UV SYSTEMS FOR RECLAIMED WATER DISINFECTION – FROM EQUIPMENT VALIDATION TO OPERATION

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ABSTRACT

The Sanitation Districts of Los Angeles County (Districts) operate seven tertiary water reclamation plants (WRPs) with a combined treatment capacity over 200 million gallons per day (MGD). Although chloramination has provided reliable and effective disinfection, the Districts decided to change this disinfection practice at one of the WRPs to ultraviolet (UV) irradiation to minimize N-nitrosodimethylamine (NDMA) formation.

During the process of designing the UV disinfection system, the Districts had an opportunity to participate in an equipment validation study that was conducted by a third party consultant. A pilot scale UV system equipped with low-pressure high-output UV lamps was validated according to *Ultraviolet Disinfection Guidelines for Drinking Water and Wastewater Reclamation*, and the equipment validation report was approved by the California Department of Health Services (DHS). Following the equipment validation testing, the Districts conducted additional UV disinfection studies, using the same pilot system, at two WRPs in 2004 and 2005. The objectives of these studies were to verify the UV dose regression model developed from equipment validation testing, and to determine if the UV dose regression model developed at one WRP could be used for design of a full-scale UV disinfection system at another WRP with similar treatment processes and water quality.

Results showed that the delivered UV doses from the Districts' tests were different from those calculated using the dose regression model. Factors that may attribute to this apparent discrepancy include differences in collimated beam testing procedures, water quality, data analysis procedures, and assumptions made to calculate doses of multiple-bank systems. The findings from this study have implications on UV system design and operation which rely on the dose regression model. It is recommended that the factors discussed in this study be considered in UV equipment validation and full-scale UV system design and operation to ensure that the full-scale UV systems function as designed and provide adequate safety factor for protection of human health.

KEYWORDS

Disinfection, ultraviolet, UV, validation, dose, water reclamation

INTRODUCTION

The Sanitation Districts of Los Angeles County (Districts) operate seven tertiary water reclamation plants (WRPs) with a combined treatment capacity over 200 million gallons per day (MGD). Approximately 65 MGD of the reclaimed effluent is reused for groundwater replenishment, landscape irrigation, industrial and agricultural applications, recreation impoundments, and wildlife habitat maintenance. Typical treatment processes employed in these WRPs include primary sedimentation, activated sludge with biological nitrogen removal, secondary clarification, media filtration, disinfection with chloramines, and dechlorination.

Although chloramination has provided reliable and effective disinfection of reclaimed effluent over the years, it was recently discovered that chloramines react with dimethylamine (DMA) to form a family of highly carcinogenic disinfection byproducts, namely nitrosamines (Mitch and Sedlak, 2004). DMA is present in the secondary effluent, and it is also a major ingredient in the Mannich polymer that is commonly used at the Districts' WRPs to enhance mixed liquor settling and for foam control. To minimize formation of nitrosamines, specifically N-nitrosodimethylamine (NDMA), the Districts decided to change the disinfection practice at the Whittier Narrows Water Reclamation Plant (WNWRP) from chloramination to ultraviolet (UV) irradiation.

UV irradiation is an effective disinfection means and is known for producing little or no potentially harmful disinfection byproducts at the disinfection doses. In the last decade, significant progress has been made in UV technologies for water and wastewater disinfection applications. Much of this knowledge has been summarized in *Ultraviolet Disinfection Guidelines for Drinking Water and Wastewater Reclamation* (NWRI Guidelines), which was most recently updated in 2003 by the National Water Research Institute (NWRI) in collaboration with the American Water Works Association Research Foundation (NWRI, 2003). The NWRI Guidelines provide a rational basis for evaluating UV disinfection equipment performance and for designing full-scale UV disinfection systems.

To design the full-scale UV disinfection system at the WNWRP, the Districts' staff considered various types of UV equipment and decided to use an open channel system with low-pressure high-output (LPHO) lamps. Two major manufacturers of LPHO UV systems were identified. Equipment from both manufacturers had previously been validated following the NWRI Guidelines. The California Department of Health Services (DHS) approved the validation reports for use in full-scale UV disinfection system design. The Districts' staff reviewed these validation reports and determined that the lamp spacing of one of the approved systems was less than optimal for the high UV transmittance (UVT) reclaimed water typically produced at the Districts' tertiary WRPs. The manufacturer of this UV system agreed to conduct another equipment validation using the same equipment, but a larger lamp spacing better suited for the high UVT reclaimed water to avoid over-dosing and excessive headloss.

