Optimizing the Energy Efficiency of Ultraviolet Disinfection Through On-Site Validation and Control Equipment Maintenance

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New York State
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NYSERDA

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Optimizing the Energy Efficiency of Ultraviolet Disinfection Through On-Site Validation and Control Equipment Maintenance

Final Report

Prepared for the
New York State
Energy Research and
Development Authority
Albany, NY
www.nyserda.org

Greg Lampman
Project Manager

and

City of Albany
Department of Water and Water Supply

William Simcoe, P.E.
Assistant Commissioner

Prepared by
Malcolm Pirnie
Albany, NY

Matthew C. Yonkin, P.E.
Project Manager

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Key Words: Ultraviolet Disinfection, On-site Validation, Inactivation Credit, Challenge Organism, Equipment Factor, Bias, Lamp Fouling/Aging, Energy Efficiency

Abstract

OPTIMIZING THE ENERGY EFFICIENCY OF ULTRAVIOLET DISINFECTION THROUGH ON-SITE VALIDATION AND CONTROL EQUIPMENT MAINTENANCE

The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) will require additional treatment for *Cryptosporidium* by all unfiltered systems and by a subset of filtered systems with elevated source water *Cryptosporidium* levels as demonstrated through monitoring. Ultraviolet (UV) disinfection is one of the few technologies accepted for high levels (2 to 3 logs) of *Cryptosporidium* inactivation. Although UV disinfection offers health and environmental benefits when compared to other traditional chemical disinfectants, it is a relatively energy intensive technology. Increasing the energy efficiency of the technology is necessary to ensure its continued success and to support the use of this promising technology.

The City of Albany (City), New York has taken a proactive approach to achieve its mission to provide the highest quality water possible to its customers by upgrading treatment and operations at the Loudonville Reservoir. The first phase of the water quality improvement project was the construction of an UV disinfection facility capable of treating up to 40 million gallons per day (MGD). The UV disinfection equipment was installed to operate in conjunction with the existing chlorine disinfection facility at the site. Incorporation of the UV facility provides multiple barrier disinfection and facilitates compliance with the requirements for uncovered storage under the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). As of the date of this report, the Loudonville UV Facility is the largest operating UV disinfection facility in a drinking water application within New York State.

While the Loudonville UV Facility is somewhat atypical from the standpoint that it is constructed at an uncovered finished water reservoir and is targeting virus inactivation, it offered a unique opportunity to gather operating data at a large-scale operating UV facility to assess opportunities to improve the energy efficiency of UV disinfection. Malcolm Pirnie, with the assistance of the City and Trojan Technologies, Inc., conducted on-site validation of the UV facility and then performed an extensive 6-month field study of the operating characteristics of the UV facility to identify opportunities for energy efficiency improvements during the planning, design, and operation of a UV disinfection project.

The results of the study are significant to the City of Albany because they will allow the City to optimize the efficiency of its UV facility and develop an operating and maintenance strategy that maintains a high level of performance. The value to other potential applications in the State of New York, and the drinking water industry in general, is that the lessons learned and data that are gathered from this project can be applied to the design, implementation, and operation of other UV facilities to improve the energy efficiency of this technology.

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Summary

The use of ultraviolet (UV) light disinfection technology is anticipated to increase significantly in both the water and wastewater sectors within the United States as drinking water quality and wastewater effluent requirements become more stringent. For chlorine-resistant pathogens, UV disinfection offers significant health and environmental benefits at a relatively low capital cost. However, UV disinfection is a fairly energy intensive treatment technology. To date, very little data are available for the use of UV disinfection for drinking water applications in the United States. The City of Albany's (City's) recently constructed Loudonville UV Facility offered a unique opportunity to thoroughly evaluate the use of UV technology in a drinking water application with the goal of identifying opportunities for energy improvement. Malcolm Pirnie, with the assistance of City personnel and Trojan Technologies, Inc., conducted on-site validation of the UV facility and conducted an extensive 6-month field investigation of the operating characteristics of the Loudonville UV Facility. The specific objectives of the study included:

- Assess the planning, design, validation, and operation processes to identify opportunities for energy efficiency improvements;
- Compare the actual capital and operating costs for the Loudonville UV Facility to the cost estimates developed by the United States Environmental Protection Agency (USEPA);
- Assess the feasibility and potential benefits of advanced controls (e.g., adjustment of the number of lamps in operation in addition to the existing power level adjustment);
- Assess the accuracy and consistency of the control equipment including the UV intensity sensors, the on-line UV transmittance (UVT) monitors, and the flow meter and evaluate the potential impact on energy efficiency through an increased frequency of calibration and maintenance;
- Evaluate lamp output decay and spectral shift and compare the findings to manufacturer's previous research;
- Evaluate lamp fouling potential and assess the energy and operational effects of fouling;
- Evaluate power quality coming into the facility and the ability of the UV equipment to handle power variations;
- Assess performance of the backup energy supply and document the downtime experienced during the study period;
- Observe and document general operating performance of the facility.

Based on the results of this study, the greatest opportunities for significant energy savings are during the planning, design, and validation phases of a UV facility project. Appropriate operation and maintenance of the UV facility is essential to protecting public health and ensuring that the UV facility operates as intended. However, there is only limited opportunity for energy efficiency improvements through more frequent maintenance or calibration of control equipment.

During the planning and design phases of a project it is important to have a sound understanding of the UVT of the water, meaning the ease with which UV light can travel through the water; the flow rates that are expected; and the lamp sleeve fouling potential, meaning the likelihood of build-up on the lamp sleeves causing a reduced amount of UV light to pass through the sleeve. Unless they occur concurrently, a designer should not base the design on the worst case UVT and the highest flow rate. To avoid over-design, and possibly reduced energy efficiency, the design should be based on the worst combination of UVT and flow rate that was actually measured or would actually be expected to co-occur.

Another factor that can easily result in the over-design of a UV facility is the fouling/aging factor that is included in the design. It is important that the selected factor be appropriate for the application. Fouling/aging factors that have typically been used in UV facility designs to date have ranged from 0.6 to 0.9, which equate to safety factors of 1.67 to 1.11, respectively. If validation is conducted using aged lamps, the water has a low fouling potential, and an automatic cleaning system is included in the design for medium pressure (MP) systems, then a smaller safety factor would be appropriate. Automatic cleaning systems are typically not available for low pressure high output (LPHO) systems. However, due to a lower operating temperature, these systems are typically less likely to foul than MP systems. If a conservative fouling/aging factor is selected for the design, then some form of lamp control can be used to maximize energy efficiency during periods when the actual lamp fouling/aging condition is better than that represented by the fouling/aging factor.

For nearly all mid-sized and larger applications, incorporation of some form of automatic lamp control is essential to maximize the energy efficiency of the UV facility. Lamp control may include adjustment of the lamp power on a fixed number of lamps, adjustment of the number of lamps that are energized, or a combination of both. The selected combination of lamp power and number of lamps must balance energy efficiency with effective dose delivery.

The validation protocol proposed in the June 2003 United States Environmental Protection Agency (USEPA) Draft Ultraviolet Disinfection Guidance Manual (2003 Draft UVDGM) relies on the use of an equipment factor to account for variations in equipment performance and uncertainties associated with measurements and monitoring. The magnitude of the equipment factor has a direct effect on the energy use of a UV facility and can range from 1.2 to 3.6 or greater. A UV facility with an equipment factor of 3.6

would consume three times as much energy to deliver the same target dose as a UV facility that has an equipment factor of 1.2. The calculation of the equipment factor is quite complicated; however, the element that has the greatest potential influence on the magnitude of the equipment factor is the challenge organism that is used during validation. Although it is understood that the 2003 Draft UVDGM is under revision, it is likely that the characteristics of the challenge organism will remain the largest component affecting the magnitude of the equipment factor. It is desirable to use a challenge organism that has inactivation characteristics as close as possible to the target organism, which in many cases will be *Cryptosporidium* of Giardia.

One organism, ϕX174, has been found to have inactivation characteristics that more closely approximate those for *Cyrptosporidium* and Giardia than the more commonly used challenge organisms – MS2 bacteriophage and *bacillus subtilis* spores. Unfortunately, for a number of reasons ϕX174 is more difficult to use as a challenge organism than MS2 bacteriophage or *bacillus subtilis* spores. As a result, to date it has rarely been used for validation testing. However, based on the study, for a utility that is targeting low levels of *Cryptosporidium* inactivation credit (less than 2.0 log) the use of ϕX174 as a challenge organism, versus the more commonly used challenge organisms, could reduce the equipment factor by 50% or more, resulting in significant energy savings. Because of its sensitivity to UV light and the limitations in the maximum concentration that can be prepared, ϕX174 cannot be used to validate high doses. Similarly, because of the greater sensitivity to UV light (when compared to adenovirus) the most commonly used challenge organisms are not able to be used to validate a UV unit for greater than 2-log virus inactivation. In recognition of the important role that the challenge organism plays in the validation process and, accordingly, the use of UV disinfection, a number of universities and organizations, including American Water Works Association Research Foundation (AwwaRF), are currently working to develop new challenge organisms that will expand the range of conditions that can be effectively validated.

Currently in the water industry, there are two predominant UV lamp technologies that are used: LPHO and MP. LPHO lamps are more energy efficient than MP lamps. However, capital cost, operating flexibility, and other operations and maintenance costs can make MP technology more attractive. If MP technology is selected, then selecting equipment with a sensor that meets specific USEPA-defined spectral response criteria and results in a conservative validation outcome will reduce the equipment factor for the UV facility. If those criteria are not met, the manufacturer's design of the UV unit and the UV absorbent that is used during validation will influence the equipment factor, and consequently the energy efficiency of the UV facility. Lignin sulphonate and instant coffee are the two UV absorbents that are most commonly used during validation testing to simulate varying water quality conditions. The use of lignin sulphonate can reduce the equipment factor by 10% to 40% when compared to instant coffee, resulting in a similar energy savings during conditions of lower UVT.

One of the most extensive existing datasets for capital and operating costs for UV facilities was developed in 2003 by the USEPA (EPA data). These data were published in the *EPA, 2003, Technologies and Costs for the Control of Microbial Contaminants and Disinfection Byproducts, Office of Groundwater and Drinking Water, Washington, D.C.* and were used as the basis of comparison for this evaluation. The Loudonville UV Facility is unique for a number of reasons, which makes direct comparison to most existing available data difficult. However, after normalizing the data collected for the Loudonville UV Facility, a reasonable comparison was possible.

At a project cost of $3.8 million, the capital cost for the 40 million gallon per day Loudonville UV Facility is very consistent with the EPA data. The electrical cost and the cost of consumables for the Loudonville UV Facility are also consistent with the EPA data. The largest deviation from the EPA estimate is labor cost. It is believed that the level of operating effort at the Loudonville UV Facility is much more representative of what will typically be required than the labor effort identified in the EPA estimate. Approximately 17 hours per week are spent operating and recording the operating conditions for the Loudonville UV Facility. Less than two hours per week were included in the USEPA's labor cost estimates for operating a UV facility under similar conditions of average flow and target dose. Given the specific monitoring and recordkeeping requirements that are recommended in the 2003 Draft UVDGM, the labor effort for the Loudonville UV Facility of approximately 0.5 hours per day per unit seems reasonable when averaged over the year.

Currently, because of the highly variable flow rate and high ultraviolet transmittance of the water at the Loudonville UV Facility, at the minimum power setting of 60%, the UV equipment is overdosing during periods of low flow. On-site validation testing demonstrated that adequate dose can be delivered to achieve the City's disinfection objectives using a reduced number of lamps under certain conditions. As a result, the use of advanced controls to allow adjustment of both lamp power and the number of energized lamps would result in improved energy efficiency at the Loudonville UV Facility, while still allowing the City to meet its disinfection objectives. It is estimated that advanced controls could reduce the energy consumption of the Loudonville UV Facility by approximately 25%.

Throughout the study period, a total of 14 separate calibration events, comprising 244 individual UV intensity sensor calibration checks, were performed. A total of eight individual sensor failures were observed. All eight of the failures occurred during unusual flow conditions that would not be expected in a more typical installation at a treatment plant. No sensor failed during two consecutive calibration events. Based on the study, there was not a difference in UV sensor calibration performance at different lamp power levels, and sensor performance did not change when a lamp was replaced between calibration checks. In general, the sensor calibration procedure was simple and the overall performance of the UV intensity sensors was good.

During the early stages of the study, the on-line UVT monitors reported inconsistent readings. As originally designed, the sample ports for the on-line UVT monitors were located at the midpoint of the pipe and at the top of the pipe. It was determined that the samples collected at the top of the pipe were occasionally erroneous due to air bubbles in the sample. To correct the problem, the sample ports for the on-line UVT monitors were modified so that all samples were collected at the midpoint of the pipe. In addition, there were several instances where small debris was drawn into the UVT monitors, causing them to malfunction. The UV plant operator installed a small screen in the sampling tube, which eliminated this problem. The 2003 Draft UVDGM does not have a procedure to assess UVT monitor calibration. Equipment performance during this study was assessed by determining the relative difference between the UVA values measured by the on-line monitors versus the UVA values measured by a bench top spectrophotometer. The relative uncertainties for UVT meter A were between 0.4% and 4.7%, indicating acceptable measurement consistency and accuracy.

Each of the UV unit trains is equipped with a Doppler-type flow meter and both an influent and an effluent control valve. As part of this study, an assessment of the influence of radial location on the performance of a Doppler-type flow meter was conducted. The variation in flow measurement at each of the tested locations was less than 3%, which is within the margin of error for the equipment. Based on these results, radial location does not affect the performance of the flow meters installed at the Loudonville UV Facility.

Lamp output decay was assessed as part of this study. Based on the results, lamp output decay observed at the Loudonville UV Facility was consistent with other studies that have been completed on the topic. A lamp output decay of approximately 5% was observed at the Loudonville UV Facility for lamps between 2,000 and 4,000 hours of operation. After 4,000 hours, the lamps continued to deliver sufficient output to meet the target dose for the City. Based on the results of this study, it is recommended that the scheduled lamp replacement frequency be changed from 4,000 hours to 5,000 hours at the Loudonville UV Facility.

Lamp sleeve fouling was also assessed during this study through regular removal and visual inspection of the lamp sleeves. During design, based on water quality data, lamp sleeve fouling was not expected to be a problem at the Loudonville UV Facility. The findings of this study are consistent with that belief. No fouling was observed while the automatic cleaning system was engaged. In addition, supplementing the automatic cleaning cycles with periodic manual cleaning provided no noticeable benefit and increased the potential for equipment damage. Fouling was observed on the lamp sleeves of a unit that was temporarily out of service, but not drained. This finding further emphasizes the importance of initiating a cleaning cycle prior to bringing units on line after a period of non-use.

In addition to the evaluation conducted during this study, the Loudonville UV Facility was also a participant in a fouling study that was conducted by Purdue University (Purdue Study). To assist in the Purdue Study, one UV unit was operated for a period of four weeks with its automatic cleaning system disabled. Based on the findings of that study, minor build-up on the lamp sleeves did occur during operation when the automatic cleaning system is disabled. Iron was the primary constituent of the foulant, representing over 80% of foulant on a molar basis. Calcium and Aluminum accounted for approximately 15% of the foulant, with manganese and zinc representing the remaining 5% on a molar basis. It was estimated that the reduction in dose as a result of the fouling was 1.20 mJ/cm^2 per day, or an approximate decrease of 10% over the 28 day test period (Waite, 2005). Given the high target dose at the Loudonville UV Facility, this reduction is relatively minor. However, for a system operating at a more typical target dose, these results illustrate the importance of preventing lamp sleeve fouling.

A power quality (PQ) monitor (I-grid) was installed in the 3 phase 480 volt incoming power feed line to the UV facility to monitor the PQ from October 2003 to June 2004. The I-grid monitors and records voltage sags and power interruptions and displays them on the I-grid website (http://www.i-grid.com), which can be accessed with the use of a secure password. During the monitoring period, the Loudonville UV Facility experienced 26 PQ events. Of those, only one PQ event tripped the UV unit and caused the lamps to lose arc. This PQ event was a voltage sag where the incoming voltage sagged to 45% of the nominal line voltage and lasted 6.2 cycles. Based on the data that were collected, it appears that the UV units at the Loudonville UV Facility are able to tolerate voltage sags between 65 and 45% of line voltage for 6.2 cycles. A shorter duration at this magnitude of voltage loss may cause the UV unit to trip, but data were not available to establish that threshold. The findings of this study indicate a higher tolerance to PQ events than described previously by the equipment manufacturer. No power interruptions occurred during the PQ monitoring period; therefore, the tolerance to power interruptions could not be determined.

An automatic transfer switch is used to switch the Loudonville UV Facility over to the emergency generator. To avoid repeated crossover during brown-outs or short duration blackouts, the Loudonville UV Facility must be manually switched back to the commercial grid. During the large blackout in August 2003, and several shorter duration blackouts that have occurred since the UV Facility began operation, the backup generators have successfully brought the UV Facility back on-line within less than one minute, with the lamps operating at full power in less than 5 minutes. Given the high quality of power at the Loudonville UV Facility and the short downtime for transfer to the emergency generator, an uninterruptible power supply is not needed.

UV disinfection is one of the technologies recognized by the EPA for inactivation of *Cryptosporidium*, and one of the few technologies accepted for high levels (2 to 3-logs) of *Cryptosporidium* inactivation. As illustrated by the Loudonville UV Facility, UV disinfection can also be effectively used in non-traditional

applications. It is hoped that this study, by identifying the wide range of items throughout the project that can significantly affect the energy efficiency and the level of inactivation credit that can be received, helps to increase the knowledge base that is available to utilities to ensure that this promising technology remains cost competitive and represents a viable long-term solution for the protection of public health.

Section 1
INTRODUCTION

1.1 STUDY OBJECTIVES

Although ultraviolet (UV) disinfection offers health and environmental benefits when compared to other traditional chemical disinfectants, it is a relatively energy intensive technology. Increasing the energy efficiency of the technology is necessary to ensure its continued success and to support the use of this promising technology.

The purpose of this New York State Energy Research and Development Authority (NYSERDA) co-funded project was to gather operating data on a large-scale operating UV facility and assess the opportunities to optimize the energy efficiency of UV disinfection through on site validation and control equipment maintenance. The results of this study are significant to the City of Albany (City) because they will allow the City to optimize the efficiency of its UV facility and develop an operating and maintenance strategy that provides peak UV facility performance and energy efficiency. The value to other potential applications in New York State, and the drinking water industry in general, is that the lessons learned and data that are gathered from this project can be applied to the design, implementation, and operation of other UV facilities to improve the long-term energy efficiency of this technology. Specific tasks completed as part of the study include:

- Conduct equipment validation using an expanded set of test conditions to assess the feasibility and potential benefits of advanced controls (e.g., adjustment of the number of lamps in operation in addition to the existing power level adjustment);
- Assess the accuracy and consistency of the UV intensity measurements of the duty sensors through ongoing execution of calibration checks using reference sensors;
- Assess the accuracy and long-term dependability of the on-line UV transmittance (UVT) monitors. Use the results to evaluate the energy and health implications of relying on an on-line UVT monitor versus periodic grab samples, bench top analysis and manual entry of the UVT value into the programmable logic controller (PLC);
- Assess the influence of flow meter configuration on its performance;
- Evaluate lamp output decay and spectral shift and compare the findings to manufacturer's previous research. Compare the results to variations in the accuracy of UV intensity sensors and assess the energy effects of these changes;
- Evaluate lamp fouling potential and assess the energy and operational effects of fouling;
- Evaluate power quality coming into the facility and the ability of the UV equipment to handle power variations;

- Assess performance of the backup energy supply and document the downtime experienced during the study period;
- Observe and document general operating performance of the facility;
- Develop a report, technology transfer Fact Sheets, and presentation of the study findings.

1.2 PROJECT BACKGROUND

The City has taken a proactive approach to achieve its mission to provide the highest quality water possible to its customers by upgrading treatment and operations at Loudonville Reservoir. The first phase of the water quality improvement project was the construction of an UV disinfection facility capable of treating up to 40 million gallons per day (MGD). The UV disinfection equipment was installed to operate in conjunction with the existing chlorine disinfection facility at the site. Incorporation of the UV facility provides multiple barrier disinfection and facilitates compliance with the requirements for uncovered storage under the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). Construction of the UV facility began in August 2002, and full-scale continuous operation commenced on April 2, 2003. As of the date of this report, the Loudonville UV Facility is the largest operating UV disinfection facility in a drinking water application within New York State.

1.3 SIGNIFICANT PAST RESEARCH FINDINGS

UV technology has been successfully used in wastewater disinfection applications since the 1980s. However, prior to the late 1990's, its use in drinking water applications within the United States was primarily limited to small groundwater systems because it was believed that the technology was ineffective against protozoa and not cost-effective for large systems. In 1998, research indicated that UV disinfection was effective against *Cryptosporidium* at low doses (Bukhari *et al.*, 1999), triggering extensive additional research on the subject. Additional work confirmed that UV disinfection is a cost-effective method of addressing *Cryptosporidium* and *Giardia* for small and large systems (Malley, 2000; Craik, et al., 2001, Danielson, et al., 2001; Hayes, et al., 2001; Oppenheimer, et al., 2002; Campbell and Wallis, 2002; Linden, et al., 2002; Mofidi, et al., 2002). These findings, in conjunction with the increased regulatory focus on microbial treatment and disinfection byproducts, have significantly increased the water industry's interest in UV disinfection.

Chemical disinfection treats water by destroying or damaging cellular structures, affecting metabolism or hindering growth of a target organism. Alternatively, UV disinfection inactivates pathogens by damaging their nucleic acid and preventing replication. Although the UV-inactivated organism may continue to survive, it cannot infect a host without the ability to replicate. UV disinfection relies on the transfer of energy in the form of UV light at germicidal wavelengths to the target organism. Studies have shown that UV disinfection at drinking water UV doses (less than 400 mJ/cm^2) does not affect the formation of

trihalomethanes or haloacetic acids for groundwater and filtered drinking water (Malley et al. 1995; Kashinkunti et al. 2003; Zheng et al. 1999; Liu et al. 2002; Venkatesan et al. 2003). This fact, when combined with the ability of UV technology to cost-effectively inactivate chlorine-resistant pathogens, is why UV disinfection has gained significant attention in recent years as the Stage 2 Disinfectants/ Disinfection Byproduct Rule (D/DBPR) and LT2ESWTR are finalized.

Because UV light relies on the damage of DNA and RNA for inactivation, research has been completed on the ability of a microorganism to repair damage that has been done by UV light (Rauth, 1965; Knudson, 1985; Linden, 2002; Linden, et al., 2002; Shin et al., 2001; Oguma et al., 2001). Bacteria have been shown to repair UV damage (Knudson, 1985); however, water containing chlorine or chloramines will inactivate bacteria in a drinking water distribution system. Viruses lack the enzyme that is necessary to repair but can use the enzyme from a host (Knudson, 1985). Research that has focused on *Giardia* and *Cryptosporidium* indicate that *Giardia* can repair but only when they are disinfected at very low doses (0.5 mJ/cm^2, Linden 2000). Research has found that *Cryptosporidium* may have the ability to undergo repair, but does not regain infectivity (Oguma et al., 2001). In general, for the purposes of drinking water treatment design, the repair of UV damage by *Cryptosporidium*, *Giardia* and viruses does not appear to be of concern.

1.4 REGULATORY AND MARKET TRENDS

The United States Environmental Protection Agency's (USEPA's) Surface Water Treatment Rule (SWTR) provides minimum disinfection requirements for systems using surface water or groundwater under the direct influence (GWUDI) of surface water. The focus of the SWTR is on the removal/inactivation of *Giardia* cysts and viruses. The Interim Enhanced Surface Water Treatment Rule (IESWTR) and Long Term 1 ESWTR (LT1ESWTR) build upon SWTR requirements by establishing baseline treatment requirements for *Cryptosporidium* by filtration systems. The LT2ESWTR will supplement these regulations by establishing additional treatment technique requirements for *Cryptosporidium* for systems with greater vulnerability to this pathogen. The LT2ESWTR will be implemented simultaneously with the upcoming Stage 2 D/DBPR.

The basis of the LT2ESWTR has been developed through the negotiations of a Federal Advisory Committee, which reached a consensus Agreement in Principle in September 2000. In essence, the LT2ESWTR will require additional treatment for *Cryptosporidium* by all unfiltered systems and by a subset of filtered systems with elevated source water *Cryptosporidium* levels as demonstrated through monitoring. The LT2ESWTR was proposed in June 2003, and the final LT2ESWTR is expected in Late 2005. UV disinfection is one of the technologies recognized for inactivation of *Cryptosporidium*, and one of the few technologies accepted for high levels (2 to 3 logs) of *Cryptosporidium* inactivation. Accordingly, there are specific requirements related to UV disinfection in the draft LT2ESWTR preamble. Because UV disinfection is a relatively new technology in the U.S. drinking water industry, the USEPA agreed to publish

UV disinfection guidelines as the "UV Disinfection Guidance Manual" (UVDGM). The purpose of the UVDGM is to facilitate planning, design, and operation of UV installations by familiarizing primacy agencies and utilities with important design, operation, and UV equipment validation issues. The LT2ESWTR proposal draft of the UVDGM was published in conjunction with the draft LT2ESWTR in June 2003. After the LT2ESWTR and the UVDGM are finalized by the USEPA, it is expected that the use of this technology will continue to increase.

