Wastewater UV Disinfection Systems–Lessons Learned During Performance Testing

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ABSTRACT

As many new ultraviolet (UV) systems are being designed and constructed for disinfection of secondary wastewater effluent, it is important to confirm both the design and the systems' ability to meet the discharge permit requirements through performance testing. Performance testing is recommended for all wastewater UV disinfection system projects and should include evaluation of the UV system under "worst-case" conditions. Additionally, it is important to confirm the actual headloss through the reactors and verify the power consumption to confirm that the system can meet the required design specifications. This case study presents the test protocols and the results of the testing.

Keywords: Ultraviolet disinfection; UV; wastewater disinfection; total suspended solids; performance testing

INTRODUCTION

With increasing risk management requirements and the desire to avoid multiple chemical feed systems (e.g., chlorination/dechlorination), many municipalities are looking to utilize ultraviolet (UV) disinfection systems at wastewater treatment facilities (WWTFs) as an alternative to conventional chlorine systems. In many instances, UV disinfection has a lower cost of operation than chlorine-based systems, if the system size, design and operations are optimized. One of the most important factors in implementing an efficient wastewater UV disinfection system is addressing the upstream processes with respect to the key parameters, UV transmittance (UVT) and total suspended solids (TSS). Even with the best operating conditions, WWTFs that do not have tertiary filtration implemented as part of the treatment train can experience periodic upsets that may result in effluent TSS concentrations that approach permit limits of up to 30 milligrams per liter (mg/L) or more.

As part of the selection and sizing of a UV disinfection system for a WWTF, it is important to conduct a rigorous evaluation of treated effluent quality. While it is not always possible to collect water quality samples if the WWTF is new construction, it is usually feasible to collect information from a similar facility within the same region that would produce a similar effluent quality. In either case, there is no certain method for predicting the exact characteristics of treated wastewater. However, the use of third-party validated bioassays, in conjunction with good estimates of treated wastewater quality, results in a system properly selected and sized to deliver the appropriate dose for a given facility. In addition to careful equipment selection and sizing, performance testing should be required for every installed UV disinfection system. Often, because performance testing is conducted at the facility near the beginning of its design life, the worst-case, specified conditions are not always tested. These test conditions should include the maximum design flows at the lowest specified UV transmittance and highest specified TSS concentrations. Testing should also be conducted to confirm system headloss and power consumption at these conditions.

This paper presents a case study of UV disinfection system performance tests that were conducted for a recently constructed wastewater UV disinfection system in Colorado Springs, Colorado at Colorado Springs Utilities' Las Vegas Street Wastewater Treatment Facility (LVSWWTF). The UV system, as shown in Figure 1, was designed to meet a peak hour flow of 135 million gallons per day (mgd). The LVSWWTF has a permitted capacity of 65 to 75 mgd depending on the time of year. Currently the plant has an average daily flow of approximately 35 mgd. During design, third-party validated bioassays were used in selecting and sizing the equipment. As a requirement of the project, performance testing was specified to confirm that the UV disinfection system is capable of meeting the final effluent *Escherichia coli* (*E. coli*) design value of 65 cfu/100mL under the specified worst-case conditions (i.e., peak flow, minimum UV dose, the lowest UV transmittance, and the highest suspended solids concentrations). Additionally, system power consumption was measured under these conditions to demonstrate that the system does not exceed the system peak power consumption specified. The specified headloss was also confirmed for each channel.

Figure 1. 135 mgd UV Disinfection Facility

TESTING PROTOCOLS

Performance Testing Protocol

The vertical UV system consists of three channels with the hydraulic and treatment capacity designed for up to 45 mgd. The UV system was designed around a minimum UV dose of 30 mJ/cm2 (based on an MS-2 bioassay) and a minimum UVT of 65 percent. In order to conduct performance testing near the peak flow, the testing protocol required routing the entire plant secondary effluent flow in to the UV influent channel. Due to the fact that the system was designed to meet future flows, there were limitations with respect to testing peak flows, thus testing was performed with available plant flows below the UV system capacity with each channel being tested independently. Each channel was tested for 48 hours resulting in a six-day test duration. Flows to the UV system peaked at approximately 37.5 mgd during the performance testing, which is approximately 83 percent of each channel's capacity.

