
Balancing Cost-Effectiveness and Conservatism in UV Disinfection Design

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INTRODUCTION

It has been 15 years since the first designs of UV disinfection systems for *Cryptosporidium* inactivation credit commenced in the United States. Those first projects were designed with significant conservatism as they predated the development of United States Environmental Protection Agency's (USEPA's) Ultraviolet Disinfection Guidance Manual (UVDGM, 2006) and were designed to provide flexibility as the regulations were developed and promulgated. The early UV disinfection projects often included design based on an MS2 reduction equivalent dose (RED) of 40 mJ/cm², a target level of inactivation of at least 2.5 log *Cryptosporidium*, room within the UV reactors for additional rows of lamps or more lamps, electrical capacity for more lamps or more reactors, and additional building space for adding reactor trains.

Today, with UV disinfection entrenched across North America, many UV design projects have followed the UVDGM framework, with validation testing that minimizes the Validation Factor, UV equipment selected based on an in-depth analysis of operations and maintenance cost, and in some cases, design based on the target level of inactivation only (e.g., 1-log *Giardia* inactivation). These approaches may result in reduced conservatism compared to the first UV designs completed in North America. While incremental cost capital and operational cost savings can be achieved in some cases, it may be accompanied by a reduced level of disinfection and less resiliency for risks. This article discusses sources of conservatism in UV systems and methods to achieve balance between a cost-effective system and a conservative design.

CONSERVATISM IN UV DESIGN AND OPERATION

The US EPA's UVDGM (2006) incorporates many sources of conservatism in its recommended UV reactor validation and UV design approaches. In addition, engineers, operators and regulators typically add additional layers of conservatism. Examples of conservatism incorporated into UV systems include:

- Applying UV disinfection as a multi-barrier treatment process when it is not required to comply with Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) (USEPA, 2006).
- Using the UV dose table provided in the LT2ESWTR to establish the required UV dose. For example, more recent analysis of the *Cryptosporidium* data used to develop the UV dose table in the UVDGM (2006) suggest required UV dose of 3 to 6 mJ/cm² for 3-log *Cryptosporidium* inactivation instead of the 12 mJ/cm² required (Qian, 2005).
- Validating UV reactor performance using a hydraulic configuration that is worse than the actual installation at the water treatment plant (e.g., installing a 90 degree elbow on the UV reactor inlet flange).
- Designing UV systems for simultaneous worst-case flow, UVT, lamp age, and fouling conditions.
- Placing the lowest output/oldest low-pressure, high-output lamp adjacent to the UV intensity sensor.
- Operating the UV system with a UV dose safety factor.

On one hand, an overly conservative design can waste energy due to overdosing. Optimizing the UV system during design can be attractive to limit capital and operating costs. On the other hand, having additional conservatism in the system can provide a buffer against unplanned water quality degradation (e.g., a drop in UVT), rapid quartz sleeve fouling, a higher than anticipated action spectrum correction factor, and greater inactivation targets in the future (e.g., an increase in LT2ESWTR Bin classification). Recent developments, which require calculating the action spectrum correction factor for medium pressure UV systems, represent a good example of how unforeseen conditions can adversely impact UV disinfection conservatism and operating approaches. Implementing additional UV disinfection capacity after the system is already installed is much more difficult and expensive than providing the added level of conservatism during the initial installation. As discussed in this article, providing additional conservatism can still be economical.

Impact of UV Transmittance (UVT)

System size and cost depend heavily on UVT. Selecting a design UVT value requires careful consideration as it can have significant cost impacts. For example, Figure 1 shows estimated capital and operating costs for a 60 MGD UV disinfection facility achieving 2.5-log *Cryptosporidium* inactivation. The estimated capital cost for 80% UVT is about \$10M, compared to \$8.4M for 95% UVT. Operating costs are impacted even more by UVT. The estimated operating costs at 80% UVT, are approximately 6 times greater than the operating costs at 95% UVT. It should be noted that capital and operating costs can vary widely due to site specific conditions. The operating costs in this example are based on medium pressure lamps and include energy costs, lamp replacements, sleeve replacements, ballast replacements, intensity sensor replacements, and intensity sensor recalibration, but excludes labor.