One factor that could have a fairly significant effect on the market growth of UV disinfection within the water industry is the Calgon Carbon Corp (CCC) patent. If CCC's patent is upheld, the cost implications to the use of the technology are considerable. Historically, energy costs have represented the largest annual cost for medium sized and larger utilities that choose to implement UV disinfection. However, Calgon's licensing fee of $0.015 (one and a half cents) per 1,000 gallons of water treated would significantly exceed the energy costs associated with the use of the technology at these larger utilities. For a system treating 100 MGD on an annual average basis, the license cost would translate to almost $550,000 per year.

1.5 DESCRIPTION OF LOUDONVILLE UV FACILITY

The Loudonville UV Facility was constructed and is operated as part of the City's water quality enhancement program being implemented at Loudonville Reservoir. The UV facility is part of a dual-barrier disinfection strategy to maximize protection of public health and is one aspect of the City's ongoing risk mitigation efforts at Loudonville Reservoir to comply with the upcoming LT2ESWTR. The LT2ESWTR will require systems with uncovered finished water reservoirs to: 1) Cover the finished water reservoir, 2) Treat reservoir discharge to the distribution system to achieve 4-log virus inactivation, or 3) receive a determination from the State or Primacy Agency that existing risk mitigation is adequate. Elements of the City's current risk mitigation include:

- Ongoing water quality monitoring;
- Annual draining and cleaning of the reservoirs;
- Periodic batch chlorination of the reservoirs;
- Perimeter access fencing and 24-hour security surveillance;
- Bird wires;
- Diversion of runoff;
- Re-chlorination;
- UV disinfection.

The Loudonville UV Facility consists of four UVSwift™ 8L24 units manufactured by Trojan Technologies, Inc. (Trojan). Each unit contains 8 medium pressure (MP) lamps mounted within a 24-inch diameter stainless steel housing. The units are installed in parallel with a common, 48-inch diameter manifold on both the inlet and outlet sides of the units. Each unit is controlled by a dedicated control panel. Operation

of the four units operation is controlled by a common, master control panel. Through the incorporation of additional control logic and valve actuation, the UV equipment was designed to accommodate the highly variable, bidirectional flow experienced at the Loudonville site during its daily distribution storage function. The UV equipment is being operated to target virus inactivation. However, validation of the UV equipment and control strategy was only confirmed for levels between 0.0 and 1.5 –log virus credit, depending on the flow and water quality conditions (described in detail in Section 3).

The 8L24 units that are installed employ a calculated dose control strategy. The UV dose depends on the flow rate, the UVT of the water, and the lamp output intensity and is calculated using a proprietary dose algorithm developed by Trojan based on extensive research and modeling. The UV equipment installed in the Loudonville UV Facility utilizes electromagnetic ballasts, which allow the lamp intensity to be adjusted automatically between 60, 80, and 100% power to maintain a user specified dose setpoint while improving the energy efficiency of the equipment. Recently, Trojan has incorporated electronic ballasts into their 8L24 units. Electronic ballasts have historically not been as durable as electromagnetic ballasts, but offer a significantly larger range of power adjustment. The current electronic ballasts used in the 8L24 allow power to be adjusted from 30% to 100% in 3% intervals.

The flow rate through each unit is measured using a dual channel, strap-on ultrasonic transducer. UVT can be either manually input or automatically recorded based on measurements by on-line UVT monitors. Typically the UV equipment operates with the on-line UVT monitor measurements being automatically transferred to the PLC. Lamp output for each lamp is measured by UV intensity sensors installed adjacent to each lamp. A schematic layout of the Loudonville UV Facility is shown in Figure 1-1 and a photograph of the facility is shown in Figure 1-2.

Figure 1-1. Schematic Layout of Loudonville UV Facility

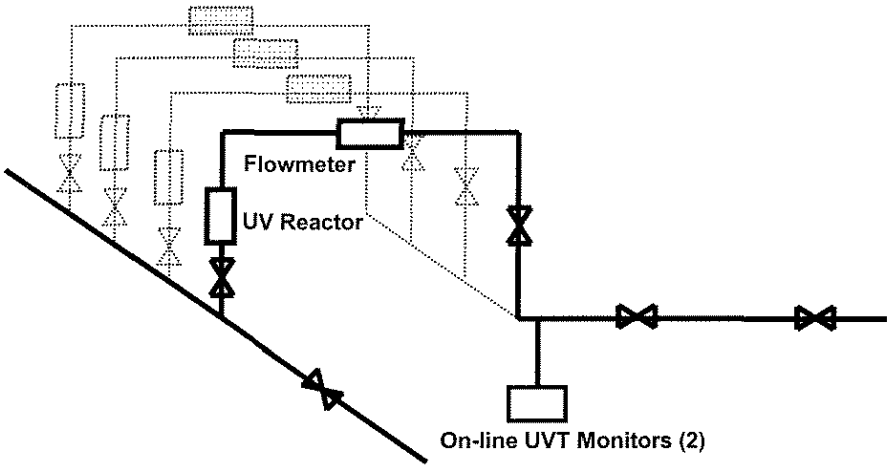
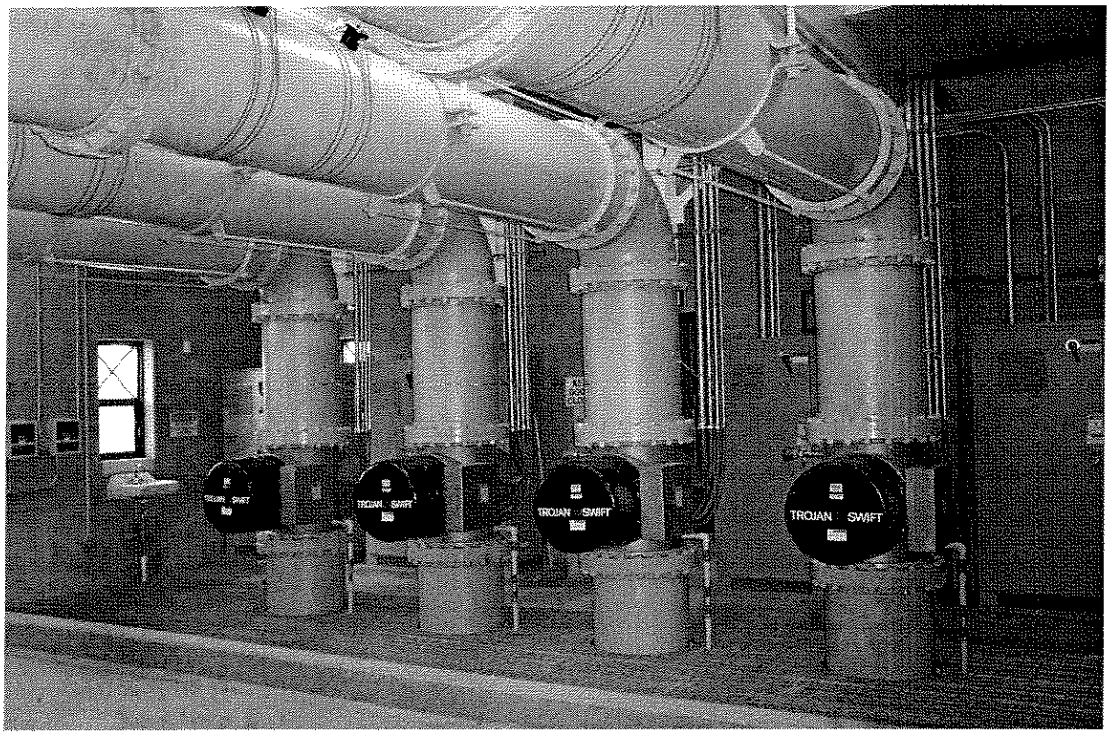


Figure 1-2. Loudonville UV Facility



Section 2

DESCRIPTION OF TECHNOLOGY

2.1 GENERAL DESCRIPTION OF UV LAMP TECHNOLOGY

UV light inactivates a target organism differently than chemical disinfectants. Chemical disinfectants inactivate microorganisms by destroying or damaging cellular structures, interfering with metabolism, and hindering biosynthesis and growth (Snowball and Hornsey, 1988). UV light inactivates microorganisms by damaging deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) and preventing the microorganisms from replicating. Because the microorganisms cannot reproduce, they are no longer able to infect a host. Variations in DNA content influence a microorganism's response to UV light and can affect the efficiency (i.e., UV dose necessary) of UV disinfection.

Although there are a variety of lamps capable of producing UV light, the most commonly used technology in the drinking water industry is mercury vapor lamps. There are currently two types of mercury vapor lamps that are typically used in large-scale drinking water applications: low pressure high output (LPHO) and medium pressure (MP). There are two primary differences between the lamp technologies:

- Germicidal Output Range - LPHO lamps emit nearly monochromatic light at 253.7 nanometers (nm). MP lamps emit light across a broad range of wavelengths between 200 and 400 nm.
- Power Output – MP lamps emit UV light at approximately 10 times the intensity of LP or LPHO lamps.

Other characteristics for mercury vapor UV lamps are provided in Table 2-1.

Table 2-1. Mercury Vapor Lamp Characteristics (USEPA, 2003)

Parameter	LPHO	MP
Germicidal UV light	Monochromatic at 254 nm	Polychromatic, including germicidal range (200 to 300 nm)
Mercury Vapor Pressure (torr)	0.76	300 – 30,000
Operating Temperature (°C)	130 – 200	600 – 900
Electrical Input (W/cm)	1.5 – 10	50 – 250
Germicidal UV Output (W/cm)	0.5 – 3.5	5 – 30
Electrical to Germicidal UV Conversion Efficiency (%)	30 – 40	10 – 20
Arc length (cm)	10 – 150	5 – 120
Relative Number of Lamps Needed for a Given Dose	Higher	Lower
Lifetime (hrs)	8,000 – 12,000	4,000 – 8,000

Despite differences in lamp characteristics, both technologies are highly effective for UV disinfection. The output of both lamps falls in the germicidal range, which is the wavelength range most responsible for inactivating microorganisms. The decision to use a specific technology is generally driven by operational

and design advantages and disadvantages that result from the differences in lamp characteristics and site-specific conditions, for instance:

- Because LPHO lamps produce light at a lower intensity, more lamps are required for a given application, resulting in larger UV units and process footprints.
- LPHO lamps have longer lamp life than MP lamps; however, the total number of lamps is typically higher for LPHO facilities, and both need to be considered when evaluating lamp replacement frequency.
- MP lamps consume more electrical energy per unit of germicidal light output than LPHO lamps.
- The higher operating temperature of MP lamps can accelerate fouling, which may increase the frequency of sleeve cleaning and also increase the frequency of replacing fouled components such as lamp sleeves and sensor windows. However, most MP units use automatic cleaning to mitigate fouling.

2.2 AVAILABLE CONTROL STRATEGIES

EPA requires monitoring of all operating UV disinfection facilities to demonstrate that adequate disinfection occurs. Because methods are not currently available to measure pathogenic organisms in real time, different strategies have been developed to monitor dose delivery. Currently, the UVDGM recognizes three fundamental approaches to monitor UV disinfection performance: the UV Intensity Setpoint Approach, the UV Intensity and UVT Setpoint Approach, and the Calculated Dose Approach.

2.2.1 UV Intensity Setpoint Approach

The first strategy for monitoring dose and controlling the UV unit uses a combination of flow rate and intensity sensor measurements. Adequate dose delivery is achieved when the measured intensity is above a setpoint value, which can change as a function of flow rate. The acceptable setpoint values for UV intensity over a range of flow rates are determined during validation testing. When using this control strategy, the UV intensity sensor is positioned at a distance from the lamp that allows it to concurrently respond to changes in lamp output as well as changes in UVT of the water. Because the location of the intensity sensor enables it to respond to changes in water quality, a separate UVT monitor is not necessary.

2.2.2 UV Intensity and UVT Setpoint Approach

The second control strategy is similar to the first; however, in this approach, the intensity sensor is placed much closer to the lamp, and a separate UVT monitor is used. Because the distance between the lamp and the sensor is short (~2-3 cm), the absorbance of the water is negligible, and the intensity sensor only responds to changes in lamp output. At a specific flow rate, adequate dose delivery is achieved when UVT and UV intensity are above setpoint values, both of which can change as a function of flow rate.

2.2.3 Calculated Dose Approach

In the third approach, the UV intensity sensor is placed close to the lamp, which is similar to the UV intensity and UVT setpoint approach. Flow rate, UVT, and UV intensity are all monitored, and the measurements are used to calculate UV dose using a validated computational algorithm developed by the UV equipment manufacturer. This is the control strategy employed by the City of Albany.

2.2.4 Validation of Control Strategies

All control strategies need to be verified through validation testing. The validation tests will determine the operating characteristics for the UV equipment. All UV units should be tested over a range of combinations of flow rate and UVT. For UV units that employ a calculated dose approach, possible lamp power settings must also be included in the matrix of validation test conditions.

Section 3
EQUIPMENT VALIDATION

3.1 VALIDATION PROCESS

Validation testing is conducted to verify the performance of the UV equipment and establish the range of acceptable operating conditions. To ensure a UV unit is appropriately-sized for a given application, validation testing should provide data on dose delivery and monitoring under design conditions of flow, UVT, and lamp output. If the UV equipment is installed to meet the LT2ESWTR, USEPA requires that the UV equipment is validated to establish the conditions that the UV unit can effectively deliver the dose needed to achieve the level of inactivation required for a given application or the level of inactivation credit sought by the utility.

3.1.1 Validation Procedure

The validation procedure determines the log inactivation for a specific pathogen and relates it to the operating conditions at the time of the testing (e.g., UVT and flow rate). The experimental portion of the validation process, called biodosimetry, consists of the following steps:

- Inject a challenge organism into the water stream;
- Measure the concentration before and after exposure to UV light;
- Calculate the log inactivation achieved through the unit.

Because the true UV dose delivered to the challenge microorganisms during biodosimetry cannot be directly measured, a separate test (called a collimated beam test) is conducted to relate the inactivation measured in the field to a measured UV dose value. In collimated beam testing, microorganisms are exposed to UV light under carefully controlled conditions in the laboratory that allow for a direct calculation of UV dose. The UV dose and observed inactivation are used to create a UV dose-response curve. The log inactivation from the biodosimetry test is then related to a UV dose from the UV dose-response curve. This dose is termed the reduction equivalent dose (RED). In validation, biodosimetry is performed over a range of flow rates, UVT, and lamp power combinations. The observed log inactivation is then correlated to operational conditions and UV intensity sensor values. Figure 3-1 illustrates this process.

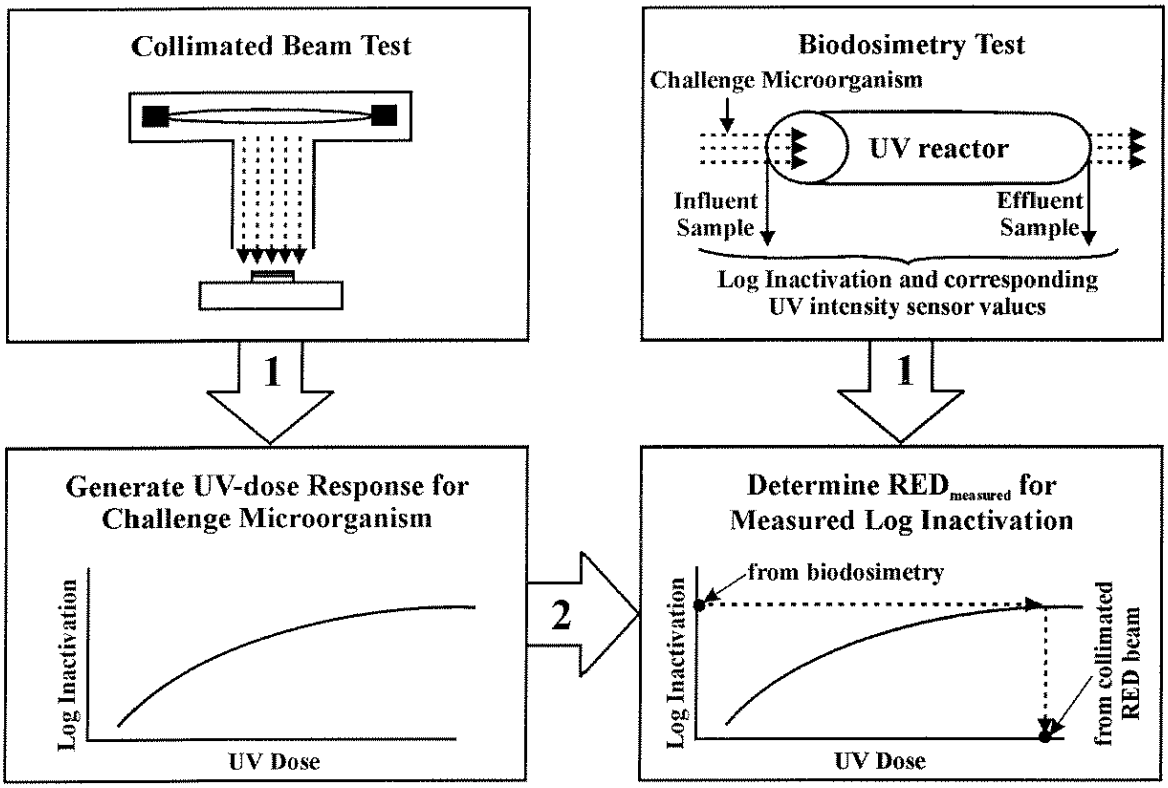


Figure 3-1. Biodosimetry Process (USEPA, 2003)

The RED that is demonstrated is then adjusted based on site-specific factors of safety that account for differences between the dose-response of the challenge organism and the dose-response of the target organism (RED bias), differences between the operating conditions during validation and those that are expected during full-scale operation (polychromatic bias), and uncertainty associated with the control equipment measurements taken during validation (uncertainty factor). The demonstrated RED is then divided by the cumulative factor of safety to determine the actual dose for which the utility will receive inactivation credit.

3.1.2 USEPA Validation Recommendations

The USEPA has a recommended validation protocol that was proposed in June 2003, updated in January 2005, and is expected to be final in late 2005. This section summarizes the most recent validation protocol from January 2005.

To account for the uncertainty associated with UV equipment validation and on-line UV dose monitoring, EPA recommends that the RED measured during validation be divided by the equipment factor (EF) to determine the validated RED (see Equation 3.1). The equipment factor accounts for the bias and uncertainty in validation and UV dose monitoring and is defined according to Equation 3.2.

$$RED_v = \frac{RED}{EF} \qquad \text{Equation 3.1}$$

$$EF = B_{RED} \times B_{Poly} \times (1 + U) \qquad \text{Equation 3.2}$$

Where,

RED_v	=	Validated RED
RED	=	Reduction equivalent dose
EF	=	Equipment factor
B_{RED}	=	RED bias
B_{Poly}	=	Polychromatic bias
U	=	Expanded uncertainty expressed as a fraction

In validation testing, the target pathogens are not directly used because they can result in infectious disease. Instead, non-pathogenic "challenge" organisms are used. However, these challenge microorganisms do not have the same UV dose-response as the regulated pathogens. Because the target and challenge microorganisms have a different dose-response, there is a bias when using the challenge microorganism to estimate the inactivation of the target microorganism. The RED bias is a correction that accounts for this difference in dose-response for the two organisms.

The polychromatic bias is a correction that accounts for polychromatic differences between validation test conditions and the actual conditions of the installed UV equipment. The polychromatic bias applies only to specific UV equipment that uses polychromatic (e.g., medium-pressure mercury-arc) UV lamps. Low pressure and low pressure high output UV equipment and medium pressure UV equipment with germicidal UV intensity sensors do not have a polychromatic bias.

The expanded uncertainty, U, accounts for error in measurements made during validation and uncertainty associated with the equipment installed at the utility. Both factors impact the uncertainty of inactivation credit achieved by the UV equipment.

EPA recommends that the validated RED (RED_v) be greater than or equal to the required UV dose ($D_{req'd}$) to achieve a given level of pathogen inactivation credit, as shown in Equation 3.3. The validated RED values can then be used to generate relationships among UV dose, flow rate, and UVT.

$$RED_v \geq D_{req'd} \qquad \text{Equation 3.3}$$

Table 3-1 shows the dose required to achieve a given level of inactivation credit for *Cryptosporidium*, *Giardia*, and viruses.

Table 3-1. UV Dose Requirements for Inactivation of *Cryptosporidium*, *Giardia* and Viruses During Validation Testing (USEPA, 2003)

	Log Inactivation							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.5
Cryptosporidium	1.3	2.5	3.9	5.8	8.5	12	-	-
Giardia	1.5	2.1	3.0	5.2	7.7	11	-	-
Virus	39	58	79	100	121	143	163	186

The validation process outlined in the 2003 Draft UVDGM was the most current USEPA approach at the time validation testing was performed at the Loudonville UV Facility. The 2003 Draft UVDGM validation protocol included two tiers of analysis. Tier 1 was a simple approach with a set EF but required equipment to meet specific, stringent criteria and could result in a more conservative RED_v. Tier 2 allowed for greater flexibility in equipment design and was generally less conservative; however, the process was much more complicated. A Tier 2 analysis was conducted for the Loudonville UV Facility because the equipment, specifically the intensity sensor, did not meet the criteria for a Tier 1 analysis. Using the Tier 2 analysis also resulted in a reduced equipment factor. It should be noted that the January 2005 UVDGM revisions combined the Tier 1 and 2 approaches into a single approach.

3.1.3 Target Pathogen

The target pathogen is typically selected during the design phase of the project. In some cases, the utility may wish to assess inactivation of more than one target pathogen (e.g., *Giardia* and viruses). The RED bias value is different for each target pathogen due to differences in the dose-response characteristics of the target pathogens. Because of the varied RED bias values, it is imperative that the utility clearly define their disinfection objectives prior to selecting the equipment or developing a validation protocol and matrix of test conditions.

Currently there is not a challenge microorganism that can demonstrate REDs above approximately 120 mJ/cm^2. Commonly used challenge microorganisms are either too sensitive to UV light or unable to be injected into the influent stream at high enough concentrations to ensure viable microorganisms are present in the effluent during validation testing. Without challenge microorganisms in the effluent from the UV unit, it is not possible to determine the actual RED_v. As a result, all that can be demonstrated is the ability to provide greater than 2-log inactivation of viruses. Therefore, even though the equipment may be delivering a much higher dose, the maximum virus inactivation credit that a utility can receive for a single UV unit is limited to 2-log. This creates difficulty for utilities that are targeting higher levels of virus inactivation credit.

3.1.4 Validation Logistics

UV equipment validation has two key logistical issues – validation location and third party oversight. Validation can either occur on-site or off-site. In on-site validation, the UV equipment is validated at the utility after it has been installed. In off-site validation, the UV equipment is pre-validated prior to installation, typically at a third-party validation test center. The advantages and disadvantages of on-site and off-site validation are presented in Table 3-2.

Table 3-2. Comparison of On-site and Off-site Validation

Validation Location	Advantages	Disadvantages
On-Site	• Validation occurs using the exact hydraulics of the installation • Water quality during validation is specific to the installation • Having provisions for on-site validation (e.g., feed and sample ports and static mixers) allows flexibility for future testing to optimize performance	• Facility is designed and constructed before equipment performance is verified • Water quality is limited to the highest UVT at the facility during the assigned validation period • Testing logistics can be complex, and cost is often higher than off-site validation • Disposing test water may require special permits
Off-Site	• A broader range of flow and water quality are tested so a unit can be validated for more than one application • Installation hydraulics are general, allowing for installation at most WTPs • The process is simpler, and cost is usually lower • Performance of units is known before design and construction of facility	• Re-validation may be necessary if site specific hydraulics and water quality do not fall within the validated ranges • Water quality may not match the installation location, potentially resulting in inefficient operations • Polychromatic bias and uncertainty may be greater resulting in less efficient operations • Validation data are not typically site-specific, limiting the ability to optimize operations

In 2003, two off-site validation testing centers were in operation within the United States, one in Portland, Oregon and the other at the Gloversville-Johnstown Wastewater Treatment Plant in Johnstown, New York. UV equipment manufacturers typically use the off-site validation centers to test their equipment under a wide range of flow rate, UVT, inlet and outlet conditions, dose targets, and lamp output conditions so that broad application of the equipment is possible. Validation results apply not only to the actual UV equipment used during validation testing, but also to all UV equipment that is manufactured to the same specifications as the validated equipment when the unit is installed under the USEPA inlet and outlet piping recommendations.

Third-party oversight is when an independent entity with no stake in the validation outcome witnesses and verifies key components of the validation testing. Individuals qualified for such oversight include engineers

experienced in testing and evaluating UV equipment and scientists experienced in the microbial aspects of biodosimetry. Oversight includes, at a minimum, witnessing the validation testing and verifying that the documented validation protocol was followed, the documented equipment was tested, and the reported data and results are accurate.

3.2 VALIDATION OF LOUDONVILLE UV FACILITY

As designed, the Loudonville UV Facility has three lamp power setpoints for the eight lamps in each UV unit. The power to the lamps is adjusted to these three settings in response to water quality, flow rate, and measured lamp intensity. The City needed to validate this control system to ensure that the installed UV equipment performed as specified under the contract with the UV manufacturer. In addition, validation tests were completed to determine if there were opportunities to improve energy efficiency and to determine what level of virus inactivation was possible.