The equipment validation was conducted in 2004 at the WNWRP by a third-party consultant hired by the equipment manufacturer. The validation was conducted following the NWRI Guidelines. The WNWRP filtered secondary effluent was fed to a pilot plant, provided by the equipment manufacturer, that is equipped with three banks of UV lamps in series. Hydraulically,

the pilot plant could handle up to approximately 4 MGD of flow. In accordance with the NWRI Guidelines, validation testing focused on determination of delivered UV doses under a wide range of operating conditions. The delivered doses were determined based on bioassay using male specific coliphage (MS-2) as the surrogate microorganism. The majority of the testing (>90%) was done using one of the three UV banks in the pilot plant. The results from the validation testing were used to develop a dose regression model that was approved by the DHS in 2005. The dose regression model provided the basis for designing and operating full-scale UV disinfection systems using the same UV lamps and similar system configuration.

OBJECTIVES

Following the validation testing, the Districts used the same UV pilot system and conducted additional UV disinfection studies at WNWRP and Saugus WRP (SWRP) in 2004 and 2005. The main objectives of the Districts' testing program included:

(1) to determine the effect of UV disinfection on formation and/or destruction of cyanide and NDMA;
(2) to determine if a UV system designed based on virus inactivation (as specified by the NWRI Guidelines) would also comply with the total coliform bacteria concentration limit specified in Title 22 of the California Code of Regulations for unrestricted reuse;
(3) to determine if a UV system designed to deliver the required 100 mJ/cm^2 dose would be effective for inactivation of adenovirus, which is known to be relatively resistant to UV irradiation;
(4) to verify the UV dose regression model, by comparing the predicted UV doses calculated using this model and the bioassay delivered doses actually measured under various operating conditions; and
(5) to determine if the UV dose regression model, developed from the validation testing at the WNWRP, could be used for potential design of a full-scale UV disinfection system at the SWRP that has similar treatment processes and water quality.

Results from (1) and (2) above were previously presented (Jalali *et al.*, 2005). Results of the adenovirus study will be presented in the future. The main focus of this paper is to address the last two objectives listed above. The results from these studies prompted the Districts to conduct a critical review of the current practice of UV equipment validation, design, field commissioning, and operation. Several issues identified from this review are discussed in this paper.

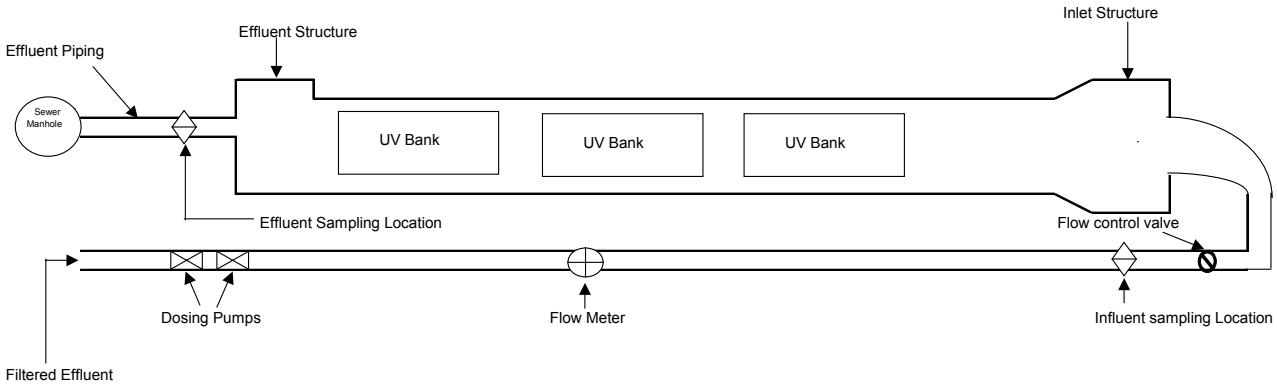
MATERIALS AND METHODS

Equipment Validation

The validation study was conducted on a pilot plant equipped with LPHO UV lamps at 4-inch lamp spacing. Figure 1 is a schematic diagram of the pilot plant. The pilot plant consisted of one stainless steel open channel reactor that housed three UV banks in series. The pilot plant

included inlet and outlet hydraulic transition structures and an 8-foot straight section before the first UV bank. A 10-inch diameter pipe carried the unchlorinated filtered secondary effluent to the pilot plant. The flow rate to the pilot plant was measured by a magnetic flow meter. Two chemical feed pumps were located approximately 50 feet upstream of the influent sampling port. These pumps were used for UVT adjustment and seeding of the surrogate microorganism, male-specific coliphage MS-2, respectively. Effluent from the pilot plant was discharged to a sewer manhole and conveyed to a downstream facility for further treatment.

Figure 1 - UV Pilot Plant Schematic Diagram (Not to Scale)



Velocities at various points in the pilot plant were first measured, according to the NWRI Guidelines, to determine the uniformity of the velocity profiles. A total of 68 test runs, each representing a unique combination of flow rate, UVT, and lamp power setting, were made during the equipment validation testing. The majority of the runs (>90%) used only one bank of UV lamps. Sampling ports were located outside of the UV reactor channel (see Figure 1). The influent sampling port was a 1-inch tap located upstream of the inlet flow control valve. The effluent sampling ports were located on the discharge lines.