During performance testing, the UV system was operated automatically, using a flow-paced control strategy, which turns the lamps on and off and controls the lamp output based on the measured flow in the downstream Parshall flume. Approximately every two hours, influent and effluent samples were collected concurrently from the channel in operation. Five sets of grab samples (a set of grab samples is defined as one influent and one effluent sample) were collected daily between 7:00 a.m. and 4:00 p.m. so that the lab could perform the required tests. All samples were collected and preserved in accordance with the *Standard Methods for Examination of Water and Wastewater (20th edition)* and tested at Colorado Springs Utilities' laboratory. The influent samples were collected 3 feet upstream of the first UV bank of modules and represented undisinfected secondary effluent. The effluent samples were collected 3 feet downstream of the last UV bank and represented disinfected wastewater. The first influent sample collected on each day of testing was analyzed for the following parameters:

- BOD_5
- Conductivity
- Calcium hardness
- Total iron
- Turbidity

Online instruments were used to record TSS, UVT, pH, temperature and particle size distribution during testing; all grab samples were analyzed for *E. coli* using the quanti-tray test method. During performance testing, the flow, number of lamps "ON," UV intensity and operational UV dose were recorded. Any alarm condition (e.g. lamp failure, low UV intensity, etc.) was logged and addressed immediately during testing.

The parameters monitored were used to characterize the secondary effluent quality and to aid in troubleshooting the UV system performance in the event that the system was not producing effluent that met the design effluent *E. coli* value. For example, the particle size distribution test was performed because particles larger than 20 microns are known to have a significant effect on decreasing UV irradiation by shielding the bacteria when compared to smaller particles (Qualls et al., 1983 and 1985).

TSS Test

As part of the performance testing, a high TSS concentration secondary effluent was artificially produced to determine whether the UV system could meet the design disinfection target. The TSS concentration in treated wastewater effluent is a key factor in UV system performance because it can have two major effects on UV disinfection. First, an increase in TSS may cause a decrease in the disinfection rate, especially at lower UV doses (Janex et al., 1998; Whitby and Palmateer, 1993). Second, it may also cause tailing of the dose-response curve (Nieuwstad and Havelaar, 1993). Even though this tailing effect does not appear until low concentrations of the target bacteria species are reached, it is often considered the primary limiting factor to reaching regulatory standards (Qualls et al., 1983). Many studies have confirmed that disinfection rate reductions are attributable to solids in treated wastewater effluent by showing an increase in UV disinfection performance with filtration (Darby et al., 1993; Johnson and Qualls, 1984; Jolis et al., 2001; Lazarova et al., 1998). However, in the U.S., it is a common practice to implement UV disinfection following secondary treatment without tertiary filtration (Bell, et al., 2011).

Currently at the LVSWWTF, UV disinfection is directly downstream of the secondary clarifiers with no tertiary filtration between the two processes. The plant has a 30-day average effluent limit for TSS of 30 mg/L. During the test period, the plant was producing an effluent with TSS concentrations between 2 and 4 mg/L. To simulate worst-case conditions, the secondary effluent needed to be spiked with solids to achieve a TSS concentration of approximately 30 mg/L. For this project, it took several attempts to get the TSS concentration up near 30 mg/L. First, mixed liquor suspended solids (MLSS) was pumped from the center-well of the secondary clarifiers to the clarifier troughs. This did not produce high TSS concentrations at the UV system because of a long residence time in the pipeline between the clarifiers and the UV channels.

Ultimately, the TSS test protocol used two vacuum trucks that collected MLSS from the aeration basins. The trucks delivered the solids to the UV influent channel, where they were pumped into the channel and mixed to produce a concentration of approximately 30 mg/L, as shown in Figure 2. Because the vacuum truck delivery capacity was limited, tests were run for a brief period; however, an adequate number of bacterial samples and other water quality data were collected during the test period to evaluate system performance under this “worst-case” scenario.

Figure 2. High TSS Secondary Effluent during Performance Testing

Headloss Test Protocol

To evaluate the conformance of the UV system headloss with specifications, a headloss test was conducted by HydroQual as part of a third-party verification of the system. During headloss testing, secondary effluent flows were routed to a single UV channel to ensure the headloss between the up- and downstream banks was less than the specified value of 9.55 inches. Flow through the UV channel was measured using the downstream Parshall flume. The Parshall flume is equipped with a calibrated ultrasonic transducer that measures the water depth and calculated the flow automatically. Flow was continuously recorded and synchronized with the water level readings in the channels. The headloss was measured in each channel by measuring the channel depths at locations up- and downstream of the installed UV modules. In order to achieve flows near the channel hydraulic capacity of 45 mgd, flow was diverted around Colorado Springs Utilities’ other treatment facility, J.D. Phillips Water Reclamation Facility, to the LVSWWTF.