The Loudonville UV Facility was designed in late 2001 before any validation centers were operational in the United States. Therefore, on-site validation was selected for the Loudonville UV Facility. In addition, the City believed on-site validation would provide a more accurate assessment of the performance of the UV equipment under their site specific water quality and hydraulic conditions, which would reduce the factors of safety necessary in design and validation. The Loudonville UV Facility is a new facility in a new building; therefore, the design of the facility could easily incorporate the necessary space and features needed to conduct on-site validation including:

- Space for storage of challenge organism and UV absorber supply;
- Ports for injection of challenge microorganism and the UV absorber;
- Sufficient pipe length between the injection port and the UV unit for thorough mixing of the challenge microorganism and UV absorber;
- Several sampling ports upstream and downstream of the UV unit;
- Ability to isolate one of the four UV units and associated piping;
- Suitable location to discharge the treated water during validation testing.

3.2.1 Purpose of Loudonville UV Facility Validation

Trojan was required under their contract to conduct on-site validation of the equipment through microorganism challenge events at varying flow rates, UVT levels, and intensity settings. There were three primary objectives for conducting on-site validation of the City's facility:

- Confirm equipment performance;
- Assess opportunities for expanded control;
- Assess the effectiveness against viruses.

The first item, confirmation of equipment performance, was to confirm the ability of the equipment to deliver a 40 mJ/cm^2 RED under peak flow and worst case UVT conditions and to establish the acceptable range of operating conditions for the UV equipment. The second objective, assessment of opportunities for expanded control, was conducted to assess opportunities of expanding lamp control (e.g., expanded range of power adjustment or added control over the number of lamps that are energized) to improve the energy efficiency of the UV equipment. The third objective, to assess the equipment's effectiveness against viruses, was conducted to determine the level of virus inactivation credit that the City could receive under specific operating conditions.

Another positive outcome of the validation testing was the ability to evaluate the separate factors included in EPA's recommended "equipment factor" to determine if there were methods of reducing the equipment factor during validation or design and thereby reduce the energy consumption of the UV equipment during full-scale operation.

3.2.2 Validation Testing Preparation

As described above, the EF consists of three elements: RED bias, polychromatic bias, and expanded uncertainty. There is an opportunity with each of these EF elements to optimize and potentially reduce the EF. To develop the validation protocol for the Loudonville UV Facility, the components that make up the equipment factor were analyzed to identify opportunities for reducing each component of the EF and to develop an estimate of the EF. An estimate of the EF is necessary to develop a target measured RED for validation testing.

The RED bias value is influenced by the target and challenge microorganisms that are selected and the level of inactivation that is desired. Although *Cryptosporidium* is not the target organism for the City, because it is the organism for which the greatest amount of validation experience exists in North America, it was selected as the basis for confirming equipment performance meets the contract requirements. All other validation testing was based on viruses being the target pathogen. The two challenge microorganisms that were most commonly used at the time of the validation planning were MS2 bacteriophage and *Bacillus Subtilis*. For *Cryptosporidium*, the RED biases were calculated based on USEPA recommendations and were estimated to range from 1.9 to 2.4 for MS2 and 1.9-2.5 for *B. Subtilis*. MS2 was selected because there is more validation experience in North America with this challenge microorganism and because the RED bias for the both organisms is very similar.

As mentioned previously, there was not an established challenge organism (i.e., MS2) that could prove greater than 2.0 log virus inactivation at the time of this project. The RED bias for the virus validation tests was set to 1.0 because the challenge microorganism is more sensitive to UV disinfection than viruses (USEPA, 2005).

The polychromatic bias only applies to medium pressure UV equipment that has UV intensity sensors that respond outside of the DNA germicidal range. The Trojan Technologies' units installed in the Loudonville UV Facility have UV intensity sensors that require a polychromatic bias to be used. When polychromatic bias applies, the bias depends on the UV absorber used during validation to reduce the UVT of water. It should be noted that a polychromatic bias only applies when the UV absorbers are applied during the validation test runs (i.e., when ambient UVT is used, there is not a polychromatic bias). Typical UV absorbers are instant coffee and lignin sulphonate. The polychromatic bias to reduce the UVT to 88% (the worst case UVT to be tested at the Loudonville UV Facility) was estimated to be 1.12 for instant coffee and 1.08 for lignin sulphonate. Instant coffee was chosen by the City because it was considered more environmentally friendly and because the overall polychromatic bias did not change substantially.

The expanded uncertainty includes numerous uncertainty terms from validation testing, including the reference and online UV intensity sensor, collimated beam tests, the calculated log inactivation, and the data analysis of all test runs. The expanded uncertainty can be reduced by careful quality assurance during validation tests and in the laboratory evaluations. The estimated expanded uncertainty was between 20% and 40%, and the expanded uncertainty was expected to be approximately 30% based on previous validation testing completed by Trojan Technologies and GAP Environmental.

In summary, the estimated EF was between 2.8 and 3.6 for the *Cryptosporidium* validation tests and between 1.4 and 1.5 for the virus validation tests. This large difference in EF between *Cryptosporidium* and virus tests is due to the RED bias.

3.2.3 Description of Validation Testing

Validation testing was completed at the Loudonville UV Facility from October 20 to 23, 2003. The entities involved in the validation testing and their overall responsibility is summarized in Table 3-3.

Table 3-3. Validation Roles

Entity	Description	Responsibility
City of Albany	Facility owner and operator	Operated UV facility during validation testing
Malcolm Pirnie	UV Facility designer	City of Albany's representative
Trojan Technologies	Supplier of UV equipment	Performed validation testing
GAP Environmental	Microbiology lab	Performed collimated beam study and analyzed microbial samples
Dr. James Malley	Professor at University of New Hampshire	Third party oversight of the contract validation
Ms. Christine Cotton, P.E.	Malcolm Pirnie Project Engineer	Third party oversight of NYSERDA validation tests

The validation test conditions encompassed a range of flow rates and lamp operating conditions as summarized in Table 3-4. The biodosimetry procedure described in Section 3.1 was generally followed in validation tests; the specific validation procedure is described in Appendix A.

Table 3-4. Validation Test Conditions

Test Date	Index #	Water Type	UVT (%/cm)	Number of lamps	Lamp Power (%)	Flow rate (USMGD)	Objective*
10/22/03	1	Reservoir	99.0	6	0	10.0	Control
10/22/03	2	Reservoir	99.2	6	0	9.9	Control
10/22/03	3	Reservoir	99.1	6	60	9.9	Power
10/22/03	4	Reservoir with coffee	87.5	6	80	9.9	Power
10/22/03	5	Reservoir with coffee	87.2	6	60	2.0	Power
10/22/03	6	Reservoir with coffee	87.4	4	60	2.0	Power
10/22/03	7	Reservoir	99.0	4	80	10.1	Power
10/22/03	8	Reservoir with coffee	88.7	4	100	10.0	Power
10/22/03	9	Reservoir	99.9	4	0	10.0	Control
10/23/03	1	Reservoir	98.5	8	0	9.8	Control
10/23/03	2	Reservoir	98.3	8	0	9.7	Control
10/23/03	3	Reservoir	98.5	8	100	9.9	Virus
10/23/03	4	Reservoir	98.6	8	60	9.8	Contract
10/23/03	5	Reservoir with coffee	87.4	8	60	9.7	Contract
10/23/03	6	Reservoir with coffee	87.5	8	100	9.9	Virus
10/23/03	7	Reservoir	98.5	8	60	5.0	Contract
10/23/03	8	Reservoir with coffee	87.8	8	60	4.9	Contract
10/23/03	9	Reservoir	98.1	8	60	2.0	Contract
10/23/03	10	Reservoir with coffee	88.0	8	60	2.0	Contract
10/23/03	11	Reservoir	98.6	8	0	10.3	Control

*Virus – Test conditions to assess the feasibility of virus inactivation at Loudonville UV Facility
*Power – Test conditions to assess energy optimization opportunities
*Control - Control test conditions to establish baseline information, source water quality, test set-up, and test validity.

3.2.4 Validation Challenges

During the validation testing and data analysis, two unexpected issues arose. First, before the validation testing began, it was discovered that there were inconsistencies between the flow measurement from two flowmeters – the flowmeter for the UV unit being tested and a downstream flowmeter in the chlorination building. To confirm the performance of the two flowmeters, a manufacturer's representative came on-site to assess the setup of both flowmeters and verify the UV unit flowmeter with a portable flowmeter. It was determined that the UV unit flowmeter was accurately measuring flow.

The second issue emerged when Trojan Technologies was evaluating the validation data. Each day, control samples were collected when no MS2 was being injected and all lamps were off to ensure that MS2 was not present in the reservoir water and that MS2 was not adhering to the sample tubing. The first control sample, collected on day one prior to any injection of the challenge organism, returned a non-detectable count for

MS2. However, subsequent control samples collected at the effluent sampling port detected MS2, even though MS2 was not reported in the influent control samples. After analyzing the data, the following conclusions were reached:

- A sidestream bleed-in of challenge organism upstream of the UV unit likely occurred in all validation runs following the initial high concentration injection;
- The sidestream bleed-in was a result of a low concentration accumulation of challenge organism within the interface of the 48-inch diameter piping downstream of the 24-inch vertical riser containing the UV unit being validated;
- The concentration and volume of the sidestream bleed-in was very small when compared to the injection concentration and total volume of water run through the UV facility during each validation run;
- The sidestream bleed-in occurred because the piping configuration relied partially on hydraulics to provide a completely isolated system for validation and, although apparently very limited, a small amount of mixing may have occurred at the hydraulic interface;
- No contamination of sample tubing, piping, or valves between the UV unit and the outlet sample point occurred.

Based on these conclusions, the validation data was deemed representative of the performance of the equipment with any error likely being on the side of conservatism.

3.2.5 Validation Results

The validation testing of the UV equipment at the Loudonville UV Facility verified the following goals:

- The UV equipment met the performance conditions established in the equipment procurement document;
- Under specific conditions, effective dose delivery could be provided with a reduced number of energized lamps;
- The UV equipment could achieve a range of virus inactivation, depending on the UVT and flow rate.

The validation results are summarized in Table 3-5.

Table 3-5. Summary of Validation Results [1]

Test Date	Index #	UVT (%/cm)	# of lamps	Lamp Power (%)	Flow rate (MGD)	RED meas[2]	Poly Bias	Equip Uncert	RED Bias		Equip Factor		Validated RED[3]		Validated Credit[4]	
									Crypto	Virus	Crypto	Virus	Crypto	Virus	Crypto	Virus
10/22/03	3	99.1	6	60	9.9	140.8	1.0	1.3	2.1	NA	2.8	NA	50.3	NA	3.0	0.0
10/22/03	4	87.5	6	80	9.9	47.4	1.3	1.3	2.1	NA	3.7	NA	12.8	NA	3.0	0.0
10/22/03	5	87.2	6	60	2.0	102.2	1.4	1.3	2.1	NA	3.8	NA	26.9	NA	3.0	0.0
10/22/03	6	87.4	4	60	2.0	58.1	1.3	1.3	2.1	NA	3.5	NA	16.6	NA	3.0	0.0
10/22/03	7	99.0	4	80	10.1	147.1	1.0	1.3	2.1	NA	2.8	NA	52.5	NA	3.0	0.0
10/23/03	3	98.5	8	100	9.9	>120.0	1.0	1.3	2.0	1.0	2.6	1.3	46.2	92.3	3.0	1.5
10/23/03	4	98.6	8	60	9.8	>120.0	1.0	1.3	2.0	1.0	2.6	1.3	46.2	92.3	3.0	1.5
10/23/03	5	87.4	8	60	9.7	37.4	1.3	1.3	2.0	1.0	3.5	1.7	10.7	22.0	2.5	0.0
10/23/03	6	87.5	8	100	9.9	65.1	1.3	1.3	2.1	1.0	3.5	1.7	18.6	38.3	3.0	0.5
10/23/03	7	98.5	8	60	5.0	>120.0	1.0	1.3	2.0	1.0	2.6	1.3	46.2	92.3	3.0	1.5
10/23/03	8	87.8	8	60	4.9	55.8	1.3	1.3	2.0	1.0	3.4	1.9	16.4	29.4	3.0	0.0
10/23/03	9	98.1	8	60	2.0	120.0	1.0	1.3	2.0	1.0	2.7	1.3	44.4	92.3	3.0	1.5
10/23/03	10	88.0	8	60	2.0	108.4	1.3	1.3	2.1	1.0	3.5	1.7	31	63.8	3.0	1.0

[1] Control tests are not shown in this table
[2] RED measurements for three test runs are shown as greater than values because MS2 was completely inactivated and there were non-detectable MS2 counts in the effluent.
[3] See Table 3.1 for USEPA required doses to compare with validated RED
[4] Validated for the Loudonville UV Facility per the June 2003 EPA proposed validation protocol using the Tier 2 method of calculating the equipment factor (i.e., safety factor)
NA – Not applicable

As mentioned previously, the approach included in the 2003 Draft UVDGM protocol to calculate the EF is relatively complex, and the USEPA recommended calculation of the EF is different for each validation test run. For these validation tests, the EF ranges from 2.6 to 3.8 for the *Cryptosporidium* tests and from 1.3 to 1.9 for the virus tests. To avoid an excessively complex control strategy for the UV equipment, a single EF is typically used. Therefore, the highest EF should be met under all conditions to ensure compliance with the validation results over the range of potential operating conditions. This approach inherently results in conservative operation and potential energy waste.

The validation tests were not able to demonstrate a high level of virus inactivation due to the challenge microorganism issues discussed in Section 3.1.3. If the City wanted to obtain 4-log virus credit using currently available challenge organisms and the current validation test results, they would need to install two UV units in series and add the validated UV doses for each UV unit. This could result in excessive energy use. The water industry has recognized the limitations of current challenge organisms in this regard and is working to identify other, suitable challenge organisms that will allow validation of much higher doses. Ideally, the organisms will be more sensitive to UV light than viruses, allowing a RED bias of 1.0 to be used, but able to be titered at sufficiently high concentrations to avoid zero counts in the effluent during validation testing.

The validation tests also assessed the Trojan Technologies' dosimeter ™. The validation tests found that the dosimeter ™ conservatively and closely predicted the RED in 13 out of 19 validation tests. The project team requested that calibration factor be adjusted such that the dosimeter ™ conservatively predict the REDs for all conditions observed during validation.

Section 4
CONTROL EQUIPMENT PERFORMANCE

The UV unit and lamp operation at the Loudonville UV Facility is controlled using a calculated dose algorithm. The calculated dose is estimated once every 15 seconds using the UV intensity measurements for all eight lamps, the UVT measurement, and the flow rate measurement. The calculated dose is compared to the dose setpoint that has been established for the application. Based on that comparison, the control panel automatically increases or decreases the lamp power to maintain the calculated dose at or above the dose setpoint as efficiently as possible. As necessary, additional units are brought on-line or taken off-line to maintain the dose setpoint. The accuracy of the algorithm was assessed during validation, as described in Section 3. This section describes the performance tests completed on the elements that influence the calculated dose algorithm, specifically the UV intensity sensors, UVT monitors, and flowmeters.

4.1 UV INTENSITY SENSORS

The manufacturer's design of the 8L24 units installed in the Loudonville UV Facility includes four sensor shafts, each of which is equipped with two UV sensors on opposite sides of the shaft to monitor the two lamps adjacent to the sensor shaft. Photographs of UV intensity sensor and sensor shafts are shown in Figure 4-1. A cross section of a UV unit showing the lamp and sensor locations is shown in Figure 4-2 (L-lamp and S-Sensor). The sensors in the 8L24 units installed in Albany respond to light in the 200-360 nm wavelengths, which does not match DNA absorbance. As such, the sensors are classified by USEPA as non-germicidal sensors (see Section 3 for implications). The measured intensities for all lamps in each unit, in mW/cm^2, are sent as a 4/20 mA signal to the UV control panel for use in the dose algorithm.

Figure 4-1. Photos of UV Intensity Sensor and Unit

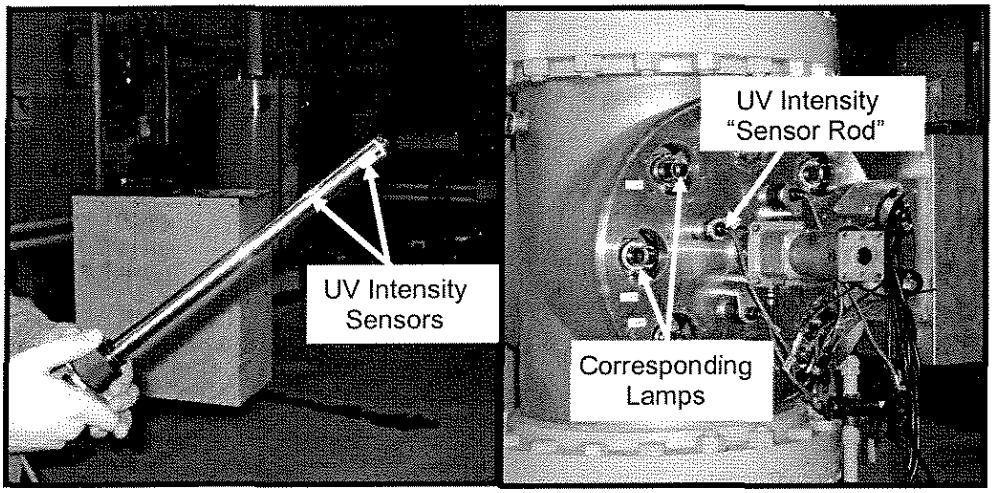
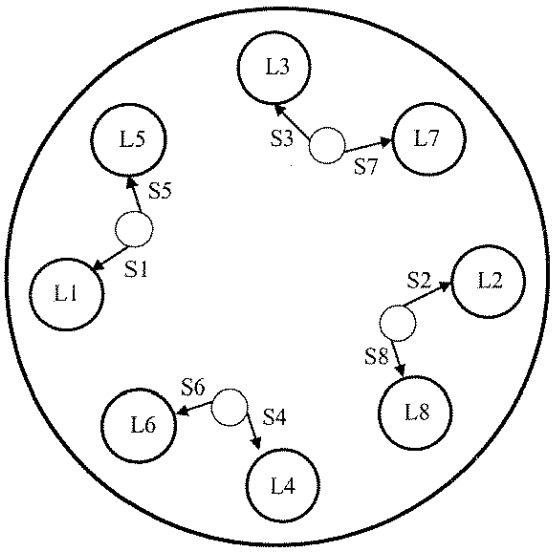


Figure 4-2. Lamp and Sensor Configuration



4.1.1 Purpose of Evaluation

While UV intensity sensors are a critical component of the UV disinfection facility, limited full-scale operating data are available in the United States regarding the accuracy and consistency of the initial calibration. In addition, there is limited information on the level of maintenance and calibration that is required to maintain optimum performance and the effect of using multiple sensors within the unit. The primary goals of the UV intensity sensor evaluation were to:

- Assess the accuracy and consistency of the UV intensity sensors;
- Determine the frequency that UV intensity sensors should be checked against the reference sensor during normal operations;
- Identify any trends in UV intensity sensor performance that may affect the operating efficiency of the equipment.

4.1.2 Methodology

Prior to installation, manufacturers calibrate the UV intensity sensors. However, over time the sensor may drift out of calibration. USEPA recommends that the calibration of each duty sensor be checked at least monthly against the reference sensor. To assess the initial accuracy and consistency of the UV intensity sensors, a manufacturer-provided reference sensor was utilized to confirm the accuracy of the UV intensity sensor measurements for the City of Albany. Although USEPA recommends monthly checks, the UV intensity sensors were checked on a weekly basis to better understand how well sensors perform and identify any short-term variations in performance. The sensor checks were performed on the UV intensity sensors for two units (Unit #2 and Unit #4), using the recommended USEPA calibration check approach

and the pre-programmed procedure in the UV unit control panel. The Trojan pre-programmed procedure for UV intensity sensor checks is included as Appendix B.

The USEPA recommended protocol to assess the UV intensity sensor calibration is described below (USEPA, 2003):

1. Measure the UV intensity with the UV intensity sensor and record the measurement result.

2. Replace the UV intensity sensor with the reference sensor in the same location (i.e., port) as the UV intensity sensor used in Step 1.

3. Measure the UV intensity with the reference sensor and record the measurement result.

4. Determine if Equation 6.1 holds true for the two UV intensity sensor readings:

$$\left(\frac{I_{Duty}}{I_{Ref}} - 1\right) * 100 \leq \left(\sigma_{Ref}^2 + \sigma_{Duty}^2\right)^{1/2}$$

Where:

I_{Ref}	=	Intensity measured with the reference sensor (mW/cm^2)
I_{Duty}	=	Intensity measured with the on-line sensor (mW/cm^2)
σ_{Duty}	=	Measurement uncertainty of the on-line UV intensity sensor (%) as provided by the UV manufacturer in the validation report
$\sigma_{Reference}$	=	Measurement uncertainty of the reference UV intensity sensor (%) as provided by the UV manufacturer in the validation report

5. Replace the UV intensity sensor with another calibrated UV intensity sensor if the relationship Equation 6.1 does not hold true.

It should be noted that the equation above does not have an absolute value around the left side of the equation. Therefore, if the discrepancy between the duty sensor and the reference sensor is conservative (meaning the duty sensor reading is less than the reference sensor reading), then any error is acceptable because the values on the left of the inequality are negative.

To illustrate this outcome, it is assumed that the reference sensor reads 10 mW/cm^2, the on-line sensor reads 5 mW/cm^2, and both sensor uncertainties are 14%. In this example, the on-line sensor would pass the above criterion because the error is conservative (the above equation holds true: $-50 < 20$). However, while assessing sensor performance in this manner ensures protection of public health, it is not reflective of the

desired level of sensor performance to address energy efficiency. If the duty sensor reading is low, then more power would be used to keep the UV unit within the validated conditions, which increases energy consumption and costs.

The majority of the reference sensor checks were performed on a unit running at 100% power; however, several checks were run at 60% or 80% power, depending on the flow conditions. When the flow through the UV units was negative (indicating the Loudonville Reservoir was in "fill" mode), the power level of the units could not be increased to 100%, due to specific programming included in the control logic. The data collected during the reference sensor checks were recorded and have been evaluated to identify any trends in UV intensity sensor performance that may affect the operating efficiency of the facility, as described in the next section.

4.1.3 Results and Conclusions

Based on information provided by the manufacturer, the duty and reference sensors have an uncertainty of 14%, which was used to assess the performance of the sensors during this study. The sensors were in calibration 92% of the time. As discussed previously, the majority of the sensor checks were conducted when the lamps were at 100% power. However, numerous sensor checks were conducted during periods when the lamp power was less than 100%. Sensor performance was not affected by the lamp power setting during the sensor check. Additionally, when lamps were replaced either due to aging or damage, the performance of the sensors was not affected. Example calibration data for one sensor is provided in Figure 4-3. Table 4-1 summarizes the number of reference checks performed per lamp for Units 2 and 4 and the percentage of acceptable calibration checks based on the uncertainty of the equipment.

Figure 4-3. Calibration Data for UV Intensity Sensor for Lamp 5, Unit 2

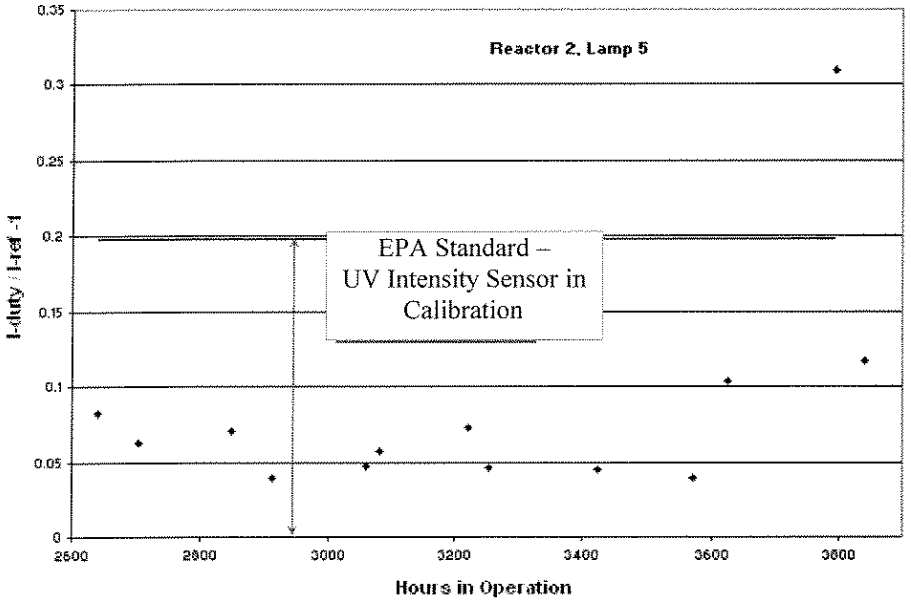


Table 4-1. Summary of UV Intensity Sensor Calibration Checks

	Unit 2 Lamp No.								Unit 4 Lamp No.							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Number of Sensor Checks	13	14	12	3	13	3	12	14	20	20	19	19	20	20	21	21
Number of Acceptable Checks	13	13	12	3	12	3	10	13	20	20	19	19	20	20	19	20
Percent Acceptable	100	93	100	100	92	100	83	93	100	100	100	100	100	100	90	95

Throughout the study period, a total of 14 separate calibration events were performed on Unit #2 and 21 separate calibration events were conducted on Unit #4. Not all sensors within a given UV unit underwent the same number of calibration checks (most noticeably Sensor #4 and Sensor #6 in Unit #2) due to problems encountered with specific sensors during some of the earlier calibration events. In all, a total of 244 individual sensor checks were performed during the calibration events with only eight individual sensor failures. To allow an ongoing assessment of sensor performance, the sensors were not sent back to be recalibrated when they failed the calibration test. Only once was the same sensor out of calibration two weeks in a row. All eight of the failures occurred during unusual flow conditions that would not be expected in a more typical installation at a treatment plant. These incidents included a change in flow direction during the sensor check, reverse flow during the sensor check, insufficient lamp warm-up time prior to conducting the sensor check, and an extreme flow change (an increase of nearly 100%) during the sensor calibration procedure.