On the day of pilot testing, the flow rate and the water level above the UV lamps were first stabilized. Sufficient time was allowed for lamp warm-up according to equipment manufacturer's specifications. Afterwards, the MS-2 solution was injected. The solution was prepared using unchlorinated filtered secondary effluent and virus stock solution with an initial MS-2 titer concentrations in the range of 10^{11} to 10^{12} plaque-forming-units (pfu) per milliliter. Instant coffee solution, in selected runs in which UVT needed to be downward adjusted, was also injected to obtain the targeted testing conditions.

Five influent and five effluent samples were usually collected for each testing condition to characterize data variability. Pilot plant influent and effluent samples were collected from the sampling ports after a minimum of four hydraulic residence times had passed. The pilot plant influent was also collected in selected runs and tested by the collimated beam apparatus to develop the dose-response curve for MS-2 inactivation. The delivered UV dose by the pilot plant was determined by matching the log inactivation of MS-2 from the pilot testing to the removal from the laboratory collimated beam testing. The collection of multiple influent and effluent samples for each run allowed the calculation of the 25th percentile delivered dose

following the statistical approach outlined in the NWRI Guidelines. A multiple regression analysis was made, using the delivered UV doses as the dependent variable and the operating conditions and water quality (UVT) as the independent variables, to develop a "dose regression model" (DRM). The DRM relates the delivered UV dose to operating conditions (flow rate and lamp power setting) and water quality (UVT), and it takes the following form:

$$DD = a \times (HL)^b \times P^c \times (UVT)^d \quad [1]$$

Where DD is the delivered UV dose in mJ/cm^2;
HL is the hydraulic loading in gallon per minute (gpm) divided by the number of UV lamps in each bank;
P is the UV lamp power setting in %;
UVT is the UV transmittance of the reactor influent at 254 nm wavelength in %; and
a, b, c, d are empirically determined coefficients from the regression analysis.

The DRM served as the basis for design and operation of full-scale UV disinfection systems. In California, DHS requires, for media-filtered secondary effluent, the UV disinfection system be designed and operated to deliver a minimum dose of 100 mJ/cm^2 after taking the lamp aging and fouling factors into account.

Districts' Pilot Testing

The Districts used the same pilot plant for the dose verification studies conducted at the WNWRP and the SWRP. The same procedures used in the equipment validation study were employed in the Districts' pilot testing. However, there were three major differences between the equipment validation testing and the Districts' verification studies. First, the Districts' microbiology laboratory conducted the collimated beam testing in the Districts' studies; while a different laboratory conducted the collimated beam testing during the equipment validation testing. Secondly, the Districts collected only two influent samples, instead of five, and one to three effluent samples for each testing condition. The limited number of samples did not allow calculation of the 25^{th} percentile delivered UV dose, as recommended in the NWRI Guidelines. Finally, the Districts conducted tests with multiple banks of UV lamps in operation. As mentioned earlier, the majority of the tests conducted during the equipment validation testing used only one bank of UV lamps.

Collimated Beam Testing and Dose Determination

The Districts' collimated beam apparatus includes a sample tray that can be adjusted to obtain different UV intensities, an electrical fixture with mirror-reflectors that incorporates four parallel LPHO UV lamps, and a 20-centimeter (cm) diameter collimating tube. A timer controls a pneumatically operated shutter for UV exposure time down to one tenth of a second. The UV lamps produce primarily monochromatic output at 254 nanometer (nm) wavelength.

Disposable 15-cm diameter Petri dishes were used to provide individual sample volumes of 250 milliliters (mL) with water depths of about 1.3 centimeter. The UV intensity at 254 nm at air-water interface at the center of Petri dish was measured using a radiometer and recorded before and after each sample exposure. A small stirrer bar with a constant rotation speed was used to provide continuous and complete mixing without creating vortices. Magnetic stirrers of same size and same rotation speed setting were used throughout the testing.

The UV dose for the collimated beam, D, in milli-Joule per square centimeter (mJ/cm^2), was calculated based on the following equation (Jalali *et al.*, 2005):

$$D = 97.5\% \times I_o \times PF \times t \times (1\text{-}10^{-kd}) \div (kd) \qquad [2]$$

Petri factor (PF) was determined by measuring the UV intensity distribution on a grid of ½ centimeter spacing within the collimated beam field. The average radiation intensity over the entire air-water interface is the radiation intensity measured at the center (I_o, in W/cm^2) times PF and discounted by 2.5% for radiation reflection from the air-water interface. The other parameters are the exposure time (t, in seconds), absorbance at 254 nm (k, in absorbance unit/cm), and the liquid depth of the sample (d, in cm). Absorbance (in a.u./cm) is related to UVT by the following relationship:

$$UVT\ (\%) = 100 \times 10^{-k} \qquad [3]$$

Microbiological Assay

The Districts' laboratory enumerated MS-2 coliphages using a double agar layer assay as described in Chapter 16 of the USEPA Manual of Methods for Virology (EPA, 1984). MS-2 coliphage (ATCC #15597B1) stocks used in seeding were purchased from GAP EnviroMicrobial Services (London, Ontario, Canada). MS-2 coliphages were enumerated on the bacterial host Escherichia coli FAMP (ATCC #700891). Appropriate quality assurance and quality control procedures were followed as specified in the NWRI Guidelines and USEPA Manual of Methods for Virology.

