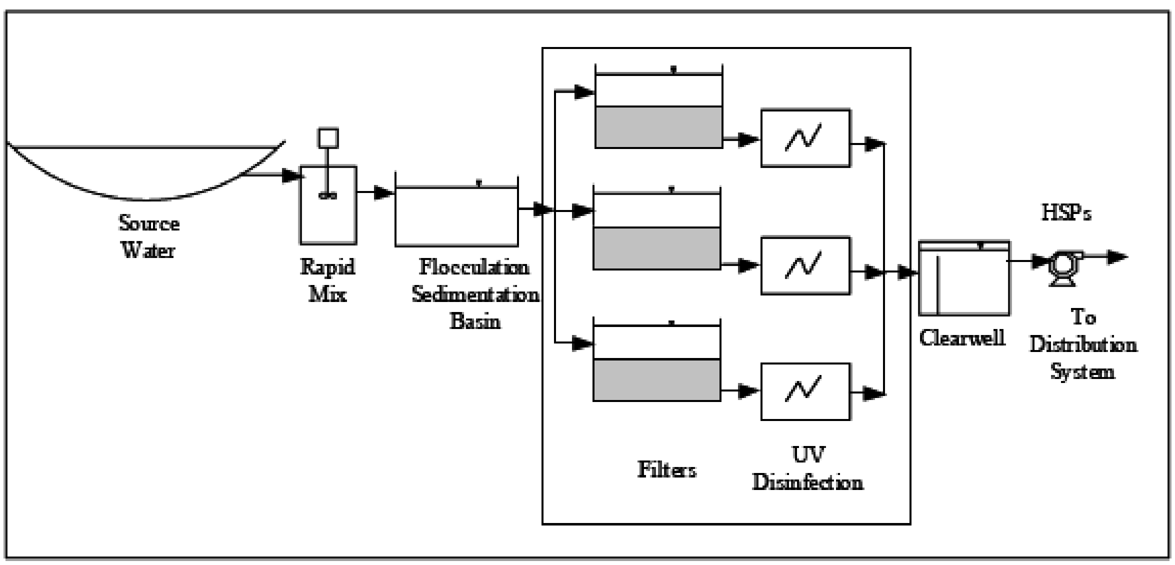
Importantly, the UV reactors' location must have adequate space and hydraulic capacity. Head losses in UV reactors are about 0.5-3 ft for the reactor itself and about 1-8 once the associated piping, valves, flow meters, and flow distributors are included. If the headloss is insufficient for a retrofit, the water plant and engineer can consider modifying the clearwell operation, e.g., lowering the water level, replacing pipes and valves, modifying the filter operation, installing booster pumps, or choosing a UV reactor with less headloss. Any modification in operation needs to consider the potential impacts on other aspects of the treatment plant, e.g., the volume needed in the clearwell, the suction head needed for any pumps taking suction from the clearwell, CT disinfection impacts if any, and possible shorter filter run times.

There are two general configurations for installing the UV reactors between the filters and clearwell, 1) a combined filter effluent and 2) an individual filter arrangement. The figure below shows a typical process diagram for a conventional treatment plant with UV disinfection between the filters and clearwell. The intent of the figure is that the effluent from all the filters enters a common distribution header for all the UV reactors. The advantages of this type of installation include independence of operation of each filter which gives more operation flexibility and avoidance of flow surges and high pressure that may occur downstream of high service pumps. A disadvantage is that existing hydraulic capacity may be insufficient.



Schematic of UV disinfection installation upstream of a clearwell (USEPA, 2003).

An individual filter effluent piping installation in which a UV reactor is installed on the effluent of each filter, usually in existing filter gallery, is shown in the figure below. It has the advantages that no new building or room is needed, but the disadvantages are that 1) there probably will not be enough room in filter gallery for reactors and ancillary equipment, 2) the filter gallery conditions may not be conducive for the electrical equipment, 3) the design options for the inlet and outlet piping may be limited and thus necessitate specialized validation for the specific water treatment plant, 4) the combined filter and UV reactor operation is less flexible and more complex, 5) more UV reactors are generally needed for this type of installation compared to a combined filter installation, and 6) the needed lamp cooling may complicate operation during and after backwash since if a lamp shuts down, then a warm up period is needed before going back on-line.