The main observations from the UV intensity sensor checks are summarized below:

- The sensors performed well;
- The calibration check procedure was simple;
- There was not a difference in UV sensor calibration performance at different lamp power levels;
- Some of the sensors were out of calibration one week and back in calibration the next week, which most likely occurred due to the flow conditions discussed above. Applications with more stable flow conditions would likely yield more consistent results;
- As expected, the sensor performance did not change when the lamp was changed in between calibration checks.

4.2 ON-LINE UVT MONITORS

The UV units operate based on a number of conditions, including flow rate, UV transmittance of the influent water, and UV intensity. The UV transmittance (UVT) is measured using two online UVT monitors (UVT-A and UVT-B) that draw water from a pipe just downstream of the UV equipment. These monitors transmit real-time UVT to the UV equipment control panel as an input to the dose algorithm. Because UV disinfection and UVT monitors are relatively new, it is not known how long UVT monitors retain their calibration.

4.2.1 Purpose of Evaluation

The primary goals of regularly sampling and measuring the UVA for the facility are as follows:

- Confirm the accuracy of the on-line UVT monitors and assess any changes that occur over time; and
- Allow a comparison of the energy use for the facility if grab samples had been the sole source of UVA measurement.

4.2.2 Methodology

As part of this study, two grab samples of the water were collected from the Loudonville UV Facility per week. The on-line UVT readings at the time of sample collection were recorded for both UVT-A and UVT-B. The grab samples were analyzed by the City of Albany laboratory located at the Feura Bush filtration plant using a bench top spectrophotometer. The results of these bench top analyses were used to confirm the accuracy of the on-line UVT monitors and assess changes in performance that occur over time.

4.2.3 Results

During the early stages of the study, the on-line UVT monitors reported inconsistent readings. As originally designed, the sample ports for the on-line UVT monitors were located at the midpoint of the pipe and at the top of the pipe. It was determined that the samples collected at the top of the pipe were occasionally erroneous due to air bubbles in the sample. To correct the problem, the sample ports for the on-line UVT monitors were modified so that all samples were collected at the midpoint of the pipe. In addition, there were several instances where small debris was drawn into the UVT monitors, causing them to malfunction. The UV plant operator installed a small screen in the sampling tube, which eliminated this problem.

When assessing the other control components, EPA recommended procedures were used. However, the 2003 Draft UVDGM does not have a procedure to assess UVT monitor calibration. When assessing the calibration of the UVT monitors, several key issues need to be considered about UVT measurement and the technology that is utilized by the UVT monitors. Because of the manner in which UVT is calculated, the level of uncertainty increases at higher values of UVT (lower UVA), which are typical of the Loudonville UV Facility.

One method to assess the uncertainty is to determine the relative difference between the UVA values measured by the on-line monitors versus the UVA values measured by a benchtop spectrophotometer (i.e., assessing performance relative to the bench top spectrophotometer measurement). Because the UVT measurement is on a log scale (i.e., the UVA measurements are on a linear scale (see equation 4.1)), the relative uncertainty was assessed based on UVA measurements. The relative uncertainty, meaning the percent difference as a fraction between the measurements recorded by UVT meter A and the measurements made using the bench top spectrophotometer, ranged from 0.4% to 4.7%. Data for the period between November 10, 2003 and March 29, 2004 are shown in Figure 4.4. The gaps in the plot are due to periods of time when the on-line UVT meter was off-line for repairs and modification. The relative differences observed were low; therefore, the UVT monitor performed well and remained in calibration during this study.

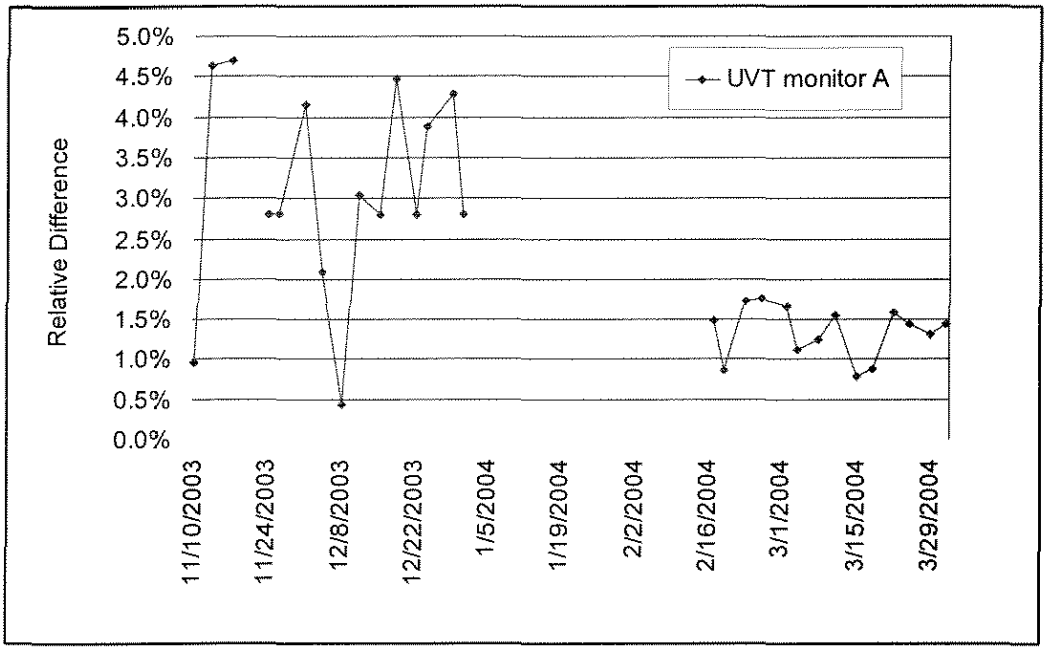
$$\% \ UVT = 100 * 10^{-UVA} \qquad \text{Equation 4.1}$$

Where,

UVT = UV transmittance at specified wavelength (e.g., 254 nm) and pathlength (e.g., 1 cm)

UVA = UV absorbance at specified wavelength as measured by modified version of Standard Method 5910B, based on 1-cm pathlength (unitless)

Figure 4.4. Relative Difference in Online UVT Monitor (UV-A) and Bench Top Spectrophotometer



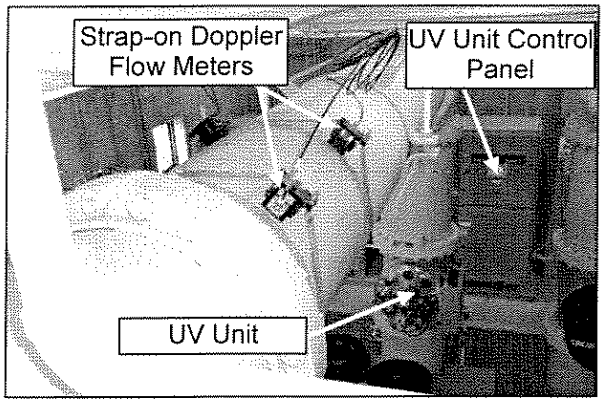
Given the issues presented on UVT measurement and the assessment of performance, additional research on the calibration of a range of UVT monitors would assist in establishing a universal method for assessing UVT monitor calibration. In the absence of a standard procedure, it is difficult to directly assess the UVT monitor calibration at the Loudonville UV Facility.

UVT has a significant affect on the lamp intensity that is needed to deliver a specific target dose. In general, there are three approaches that can be used to account for UVT when controlling a UV facility. The first is to manually enter the worst case historic UVT value into the control system for the equipment and collect periodic grab samples for benchtop analysis to confirm that the entered value is conservative. This method provides a fairly high level of protection of public health, but is not energy efficient. The second approach is to collect grab samples for benchtop analysis at regular intervals (e.g., daily, twice per week, etc.) and manually enter the measured values. This approach provides a greater level of energy efficiency, but provides a lesser degree of certainty that the disinfection objectives are being met because there is the potential that the actual UVT is lower than that measured with the previous grab sample, resulting in a reduced dose delivery. The third approach, and the one used at the Loudonville UV Facility, is to utilize on-line UVT monitors to measure and record UVT in real-time. As long as the UVT monitors are accurately measuring UVT, this alternative is the most energy efficient approach and provides the greatest level of protection for public health. While the use of on-line UVT monitors typically represents the highest capital cost of the three alternatives, it may provide the lowest life-cycle cost for certain applications due to reduced labor and improved energy efficiency. The most appropriate approach for a utility will depend upon the level of variation that is seen in the UVT of the water, the rate at which UVT changes, the potential energy savings that could be realized, and the disinfection objectives of the facility.

4.3 FLOW METERS

The Loudonville UV Facility utilizes strap-on Doppler-type flow meters for flow measurement through each of the UV laterals. The flow measurements are the final inputs that are sent to the PLC for use in the UV dose calculation. Figure 4-5 illustrates the flow meter configuration for Unit #4.

Figure 4-5. Photo of Flow Meter for Unit #4



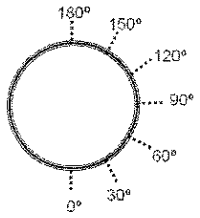
4.3.1 Purpose of Evaluation

Generally, the accuracy of a flow meter will vary based on its upstream and downstream separation distance from any bends, valves, or other hydraulic disturbances. In this case, the manufacturer recommended that the meter be installed equidistant from the 90 degree bends to reduce their influence on the flow measurement. Therefore, the location was not further evaluated as part of this study. However, the strap-on ultrasonic flow meters can also vary their position along the circumference of the pipe, which could also influence the flow measurements. The influence that radial position has on the flow measurement was evaluated.

4.3.2 Methodology

Each of the UV unit trains has both an influent and an effluent control valve. This analysis was performed during validation testing when the UV facility was isolated from the distribution system and there were no variations in static or dynamic pressure. To conduct this evaluation, the downstream control valve was positioned to establish a steady flow rate of approximately 10 MGD. This valve position remained unchanged and the flow meter was rotated radially around the horizontal pipe section to assess the effect that the radial location has on the accuracy of the flow meter. Figure 4-6 illustrates the meter configurations as tested.

Figure 4-6. Flow Meter Locations Assessed



4.3.3 Results and Conclusions

As shown in Table 4-2, the percent difference in measured flow versus the average of all readings is less than three percent for all radial positions that were evaluated. Therefore, the radial location of the flow meter does not noticeably affect the accuracy of the flow measurement and UV dose calculation.

Table 4-2. Flow Measurements at Different Configurations

Flow Meter Position	Velocity Measurement	Flow (MGD)	Percent Difference (based on average flow of 10.13 MGD)
30°	4.74	10.27	1.4%
60°	4.71	10.21	0.7%
90°	4.66	10.13	0.0%
120°	4.66	10.15	0.2%
150°	4.53	9.89	2.4%

Section 5

POWER QUALITY ASSESSMENT

5.1 PURPOSE OF EVALUATION

UV lamps can potentially lose their arc (i.e., UV lamps go out) if a voltage fluctuation, power quality (PQ) anomaly, or a power interruption occurs. The specific power quality tolerances depend on the UV equipment design and vary significantly among UV manufacturers (Table 5-1). Because common water treatment processes are not as sensitive to these PQ fluctuations, WTPs may not be aware that their PQ can cause significant problems with UV units. In addition, the water industry did not have a significant amount of data on PQ at WTPs until a recent American Water Works Association Research Foundation Study (Cotton et al., 2005).

Table 5-1. Power quality triggers for a range of UV manufacturer equipment (Cotton et al, 2005) *

Power Quality Event		LPHO Manufacturer #1	LPHO Manufacturer #2	MP Manufacturer #1	MP Manufacturer #2
Voltage Sag /Swell Tolerance	Voltage †	+/- 20%	+/- 10%	+/- 30%	+/- 20%
	Duration ‡	2 sec	> 2 cycles	> 1 cycle	2 sec
Power Interruption Tolerance§	Duration ‡	> 3 cycles	> 2 cycles	> ½ cycle	> 3 cycles

* Information shown in table is compiled from Calgon Carbon, Trojan, and Wedeco.
† Percent of line voltage. For example, a 10% voltage loss is when the voltage is at 90% of the line voltage
‡ 1 cycle is =0.017 sec
§ Power interruption assumes total voltage loss.

After a PQ event, low-pressure lamps generally can return to full operating status within 15 seconds after power is restored. However, low-pressure high output (LPHO) and medium-pressure (MP) facilities that are more typically used in drinking water applications exhibit significant restart times. The start-up and restart behavior for LPHO and MP lamps are summarized in Table 5-2. Recent discussions with UV manufacturers indicate that UV units currently do not incorporate supplemental power conditioning equipment to address PQ issues.

Table 5-2. Range of start and restart times for LPHO and MP lamps (Cotton et al., 2005)[1]

Lamp Type	Cold Start [2]	Warm Start [3]
LPHO	0-2 min warm-up + 4-5 min to full power total time: 4 – 7 minutes	0-2 min warm-up + 2-5 min to full power total time: 2 – 7 minutes
MP	No warm-up or cool-down + 1-5 min to full power [4] total time: 1 - 5 minutes	2-5 min cool down + 2-5 min to full power [4] total time: 4 - 10 minutes

[1] Information shown in table is compiled from Calgon Carbon, Trojan, and Wedeco. The manufacturer needs to be contacted to determine the start and restart times for specific equipment models.
[2] A cold start occurs when UV lamps are started when they have not been operating for a significant period of time.
[3] A warm start occurs when UV lamps are started after they have just lost their arc (*e.g.*, due to voltage sag).
[4] 60% intensity is obtained after 3 minutes.

During these restart periods, the water flowing through the UV unit is not being adequately disinfected, and there may be an increased pathogen risk. If a WTP has PQ problems, this could result in a significant amount of time that under-disinfected water is sent to the customer. In addition, USEPA will limit the amount of water distributed under these conditions (i.e., off-specification). The main objective of this research was to determine the prevalence of PQ problems at the Loudonville UV Facility and what PQ events would trigger the UV units to shut-down for the actual installed equipment.

5.2 METHODOLOGY FOR EVALUATION

A PQ monitor (I-grid monitor) was installed in the 3 phase 480 volt incoming power feed line to the UV facility to monitor the PQ from October 2003 to June 2004. The I-grid monitors and records voltage sags and power interruptions and displays them on the I-grid website (http://www.i-grid.com), which can be accessed with the use of a secure password. The I-grid collects 96 voltage measurements and records 32 of these measurements for every 60-hertz cycle (Divan et al, 2002). The researchers compared the PQ events documented by the PQ monitor to the SCADA data and system alarms to identify those PQ events that caused the UV lamps to lose their arc.

5.3 RESULTS

The power quality data collected from the I-grid monitor is summarized in Table 5-3. Overall, the Loudonville UV Facility experienced very few power quality events, and only voltage sags were observed (i.e., no interruptions). Although not specifically observed in Albany, the other categories of PQ events that are monitored by the I-grid are also shown in Table 5-3.

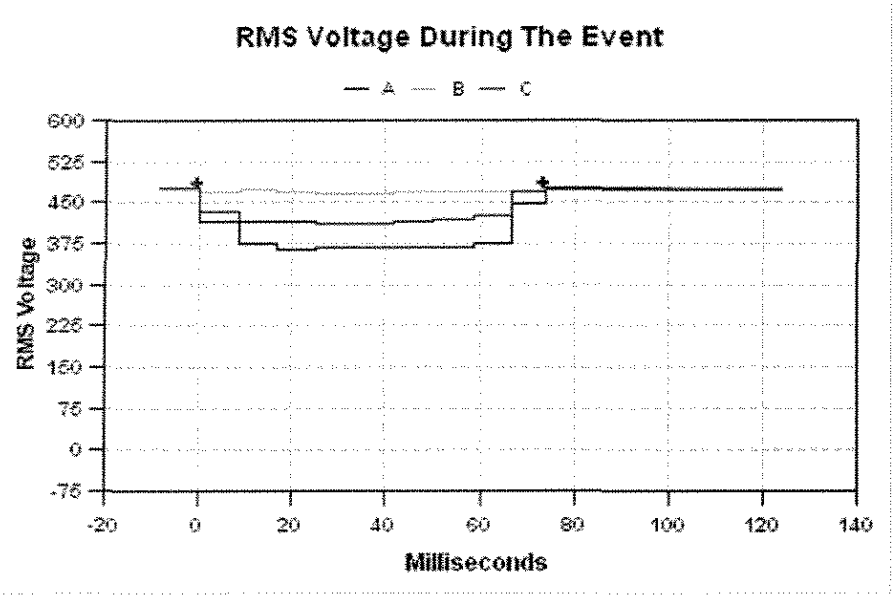
Table 5-3. Summary power quality events from October 2003 to June 2004

Power Quality Event	Voltage (percent of nominal)	Range of Duration of Event	Total	Monthly Average	Maximum Month
Instantaneous Voltage Sag	10 to 90	0.5 to 30 cycles[1]	25	2.78	6
Momentary Voltage Sag	10 to 90	30 cycles to 3 seconds	1	0.11	1
Temporary Voltage Sag	10 to 90	3 seconds to minute	0	0	0
Instantaneous Swell	> 110	0.5 to 30 cycles[1]	0	0	0
Instantaneous Interruption	< 10	0.5 to 30 cycles[1]	0	0	0
Momentary Interruption	< 10	30 cycles to 3 seconds	0	0	0
Temporary Interruption	< 10	3 seconds to minute	0	0	0
Sustained Deep Undervoltage	10 to 90	Over 1 minute	0	0	0
Sustained Interruption	< 10	Over 1 minute	0	0	0

[1] 1 cycle equals 0.017 seconds

As shown above, the Loudonville UV Facility experienced 26 PQ events during the 9 month monitoring. However, only one PQ event tripped the UV unit and caused the lamps to lose arc. This PQ event was a voltage sag where the incoming voltage sagged to 45% of the nominal line voltage and lasted 6.2 cycles. In Albany, voltage sags that ranged from 65% of line voltage for 4.8 cycles to 81% of line voltage for 31 cycles did not cause the UV units to trip. Based on these data, it appears that voltage sags that would cause a UV unit to trip are between 65 and 45% of line voltage for at least 6.2 cycles. A shorter duration at this magnitude of voltage loss may cause the UV unit to trip, but data were not available to establish that threshold. The findings of this study indicate a higher tolerance to PQ events than described previously by the equipment manufacturer. Again, it should be noted that Albany did not experience any power interruptions during their PQ monitoring; therefore, the tolerance of power interruptions could not be determined for the Loudonville UV Facility. A plot of the incoming line voltage around the period of the momentary voltage sag as recorded by the I-grid and downloaded from the I-grid website is shown as Figure 5-1.

Figure 5-1. Plot of Incoming Voltage



In general, UV units may have unique PQ tolerances that may be better or worse than shown previously in Table 5-1 because of different electrical and ballast designs. As discussed above, the UV equipment installed at the Loudonville UV Facility performed better under the installed conditions than expected based on manufacturer's data. More information is needed to determine the PQ tolerances of the different UV equipment available or the same equipment if it were to be installed in a different application or configuration. It may be helpful for water utilities to request the PQ tolerances of each UV unit and to have the tolerances independently verified to ensure these tolerances are accurately reported.

Section 6

VARIATIONS IN LAMP OUTPUT

6.1 PURPOSE OF EVALUATION

The amount of UV light that reaches the water and subsequently the pathogens are reduced over the lifetime of a lamp. The two primary causes of the reduction in delivered UV light are:

- **Lamp aging** - a decrease in lamp intensity or a shift in spectral output over time;
- **Sleeve fouling** – an accumulation of deposits on the lamp sleeve, which can block the UV light from reaching the target organisms.

The rate at which a lamp ages is a function of the lamp technology, the number of operating hours, the number of on/off cycles, and the total power applied per lamp length. In LP lamps, aging is limited to a decrease in lamp output at the 253.7 nm wavelength. For MP lamps, aging can consist of a decrease in output at various wavelengths and a shift in the spectral output. The rate of fouling depends on water quality, sleeve temperature, and the effectiveness of the cleaning system or cleaning regime that is used. This evaluation discusses the importance of selecting the appropriate fouling/aging factor, examines previous studies that have been done on lamp fouling and lamp aging, and describes the specific methodology and findings of this study.

6.2 IMPORTANCE OF FOULING/AGING FACTOR

Currently, general industry practice is to account for the effects of lamp aging and sleeve fouling when designing a facility through the use of a lamp fouling/aging factor. This factor is intended to prorate the output of a lamp to its expected end-of-life output, which is the lamp output that the UV manufacturer uses to determine the UV unit design. The fouling/aging factor is developed by the designer based on lamp aging characteristics provided by the manufacturer and an assessment of the fouling potential of the proposed installation. Typical fouling/aging factors range from 0.5 to 0.9. The Loudonville UV Facility was designed and validated using a fouling/aging factor of 0.6. Selecting an appropriate fouling/aging factor is very important. Applying a factor that is too conservative to the design can result in significant over-design, higher capital costs, and increased energy use during operation. Applying a fouling/aging factor that is not conservative enough can place public health at risk, significantly increase the frequency of lamp replacement and cleaning, or limit operating flexibility. The correct fouling/aging factor balances these three items.

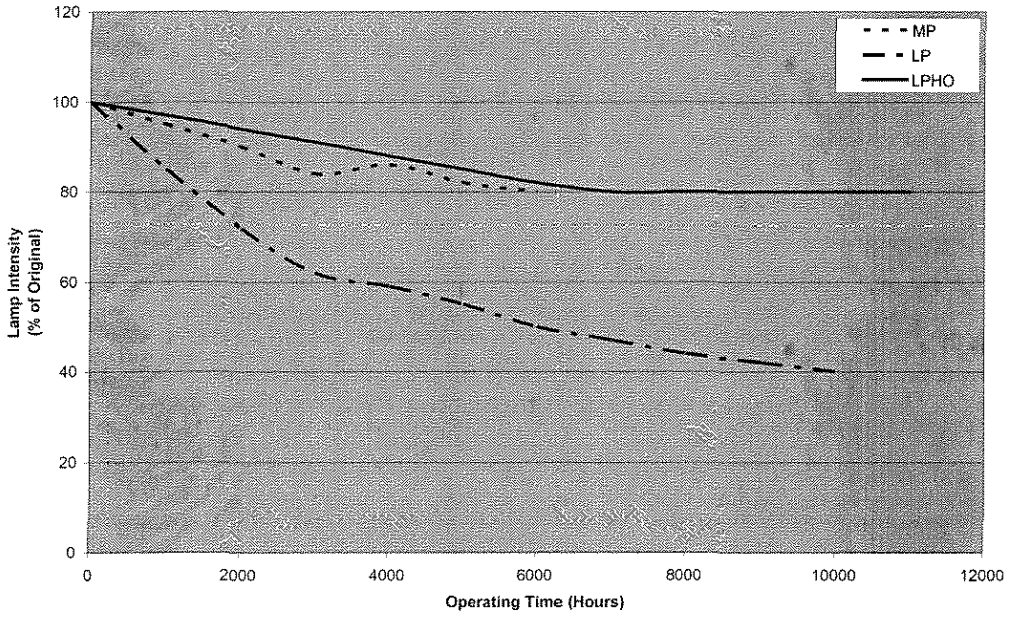
6.3 RESULTS OF PREVIOUS STUDIES

Data regarding lamp aging and fouling are somewhat limited because there are few studies and many have not published their results. This section will summarize the most current industry research, recognizing that future research may differ.

6.3.1 Aging Studies

Lamp aging can be described as a decrease in lamp intensity or a shift in spectral output over time. The 2003 Draft UVDGM and the ultraviolet disinfection industry accept that there is a decline in lamp intensity over time. Lamp output for all lamp technologies degrades rapidly in the first. After approximately 5,000 hours of operation, LP lamps have lost approximately 40% of their output (Schenck, 1981). After approximately 4,000 hours of operation, MP and LPHO lamps have lost approximately 15 to 20% of their output (Sharpless et al., 2003). Sharpless (2003) also observed a greater decrease in lamp output at lower wavelengths (below 240 nm) than at higher wavelengths. Figure 6-1 graphically illustrates the approximate intensity output decay characteristics for MP, LP and LPHO lamps as a function of operating time.