Comparison of Predicted and Measured UV Delivered Dose

For the verification studies, the UV delivered dose was calculated using equation [1] for each set of test conditions (hydraulic loading, power setting, and UVT of the water). The same surrogate microorganism used in the equipment validation testing, MS-2 coliphage, was seeded to the UV pilot plant influent. Influent and effluent samples were collected to determine the log inactivation of MS-2. Collimated beam testing was conducted to generate the dose-response curves which were used to determine the actually delivered UV dose.

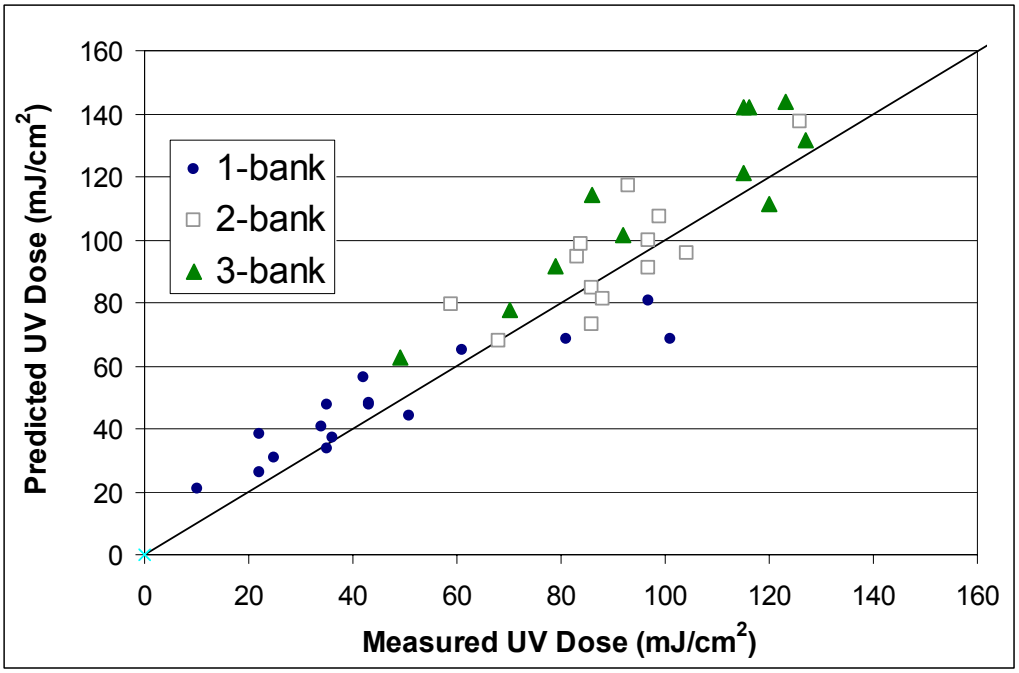
RESULTS

Table 1 summarizes the testing conditions evaluated at the WNWRP and the SWRP. Figures 2 and 3 compare the predicted and the actually measured UV delivered doses for the studies conducted at the WNWRP and the SWRP, respectively.

Table 1 – Testing Conditions at Whittier Narrows and Saugus WRP

	Whittier Narrows WRP	Saugus WRP
Flow Rate (gpm)	1,000 – 2,500	1,100 – 2,250
Lamp Power Setting (%)	60 – 100	60 – 100
UVT (%)	63 – 79	69 – 78
Total Number of Runs	39	27
One Bank	16	10
Two Banks	13	10
Three Banks	12	7

Figure 2 - Delivered UV Doses: Predicted vs. Actually Measured – Whittier Narrows WRP



Figures 2 and 3 indicate that the predicted UV doses using the DRM often over-estimate the actually measured doses, as more points are located above the line with a 1:1 slope ratio. Table 2 shows that the chances of the calculated doses matching the actually measured doses, at both the WNWRP and and the SWRP, were only 4% (1 out of 26 runs), 4% (1 out of 23 runs), and 0% for operation with one-, two-, and three-bank of UV lamps, respectively. For one-bank operation,

there was a 73% (19 out of 26 runs) chance that the DRM overestimated the actually measured dose. For two-bank and three-bank operations, these chances were 70% (16 out of 23 runs) and 95% (18 out of 19 runs), respectively.