Schematic of individual filter piping installation in the filter gallery (USEPA, 2003).

The UV reactors can also be located downstream from the clearwell, most likely after the high service pumps. Location after the high service pumps is the least desirable option because 1) the high pressure may necessitate more UV reactors design, 2) the greater flow variation from the pumps may necessitate more UV reactors, 3) water hammer may break the lamp sleeves and possibly the lamps themselves, and 4) there may be some loss of system-wide pressure due to the UV reactor headloss.

Design flow rate. For retrofits, the design flow for a UV reactor on a single filter is just the rated capacity of filter. For a combined filter effluent or post high service pumps installation, the design flow rate will be the capacity of all the filters or pump station. Of course, future capacity expansions should be considered.

Since with a combined effluent type of installation, exactly equal distribution between UV reactors may not always occur, the maximum design flow rate should account for potential flow imbalances according to the following equation:

$$Q_{reactor} = \frac{Q_{total} \cdot (1 + E)}{N}$$

where:

$Q_{reactor}$ = UV reactor design flow
Q_{total} = Plant maximum design flow
E = Calculated maximum flow distribution error (percentage as a decimal, e.g., if the split were actually 60/40 rather than 50/50 between two reactors, then E is (60-50)/50 = 0.2)
N = Number of on-line UV reactors

As far as redundancy, *Ultraviolet Disinfection: Guidelines for Drinking Water and Water Reuse* states that standby equipment should a minimum equivalent of 20% of the UV disinfection equipment required for disinfection at peak flows which was also assumed by Cotton et al. (2001) or at least two reactors. The draft *Ultraviolet Disinfection Guidance Manual* indicates one redundant reactor for combined effluent operation and consulting state requirements and treatment objectives for others.

Water quality. In considering water quality issues, it is again assumed that the UV reactors are installed after filtration and that the water has low turbidity. Several water quality considerations include:

! If the intent of installing UV disinfection is to allow a lower chemical pre-disinfectant dosage, then the effect of the lower chemical dosage on water quality at the UV reactor needs to be considered.

! The utility should determine the UV light absorbance characteristics of the water applied to the UV reactor at the 254 nm wavelength, i.e., A_{254}. The manufacturer will use the A_{254} in choosing an appropriate reactor. Absorbance characteristics should be determined over long time periods for waters with variable quality and even a cumulative frequency diagram would be valuable for deteremining the appropriate design A_{254}. Absorbance over the complete interval of 200-400 nm is useful for MP lamps. The reader is referred to the draft *EPA Ultraviolet Guidance Manual* (2003) for further details.

- In order to assess the potential for fouling of lamp sleeves and sensors, the utility should know the pH, hardness, alkalinity, and iron and manganese of the water entering UV reactors. According to Mackey et al. and Mackey and Cushing as reported in the draft *EPA Ultraviolet Guidance Manual* (2003), standard cleaning protocols and wiper frequencies (one sweep every 15 min.) are adequate for total calcium and hardness less than 140 mg/L and iron less than 0.1 mg/L at sites tested.

Cushing et al. (2001) studied the impact of common treatment chemicals on UV disinfection. They concluded:

- greater removal of absorbing substances increased the UV light transmittance,
- ammonia, ammonium ion, calcium ion, ferrous iron ion, hydrogen peroxide, hydrogen ion, hypochlorite ion, magnesium ion, manganese ion, permanganate ion, phosphate species, sulfate ion, sulfite ion, and zinc ion had insignificant effects on transmittance in water plants
- ozone and ferric iron could significantly reduce transmittance
  - ozone should only be an issue in situations where the ozone does not have a chance to dissipate or is not quenched prior to the UV reactor
  - if ferrous iron is present such as in some groundwater systems, ferrous oxidation should be inhibited.