Figure 6-1
Lamp Intensity as a Function of Operating Time (Adapted from Schenck 1981)



Non-uniform aging of MP lamps may result in a shift in output spectrum. Although the 2003 Draft UVDGM recognizes this phenomenon, Sharpless et al. (2003) did not observe any shift in the spectral output of MP lamps after 4,000 hours of operation. Studies completed by Trojan Technologies, Inc., also show no noticeable spectral shift in output. There is a current research study sponsored by the AwwaRF that is also examining this effect; however, results from that study are not yet available. Figure 6-2 and Figure 6-3 illustrate Trojan Technologies, Inc. findings. Figure 6-2 shows the spectra for lamps with

100 hours and 5,000 hours in arbitrary units and spectra normalized by the area under the 365nm peak. Figure 6-3 presents the normalized total output energy as a ratio for the aged and new lamps. The ratios are based on the total output for each of the five spectral ranges presented in Figure 6-2.

Figure 6-2. Spectral output after 100 and 5,000 hours (Trojan Technologies, Inc.)

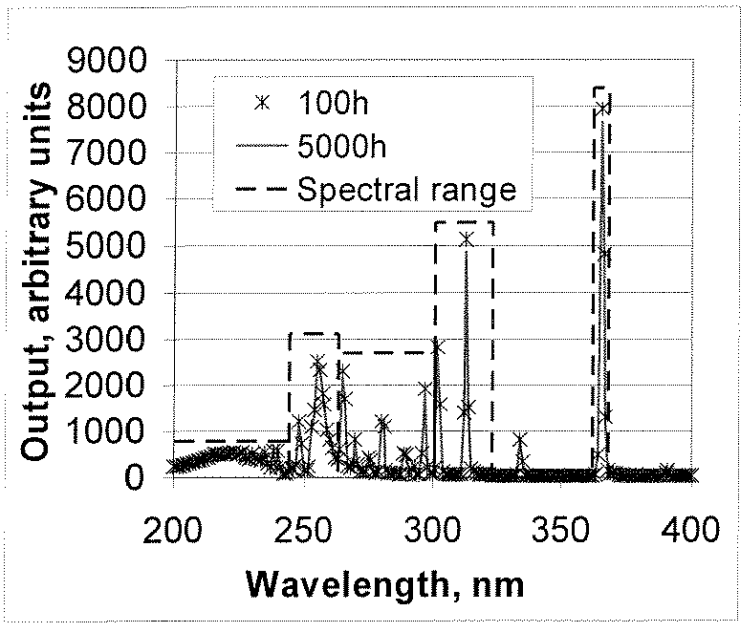
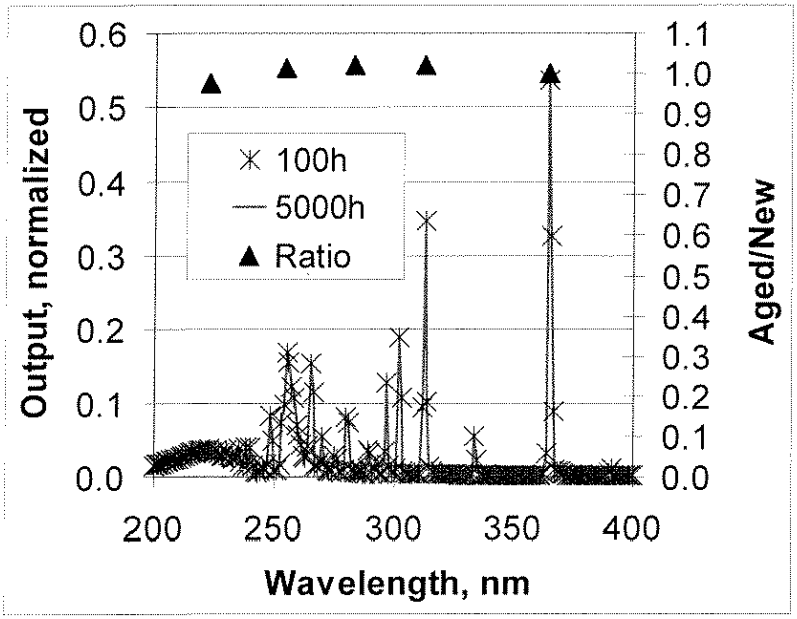


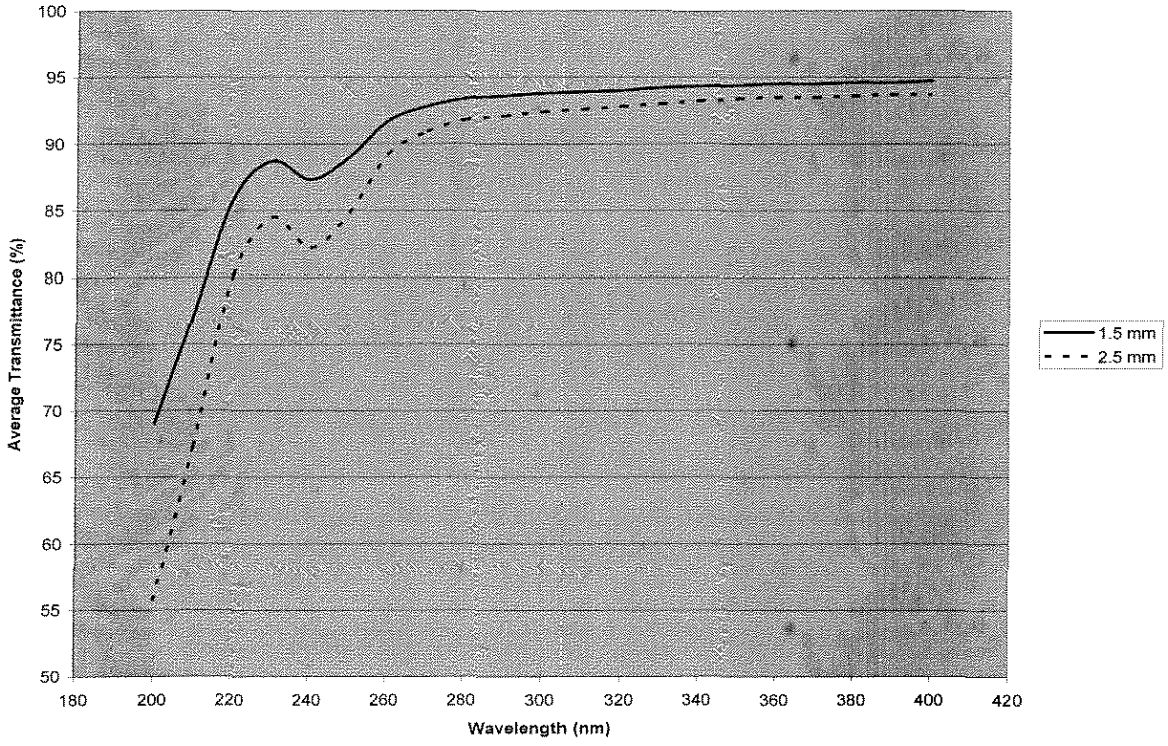
Figure 6-3. Ratio of spectral output after 100 and 5,000 hours (Trojan Technologies, Inc.)



6.3.2 Fouling Studies

The transmittance of UV light through the lamp sleeve is critical to ensuring the performance of a UV disinfection facility. It should be noted that the quartz sleeve itself has specific UV transmittance characteristics. The ability of the sleeve to effectively transmit UV light to the treated water is related to energy use needed to deliver a given target dose. If the raw material specifications or sleeve design result in less efficient transmission of UV light, then the amount of energy required to deliver the same dose will be greater. Figure 6-4 illustrates the average transmittance of UV light for wavelengths between 200 nm and 400 nm for Type 214 fused quartz sleeves. Data gathered by Trojan for a sleeve wall thickness of 1.5 mm and 2.5 mm are presented. The findings are consistent with UVT data published by a major manufacturer of Type 214 fused quartz, GE Scientific. As expected, UVT decreases with increasing wall thickness. Sleeves must be designed to withstand the expected operating pressures, including possible surge conditions. As such, manufacturers must balance the increased strength provided by thicker sleeve walls with the reduced UVT that is provided.

Figure 6-4
UV Transmittance of Type 214 Fused Quartz Sleeve (Trojan Technologies, Inc.)



The rate of sleeve fouling depends on several water quality parameters (hardness, alkalinity, pH, iron concentration, calcium concentration, temperature), the effectiveness of the sleeve cleaning equipment or regime, and lamp temperature. Fouling is typically caused by precipitation of compounds with low solubility or compounds where the solubility decreases as temperature increases (e.g., $CaCO_3$).

In general, MP lamps are more susceptible to certain types of fouling than LPHO lamps because of their higher operating temperatures. However, fouling data from several pilot scale studies indicates that for a calcium hardness below 140 mg/L and iron concentration less than 0.1 mg/L, standard sleeve cleaning protocols are sufficient to control sleeve fouling and keep UV light delivery at levels suitable for effective disinfection (Mackey et al. 2004). Extensive, full-scale operating data related to fouling are not available, making it difficult to reliably predict lamp sleeve fouling based solely on water quality. Site-specific evaluations are typically needed to determine the fouling potential as well as the effect it has on lamp output and disinfection effectiveness.

6.4 METHODOLOGY FOR EVALUATION

6.4.1 Visual Assessment

On a weekly basis, two lamps were removed from units #2 and #4, and visually inspected them for physical markings, such as spots, cloudiness, fouling at lamp ends, fiberglass "hairs", and glass condition. The interior and exterior condition of the lamp was recorded, along with the length of fouling and darkening at the ends of the lamp, and the degree of visible necking. Lamp #2 (from both units) was inspected every week, and the second lamp was rotated amongst the other 7 lamps. Once per month, the units were drained, and the corresponding sleeves were inspected and observations were recorded for the interior and exterior condition (i.e., electrode "burns" and other blemishes) and the general condition of the quartz (i.e., chipped, cracked, etc.). Throughout the study period, the automatic cleaning mechanisms for both Unit #2 and Unit #4 were enabled. In addition to automatic cleaning, supplemental manual cleaning of the lamp sleeves for Unit #4 was conducted on a monthly basis. The monthly schedule that was followed during the four month study period is summarized below:

- Week 1:
  - Unit 2: Remove and Inspect Lamps 2 and (1, 3, 4, 5, 6, 7, or 8)
  - Unit 2: Remove Corresponding Sleeves and Inspect (do not clean)
  - Unit 4: Remove and Inspect All Lamps
  - Unit 4: Remove, Inspect and Clean Corresponding Sleeves
- Weeks 2, 3, and 4:
  - Unit 2: Remove and Inspect Lamps 2 and (1, 3, 4, 5, 6, 7, or 8)
  - Unit 4: Remove and Inspect Lamps 2 and (1, 3, 4, 5, 6, 7, or 8)

6.4.2 Data Assessment

A large number of alarm conditions and status indicator tags are continuously monitored and recorded for the Loudonville UV Facility. Among these tags are UVT, flow rate, power setting, calculated dose, and lamp run time. These tags were downloaded for the period from October 2003 through April 2004 and

were evaluated to identify possible trends in lamp intensity output decay. Because of the limited number of tags available in the PLC, lamp intensity is not directly recorded. However, by identifying operating points at which the UVT, power setting, and flow rate were nearly identical, variations in intensity were able to be interpolated from the calculated dose, which is recorded.

6.5 RESULTS

6.5.1 Sleeve Fouling

The water quality criteria used in the design of the Loudonville UV Facility are summarized in Table 6-1.

Table 6-1. Summary of Water Quality Criteria Used in Facility Design

Parameter	Minimum	Average	Maximum
Turbidity (NTU)	0.12 NTU	0.23 NTU	0.54 NTU
Total Hardness (as $CaCO_3$)	50.0 mg/l	54.2 mg/l	58.0 mg/l
Total Alkalinity (as $CaCO_3$)	35.7 mg/l	40.9 mg/l	48.3 mg/l
Iron	<0.03 mg/l	<0.03 mg/l	0.03 mg/l
Manganese	<0.03 mg/l	<0.03 mg/l	<0.03 mg/l
Aluminum	---	0.07 mg/l	---
Specific Conductance	148.0 m-mhos/cm	175.8 m-mhos/cm	211.0 m-mhos/cm

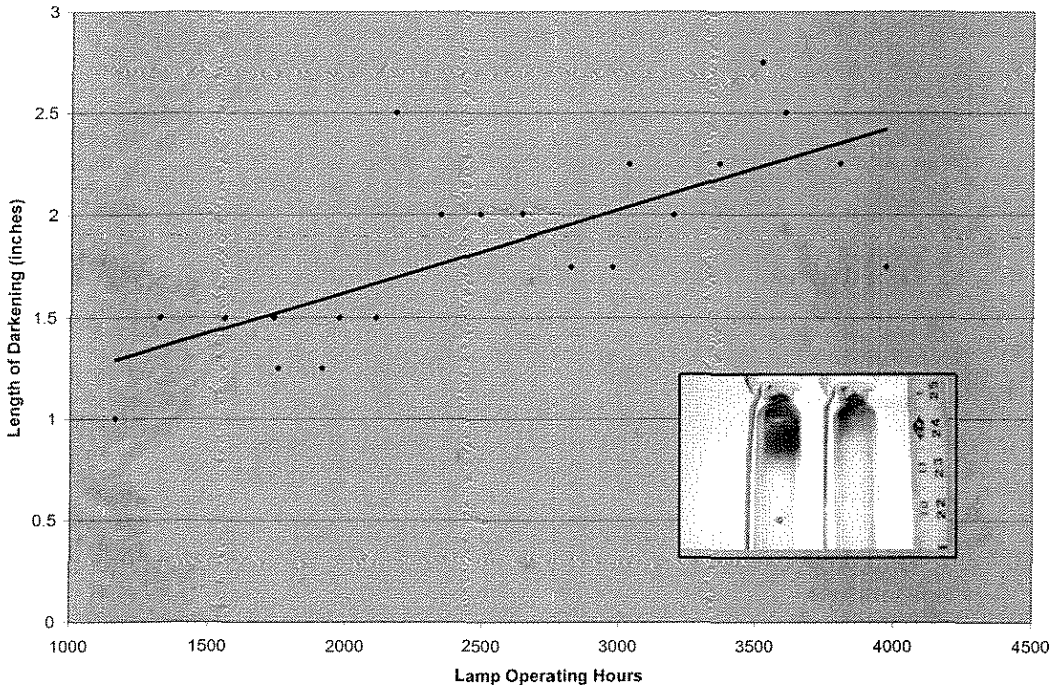
Based on water quality data at the City of Albany, fouling was not expected to be a significant issue. This was confirmed by observations made during this study.

After several months of supplemental manual cleaning of the sleeves from Unit #4, a significant difference in the condition of these sleeves was not observed when compared to the sleeves in Unit #2, which were cleaned only by the wiper mechanism,. There was little to no fouling observed on the exterior of the sleeves as long as the wiper mechanism was functioning properly and water was not allowed to stand stagnant in the unit. Due to equipment downtime, at one point during the study period water was allowed to stand stagnant in a unit for approximately one month. When the unit was opened to install the replacement parts, a film was observed on the lamp sleeves. The film was easily removed by the automatic cleaning mechanism prior to start-up of the unit. However, should a unit be shut down for a period of time with water present within the vessel, either a manual or automatic cleaning cycle should be completed prior to bringing the unit back on line.

One condition that was observed during the visual assessments of the lamps was end darkening. A photograph that illustrates the phenomenon of end darkening is shown in Figure 6-5. No direct correlation between end darkening and reduced lamp output was observed. However, a correlation between operating

hours and extent of lamp darkening was observed as shown in Figure 6-5. Any unusual variations in the length of darkening (e.g., apparent reduction in length between consecutive weeks) were likely due to the measurements being conducted by different personnel, and should not be considered significant.

Figure 6-5
End Darkening - Unit #4, Lamp #2



Each lamp has a fiberglass rope "gasket" located on both ends of the lamps. It was observed that regular removal and replacement of the lamps caused condensation and fiber accumulation on the interior of the sleeves. Also, frequent removal and replacement allowed moisture to enter the sleeve and fiber hairs to shed off of the lamp. The interior and the exterior of the lamp sleeves for Unit #4 were cleaned to remove such accumulation. When fibers were not completely removed, spotting of the sleeves often occurred as a result of the fibers being exposed to the high temperatures on the interior of the sleeve. During normal operating conditions (i.e., when the lamps are not removed on such a regular basis), this would probably not be an issue.

In addition to the evaluation conducted during this study, the Loudonville UV Facility was also a participant in a fouling study that was conducted by Purdue University (Purdue Study). To assist in the Purdue Study, the City disabled the cleaning mechanism on the lead UV unit for a period of four weeks. All eight existing sleeves were replaced with new sleeves. Four of the new sleeves were removed, replaced, and sent to Purdue University for analysis after the first two weeks of operation and the remaining four original sleeves were removed, replaced, and sent to Purdue University for analysis at the end of the four week test period.

Based on the findings of the Purdue Study, included as Appendix B, minor build-up on the lamp sleeves did occur during operation when the automatic cleaning system is disabled. Iron was the primary constituent of the foulant, representing over 80% of the foulant on a molar basis. Calcium and Aluminum accounted for approximately 15% of the foulant, with manganese and zinc representing the remaining 5% on a molar basis. It was estimated that the reduction in dose as a result of the fouling was 1.20 mJ/cm^2 per day, or an approximate decrease of 10% over the 28 day test period (Waite, 2005). Given the high target dose at the Loudonville UV Facility, this reduction is relatively minor. However, for a system operating at a more typical target dose, these results illustrate the importance of preventing lamp sleeve fouling.

6.5.2 Lamp Output Decay

As described above, because lamp intensity was not directly recorded, the assessment was conducted by interpolating lamp intensity from the calculated dose. To allow interpolation from the calculated dose, it was necessary to identify a series of operating points throughout the study period at which the UVT, power setting, and flow rate were nearly identical. The operating points that were used in the assessment are summarized in Table 6-2.

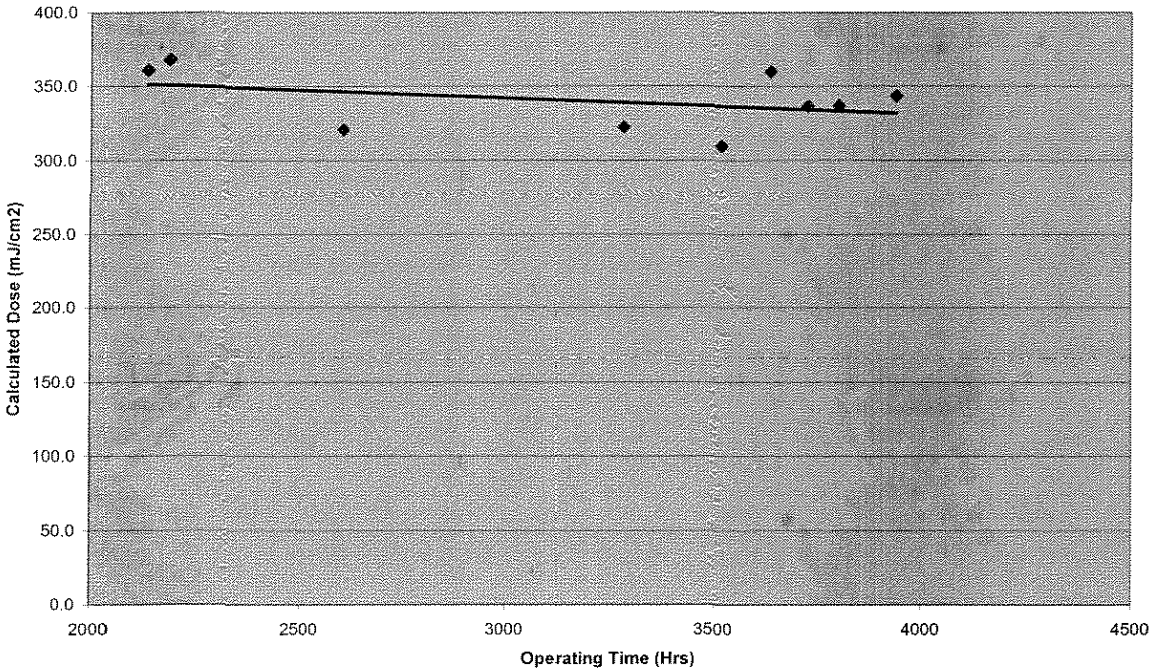
Table 6-2. Summary of Operating Points for Output Decay Assessment

Date	Time	Operating Hours	Power Level (%)	UVT (%)	Flow Rate (MGD)	Calc. Dose (mJ/cm^2) [1]
1/16/04	1400	2,130	60	97.8	5.0	360.7
1/22/04	1730	2,180	60	97.8	5.1	367.7
2/10/04	1300	2600	60	97.0	5.0	320.5
3/14/04	2130	3,280	60	97.9	5.0	322.3
3/25/04	0900	3,515	60	97.7	4.9	309.4
4/5/04	1200	3,635	60	97.9	4.9	359.6
4/11/04	0930	3,725	60	97.7	5.1	336.2
4/14/04	1800	3,800	60	97.4	5.0	313.5
4/21/04	0700	3,940	60	97.8	5.0	343.2

[1] The calculated doses shown should be considered estimates. Due to the reasons described in Section 3, the calculated dose was not able to be validated to these levels.

This approach resulted in a somewhat limited dataset for evaluation. However, the general trends that were seen at the Loudonville UV Facility were consistent with other studies that have been completed on MP lamp output decay. A lamp output decay of approximately 5 percent was observed at the Loudonville UV Facility for lamps between 2,000 and 4,000 hours of operation. After 4,000 hours, the lamps continued to deliver sufficient output to meet the target dose for the City. To normalize the minor variations in UVT and flow rate, a linear trend line was plotted. Findings from this study are illustrated graphically in Figure 6-6.

Figure 6-6
Lamp Output Decay as a Function of Operating Hours



Section 7

OPERATIONS AND COST ASSESSMENT

7.1 OPERATIONS INFORMATION

The Loudonville UV Facility was constructed and is operated as part of the City's water quality enhancement program being implemented at Loudonville Reservoir. The UV facility is part of a dual-barrier disinfection strategy to maximize protection of public health and is one aspect of the City's ongoing risk mitigation efforts at Loudonville Reservoir to comply with the upcoming LT2ESWTR. The UV facility is being operated to target virus inactivation. Additional detail on validation testing and performance of the UV facility is provided in earlier sections.

7.1.1 Description of Operations and Maintenance Tasks

The following operational tasks are regularly performed at Loudonville UV Facility:

- Daily overall visual inspection of the UV units;
- Daily check of the control system to ensure it is in automatic mode;
- Daily check of the control panel display for status of facility components and alarms;
- Daily check of on-line analyzers, flow meters, and data recording equipment;
- Daily review of 24-hour monitoring data to ensure that the unit has been operating properly;
- Daily check of cleaning mechanism operation;
- Daily check of lamp run time;
- Daily check of ballast cooling fans for unusual noise;
- Weekly check of valve operation.

In addition, the following maintenance tasks are performed at the Loudonville UV Facility:

- Monthly calibration check of UV intensity sensors.
- As-needed calibration check of UVT monitors. Due to the sensitivity of these monitors and re-calibration difficulties described in section 4, the calibration of these monitors is only checked when there are problems (every few months). The calibration was formerly checked weekly.
- Quarterly to annual check of unit housing, sleeves, and wiper seals for leaks.
- As-needed replacement of the duty sensor with a calibrated back-up sensor. Through 2004, no duty sensors were replaced.

- Annual check of the cleaning system efficiency by inspecting and manually cleaning the sleeves. This maintenance was previously performed quarterly.
- Quarterly check of the cleaning fluid reservoir.
- Annual calibration of the reference sensor by the manufacturer.
- As-needed replacement of lamps that have broken or are at the end of their lamp life (5,000 hours). Through 2004, approximately 20 lamps had been replaced.
- As-needed replacement of sleeves that have broken or fouled. Through 2004, approximately 3 sleeves have been broken and replaced.
- As-needed cleaning and calibration of UVT monitors.
- As-needed inspection of cleaning system drive mechanism.
- As-needed inspection of ballast cooling fan.

7.1.2 Labor Hours for Operations and Maintenance Tasks

Regularly scheduled daily and weekly operational tasks are estimated to take approximately one hour per day, seven days per week. Prior to the personnel changes and schedule modifications that occurred at the UV facility, the as-needed and reduced frequency operational and maintenance tasks took an estimated eight hours per week per unit (32 hours per week total). The changes have reduced the scheduled labor to approximately two hours per week per unit (8 hours per week total), with an additional 8 hours per month being spent on troubleshooting.

7.2 COST ASSESSMENT

7.2.1 Purpose of Cost Assessment

Currently there is a limited amount of full-scale operating data available for UV facilities within the United States. As part of this study, the actual capital cost and operations and maintenance costs for the Loudonville UV Facility were collected for comparison to existing data and to expand the available dataset for full-scale operating UV facilities in the United States.

7.2.2 Methodology

To assess the operating and maintenance costs for the Loudonville UV Facility, vendor invoices and utility bills were obtained from the City for the period from April 2003 through 2004. In addition, operating personnel were interviewed to discuss the level of effort required for each of the scheduled and non-scheduled tasks that were completed during that time period. These costs were then combined and compared to existing cost data that are available to identify any significant discrepancies.

One of the most extensive existing datasets for capital and operating costs for UV facilities was developed in 2003 by the United States Environmental Protection Agency (EPA data). These data were published in the *EPA, 2003, Technologies and Costs for the Control of Microbial Contaminants and Disinfection Byproducts, Office of Groundwater and Drinking water, Washington, D.C.* and were used as the basis of comparison for this evaluation. Because of the high target dose at the Loudonville UV Facility and its large size, a direct comparison with the cost data presented in a project previously funded by NYSERDA, *Evaluation of UV Disinfection Technologies for Surface Water Treatment Plants*, Final Report 02-06 dated April 2002, could not be conducted.