Figure 3 - Delivered UV Doses: Predicted vs. Actually Measured - Saugus WRP

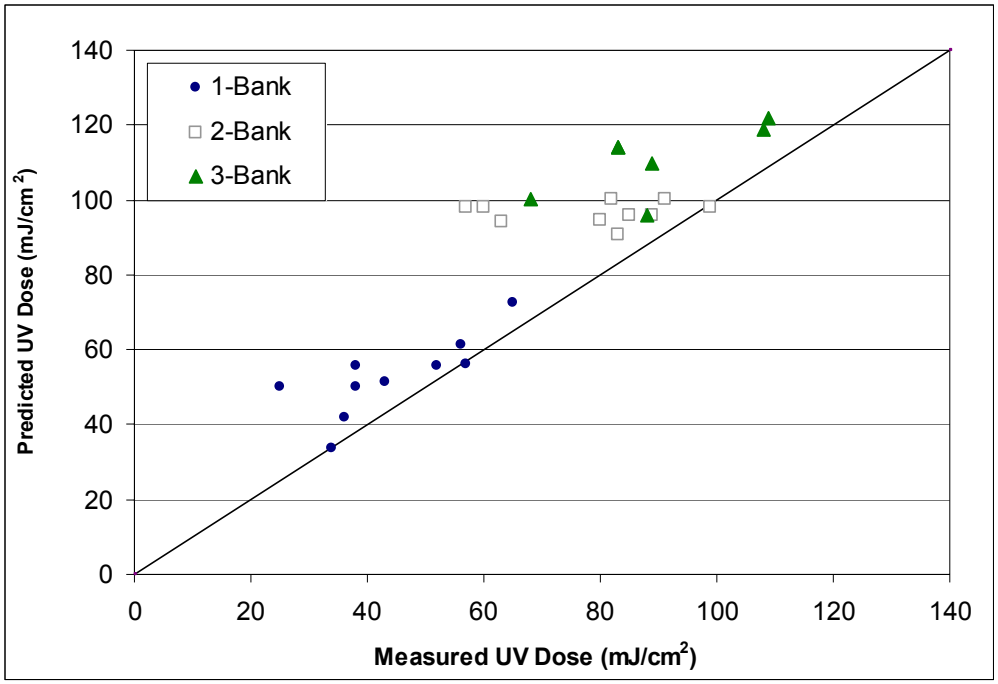


Table 2 – Verification of Dose Regression Model (DRM)

Whittier Narrows WRP	Total No. of Runs	No. of Runs that DRM Overestimating Actual Dose	No. of Runs that DRM Underestimating Actual Dose	No. of Runs that DRM Accurately Predicting Actual Dose
One Bank	16	11	5	0
Two Banks	13	7	5	1
Three Banks	12	11	1	0

Saugus WRP	Total No. of Runs	No. of Runs that DRM Overestimating Actual Dose	No. of Runs that DRM Underestimating Actual Dose	No. of Runs that DRM Accurately Predicting Actual Dose
One Bank	10	8	1	1
Two Banks	10	9	1	0
Three Banks	7	7	0	0

The lack of agreement between the predicted and the actually measured delivered doses may be caused by various reasons. Some of the plausible causes and the implications of these results on UV equipment design and operation are discussed below.

DISCUSSION

Plausible causes for the apparent discrepancy between the predicted delivered doses and the actually measured delivered doses include differences in collimated beam testing procedures, water quality, data analysis procedure, and assumptions used to calculate doses of multiple-bank systems. The following section discusses these factors.

Collimated Beam Testing

As mentioned earlier, collimated beam testing was used to determine the delivered UV doses from the UV pilot system. This procedure is specified in the NWRI Guidelines. The collimated beam testing establishes the relationship between the UV doses and log inactivation of a surrogate microorganism (typically MS-2 coliphage). Results are presented as dose-response curves. In UV pilot plant testing, log inactivation of the same microorganism is determined and the delivered dose is determined from the dose-response curve. Although the protocol of collimated beam testing is suggested in the NWRI Guidelines, the testing procedures have not been standardized. Several issues related to collimated beam testing have been raised in literature (Kuo *et al.*, 2003; Kuo *et al.*, 2005; Bolton and Linden, 2003). Without a standardized protocol, the dose-response curves generated by two different laboratories, using the same sample, may be different. Consequently, the resulting UV delivered dose would be different. The NWRI Guidelines require that the collimated beam data fall within a range defined by the following two equations:

$$-\log_{10}(N/N_0) = 0.040\ (\text{UV dose, mJ/cm}^2) + 0.64 \qquad [4]$$

$$-\log_{10}(N/N_0) = 0.033\ (\text{UV dose, mJ/cm}^2) + 0.20 \qquad [5]$$

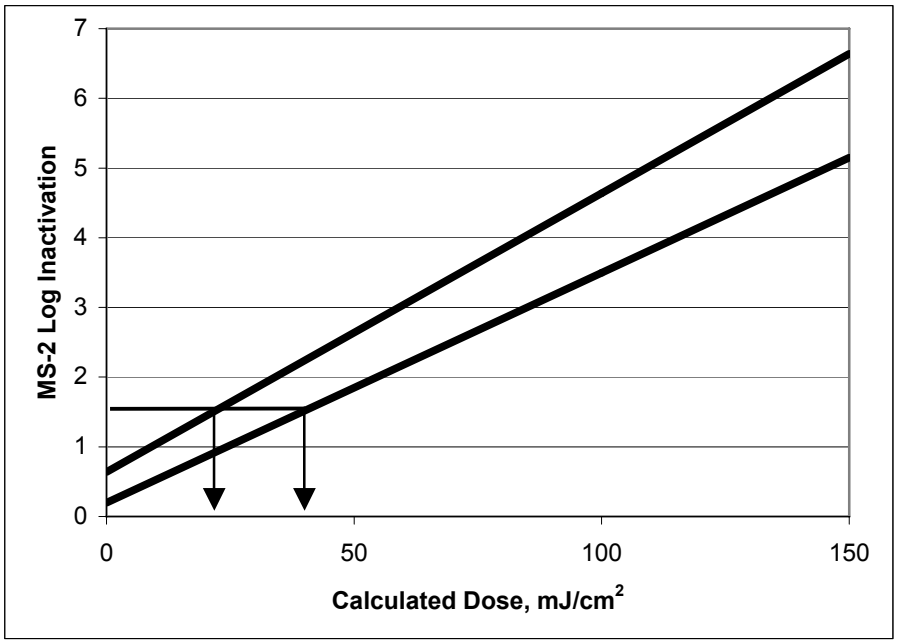
where N_0 and N are the concentrations of infective MS-2 at dose zero and after UV exposure, respectively.

To illustrate the potential effect of the differences in collimated beam testing results on UV delivered dose, lines representing equations [4] and [5] are plotted in Figure 4. If a log inactivation of 1.5 was observed from pilot testing, the delivered UV dose could range from 21.5 mJ/cm^2, if the dose-response curve is close to the top boundary (i.e., equation [4]), to 39.4 mJ/cm^2, if the dose-response curve is close to the lower boundary (equation [5]). This difference in these delivered doses is significant!

During the equipment validation testing, the dose-response curves generated were typically in the lower half of the range as defined by equations [4] and [5]. Samples produced from the Districts' verification studies were analyzed by the Districts' microbiology laboratory, and the dose-response curves were located mostly in the upper half of the acceptable range. This may

partially explain why doses determined from the verification studies tend to be lower than those determined from the validation testing. A round-robin testing of the same sample by different microbiology laboratories, which use different collimated beam apparatus, is currently being conducted by the Districts to further investigate the potential effect of collimated beam testing on UV delivered doses.

Figure 4 – MS-2 Inactivation Dose-Response Curve



Impact of Water Quality

To assess UV system performance on water with low UVT value, additives such as instant coffee are often used during equipment validation testing to artificially reduce the UVT. UVT and particle sizes are two of the most important water quality parameters affecting UV system performance. The DRM includes UVT as an independent parameter, but the size distribution of the particles present in the UV reactor influent is not necessarily reflected in UVT. Larger particles have a greater potential to shield the microorganisms and impede the performance of a UV system (Darby *et al.*, 1999).

The treatment processes employed at the WNWRP and the SWRP are essentially the same. They include primary sedimentation, activated sludge with biological nitrogen removal using the modified Ludzack-Ettinger configuration, secondary clarification, media filtration, disinfection with chloramines, and dechlorination. The UVT values of the filtered effluent at both plants are similar (typically between 70 and 75%). However, the WNWRP employs dual-media gravity filters, and the SWRP uses dual-media pressure filters. While the particle size distribution of the filtered effluent from neither plant was measured in the verification studies, the results suggest that the DRM matched the actually measured UV doses at the WNWRP better than those at the SWRP. For example, the deviation of delivered UV dose from the 1:1 slope line is much greater

with the SWRP data than is with the WNWRP data in the 60 to 80 mJ/cm^2 dose range (see Figures 2 and 3). These observations imply that water quality difference, not captured in the DRM, may contribute to the disagreement between the predicted and the actually measured delivered UV doses.

Data Analysis Procedures

Another possible source leading to the differences in the predicted and the actually measured UV doses is the data analysis procedures. In the equipment validation testing, multiple influent (5) and effluent (5) samples were collected according to the NWRI Guidelines. The multiple samples allow data to be statistically analyzed to obtain the 25th percentile dose. This procedure was not used in the Districts' verification studies due to limitations in laboratory resources. The Districts collected only two influent samples, instead of five, and one to three effluent samples for each testing condition. The limited number of samples did not allow calculation of the 25th percentile delivered UV dose. Consequently, the statistical data analysis procedures recommended in the NWRI Guidelines were not implemented in the dose calculations.