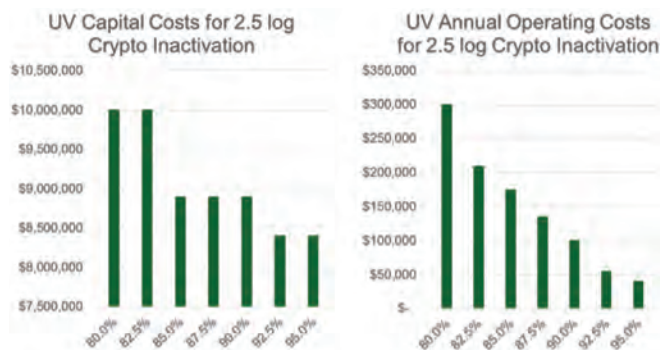


Figure 1. Estimated Capital and Operating Costs for 2.5 log *Cryptosporidium* Inactivation for 60-MGD Medium-Pressure UV Facility

By looking at the water treatment plant as an integrated system, design and operation of the UV system can be enhanced. For systems with low UVT, optimization of upstream water treatment processes for organics removal (e.g., enhanced coagulation, enhanced softening, biological filtration) may be desirable to improve UVT and reduce capital and/or operating costs.

Level of Inactivation

System size and cost also depend on the target level of inactivation selected as the basis of design. The level of inactivation may be driven by regulatory requirements or by the level of conservatism desired by the utility. Figure 2 shows the estimated capital costs for 1-log and 2.5-log *Cryptosporidium* inactivation for 20 MGD, 100 MGD, and 150 MGD facilities with 90% UVT. The capital cost increase to achieve 2.5-log *Cryptosporidium* inactivation instead of 1-log inactivation is about \$210,000 (8%), \$430,000 (6%), and \$2,500,000 (19%), respectively. For smaller systems, the capital cost impact tends to be minimized when log-inactivation is increased since modifying reactor size or number of lamps may be able to be accomplished in lieu of adding additional UV reactors.

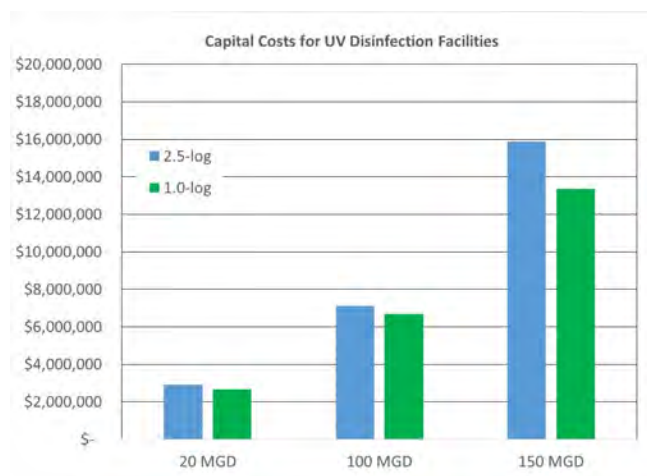


Figure 2. Estimated Capital and Operating Costs for 2.5-log *Cryptosporidium* Inactivation

Although these results will vary based on site specifics, the cost increase associated with higher log inactivation levels is on par with other facility design decisions with cost impacts. For example, decreasing the header pipe sizing, building area, or building materials of construction could save more than \$1 million for a 100 mgd facility. Overall project costs could be even less if UV can be retrofit into an existing facility.

Validation Test Challenge Organism

In addition to the target level of log inactivation, the validation testing challenge organism (e.g., MS2, T1, T7) also impacts UV capital and operating costs. MS2 phage has been the most commonly used challenge organism for UV reactor sizing, but alternatives like T1 phage have recently become more prevalent. The challenge organism used on a project should be discussed with the primary regulatory agency and UV system manufacturer during the design phase as there may be limitations on which organism can be used.

Figure 3 compares the estimated operating costs for three scenarios: MS2 RED of 40 mJ/cm², MS2 RED based on UVDGM guidance, and T1 RED based on UVDGM guidance. Both medium pressure and low-pressure, high-output reactor costs are shown. Operating costs are based on an example UV facility with an average flow of 45 mgd, 93% UVT, and 2.5-log *Cryptosporidium* inactivation and includes energy and lamp, sleeve, intensity sensor, and ballast replacement. In this example, operating the system based on an MS2 RED per UVDGM guidelines reduces operating costs by about 50% compared to using an MS2 RED of 40 mJ/cm². Utilizing T1 RED reduces operating costs by another 20%. In this example, utilizing low-pressure, high-output lamps further reduced operating costs compared to medium-pressure lamps, excluding labor, due to the specific assumptions on unit power cost and the exclusion of labor from the estimates.