Based on correspondence with personnel involved in the development of the EPA data, the capital costs were based on equipment costs provided by the manufacturers. In addition, manufacturers provided estimates of the labor hours that are required for operation and maintenance, costs for consumables, and the anticipated useful life for each of the primary components of a UV facility. These costs were then used to develop operating and maintenance costs for the each of the design flow rates that was considered. The EPA data should offer a reasonable estimate of the capital, operating, and maintenance costs for typical UV facilities, but it is likely that they will require further adjustment as more full-scale operating data become available.

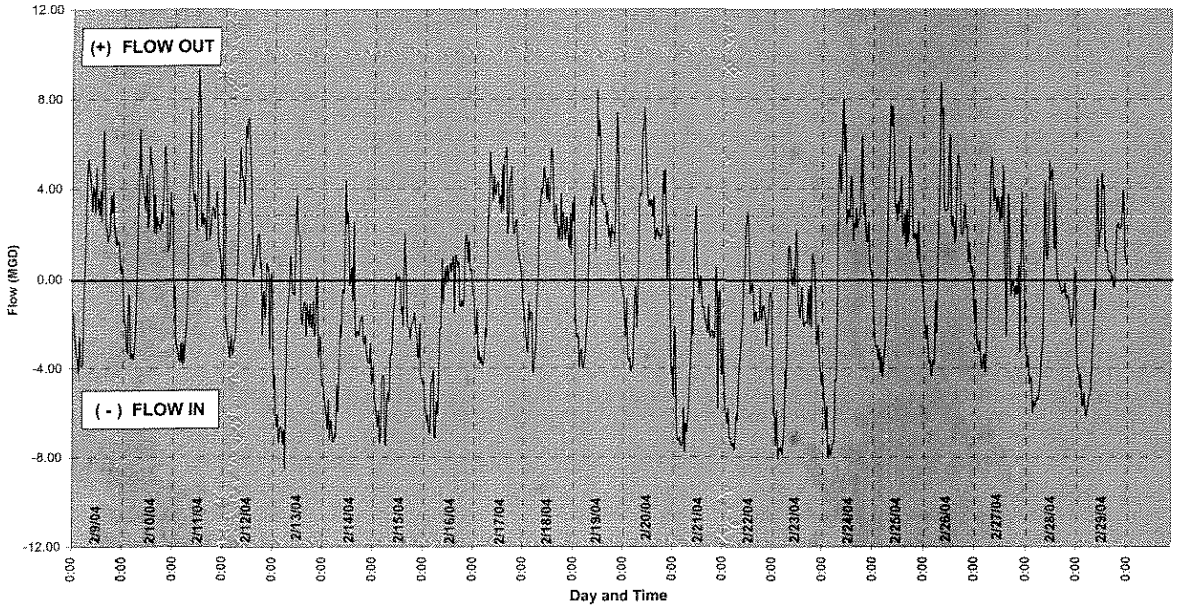
The Loudonville UV Facility is unique for a number of reasons, which makes direct comparison to most existing available data difficult. The specific elements of the Loudonville UV Facility that differ the most from what is expected to be more typical of UV disinfection facilities that are constructed for compliance with the LT2ESWTR are summarized below:

- The UV facility was constructed in a new building at the City's uncovered finished water storage reservoir as opposed to a retrofit within an existing water treatment plant.
- The installation included a significant amount of yard piping modification.
- The installation was required to address bi-directional flow, with flow rates ranging from a peak inflow of 12.0 MGD to a peak outflow of 40 MGD.
- The installation is part of the City's risk mitigation plan for their uncovered finished water storage and is operated to target virus inactivation (e.g., very high dose) during the majority of expected operating conditions.

Because the Loudonville Reservoir functions as both emergency storage and distribution storage, flow through the UV facility is bi-directional. Based on cumulative measurements of all four flow meters installed as part of the UV facility construction, during the study period from October 1, 2003 through April 22, 2004, a total of 321 MG was discharged from the reservoirs to the distribution system (outflow), which equates to an average daily outflow of approximately 1.6 MG. In addition, 374 MG flowed into the

reservoirs during that time period (inflow), which equates to an average daily inflow of approximately 1.8 MG. The difference between the volume of inflow and the volume of outflow is likely due to draining of the Reservoirs to waste to allow maintenance activities to occur. Figure 7-1 provides a representative illustration of typical flow patterns at the facility.

Figure 7-1
Plot of Flow for Weeks 2/9, 2/16, & 2/23



The Loudonville UV Facility has a design capacity of 40 MGD to handle those periods when the reservoir system is being used as an emergency supply. Accordingly, for comparison with the EPA capital cost data a design capacity of 40 MGD is appropriate. However, when the reservoirs are serving their primary function of distribution storage, the typical daily flow rate through the facility is much less, with daily peak flow rates in both directions of approximately 8 MGD and average daily flow rates in each direction of less than 2 MGD. Because the facility has bi-directional flow and the lamps are energized regardless of flow direction, the sum of the inflow and outflow offers the best representation of the total flow rate being treated for the purposes of comparison with the EPA operating and maintenance cost data. As described above, the average daily flow rate to be considered for comparison with the EPA operating and maintenance cost data is 3.4 MGD.

7.3 FINDINGS

7.3.1 Operating and Maintenance Costs

Between April 2003, when full scale operation began, and October 2004, a total of 782,400 kWh of electricity was used at the facility. During that same period, the monthly peak electrical demand at the facility ranged from approximately 125 KW to 285 KW, with an average monthly peak demand of 200 KW. The average electric demand during the 2004 was approximately 220 KW with an average monthly

electrical consumption of approximately 44,000 KWH. The operations and maintenance cost for 2004 was approximately $91,000, excluding labor costs. Of that, $21,500 was for consumables (e.g., lamps, sleeves, gaskets, cleaning solutions, etc.) and the remaining $69,500 was for electricity costs. In general, as described above, labor associated with the operation and maintenance of the UV facility is approximately 17 hours per week. Assuming an average loaded hourly rate of $35/hour, the annual labor cost for operating and maintaining the UV facility is $30,900, bringing the total combined operating and maintenance cost during 2004 to approximately $122,000.

For the purposes of the EPA data, operations and maintenance cost is broken down into replacement parts, power/electricity costs, and labor costs. Table 7-1 compares the EPA estimated costs for a 200 mJ/cm^2 target dose at 3.4 MGD to the actual costs recorded at the Loudonville UV Facility during 2004.

Table 7-1. Comparison of EPA Estimates to Actual O&M Costs at Loudonville UV Facility

Item	EPA Estimate at 3.4 MGD[1]	City of Albany (Avg. 3.4 MGD)
Replacement Parts/Consumables	$12,532	$21,500
Power/Electricity	$64,108	$69,500
Labor	$2,012	$30,900
Total	$78,652	$121,900

[1]The values shown are interpolated from the EPA data. EPA estimates were provided for a flow rate of 3 MGD and 7.8 MGD.

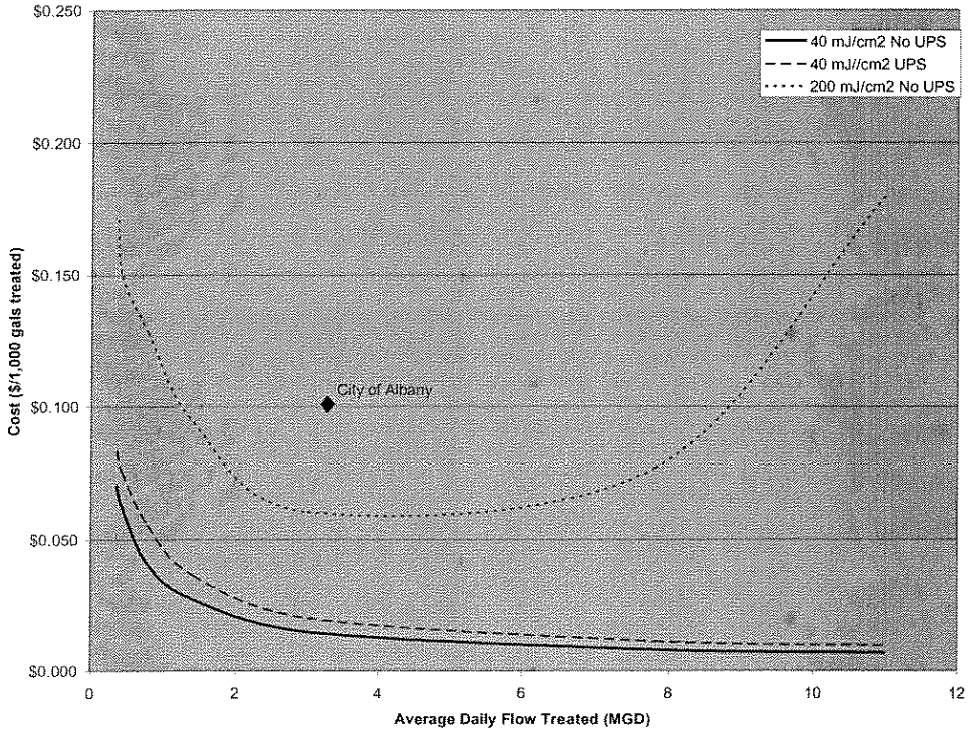
The costs for replacement parts and for electrical power as estimated by the EPA are supported by the findings of this study. Nearly $6,000 of the discrepancy in replacement parts is due to issues with one of the valve actuators and some minor programming work that was required, which are more related to start-up than actual facility operation. The difference in electricity costs is likely due to the higher target dose for the City of Albany (240 mJ/cm^2 versus 200 mJ/cm^2). However, because the water being treated at Albany has a higher UVT than that used when developing the EPA data, the energy consumption effects of the higher target dose were minimized (i.e., at higher UVT less power is required to deliver the same dose). Another source of discrepancy in the costs is the unit cost rates used for labor and electricity.

The largest deviation from the EPA estimate, and one that cannot be explained by the slight differences in unit cost rates, is the labor costs. The level of operating effort at the Loudonville UV Facility appears to be much more representative of what will typically be required than the labor effort identified in the EPA estimate. As discussed above, approximately 17 hours per week are spent operating the Loudonville UV Facility. Approximately 17 hours per week are spent operating and recording the operating conditions for the Loudonville UV Facility. Less than two hours per week were included in the EPA's labor cost estimates

for operating a UV facility under similar conditions of average flow and target dose. Given the specific monitoring and recordkeeping requirements that are recommended in the 2003 Draft UVDGM, the labor effort for the Loudonville UV Facility of approximately 0.5 hours per day per unit seems reasonable when averaged over the year.

Figure 7-2 is based on the EPA data and illustrates the estimated operations and maintenance cost relative to the average daily flow rate that is treated at the UV facility. Cost data for facilities ranging in size from 0.2 MGD to 11 MGD are presented. The costs for the Loudonville UV Facility, based on the costs and flow rates discussed above, is also depicted on the figure.

Figure 7-2
Comparison of O&M Costs to Volume of Water Treated



7.3.2 Capital Costs

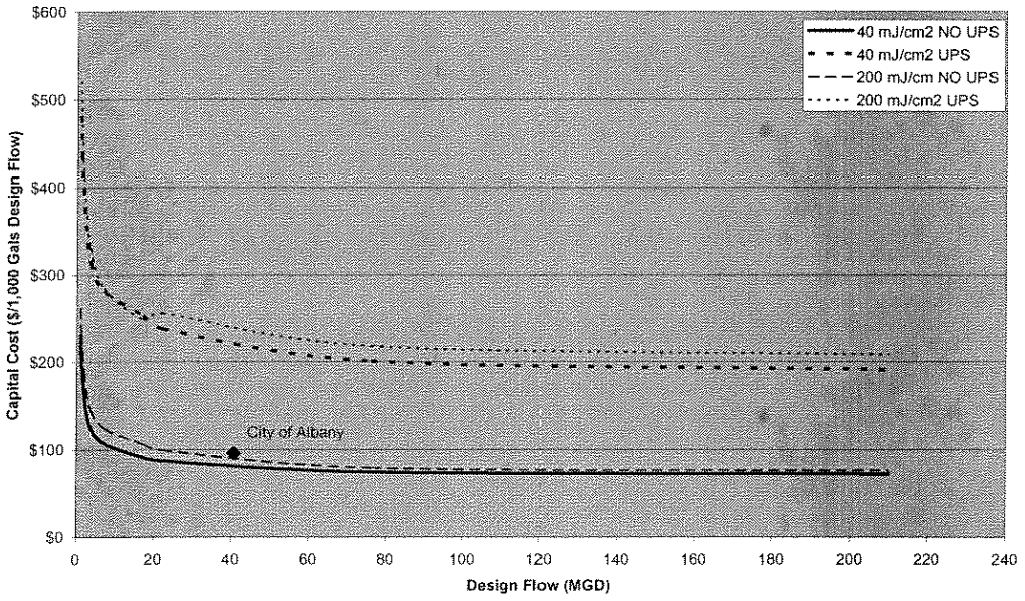
The approximate capital cost for the Loudonville UV Facility was $3,800,000. The UV equipment, large diameter piping, and valves were pre-purchased by the City. Due to security concerns, construction was completed on a cost plus fixed fee basis by the City's emergency contractors whom were competitively selected for term assignments with the City. Major capital cost components for the facility are shown in Table 7-2.

Table 7-2. Comparison of EPA Estimates to Actual Capital Costs at Loudonville UV Facility

Item	Cost
UV Equipment and Validation	$510,000
Pre-purchased Piping, Valves, and Fittings	$220,000
Building Construction	$580,000
Instrumentation and Controls	$50,000
Electrical and HVAC	$440,000
Site Work and Yard Piping	$1,040,000
Planning, Design, Construction Oversight, and Start-up	$670,000
Contractor Overhead and Profit	$290,000
Total Project Capital Cost	**$3,800,000**

The capital costs for the Loudonville UV Facility ($95 per 1,000 gallons of treatment capacity) are consistent with USEPA estimates for a facility of this size, as illustrated in Figure 7-3. As illustrated, incorporation of an uninterruptible power supply significantly increases the capital cost for a UV facility.

Figure 7-3
Comparison of Capital Cost to Design Flow



Section 8

OPPORTUNITIES FOR ENERGY AND COST SAVINGS

8.1 OVERVIEW

The use of ultraviolet light disinfection technology is anticipated to increase significantly in both the water and wastewater sectors within the United States as water quality and effluent requirements, particularly with regard to disinfection byproducts and specific pathogens, become more stringent. When compared to traditional chemical disinfection processes, ultraviolet disinfection offers significant health and environmental benefits at a relatively low capital cost. However, ultraviolet disinfection is a fairly energy intensive treatment technology. To date, limited data are available for the use of UV disinfection for drinking water applications in the United States. The City of Albany's recently constructed Loudonville UV Facility offered a unique opportunity to thoroughly evaluate the use of UV technology in a drinking water application with the goal of identifying opportunities for energy improvement throughout the planning, design, validation, and operation and maintenance phases of a project.

This section discusses the energy efficiency opportunities that were identified during the study, and quantifies the potential energy savings that are available. While the conclusions are based on the specific installation that was evaluated, to the extent possible the findings of this study were extrapolated to expand their applicability to the water industry as a whole.

8.2 ENERGY EFFICIENCY IMPROVEMENTS THROUGH PLANNING AND DESIGN

The amount of electricity used for UV disinfection is related to the number of lamps and the lamp power that is required to deliver the UV dose needed to achieve a utility's specific disinfection objectives. Decisions made during the planning and design phases of a project can significantly affect the ability of a facility to deliver the necessary dose to meet the utility's objectives in an energy efficient manner.

8.2.1 Flow Rate and Ultraviolet Transmittance

From an energy efficiency perspective, the most important aspect of the planning and design process is a sound understanding of the ultraviolet transmittance (UVT) of the water and the flow conditions for the application. These two parameters have the greatest effect on the energy use required to effectively deliver the target dose. If there is a highly variable flow, as is the case with the Loudonville UV Facility, it is important to incorporate a flexible control strategy, either through the use of multiple UV units, adjustable lamp settings (e.g., power level or number of lamps that are energized at any time), or a combination of both. Likewise, if there are fluctuations in UVT, it is important to determine the appropriate design value to avoid overdosing during periods of higher water quality or to incorporate sufficient operating flexibility, possibly including on-line UVT monitors, to allow the lamp settings to be adjusted to more closely match the changing water quality.

Many water treatment plants will have flow rate and UVT data readily available. In the case of the Loudonville UV Facility, because the installation was at an uncovered finished water storage reservoir as opposed to the WTP, only limited UVT data were available. To address this, a short duration UVT monitoring program was developed and implemented at the reservoir prior to facility design. The amount of data that are necessary to design a UV facility will be site-specific. In general, it is important to have sufficient data to understand daily and seasonal flow variations as well as seasonal UVT variations. The duration and breadth of the monitoring program that is developed should be proportional to the potential impact of the findings. If there is little potential for cost savings through refinement of the design criteria, then erring to the side of conservatism is a reasonable design approach.

It is important to note that, at a given input power, the flow rate that can be treated to achieve a specific target dose is not linearly correlated to the UVT of the water, particularly within the range of typical values for filtered water (e.g., 86 to 92% UVT). As a result, minor variations in UVT within this range can have a significant influence on the required input power to achieve the target dose. Capacity data for one manufacturer's equipment shows that, at a flow rate of 15 MGD, it takes 60 KW of input power to deliver the same dose at a UVT of 88% as can be delivered with only 46 KW of input power at a UVT of 92% (i.e., a 4.5% increase in UVT can result in a nearly 25% decrease in the required input power). Based on this, it would appear that, unless a facility has an extremely stable UVT and flow rate or is very small, some level of power adjustment or control of the number of operating lamps should be incorporated into nearly all designs. Lamp control may include adjustment of the lamp power on a fixed number of lamps, adjustment of the number of lamps that are energized, or a combination of both. The selected combination of lamp power and number of lamps must balance energy efficiency with effective dose delivery. A determination of whether it is better to have fewer lamps at full power of more lamps at reduced power will be based on the proposed application, water quality, and the lamp configuration used in the specific manufacturer's equipment design.

To avoid an overly conservative design, a designer should not simply take the worst case UVT that is measured and the maximum daily flow that is measured and design the facility around those criteria. Unless the monitoring data indicate the two events occur simultaneously, approaching the design in this manner would result in an overly conservative, and potentially inefficient, design. To the extent possible, the designer should review concurrent UVT and flow data and select the worst case combined condition.

In the case of the Loudonville UV Facility, the worst case flow condition of 40 MGD occurs if the Loudonville Reservoir is used as an emergency water supply during the summer months. Because of significant schedule constraints associated with this project, the majority of the UVT data that were reviewed were from the filtration plant in Feura Bush (WTP), which is approximately 20 miles away from

the Loudonville Reservoir, with only limited UVT measurements at the Loudonville Reservoir itself. The lowest UVT of 88.3% was measured at the WTP in the late fall. The lowest UVT measured during the summer months at the WTP was 90.4%. UVT measurements from the reservoir, while within the same range as those measured at the WTP, did not correlate directly. As a result, the minimum measured UVT of 88.3% was used as the worst case design condition. The use of a variable operating strategy and the incorporation of multiple units into the facility design maximized the energy efficiency, given the use of the conservative design UVT. Had additional time been available during facility design, it would have been beneficial to collect additional UVT measurements from the reservoir to establish with certainty the actual worst case UVT during the peak flow period of the summer.

8.2.2 Fouling/Aging Factor

Because of the relative "newness" of using UV disinfection in the water industry, there may be a tendency on the part of the designer to be conservative when establishing the lamp fouling/aging factor. This can result in increased capital, operating, and maintenance costs and decreased energy efficiency and applicability of the technology. Aside from the equipment factor applied during validation testing (discussed in Section 3), the most commonly used design safety factor is the fouling/aging factor, which typically ranges from 0.6 to 0.9.

The lamp aging/fouling factor that is chosen by the designer should be based on the following:

- The fouling potential of the water;
- Whether or not an automatic cleaning mechanism is included and, if so, the effectiveness of the facility in similar applications;
- The regularity and effectiveness of a manual cleaning regime in similar applications if automatic cleaning is not included;
- The type of lamp technology that is selected and its output decay characteristics;
- The conditions under which validation is conducted (e.g., age of lamps);
- The length of time which the utility will allow lamps to operate prior to change out;
- The consistency and dependability of the utility in following the lamp change out procedure.

For a variety of reasons discussed in Section 6, the fouling/aging factor of 0.6 (meaning a factor of safety of 1.66) that was used in the design of the Loudonville UV Facility was quite conservative. However, given the limited information that was available on lamp fouling at the time of the design and the limited number of large UV facilities in operation, the use of a conservative factor was appropriate. Because the Loudonville UV Facility was designed with variable lamp intensity adjustment, sufficient operating flexibility is incorporated to minimize the potential energy consumption resulting from the conservative

fouling/aging factor. Had variable lamp intensity adjustment not been included, the use of a fouling/aging factor of 0.6 rather than 0.9 would have resulted in 50% more energy being used to deliver the same target dose.

8.3 ENERGY EFFICIENCY IMPROVEMENTS THROUGH VALIDATION

As discussed in Section 3, the validation protocol established in the 2003 Draft UVDGM relies on the use of an equipment factor to account for variations in equipment performance and uncertainties associated with measurements and monitoring. The magnitude of the equipment factor has a direct effect on the energy use of a UV facility. The elements that directly influence the equipment factor are:

- The dose response of the challenge organism versus the dose response of the target organism (RED bias).
- The differences between the validated test conditions and the actual operating conditions for facilities that use medium pressure lamps with sensors that respond to UV light outside of the DNA germicidal range (polychromatic bias).
- The uncertainty of measurements taken during validation and used with dose delivery monitoring (uncertainty factor).

8.3.1 RED Bias

If the challenge organism that is selected for validation is the same or more sensitive to UV light than the target pathogen, then the RED bias has a value of 1.00. If the selected challenge organism is less sensitive (more resistant) to UV light than the challenge pathogen, then the factor can be fairly significant. In the case of the Loudonville UV Facility, MS2 bacteriophage (MS2) having a UV sensitivity of approximately 18 mJ/cm^2 per log inactivation was used to validate the UV unit. If the facility were pursuing credit for inactivation of *Cryptosporidium*, which has a UV sensitivity of approximately 2.9 mJ/cm^2 per log inactivation, then the challenge organism is more resistant than the target pathogen and an RED bias of approximately 2.30 is calculated. Since the Loudonville UV Facility is targeting adenovirus, which has a UV sensitivity of approximately 50 mJ/cm^2 per log inactivation, the RED bias is 1.00.

Unlike the Loudonville UV Facility, most facilities that install UV disinfection in response to LT2ESWTR will be doing so to target *Cryptosporidium*. As such, it is important to select the appropriate challenge organism for validation. Currently, MS2 and *bacillus subtilis* spores are the most commonly used challenge organisms. ϕX174 has also been successfully used as a challenge organism on several occasions. To ensure representative validation of UV equipment for a wide range of target organisms and to reduce the impact of the RED bias other challenge organisms are being developed.

The use of ϕX174, which is generally more susceptible to UV light than *Cryptosporidium*, allows an RED bias of 1.00 to be used when determining the dose that must be delivered for given amount of inactivation

credit. However, because of ϕX174's sensitivity to UV light, it is very difficult to validate at higher doses, which may limit the level of inactivation credit that can be received. Of the challenge organisms identified above, from an energy efficiency perspective ϕX174 is most appropriate for the validation of facilities targeting low levels of *Cryptosporidium* inactivation credit (typically less than 2.0 log). However, to date it has been rarely used. Other organisms under evaluation also will be able to provide these benefits if their UV sensitivity is similar to that of the target organism.

The use of ϕX174 instead of MS2 or *bacillus subtilis* spores for validation of a facility that is pursuing credit for *Cryptosporidium* inactivation will reduce the RED bias, and consequently the energy use, for the same level of inactivation credit. The amount of the reduction is dependent upon the actual installation and the magnitude of the polychromatic bias and uncertainty factor for the specific installation, but could easily approach 50% or more. For the Loudonville UV Facility, had *Cryptosporidium* been the target pathogen, the use of ϕX174 instead of MS2 would have resulted in a reduction in the equipment factor of between 50 and 55%, dependent upon the operating conditions. This in turn would have resulted in a similar reduction in energy use.

8.3.2 Polychromatic Bias

The polychromatic bias accounts for spectral differences in lamp output, lamp sleeve UV transmittance, UVT, and the action spectrum of the challenge organism. This bias is intended to address differences between the dose delivered during validation testing and the dose delivered during full-scale operation at the proposed installation because of differences in the UVT at these two locations. No polychromatic bias is required if low pressure or low pressure high-output lamps are used. Similarly, if medium pressure lamps are used in conjunction with sensors that meet Tier 1 criteria for spectral response (measure only the germicidal range) and result in a conservative validation outcome, then the polychromatic bias equals 1.00. If the sensor fails to meet Tier 1 criteria or the ratio of RED during validation to RED at the WTP is greater than one, then the polychromatic bias must be calculated and included in the equipment factor. Aside from the selection of lamp technology, by and large, the factors that influence the polychromatic bias are dictated by the equipment manufacturer not the utility.