Single-Bank vs. Multiple-Bank Testing

Another difference between the Districts' testing and the equipment validation study is the number of UV banks used in the tests. A full-scale system typically consists of multiple UV banks in series. The number of banks depends on the requirement of log inactivation of pathogens, headloss consideration, and redundancy requirements specified in the NWRI Guidelines. Use of one UV bank for equipment validation testing is a common practice, however, because a much smaller amount of seeded virus is required than using multiple banks. The validity of this approach depends on a critical assumption that the banks are hydraulically independent and identical. The NWRI Guidelines states "in theory, if sequential reactors in a reactor train are hydraulically independent and identical, the process behavior (e.g., dose distribution) delivered by each bank will be identical and can be assumed to be additive." If the test organism displays the first-order dose-response behavior, additivity can also apply to log inactivation. In practice, however, the process behavior by each bank during any pilot testing including equipment validation is rarely independent and identical.

The Districts' verification studies, with both single and multiple UV banks in operation, allowed an evaluation of the dose additivity and log inactivation additivity assumptions. Figure 5 plots log inactivation of MS-2 from a single UV bank versus those from two and three UV banks under the same operating and water quality conditions. The data were obtained from the Districts' testing at the WNWRP. The two lines in the figure represent lines with 2:1 and 3:1 slope ratios, respectively. If the log inactivation among the banks was additive, then the points would fall on these lines. As shown in the figure, most of the points are actually below the lines indicating that the log inactivation of MS-2 across the banks was less than additive.

Figure 6 plots the actually measured delivered doses from single-bank operation versus those from operation with two and three banks of UV lamps. These points scattered around the 2:1

and 3:1 slope lines with no clear trend. The actually measured delivered dose of a multiple-bank system could be larger or smaller than the actually measured dose delivered by a single bank of UV lamps multiplied by the number of operating banks. This figure indicates that the assumption that dose being additive is not always valid.

Figure 5 – Additivity of Log Inactivation – WNWRP Verification Study

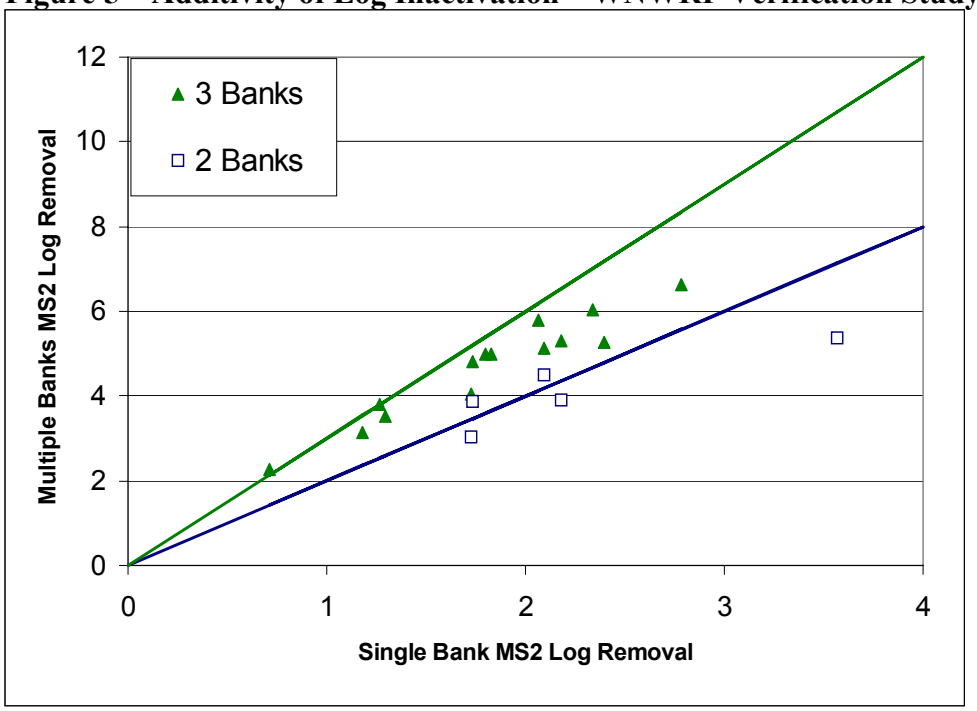
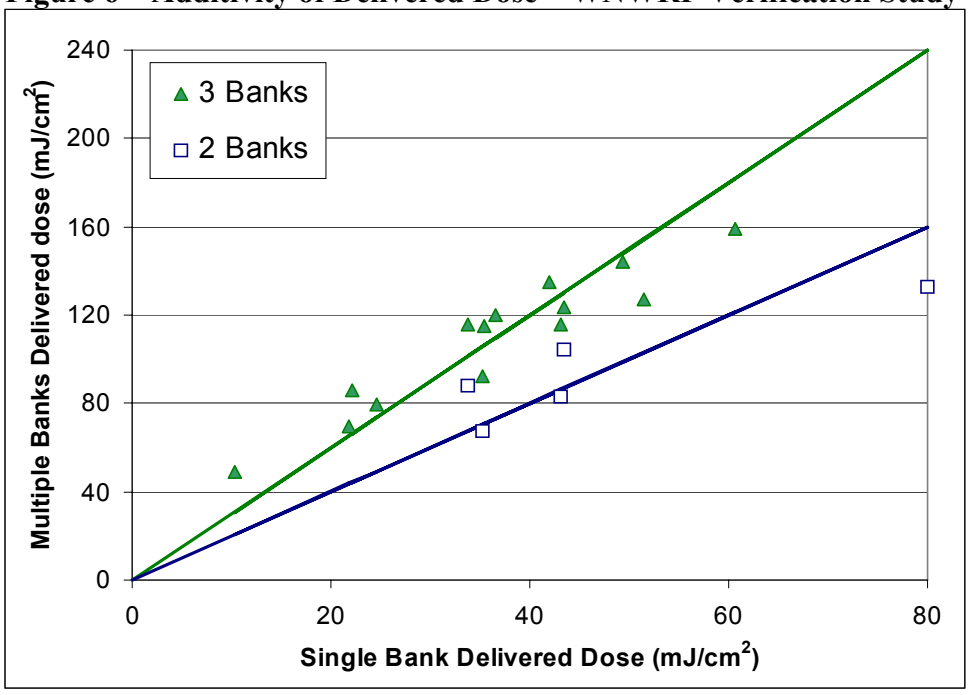