Depth measurements were taken at zero flow in each channel and were used as the channel baseline conditions. These elevations were used to adjust the upstream water depths to a common datum due to the UV channels having “step-downs” on the channel floor between UV banks. The “step-downs” account for approximately 5-inches channel floor difference. Flow depth measurements were collected approximately 3 feet upstream of the first UV bank and 3 feet downstream of the last UV bank in each channel. Seven measurements were taken at equal segments across the width of the channel at the upstream side of each channel, with the first reading being ½ the segment length at the channel wall. The downstream depth measurement only had six measurement readings taken as a result of a mud valve obstructing the reading at the 7th measurement position. For channel one, depth readings were performed at six different flow rates, ranging from approximately 16 through 44 mgd. Depth readings in channels two and three were only performed for a single flow rate that was near the maximum design flow per channel.

For the depth measurements, a wooden board was placed across the channel directly above the open edge of the eyeshield (located 3 feet up or downstream of the UV banks), and was used to support the measuring rod and mark the cross-channel measurement locations. A measuring rod was inserted in the bottom of the channel using the board edge as a brace. True vertical was maintained with two levels attached to the measurement bar. The water depth was then read and recorded, along with the time of the measurement.

Power Consumption Test Protocol

As part of the startup the installed UV system was tested to verify that the energy consumption was within that specified by the manufacturer during the analysis phase. Typically a 20-year life cycle cost analysis is performed to compare different systems. Energy costs compose the highest fraction of the annual operations costs for most UV systems. Often, specifications for power consumption rates can result in liquidated damages if the system does not meet the contract specifications. Power consumption testing for this project was performed by a third party, Square D Engineering Services. The power consumption was measured on one randomly selected UV bank that was set to manually operate at full intensity (all lamps ignited at 100 percent output) and a portable Square D–ION meter, model 7650, was installed at the primary of channel one, bank one's isolation transformer to measure power draw. Power measurements were logged every 15 minutes during a 24-hour test period; following the test period, power consumption data were downloaded and analyzed.

RESULTS

Performance Test Results

Results of the performance testing provided valuable effluent water quality data and indicated the UV system's ability to disinfect the secondary effluent. Performance testing confirmed that the system consistently met the disinfection target of 65 cfu/100mL of *E. coli*. During the six-day performance test, influent *E. coli* concentrations ranged from 2,130 to 10,460 cfu/100mL, with the influent geometric mean concentration being 4,340 cfu/100mL. The effluent *E. coli* concentration ranged from non-detect to a maximum *E. coli* concentration of 8 cfu/100mL, well below the disinfection target of 65 cfu/100mL. During testing, the average UVT value was 72 percent, with the minimum UVT of 69.4 percent being notably better than the design UVT of 65 percent. The influent and effluent *E. coli* concentrations have been plotted with UVT on the secondary axis in Figure 3. There were two missing influent and effluent *E. coli* test results due to laboratory issues.

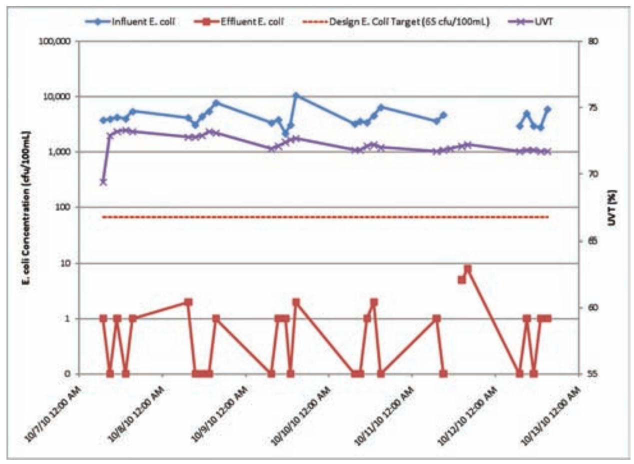

Figure 3. Performance Testing Results

During the six-day performance test period, TSS ranged between 2 and 4 mg/L, which is well below the 30-day average TSS limit. Also, as previously discussed, particle sizes greater than 20 microns have been shown to have an impact on the UV system's ability to effectively treat the wastewater. During the performance testing, the particle sizes greater than 20 microns ranged between 3 and 5 percent.