Generally, LP and LPHO lamps are more energy efficient than medium pressure lamps. However, capital cost, operating flexibility, and other operations and maintenance costs can make medium pressure technology more suitable. If medium pressure technology is selected, then equipment with a sensor that meets Tier 1 spectral response criteria and results in a conservative validation outcome will allow a polychromatic bias of 1.00 to be used, allowing a reduced equipment factor to be used and potentially enabling more energy efficient delivery of the target dose. If the equipment that is selected does not utilize a sensor that meets Tier 1 criteria or the validation outcome results in an RED during validation that is

greater than the RED at the WTP, then a polychromatic bias must be calculated. The factors that influence the polychromatic bias are the spectral response of the sensor, the UV absorbent that is used during validation, and the sensor to lamp water layer. Of these, the utility can only control the UV absorbent.

Instant coffee and lignin sulphonate are the two UV absorbents that are most commonly used during validation. Regardless of which absorbent is used, the polychromatic bias increases as the UVT decreases (i.e., the more absorbent that must be used to achieve a given UVT, the greater the bias). Likewise, as the distance between the sensor and the lamp increases, the polychromatic bias increases. Generally, lignin sulphonate results in a lower polychromatic bias than instant coffee. Under worst case conditions (e.g., a large distance between the sensor and the lamp and low UVT), choosing coffee over lignin sulphonate can result in greater than a 70% increase in the value of the polychromatic bias. The actual effect that the UV absorbent has on the polychromatic bias is dependent upon the configuration of the equipment and the water quality conditions that are being tested, but generally ranges from less than 10% to about 40%.

In the case of the Loudonville UV Facility, the selected equipment utilizes a sensor that fails to meet the Tier 1 criteria for spectral response. Accordingly, a polychromatic bias needed to be calculated. To reduce the effect of this bias, lignin sulphonate was originally proposed for use as the UV absorbent during validation. However, due to a number of reasons, instant coffee was substituted for lignin sulphonate. Depending upon the test conditions, the polychromatic bias ranged from 1.00 for those validation runs when no UV absorbent was injected to 1.38 under low flow, low UVT conditions. Had lignin sulphonate been used instead of instant coffee, the polychromatic bias would have ranged from 1.00 to 1.19, resulting in an approximately 15% decrease in the polychromatic bias under the worst case conditions, and accordingly a 15% decrease in energy use under these conditions. Since installation, the Loudonville UV Facility has been operating primarily under conditions of high UVT, where the effect of the polychromatic bias is much less. As a result, the overall effect of the polychromatic bias on the energy efficiency of the facility has been minimal.

If a utility is required to apply a polychromatic bias to its equipment factor and expects to operate under conditions of low UVT for extended periods of time, it is important that the energy use implications associated with the selected absorbent be understood. To minimize the effect of the polychromatic bias, lignin sulphonate can be used rather than instant coffee. To eliminate the polychromatic bias altogether, the equipment could be validated using the actual source water over a series of events that represent the range of UVT for the source water. In many cases the potential savings may not justify the cost of multiple on-site validation events. However, for large facilities that will frequently operate under conditions of low UVT, the 20 to 40% reduction in the polychromatic bias, and accordingly energy use, may justify the increased validation costs. If this approach is selected, on-site validation could be conducted prior to design using the proposed equipment, but in a temporary installation that is constructed solely for the purpose of

validation, or following construction of the UV facility.

8.3.3 Uncertainty Factor

The expanded uncertainty, U, accounts for errors in measurements made during validation and the uncertainty associated with the equipment installed at the utility. Per the current UVDGM validation protocol (EPA - January 2005), the expanded uncertainty is calculated at the 80% confidence level for each of the following:

- The level of uncertainty associated with the log inactivation through the UV unit;
- The level of uncertainty associated with the collimated beam dose calculation;
- The level of uncertainty associated with the validation UV intensity sensor;
- The level of uncertainty associated with the WTP on-line UV intensity sensor;
- The level of uncertainty associated with the WTP reference UV intensity sensor;
- The level of uncertainty of knowing the output of each lamp.

For the Loudonville UV Facility, the expanded uncertainty had a value of approximately 30%, meaning an uncertainty factor of 1.3. It is generally very difficult to achieve an expanded uncertainty much less than 20%. So, while any reduction in U will result in a direct reduction in energy use, it is difficult to significantly reduce this factor. Like the polychromatic bias, the uncertainty factor is largely outside the control of the utility – it is primarily influenced by the biodosimetry process and equipment design. However, a utility should consider the elements that affect the expanded uncertainty and work to minimize their effect.

8.3.4 Tier 1 Versus Tier 2 Analysis

The 2003 Draft UVDGM offers two alternatives for validation: Tier 1 and Tier 2. Tier 1 is a much simpler approach but requires that the UV equipment and validation methodology meet specific, pre-established requirements. The UV equipment and validation methodology used in the Loudonville UV Facility did not meet all Tier 1 criteria. As a result, a Tier 2 validation analysis was conducted. In addition, because the City's UV equipment was going to be validated on-site, it was believed that the use of a Tier 2 analysis would allow a reduction in certain elements of the equipment factor. Table 8-1 presents the Tier 1 equipment factors for various levels of log inactivation credit for *Cryptosporidium*, and virus had such an analysis been possible for the City. For comparison purposes, the equipment factors calculated for the Loudonville UV Facility using a Tier 2 analysis are also shown. It should be reiterated that, while results for *Cryptosporidium* credit are shown, the target pathogen for the Loudonville UV Facility is virus. In addition, it is recognized that the latest modifications to the UVDGM (January 2005) combined the two approaches into a single approach.

Table 8-1. Comparison of Tier 1 and Tier 2 Equipment Factors

Inactivation Credit	Tier 1 Equipment Factor	Tier 2 Equipment Factor[2]		Energy Savings [2]	
		Minimum	Maximum	Based on Minimum	Based on Maximum
2.5 Log Crypto	3.76	---	3.5	---	6.9%
3.0 Log Crypto	3.50	2.6	3.8	25.7%	-8.6%
0.5 Log Virus	1.62	---	1.7	---	-6.3%
1.0 Log Virus	1.62	---	1.7	---	-6.3%
1.5 Log Virus	1.62	---	1.3	---	19.8%

[1] The Tier 1 Equipment Factor shown is calculated by dividing the Tier 1 RED targets identified in the UVDGM for MP lamps by the dose requirements used during validation testing identified in the UVDGM.
[2] An equipment factor was calculated for each test condition included in the validation matrix. As such, there were multiple test conditions that were validated for the same level of inactivation credit, each with a different equipment factor. The Energy Savings are shown for the minimum and maximum equipment factor calculated for each level of inactivation credit.

Under all test conditions in which unadjusted source water was used (i.e., no use of absorbent), the calculated Tier 2 equipment factor for both *Cryptosporidium* and virus inactivation credit was approximately 20 to 25% less than the equivalent Tier 1 equipment factor. For conditions in which UV absorbent was used, the Tier 1 and Tier 2 equipment factors were within less than 10% of one another. Under some conditions the Tier 1 equipment factor was less and under others the Tier 2 equipment factor was less. For smaller facilities, the additional effort required to conduct on-site or site-specific validation testing with a Tier 2 analysis may not be warranted. Additionally, there may be little benefit to conducting a Tier 2 analysis of the results from a generic off-site validation setup. However, for larger facilities the potential energy savings resulting from a reduced equipment factor may justify the added cost of on-site or site-specific validation and a Tier 2 analysis. If pre-validated UV equipment (meaning the UV equipment design has been validated off-site prior to purchase) is used, it is expected that UV equipment manufacturers will choose to use the analysis that yields the lowest equipment factor to maximize the approved capacity of their UV equipment.

There are also significant differences between the equipment factors for applications that use LP/LPHO lamps versus MP lamps; the difference is from the polychromatic bias with MP lamps. In general, the Tier 1 equipment factors for LP/LPHO lamp applications are 10 to 20% less than the equipment factors for an equivalent level of inactivation credit using MP lamps. This fact, when combined with the higher "wire to light" efficiency of LP/LPHO lamp technology result in LP/LPHO lamp technology being a more energy efficient solution for most applications. However, because of the increased number of lamps required to deliver the same dose, LP/LPHO may result in a greater equipment footprint, higher capital cost, and greater labor effort needed to monitor, clean, and replace lamps, making MP lamp technology a more

appropriate choice for utilities with high labor costs and low power costs. A comparison of the Tier 1 equipment factors for 2-log and 3-log inactivation of *Cryptosporidium*, Giardia, and virus is shown in Table 8-2. It should be noted that, as of the date of this report, the EPA is in the process of developing a process to replace the Tier 1 and Tier 2 concepts with a single approach that combines elements of both. The new approach is intended to be simpler to use and result in a less conservative outcome than the current Tier 1 approach.

Table 8.2. Comparison of Tier 1 Equipment Factors for LP/LPHO and MP Lamps

Target Pathogen	LP/LPHO	MP	Difference
2-Log Inactivation Credit			
Cryptosporidium	3.62	4.14	14.4%
Giardia	3.85	4.42	14.8%
Virus	1.39	1.61	15.8%
3-Log Inactivation Credit			
Cryptosporidium	3.00	3.50	16.7%
Giardia	3.09	3.64	17.8%
Virus	1.39	1.62	16.6%

8.4 ENERGY SAVINGS THROUGH OPERATION AND MAINTENANCE

The greatest opportunities for energy savings associated with UV disinfection are through design and equipment validation. However, proper operation and maintenance of the UV facility is essential to the protection of public health and may offer an opportunity for minor energy savings. The uncertainty associated with a given piece of equipment's performance is typically based on a manufacturer's recommended maintenance and calibration schedule. To ensure that the equipment meets the performance criteria used during validation and adequately protects public health, this maintenance and calibration schedule must be followed. In addition, the USEPA has required and recommended maintenance tasks described in the 2003 Draft UVDGM.

For some equipment, an increased frequency of calibration or regular maintenance may reduce the level of measurement uncertainty, thereby reducing the expanded uncertainty component of the equipment factor that is calculated from validation testing. The utility should discuss the potential for improving performance with increased maintenance and calibration with the manufacturer. For most control equipment, a significant improvement in performance through increased maintenance and calibration, and consequently a significant improvement in energy efficiency, is unlikely. However, as discussed below more frequent calibration checks can reduce the duration over which control equipment may be overly conservative in their measurements, thereby minimizing wasted energy.

8.4.1 UV Intensity Sensors

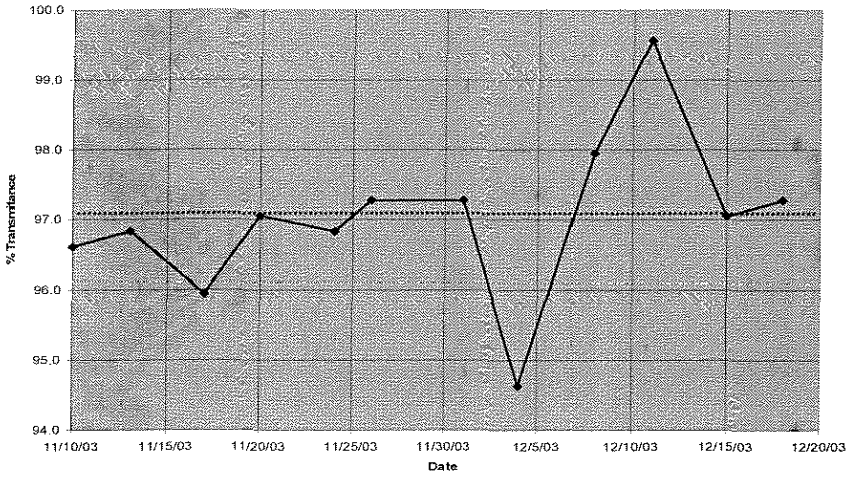
As discussed in Chapter 4, the UV intensity sensors are a critical component of the UV equipment. During the study, calibration checks were performed on a weekly basis. Since that time, the frequency has been reduced. No correlation between an increased frequency of calibration checks and sensor performance was observed. However, more frequent calibration checks limit the duration over which a sensor may be out of calibration, which reduces the risk to public health. In addition, more frequent calibration checks reduce the possibility of inefficient operation resulting from an overly conservative sensor measurement (i.e., duty sensor lamp intensity measurement is lower than the actual lamp intensity output).

8.4.2 On-line UVT Monitors

For facilities with a variable UVT, the use of an on-line UVT monitor will help ensure the utility's disinfection objectives are continuously met and that the energy efficiency of the facility is optimized. However, like the UV intensity sensors and most other control equipment, there is a level of uncertainty inherent in the equipment performance. As long as the equipment performs within the expected range of uncertainty included in the equipment factor, then the disinfection objectives of the UV facility will be met. However, the utility needs to understand that using control equipment with greater levels of uncertainty does adversely affect the energy efficiency of the UV equipment by increasing the expanded uncertainty component of the equipment factor that is calculated from validation testing. It was not evident that calibrating the on-line UVT monitors more often than the manufacturer's minimum recommendations improved the reliability or accuracy of the equipment.

Figure 8-2 illustrates the bench top UVT measurements at the Loudonville UV Facility for six consecutive weeks during the study period. During that time, the UVT ranged from 94.6% to 99.6%, with an average of approximately 97%.

Figure 8-2. Results of Bench Top UVT Measurements



The 2003 Draft UVDGM recommends that UVT be measured continuously and recorded at a minimum of once every four hours. For very small facilities that rely solely on manual readings and recording, the 2003 Draft UVDGM indicates that the frequency should not be less than once per day and should be approved by the State. Since continuous UVT measurement is only a recommendation, it is probable that some utilities will choose to use periodic grab samples and a bench top spectrophotometer to monitor the UVT of the water.

Because the UVT is consistently very high and relatively stable at the Loudonville UV Facility, the use of grab samples every four hours would likely have provided a reasonable alternative to on-line UVT monitors. However, because the Loudonville UV Facility is largely unmanned, the additional labor required to collect grab samples at a four hour interval and conduct the bench top analyses was not practical. In addition, if periodic grab samples are used instead of continuous on-line measurement of UVT, there is the potential to be operating based on an incorrect UVT measurement between sampling events. For example, if a grab sample is collected at 10:00 am and the UVT measurement is 88.0% and another grab sample is collected at 2:00 pm and the UVT measurement is 92.5%, then the unit was potentially overdosing, and thereby consuming more energy than needed to deliver the target dose, for a period of up to 4 hours. The same situation could occur in which the UVT decreases between sampling events, resulting in a utility's disinfection objectives failing to be met for a portion of time during that period.

8.4.3 Flow Meters

No specific maintenance or calibration was performed on the flow meters at the Loudonville UV Facility. Typically, calibration certificates are provided by the manufacturer at the time of equipment delivery and, as long as the installation configuration meets specific criteria and remains unchanged, the meters should continue to perform within their range of uncertainty. Like the other control equipment, the smaller the uncertainty, the greater the energy efficiency of the UV equipment. Since the flow meters are essential to monitoring and controlling the UV equipment, it is recommended that the accuracy of the flow meters be periodically confirmed using a strap-on flow meter or other methodology.

8.4.4 Lamp Sleeve Cleaning and Lamp Replacement

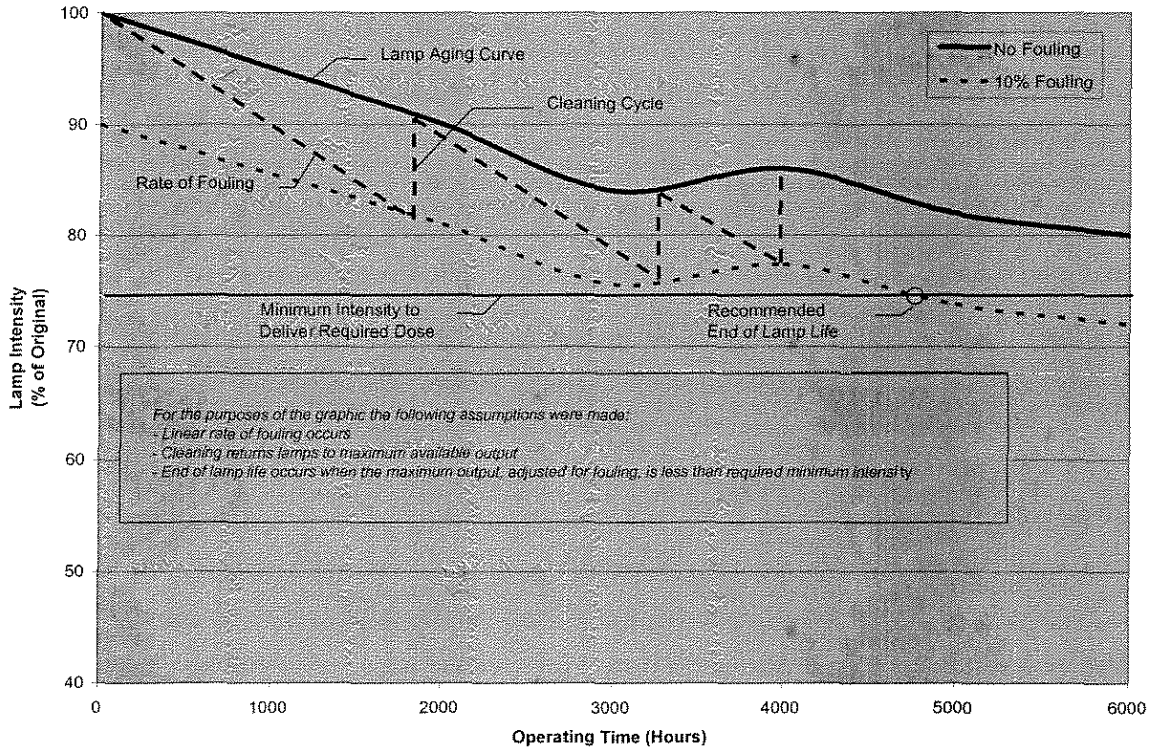
As discussed in Chapter 6, it is important that the cleaning and lamp replacement regime that is selected for a UV facility be consistent with the fouling/aging factor used during the design. Of the maintenance and operation activities considered, lamp replacement and sleeve cleaning are the most important in terms of energy efficiency of the UV equipment. As a lamp ages, the same electrical input produces less UV light, resulting in an increased energy use to deliver the same lamp intensity. The utility must balance this reduction in lamp output efficiency with the cost of lamp replacement. Similarly, the more fouled a lamp sleeve is allowed to become the less UV light is transferred to the water. As a result, more energy is

required to deliver the same dose. Not only is the fouling potential of a given source water site specific, but the degree to which the fouling absorbs UV light is also dependent upon the specific application, as well as the equipment design. In general, the less fouling that is permitted to occur, the less energy that is required to deliver the necessary UV light intensity to achieve the target dose.

A utility can ensure that their disinfection objectives are met by simply incorporating a large fouling/aging factor into the design of their facility. However, this will result in inefficient operation during times when the actual aging/fouling factor is less than the conservative factor used in the design. Incorporating some form of lamp intensity adjustment into the control strategy minimizes the negative effects on energy use. However, to eliminate the negative effects on energy consumption it is essential that the "turndown" capabilities of the selected equipment are sufficient to cover the full range of lamp aging/fouling conditions that are expected under all operating conditions, including conditions of high UVT, reduced flow, and new lamps.

Figure 8-3 graphically illustrates how to determine the minimum cleaning frequency and lamp replacement schedule for a UV facility. The graphic is for illustrative purposes only and is based on a hypothetical application in which the utility has determined that they will manually clean their lamp sleeves whenever fouling results in a 10% decrease in the expected lamp output. The top, solid line represents the lamp output decay curve provided by the manufacturer or developed based on the utility's operating experience. The dashed line that parallels the lamp output decay curve represents the 10% lamp output reduction that the utility has selected as the allowable level of reduction due to sleeve fouling. For this example, the utility would conduct a cleaning cycle each time sleeve fouling results in a measured lamp intensity that is 10% less than the expected lamp output. Scheduled lamp replacement would occur when the lamp output, adjusted for the allowable fouling, drops below the minimum intensity required to delivery the target dose, in this case approximately 4,800 hours. In this example, the lamp life could possibly be extended by increasing the frequency of sleeve cleaning to reduce the output reduction due to fouling.

Figure 8-3. Illustrative Example of Sleeve Cleaning/Replacement Regime



If an automatic cleaning system is used at a frequency that eliminates any lamp output reduction due to fouling, then a lamp would be replaced when aging prevents it from producing the minimum intensity required to deliver the target dose. The City of Albany replaces its lamps after 4,000 hours of operation, or whenever they fail to deliver the required minimum intensity, whichever comes first. Based on the lamp aging data gathered at the Loudonville UV Facility, it appears that the lamps continue to deliver the required light intensity for a longer duration than 4,000 hours. However, the City prefers to replace the lamps on a scheduled frequency rather than on an as-needed basis.

8.5 SUMMARY OF POTENTIAL ENERGY SAVINGS

The potential for energy savings with UV disinfection are significant. As described above, the greatest opportunities for energy savings are during facility design and equipment validation, with minor energy savings possible through equipment maintenance and calibration. Because UV disinfection is a physical process that relies on the direct conversion of electrical power to UV light output, a utility must strike a delicate balance between optimizing the energy efficiency of the UV equipment and incorporating sufficient flexibility and conservatism into their UV facility design to ensure the continuous protection of public health.

The data collected from the Loudonville UV Facility will be used to illustrate the potential energy savings, in terms of electrical consumption and dollars, that each of the energy savings approaches described above can provide to a utility. For the purposes of this example, the following assumptions and adjustments have been made:

- The City of Albany is currently targeting 3-log virus inactivation credit with a calculated dose of 240 mJ/cm^2, which, as described previously, must be considered an estimate since the UV unit was not able to be validated to that high of a dose. To make this application more representative of a typical application targeting 3-log *Cryptosporidium* inactivation credit (a dose of approximately 40 mJ/cm^2), the energy consumption for the Loudonville UV Facility has been adjusted in proportion to the targeted dose (i.e., divided by six).

- To eliminate the energy savings currently being realized from the adjustable lamp power control strategy, the energy consumption calculated in the first bullet is multiplied by 1.2. This is done to establish a baseline energy consumption that is consistent with a typical installation that does not employ an adjustable lamp power control strategy.

- To simplify the illustration, it has been assumed that the "wire to light" efficiency of LPHO is twice that of MP (i.e., 30% versus 15%) and that the equipment factor for LPHO is 15% less than that for MP.

- To simplify the illustration, it has been assumed that the lamp power setting is 60% approximately 50% of the time and that the UV equipment still overdoses approximately 25% of the time. These values are supported by the data recorded during the study.

- To simplify the illustration, it has been assumed that the control strategy would allow all potential energy savings to be realized. In actuality, given the stepped nature of the lamp power adjustment and the fact that it cannot go below 60%, the actual energy savings could be less.

- The average UVT of the treated water is 95%, resulting in a polychromatic bias due to the use of instant coffee of approximately 1.1.

- The average cost of electricity is $0.132/KWH.

As shown in Table 8.3, the potential effects on the energy efficiency of a UV facility of each of the items described in this section are significant. It is expected that the ratio of energy savings that is shown would be fairly consistent regardless of facility size.

Table 8.3 Summary of Potential Energy Savings

Item	Annual Electrical Consumption (KWH)	Annual Electrical Cost ($)	Incremental Savings (Cost Increase)	Percent Savings
Baseline Energy Use [1]	**105,600**	**$13,939**	---	---
Using LPHO versus MP Lamps	44,880	$5,924	$8,015	58%
Using a Variable Lamp Power Setting	88,000	$11,616	$2,323	17%
Modifying PLC to Allow Adjustment of Number of Lamps	79,200	$10,454	$3,485	25%
Using a Fouling Factor of 0.9 versus 0.6	79,200	$10,454	$3,485	25%
Using MS2 as the Challenge Microbe	242,880	$32,060	($18,121)	-130%
Using PHI X 174 as the Challenge Microbe	105,600	$13,939	$0	0%
Using Lignin Sulphonate as UV Absorber During Validation	97,152	$12,824	$1,115	8%
Using no UV Absorber During Validation	89,760	$11,848	$2,091	15%
Reducing the Expanded Uncertainty to 20 Percent	97,477	$12,867	$1,072	8%
Relying on a Tier 1 Analysis	142,154	$18,764	($4,825)	-35%

Notes:

[1] Assumptions Made for Baseline Energy use:

- *Target dose of 40 mJ/cm^2.*
- *Calculated as 1/6 (ratio of target dose) the actual energy use recorded at the City of Albany UV Facility.*
- *Multiplied by 1.2 to eliminate energy savings from lamp power adjustment.*
- *Use of medium pressure lamps.*
- *RED bias of 1.00.*
- *Use of instant coffee as an UV absorbent during validation.*
- *An expanded uncertainty of 30 percent.*
- *Use of a Tier 2 Analysis.*

[2] The incremental increase/decrease shown for each item are not mutually exclusive.

8.6 RECOMMENDATIONS FOR THE LOUDONVILLE UV FACILITY

8.6.1 Findings

For the Loudonville UV Facility, the areas that offer the greatest opportunity for energy savings, operations improvement, and cost savings are:

- Modifying the PLC to allow adjustment of the number of lamps that are ignited during low flow or reverse flow periods. This will minimize the amount of time that the UV facility is overdosing, which will improve its energy efficiency and help reduce the dechlorination effects of the UV light.