Figure 6 – Additivity of Delivered Dose – WNWRP Verification Study



Implications on UV Systems Design and Operation

The results from the verification studies conducted at the WNWRP and the SWRP indicated that there is a high probability that the DRM developed from the equipment validation testing may overestimate the actually delivered UV dose (see Table 2). Current practice of UV system operation usually uses the DRM to control the lamp power setting and/or the number of duty banks and reactor trains in operation. Depending on flow and UVT of the UV reactor influent, lamp power setting may be adjusted, or turned down, to avoid overdosing and to save energy costs. The verification study results suggest that this operating strategy has the potential of underdosing the water to be disinfected, which may lead to noncompliance with the disinfection requirement. Therefore, it is recommended that full-scale UV disinfection systems be conservatively operated instead of relying fully on the use of DRM.

The other implication from the verification study results is that DRM developed at one facility may not be fully applicable for design and operation of a field-scale UV disinfection system at other facilities. This is evidenced by the poor correlation observed between the predicted and the actually measured delivered UV doses from testing conducted at the SWRP. There were instances that the DRM overestimated the actual delivered dose by 40%. This observation suggests that site specific pilot testing should be considered when it comes to full-scale system design instead of using a DRM that is developed from a one-time equipment validation testing, even though the validation testing may cover a wide range of testing conditions. The NWRI Guidelines requires a field commissioning test before new full-scale UV disinfection systems are placed into service. Although the scope of field commissioning test is not clearly specified in the NWRI Guidelines, a "checkpoint bioassay" is currently required in California to show that the full-scale UV system will deliver the required dose under actual operating conditions. Based on results obtained from the verification studies conducted at WNWRP and SWRP, meeting the requirement for field commissioning test could present a challenge if the design was based on using the DRM.

SUMMARY AND RECOMMENDATIONS

The Districts conducted pilot-scale UV verification studies at two WRPs to determine if the delivered UV doses predicted by the use of a DRM match the actually measured delivered doses and whether the DRM developed at one facility can be used for design of full-scale UV disinfection systems at other facilities with similar treatment processes and water quality. Findings of these studies include the following:

- The studies showed that delivered UV doses predicted by the DRM might overestimate the actually measured delivered doses.
- One reason that may contribute to the discrepancy between the predicted doses and the actually measured doses is that the collimated beam testing was conducted at different laboratories. Different laboratories may produce different dose-response curves due to the lack of standardized collimated beam testing protocol.
- Equipment validation testing is usually conducted with only one bank of UV lamps. Assumptions of reactor independence and identical performance are usually made during

the validation testing and for full-scale UV disinfection system design. Pilot testing conducted by the Districts included both single and multiple banks of UV lamps. The results indicated that the assumptions of log-inactivation of surrogate microorganisms and delivered dose across the UV banks being additive are not always valid.

- The DRM developed from one facility may not be applicable for designing full-scale UV disinfection systems at other facilities with similar treatment processes and water quality. Important water quality characteristics affecting UV system performance, such as particle size distribution, may not be fully reflected in UVT which is the only water quality parameter included in the DRM.

The findings from the studies lead to the following recommendations:

- In conducting equipment validation testing, the assumptions of dose and log inactivation being additive should be carefully evaluated to determine their validity.
- The existing practice of using DRM to adjust UV lamp power setting may not be sufficiently conservative to ensure compliance with disinfection requirements.
- For full-scale UV system design, it is recommended that site-specific pilot testing be conducted using a pilot plant configuration and number of banks that are the same as the full-scale system. This approach would produce more representative design than using a DRM developed from other facilities.

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