Jesky et al. (2001) studied the effect of other substances on UV disinfection and concluded:

- citing a 1999 USEPA report, pH, temperature, alkalinity, and total inorganic carbon should not impact UV disinfection unless fouling of the lamp sleeves occur,
- dissolved inorganic compounds have little influence on UV transmittance although hypochlorite and chloramines show higher absorbance,
- suspended solids have a significant but not overwhelming effect,
- humic acids, phenolic compounds, lignin sulfonates, copper, iron, and compounds that color water tend to absorb UV light and decrease transmission and pretreatment may be necessary to reduce these

Lamp aging. Lamp aging and sleeve fouling will reduce the UV intensity delivered by the lamp over time. These effects are considered in design by choosing, based on experience and manufacturer's information, a site specific lamp 'fouling/aging' factor which ranges from 0.5 to 0.9. For example, a factor of 0.5 means that the needed UV dose can be achieved at ½ of the initial lamp output after 'burn-in' so that the lamp has significant excess UV output in order to account for aging. The aging factor is usually tied to a guaranteed lamp life and involves a balance between operating and capital costs. A lower factor means less frequent bulb replacement but a larger reactor.

Hydraulics and flow measurement. The inlet and outlet for the UV reactor should meet the validation conditions as specified in the table below. The table below show several options for insuring the installed reactor meets validation conditions. Note that turbulent flow conditions are desired.

Summary of recommended hydraulic configurations for validation and installation (USEPA, 2003)

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

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

The flow in each reactor must be known in order to be certain that each reactor meets validation conditions. The state could require a flow meter on each reactor or could allow one flow meter with flow splitting such that flow to each reactor known. Providing individual flow meters and control valves to adjust flows gives the greatest control.

Magnetic flow meters, doppler or other meters that don't protrude into the flow are best in order to minimize the effect on the validated inlet and outlet hydraulics. The reader is referred to the draft

Ultraviolet Disinfection Guidance Manual for the advantages and disadvantages of various metering and flow control options.

The UV reactor installation needs water level control in order to insure that the UV reactors are filled with water when operating. Possible level controls include a weir at a set elevation or other hydraulic control valves.

Miscellaneous valving and appurtenances include:

- Air release valves or similar devices may be needed to prevent air accumulating in UV reactors.
- Valving is needed to isolate each UV reactor for servicing
- If isolation valves are used to control flow, the preference is to use the downstream valve in order to minimize disruption of flow entering reactor.
- Provision must be made to discharge to waste water that flows through a UV reactor during its start-up.
- Sample taps are recommended upstream and downstream of the reactor.

Operating off-specification. As far as is feasible, monitoring and control systems should prevent water from entering distribution system if UV reactor is operating outside of validated conditions, i.e., off-specification. The proposed LT2ESWTR requires that no more than 5% of the water delivered can be off-specification for unfiltered systems. There currently are no off-specification requirements in the proposed LT2ESWTR for filtered or groundwater systems.

Electric power. The power supply should be reliable for stable UV lamp operation. For example, a 0.03 to 0.08 sec drop in voltage of 10-15% may cause the lamps to lose arc. LP lamps can return to full output within 15 seconds but LPHO and MP lamps can take from 4 to 10 minutes or longer depending on conditions (Cotton et al. 2002). The concern is not to violate the off-specification requirements of the LT2ESWTR. The water treatment plant may wish to consider a backup generator or a second independent power source, but these would be unlikely to help short term transients. The plant may also consider installing an uninterruptible power source (UPS), which can handle short term transients and outages less than a couple of minutes, depending on battery size.

There are many other electrical needs and issues to consider but the focus of this module is the UV disinfection treatment aspects. The reader is referred to the draft *Ultraviolet Disinfection Guidance Manual* (USEPA, 2003) for further discussion of such issues as power requirements, backup power supply, ground fault interrupt and electrical lockout.