TSS Test Results

During the TSS test, the spiked TSS concentration ranged between 9 and 35 mg/L, with the average concentration being 20 mg/L. As a result of injecting MLSS into the secondary effluent, the influent *E. coli* concentration was greatly increased, ranging from 5,460 to 43,520 cfu/100mL, with the geometric mean concentration being 18,166 cfu/100mL. Although the influent suspended solids and *E. coli* concentrations increased, disinfected effluent still met the discharge *E. coli* requirements with concentrations ranging between 2 and 36 cfu/100mL, and a geometric mean of 11.4

cfu/100mL. The TSS concentrations and influent and effluent *E. coli* concentrations throughout the testing are provided in Figure 4. It is evident, from Figure 4 that spiked TSS concentrations resulted in secondary effluent that contained more solids particles. The additional solids in the secondary effluent resulted in wastewater that was more difficult to disinfect, however it resulted in only slightly higher effluent *E. coli* concentrations, when compared to the previous performance testing where the TSS concentrations ranged between 2 to 4 mg/L.

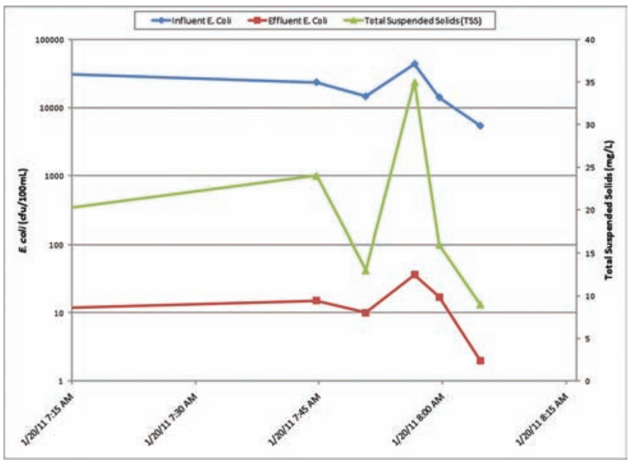

Figure 4. TSS Testing Results

Due to delivery capacity limitations with the vacuum trucks, two trucks were used to supply MLSS to the injection point. The decrease in the TSS concentration in the data series is a result of the vacuum trucks not being able to supply a continuous dose of MLSS to the injection point. The trucks needed to refill with more MLSS from the aeration basins. However, the variation of TSS concentrations demonstrated disinfection capabilities over a range of operating conditions. The UVT during the test ranged between 62.7 and 67.3 percent, with the average being 66.1 percent. UVT values during the TSS test dropped below the typical UVT values at the plant, which are normally above 67 percent. No correlation was evident between the UVT and the TSS concentration.

Headloss Test Results

Using the upstream (adjusted for baseline) and downstream water depths recorded for channel one, the data points were correlated with the flows by linear regression and are presented in Figure 5. The equations derived for the influent and effluent depth-flow relationship are as follows:

Influent Depth (inches) = 0.3266Flow (mgd) + 60.137
Effluent Depth (inches) = 0.1095Flow (mgd) + 62.013

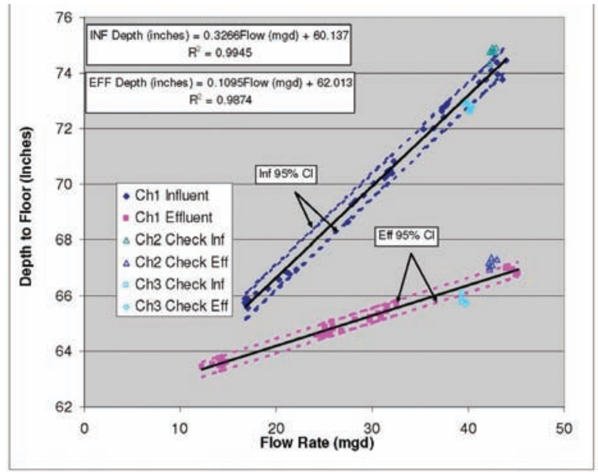

Figure 5. Influent and Effluent Depth-Flow Relationship

Correlation coefficients (R2) in both cases are greater than 0.98. Figure 5 also shows the 95th-percentile confidence interval (CI) plotted for each regression line. The high flow checks for channels two and three are also plotted on Figure 5. Although the data are offset slightly from channel one, the differential (between influent and effluent measurements) is similar to that shown for channel one.