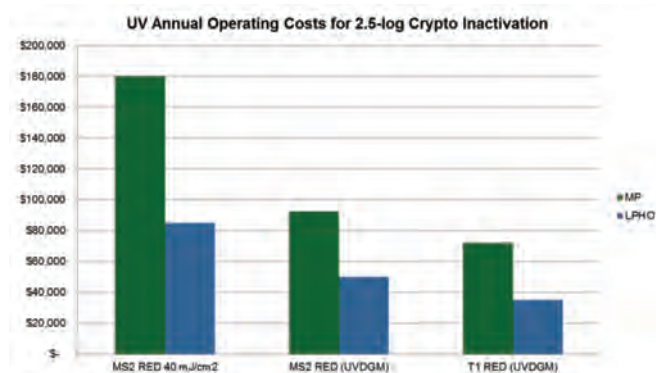


Figure 3. Example annual operating costs for 45 mgd facility with 93% UVT, and 2.5-log *Cryptosporidium* inactivation and \$0.14/kWh electrical cost.

Case Study Example

The Syracuse Water Department (SWD) is an unfiltered system with an open finished water reservoir and therefore was required to modify their treatment approach to comply with LT2ESWTR. The SWD chose to provide UV disinfection at both Woodland and Westcott Reservoirs to comply. Figure 4 shows a

photograph of one of the UV installations. To minimize the cost impacts, SWD negotiated with the State of New York Department of Health (DOH) to allow the use of T1 phage as the basis of the operating UV dose. To our knowledge, this was the first acceptance of a UV dose less than 40 mJ/cm² in the State of New York by the DOH and will save SWD an estimated \$40,000 per year in electrical costs.



Figure 4. Photograph of the low-pressure, high-output UV reactors at a SWD UV disinfection facility.

The UV system was still designed to accommodate an MS2 RED of 40 mJ/cm². Therefore, obtaining a high range of UV dose turndown was important to take advantage of the T1 phage operating dose. Through a preselection process, low-pressure, high-output UV reactors by Xylem, Inc. were selected for installation at the 3 UV disinfection facilities. The greater power turndown and lower power draw associated with the low-pressure, high-output UV reactor proved beneficial for SWD given the high local electrical cost of \$0.14/kWh. The large turndown potential of the low-pressure, high-output UV reactor was able to be leveraged to minimize the total power consumption of the UV reactor, saving the City of Syracuse approximately \$150,000 per year in energy costs compared to medium pressure reactors. The City of Syracuse also had a City-wide initiative to incorporate “green” design concepts into new SWD facilities. For the new UV system and associated finished water reservoir, a hydro turbine and solar panels were installed at one of the sites. The combined energy production is returned to the local electrical utility for credit, which will offset some of the additional operating costs of the UV system for years to come.

CONCLUSION

USEPA's UVDGM provides a solid basis for public health protection and should continue to serve as the "go-to" reference for UV system design. Attempting to achieve the minimum capital cost UV approach may not be the best long-term decision, as it may limit flexibility to achieve higher levels of disinfection or protect against unforeseen conditions. Instead, focusing on ways to minimize capital and operating cost while maintaining adequate conservatism in the overall system design is recommended. In the author's opinion, the design level of inactivation is not the first place to skimp to save cost. For example, the incremental cost to provide 2.5-log vs. 1.0-log inactivation is commonly small compared to the overall cost to implement UV. Also, retrofitting a UV system into an existing facility could save significant capital costs that far outweigh the cost for higher disinfection levels.

Recommended considerations for new UV systems include:

- Design for higher level of pathogen inactivation for capital sizing, while considering operating at a lower level of inactivation to meet current disinfection targets
- Evaluate full project cost impacts for the UV system facility and identify ways to reduce costs without negatively impacting UV design conservatism
- Provide space within reactors to add lamps or rows of lamps, space for an additional reactor, and/or additional electrical capacity to accommodate future expansion
- Provide a range of validated conditions that is wider than anticipated conditions to account for decreases in UVT or increases in flow
- Include a well-designed flow split or flow control to prevent non-optimized operating conditions
- Evaluate UV reactor turn-down capabilities to avoid over-dosing during low flow or high UVT conditions

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