Typical characteristics of different equipment. The engineer and utility will need to make many decisions on equipment. Some typical equipment characteristics are listed below:

- LPHO and MP lamps are the typical lamps for municipal drinking water,
- LPHO and MP reactors are typically in-line, i.e., like a pipe,
- LPHO reactors usually have a larger footprint than MP because more UV lamps are needed

for the same dose as MP reactors; MP reactor footprints also vary depending on lamp orientation, e.g., horizontal and parallel vs horizontal and perpendicular,

- The warranteed lamp life for LPHO lamps ranges from 8,000-12,000 hrs and for MP 4,000-8,000 hrs; it should be remembered that LPHO have less output per lamp than MP so the number of lamp replacements per time period may actually be greater for LPHO and the costs for labor for lamp replacement need to be considered in any cost analyses,
- MP lamps are typically less power efficient than LPHO so power costs may be higher for MP,
- LPHO reactors may have to be taken off line to clean since they may not have mechanical cleaning due to the larger number of lamps compared to MP,
- Type of ballasts:
  - Transformers are often more stable than electronic or electromagnetic ballast and allow greater distance between the UV reactor and control panel, but most allow only step adjustments to lamp intensity,
  - Electronic ballasts allow nearly continuous adjustment of lamp intensity but may increase lamp aging and spectral shift,
  - The manufacturer should be consulted regarding cooling needs, separation distances between reactor and control panel, and intensity adjustment.

Alarms. Several types of alarms may be installed depending on the facility including alarms for lamp age, calibrate UV intensity sensor, low UV dose, low UV intensity, low UV light transmittance, high/low flow, lamp ballast failure, low liquid level, high temperature, and mechanical wiper function failure.

Specifications and warranties. Typical aspects of UV reactor specifications are given in the table below. There should be a warranty for the lamp output for a minimum number of hours (perhaps with the manufacturer's liability prorated depending on the hours of use).

Recommended content for UV reactor specifications (USEPA, 2003)

Specification Item	Purpose/Description
Flowrate	Maximum, minimum, and average flowrates should be clearly identified. The minimum and maximum flowrates must be within the range of validation flowrates. The minimum flowrate is important to avoid overheating with MP reactors.
UV Dose	The required reduction equivalent dose as well as the validation technique that will be used to measure the dose should be established
Water Quality and Environment	The following water quality criteria should be included: influent temperature, turbidity total hardness, pH, iron, UV transmittance at 254 nm, lamp aging/fouling factor, spectral absorbance 200-300 nm (MP reactors only). For some parameters, a design range may be most appropriate.

UV Intensity Sensors	It is recommended that at least one UV intensity sensor be specified per UV reactor. The number of reference sensors should be determined based on the time and labor associated with checking and maintaining the duty sensors.
Redundancy	If combined filter effluent UV reactors are used, it is recommended that at least one completely redundant UV reactor be specified as a standby. For other configurations, the designer should determine the appropriate redundancy based on the State's requirements and the utility's disinfection objectives.
Hydraulics	The following hydraulic information should be specified: - Maximum system pressure at the UV reactor - Maximum allowable headloss through the UV reactor - Special surge conditions that may be experienced - Hydraulic constraints based on site-specific conditions and validated conditions (e.g., upstream and downstream straight pipe lengths)
Size/Location Constraints	Any size constraints or restrictions on the location of the UV reactor or control panels (e.g., space constraints with in-line installation).
Validation	The specifications should establish the validation protocol that will be followed, provide the conditions under which the validation will be conducted (e.g., water quality, flow range, hydraulic conditions, UVT), and require the submittal of a validation report (40 CFR 141.730).
Control Strategy and Operating Sequence	The specification should provide a narrative description of the operating sequence and control strategy for the UV reactors.
Lamp Sleeves	At a minimum, the following items should be specified: - Lamp sleeves should be annealed to remove internal stress. - UV equipment manufacturer should perform QA / QC checks of a fraction of each lot using a polarized light or other approved method. - UV equipment manufacturer should submit documentation on the integrity of their sleeve, monitoring practices, and rationale for using a given internal QA / QC frequency. - UV eqiupment manufacturer should submit calculations showing the maximum allowable pressure for the lamp sleeves and the maximum bending stress experienced by the lamp sleeves under the maximum specified flow conditions.
Safeguards	At a minimum, the following UV reactor alarms should be specified: - Lamp or ballast failure - Low UV intensity or low UV dose (dependent on control strategy used) - High temperature - Low or high flow - Wiper failure (as applicable) - Other alarms discussed in 3.3.3.8 of the *UV Guidance Manual*, as appropriate

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