The influent and effluent water elevation differential was calculated and the resulting headloss and 95th-percentile CI (determined by adding the upper and lower 95th percentile bounds from both the influent and effluent depth measurements) were plotted in Figure 6, showing headloss as function of flow. Note that channel two and three high flow checks agree with the predicted line. The resulting equation to estimate the headloss at any given flow is determined by linear regression:

Headloss (inches of Water) = 0.2171(Flow, mgd) - 1.876

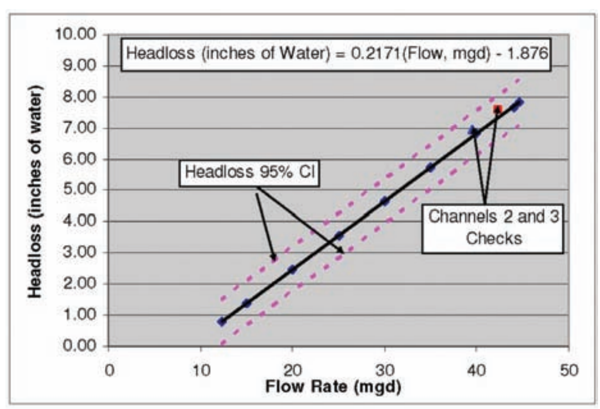

Figure 6. Headloss Equation

The headloss determined at the maximum flow tested (44.6 mgd) is 7.81 inches, well below the maximum allowable headloss of 9.55 inches. The upper 95th-percentile at this flow is 8.52 inches, also below the maximum allowable. Note that this equation can be used only within the actual flow range tested, 12.3 to 44.6 mgd. Based on the results of the headloss test, it was determined that the installed UV system met the specification requirements.

Power Consumption Test Results

The contract documents for this project required that the power consumption on the line side of the isolation transformer not exceed 46.66kW and that the power factor be at least 0.98. Upon analyzing power consumption data from the 24-hour test, it was determined that the input power factor remained above 0.98 and that the power consumption measurements to the UV bank averaged approximately 46.6kW over the 24-hour test period as shown in Figure 7. The initial data points were eliminated because UV lamps were warming up, and operators were adjusting the UV system to operate manually at full intensity. Based on the results of the power consumption test, it was determined that the UV system met the specified requirements.

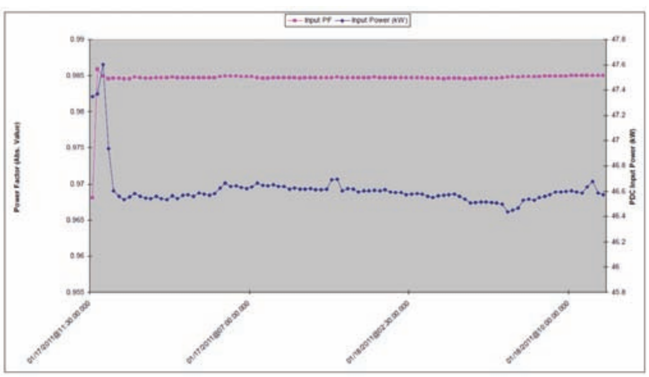

Figure 7. Power Consumption Test Results

DISCUSSION AND CONCLUSIONS

This case study, based on a recently constructed 135-mgd UV facility at the LVSWWTF in Colorado Springs, Colorado, provides information on testing protocols for disinfection performance testing installed UV equipment. The system headloss and power consumption testing that were conducted during startup was also described. Results of the performance tests for disinfection as well as for headloss and energy consumption show that the system selection, design and installation is meeting performance requirements as specified. Similar testing should be performed on every UV disinfection system during startup to confirm the design and operation of the UV system, including determining whether the design dose is adequate in meeting the disinfection goals for the "worst-case" design conditions.

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