- Identifying a challenge organism that can be used to validate the high target dose that is desired. This will allow the City to accurately determine the dose that is required to obtain their desired inactivation credit. It will also allow the dosimeter algorithm to be confirmed and calibrated to ensure operation is as efficient as possible while meeting the City's disinfection objectives.

- Modify the lamp replacement schedule. Rather than replacing lamps on a fixed interval of 4,000 hours, allow the lamps in one UV unit to operate for an extended period to determine the actual point at which the lamps are no longer able to produce the necessary light output to deliver the target dose. Based upon those findings, the City should either establish a new lamp age at which all lamps will be replaced, or simply replace lamps when they are no longer able to produce the necessary light output due to lamp aging.

- Based on the study, there is no benefit to regularly scheduled supplemental manual cleaning of the lamp sleeves. As such, it is recommended that the City simply rely on the automatic cleaning system to prevent fouling. It is still recommended that City personnel manually clean the lamp sleeves when the UV units are dismantled for cleaning of the vessel.

- Based on the study, there is no noticeable improvement in control equipment performance as a result of more frequent calibration or calibration check. It is recommended that City personnel follow the manufacturer's recommended frequency of calibration and maintenance. It should be noted again that overly conservative measurements will result in unnecessary energy use.

8.6.2 Potential Savings and Simple Payback of Recommended Modifications

Modifying the PLC to incorporate adjustment of the numbers of lamps that are ignited during low flow and reverse flow periods could reduce the energy used by the Loudonville UV Facility by approximately 15 to 25%. This equates to a reduction of between 78,000 and 130,000 KWH/year at a cost savings of $10,000 to $17,500/year. To maximize the benefit of this programming modification, additional validation testing would be required to expand the matrix of validated test conditions with the reduced numbers of lamps.

Based on correspondence with Trojan, modifying and reprogramming the PLC to expand its capabilities to include adjustment of the number of ignited lamps would cost approximately $75,000. Additional on-site validation to establish the validated operating points for the reduced number of lamps is estimated to cost approximately $40,000, bringing the total cost of this modification to $115,000. At the projected savings, this would result in a simple payback of 6.5 to 11.5 years. If a more appropriate challenge organism is

identified for the validation of high doses, the City could conduct a single on-site validation event that establishes the validated operating conditions for the reduced number of lamps as well as the actual operating conditions that are required to deliver the necessary dose for 3-log virus inactivation credit. This would allow multiple objectives to be met without significantly affecting the cost of the validation testing.

Based on current operating data, cumulatively the four UV units at the Loudonville UV Facility run approximately 75,000 lamp-hours per year. At the current lamp replacement schedule of 4,000 hours, 18 lamps are replaced each year due to aging, at a cost of approximately $11,000. If the lamp replacement schedule is extended to 5,000 hours or longer, the lamp replacement cost would be reduced by at least $2,200/year. There is no additional cost to make this modification, resulting in an immediate payback.

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APPENDIX A

Trojan UVSwift™-24 Equipment Validation Protocol
Loudonville, NY Water Treatment Plant

Trojan UVSwift™-24 Equipment Validation Protocol
Loudonville, NY Water Treatment Plant

1. Introduction

The UVSwift™ Model 8L24 will be tested to demonstrate:

- Contract (November 2001) requirements to demonstrate delivered MS-2 dose of 40 mJ/cm^2, using an 8L24 under operating conditions relevant to the proposed operation of the Albany facility. The lamps used for the testing will have been aged for a minimum of 2000 hours of operation prior to the testing.
- Additional bioassay validation work at Albany, NY UV facility, to demonstrate virus inactivation between 0.5 and 3.5 log using an 8L24 under operating conditions relevant to the proposed operation of the Albany facility. The lamps used for the testing will have been aged for a minimum of 2000 hours of operation prior to the testing. This objective does not form part of the required contractual validation of the UV disinfection equipment.

The reactor challenges will be performed at the Loudonville UV Facility. Only one UV reactor shall be validated as all reactors are of identical design and equipment, including hydraulic inlet and outlet conditions.

The entire validation effort shall be audited by an independent UV expert, Dr. James P. Malley, Jr. (University of New Hampshire). Trojan personnel will operate the UV system, perform the on-site water quality analyses, the reference sensor checks, collect all samples, record all sample collection data, all water quality data, and spot-check reactor operating values for sensors, flow, UVT and lamp power settings during the validation under the supervision of the third party. Staff from Trojan will ship all samples for delivery to GAP EnviroMicrobial Services for microbiological enumerations. Dr. James P. Malley, Jr. will take custody of all bench sheets and equipment calibration documentation.

All microbiological samples will be analyzed by GAP EnviroMicrobial Services, an accredited lab facility. Raw data will be distributed directly to Dr. Malley from GAP (i.e. not through Trojan) and Dr. Malley will distribute to Trojan. Trojan will perform the data analysis, which will be checked and verified by Dr. Malley. To validate performance of the UVDosimeter™ Dr. Malley will provide Trojan with operational parameters and calibration data. Trojan will then return predicted performance of the UVDosimeter™ for all tests to Dr. Malley, at which point Dr. Malley shall provide the reactor microbiological data to Trojan to complete the validation analyses.

Dr. Malley shall provide comments and final approval of the collimated beam, culturing, sample analysis and overall test protocol(s), to check and verify all calculations, and to confirm the accuracy of the conclusions. Dr. Malley shall provide certification of the validation.

2. Methodology

2.1 Test Facilities and Set-Up

The UVSwift™ 24 will be tested at the Loudonville Water Treatment Plant, located in Loudonville, NY, USA. The test system set up is diagramed in Figures 1 & 2.

The UVSwift™ 24 will be installed on a 24" line teed from a 48" line. The pump is capable of supplying up to 40 USMGD of water into the 48" line but during the validation tests will only provide the maximum flow rate of 10 USMGD.

The reactor is supplied from an 18 foot length of 48" pipe that "T's" vertically into a 24" pipe, on which the reactor is installed. There are 10 feet of 24" pipe upstream of the reactor and 6 feet downstream of the reactor. The 24" pipe then turns 90° and runs horizontally for 22 feet, turns 90° again and descends 18 feet to another 48" manifold pipe. (Fig 1 and 2).

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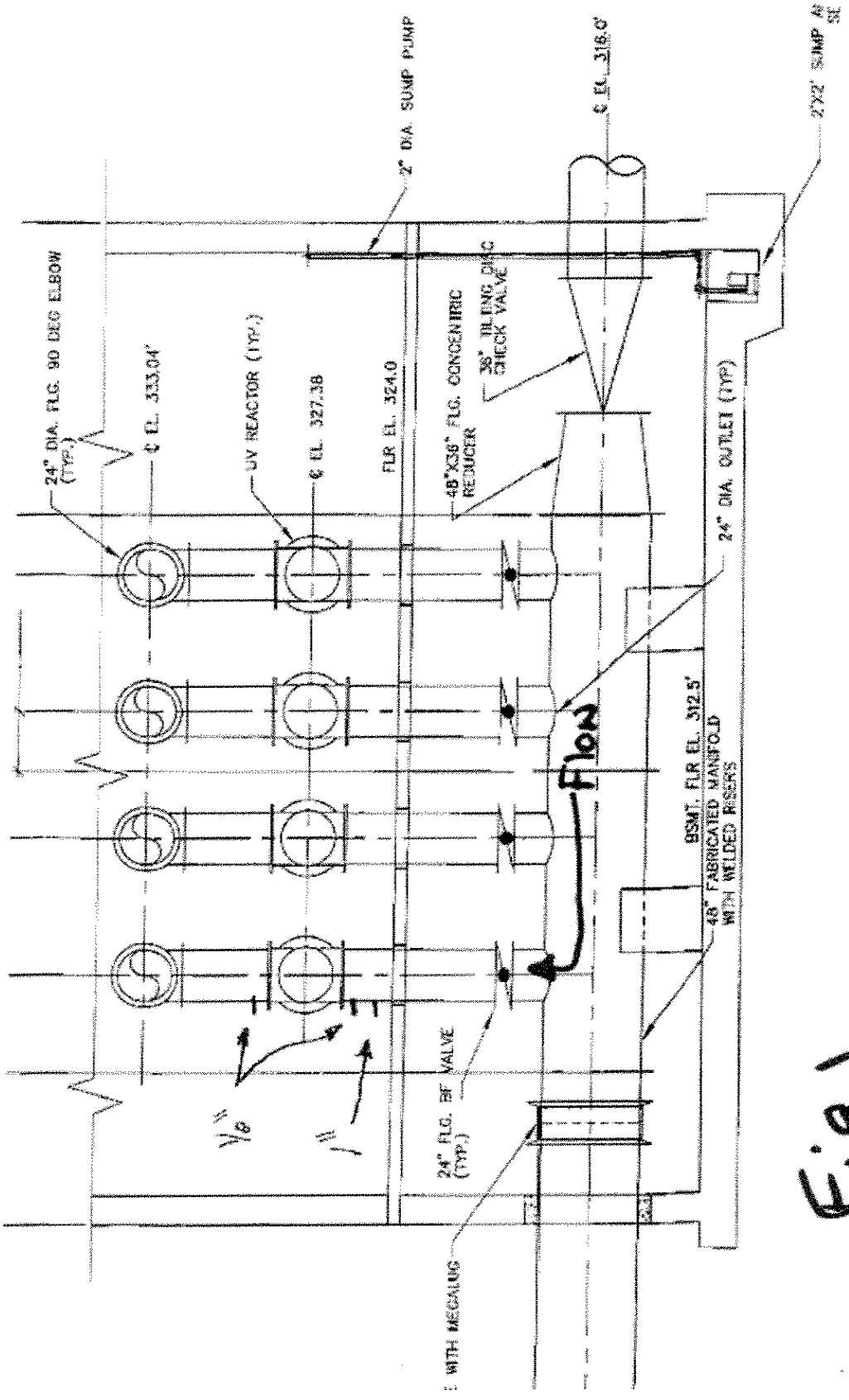

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Trojan Technologies Inc.

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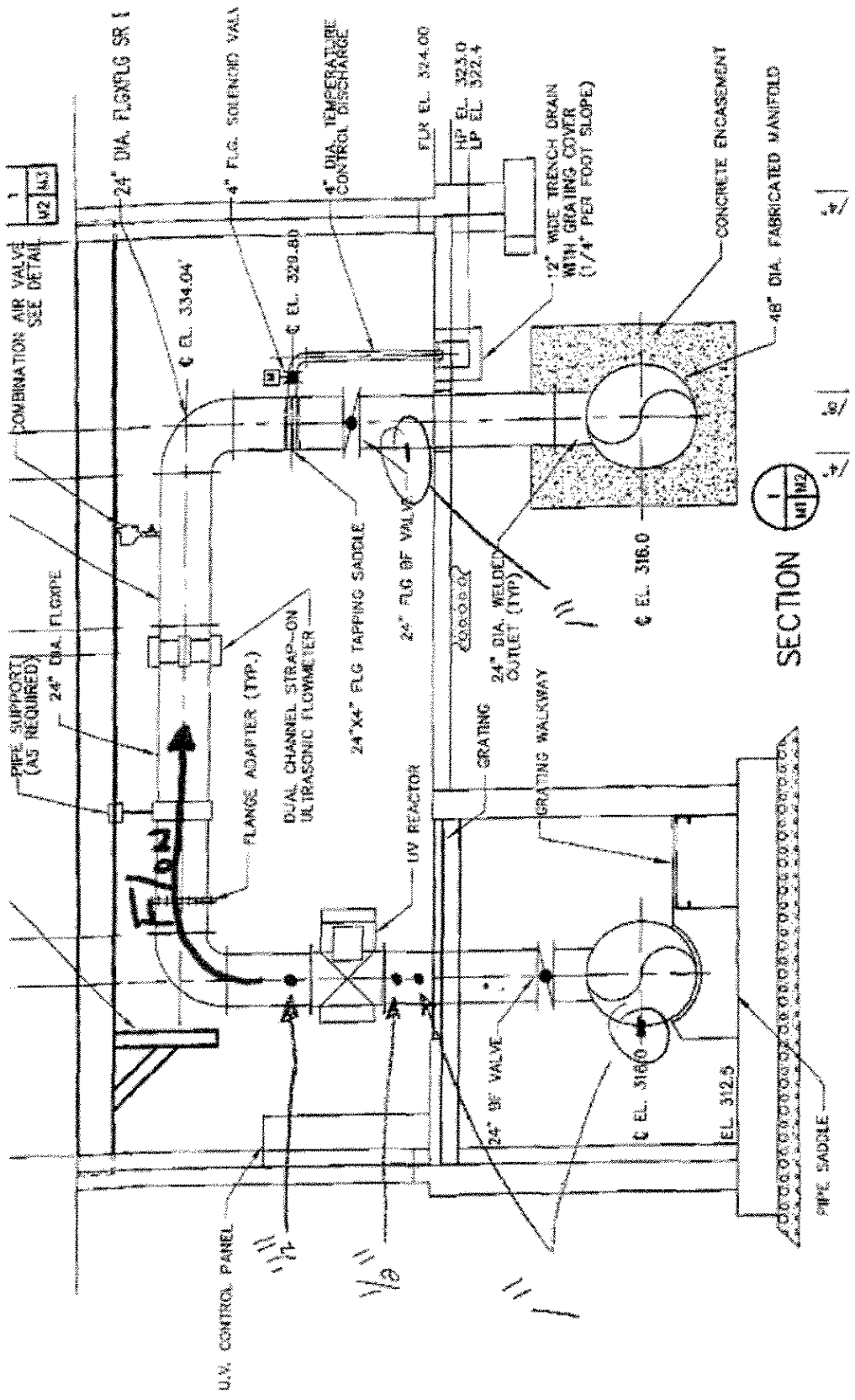

Fig 2

The ultrasonic flow meter is mounted in the middle of the horizontal 24" pipe, 21 feet downstream of the reactor and approximately11 feet downstream of the 90° turn. A modulating valve is installed on the descending arm of the 24" pipe 5 feet downstream of the 90° turn and 4 feet upstream of the outlet sampling port.

The raw water is treated water sourced from a reservoir cell. Typically of potable quality (turbidity <0.6 NTU and transmittance approximately 97.5 %/cm at 254 nm) chlorination was terminated several days before the validation resulting in chlorine readings of <0.03 ppm free chlorine. Water quality criteria for testing the UV system will be set at < 5 NTU turbidity and > 95 %/cm transmittance (at 254 nm). These parameters will be monitored regularly during the testing period. Chlorine, which can be dosed into the reservoir cell will be monitored for its absence, verified by chemical tests.

Dissolved instant coffee will be used for altering UV Transmittance. UVT modifier and the test surrogate organism will be injected separately into the 48" line using gear pumps at a reducer connecting a 36" line to the 48" pipe 18 feet upstream of the 'T'd' 24" pipe, on which the UV reactor is installed. The injectors to be used consist of stainless steel tubing set across the flow of the pipe, with small (1 mm diameter) holes along their lengths to distribute the injected liquids across the flow stream.

Ports for collecting samples are situated upstream and downstream of the UV reactor and samples are taken from the wall of the pipe. Each sample port is fitted with a ball valve or tap that is left open during the entire day of testing. The sample lines (Tygon™ tubing) are of minimum length and will be flushed continuously (at approximately 1 USgpm), even in-between runs. To ensure adequate flushing, a minimum of 15 volumes of the piping set up will be allowed to turn over prior to beginning the next run. Fresh Tygon™ tubing will be used on each day. The upstream sampling port will be located 11 ft upstream of the UV reactor (3 feet of 48" pipe, 90° 'T' join to the 24" pipe and 8 feet of 24" pipe length). The downstream sampling port will be located 30 feet downstream of the reactor (including 2 feet downstream of a modulating valve) resulting in a mixing length of 15 pipe diameters from the end of the reactor to the port, (along with two elbows to provide additional mixing). Using dissolved instant coffee, tracer tests of complete mixing will be conducted for both sample ports. The results of these tests will be provided to Dr. Malley for review and approval of the sampling locations prior to beginning the validation tests. This documentation, the review comments and the approval forms will be included in the final report.
Christine, can you provide:

Figure 1. Photographs of the piping supply for the UVSwift™ 24 illustrating locations of sampling ports, flow meter, injection diffusers.

2.2 Flow Measurement

Flow will be measured using a calibrated Panametric, model DF868 ultrasonic flow meter, situated downstream of the UV reactor on the 24" pipe line. The flow meter is factory calibrated and degradation is accounted for in the electronics. The flow meter comes with a calibration certificate. Dr. Malley will check the calibration certificate against the serial number prior to testing, and will also check the input variables into the flow meter (density, pipe diameter, etc.) to ensure that this information is accurate.

During a test, flow meter readings will be recorded electronically. For the period of the sampling event the minimum, maximum and mean values may be calculated, with the mean being reported as the system flow rate for each test.

2.3 Water Quality Measurements

UV transmittance (UVT) of the water at 254 nm will be constantly monitored using a Trojan On-Line UV Transmittance meter. The meter draws water from the 48" pipe approximately 30 feet downstream of the outlet sampling port. The 4-20 mA signal from this meter will be fed into the controller as an input to the on-line UVDosimeter™ dose calculations.

In addition, the UVT (absorbance) will also be measured on-site with a Varian Cary 50 spectrophotometer. These measurements will be used to confirm the readings from the on-line UVT and will be used to determine the recorded absorbance for a given test run. The Cary 50 is calibrated by the manufacturer. A copy of the calibration certificate will be provided and Dr. Malley will check the certificate against the serial number prior to testing. The calibration will be checked each day with certified potassium dichromate absorbance standards (certificate number 13232). The reference standard blank will be used to blank the spectrophotometer over the course of each day.

Duplicate (beginning and end of run) inlet and outlet samples for absorbance measurement (254 nm) will be collected into sterile 50 mL sample tubes for each test. An absorbance scan from 200-400 nm will be performed for one of the two inlet samples taken on each run (selected randomly).

The turbidity of one sample from each run will be measured using a Hach 2100AN turbidity meter to verify the on-line turbidity measurements. Chlorine levels will be measured and verified for absence over the course of the day of validation by chemical tests.

2.4 Sensor Measurements

The UV Intensity Sensor readings will be recorded from the Control Power Panel in mW/cm^2 and as a 4-20 mA signal using a calibrated Fluke multimeter. The serial number of the multimeter will be recorded to verify the calibration documents.

2.5 Lamp Power Measurements

The arrangement of lamps and their associated serial numbers will be recorded for each run. The power level will be recorded from the operator interface on the Control Power Panel and once at each setting the current to each lamp will be measured using a calibrated Fluke multimeter to verify that the settings are correct.

The calibration certificates for the multimeter will be provided during validation and Dr. Malley will check the certificate against the serial number for each unit.

2.6 Dose Calculations/Predictions

The Dose Delivered will be recorded from the operator interface during the sampling for each run. After the completion of the testing (prior to receiving any reactor results), the Dose Calculations will be re-run based on the actual absorbance (UV Transmittance) measured for the sample, the mean flow recorded, and the D_{10} (dose required for 1-log inactivation) for the MS-2 as determined by the Collimated Beam calibration curves. These calculated Delivered Doses (RED's) will serve as the basis for comparison to bioassay values. Inputs into the dose calculation during the test, and measured values input for the later calculations, should be close in magnitude, and the two dose calculations should not differ greatly. Thus the In-Test Dose Calculations will be used to verify that the Post-Test Dose Calculations were not done with a different algorithm.

The values recorded from the operator interface will provide a benchmark.

2.7 Mixing Tests

Mixing tests shall be performed prior to testing at this facility to verify that complete mixing is achieved from the injectors to the upstream sampling tap and to the downstream sampling port. The results of these tests will be provided to Dr. Malley prior to beginning the validation testing, for his review and approval of the sampling locations. This documentation, the review comments and the approval forms will be included in the final report.

2.8 UV Dose Determinations

GAP Enviromicrobial Services will provide microbial stock of MS-2 for the purpose of the testing. The stocks will be assayed by GAP prior to sale to provide a baseline for comparison of control samples. Each litre of stock provided will have an independent serial number.

The microbial stock will be diluted approximately 4:1 (dependent on titre) with the same water that is being used to test the UV system. The total volume of each batch will be 10 – 20 L. Dissolved instant coffee will be added to a concentration of 20-30 ppm as a precaution to guard against chelation and agglomeration. For each stock and each batch, control samples of approximately 5 mL will be taken into sterile 10 mL centrifuge tubes (Trip Controls). All reactor microbiological samples will be collected into sterile 300 mL sterile plastic sample bottles. The

control samples will be placed in coolers and treated the same as test samples. Comparison of the control assays to expected values (from pre-sale stock assays and calculated dilutions for the batches) will be used to identify any problems with the stocks or with the diluted batches, as well as any problems resulting from storage or transport.

A UV dose calibration curve will be generated for each day, chemical and batch of diluted organisms. It is expected that one batch of organisms will be sufficient for one day of testing. Calibrations may differ day to day due to differences in resistance arising from differences in batches of microorganisms, or from changes in the chemical matrix of the water being treated. Generating calibration data on each date will ensure completely valid calibrations for all runs. The collimated beam dose calibration procedure inherently takes UVT into account, so only one collimated beam will be performed for each batch. The following UV doses will be applied to MS-2 in the collimated beam tests:
0, 10, 20, 40, 60, 80, 100, 120 mJ/cm^2
corresponding to a series of log reductions approximating 0.5, 1,2,3,4,5,6 log reduction. Samples for generating UV dose calibration curves will be collected in duplicate from the upstream sampling port into sterile 1L bottles, and stored on ice ready for delivery to GAP (see Appendix ## for SOP methodology for GAP EnviroMicrobial Services Collimated Beam Analysis). Triplicate irradiations will be done to generate each collimated beam calibration curve.

Reactor challenges will be performed for a number of flow, absorbance and lamp power conditions. Flow will be maintained through the system throughout the course of the testing. When flow or lamp powers are changed, the system will be given adequate time to achieve steady state. Once at steady state, injection of instant coffee will begin. The coffee injection rate will be set based on the flow rate and target UVT for each run. The system will be given adequate time to achieve steady state. Check samples will be taken, and absorbance measured. Absorbance-modifier injection rates will be adjusted as necessary to reach the desired absorbance (+/-5% ABS from target) for the test run. Once at the desired absorbance, injection of the surrogate organism will begin. A minimum of 15 residence volumes will be allowed to pass to guarantee steady state. Organism injection rates will be scaled to the system flow rate, so that each test will have the same approximate inlet concentration (if we need to bump up the injection conc this may change for the different flow rates). An injection rate of approximately 40 mL/min will be used at 2 MGD, 100 mL/min will be used at 5 MGD and 200 mL/min at 10 MGD. Duplicate samples for water quality analyses will be collected from both the upstream and downstream sampling ports into sterile 50 mL centrifuge tubes: one at the beginning of the run and one at the end. Three samples for enumeration will be collected from both the upstream and downstream sampling ports into sterile 300 mL sample bottles. Replicate samples will be taken at a time interval of 1 minute. The different types of microbial samples (upstream vs. downstream) will be stored separately in different coolers and stored on ice.

2.9 Test Conditions

The UV Reactors will be tested under conditions that bracket the expected operation at the Loudonville plant. The test conditions and objectives are as follows.

Run No.	Flow	# Lamps On	Objective	UVT	UVT modifier	Organism	Lamp Power (%)
Day 1							
1	10 mgd	0	Control	Bkgrd (97)	none	none	0
2	10 mgd	0	Control	Bkgrd (97)	none	MS-2	0
3	10 mgd	8	RED >/=120	Bkgrd (97)	none	MS-2	100
4	10 mgd	8	RED >/=40	Bkgrd (97)	none	MS-2	60
5	5 mgd	8	RED >/=40	Bkgrd (97)	none	MS-2	60
6	2 mgd	8	RED >/=40	Bkgrd (97)	none	MS-2	60
7	10 mgd	8	RED >/=40	88	Coffee	MS-2	60
8	10 mgd	8	RED >/=100	88	Coffee	MS-2	100
9	5 mgd	8	RED >/=40	88	Coffee	MS-2	60
10	2 mgd	8	RED >/=40	88	Coffee	MS-2	60
11	10 mgd	0	Control	Bkgrd (97)	none	none	0

Runs 1, 2, and 11 will be control runs. During these runs the reactor will be turned off (no germicidal input). The power levels for all other validation runs have been selected to obtain a dose of 40 mJ/cm^2 or greater based on previous bioassay results with MS-2. Runs 3 and 8 will be validated by third party but DO NOT form part of the contractual validation criteria and regardless of the RED results WILL NOT form part of the pass/fail criteria.

Run 1 will be used to quantify the background levels of MS-2 in the reservoir water supply (Reactor blanks).
Run 2 will be used as a baseline to demonstrate that there are no negative impacts to the indicator by passing through the reactor (Reactor controls).
Run 11 will be used to demonstrate that there are no adsorption-of-microbe effects as a result of the Tygon tubing and sampling set up that are affecting the results.

2.10 Responsibility Matrix

The table below details the responsibilities of each party involved in the testing as it pertains to specific tasks to be performed.

Tasks	Trojan w. 3rd Party Oversight	Owner/ Engineer	Independent 3rd Party
Test protocol development	Trojan and MP		
Test protocol review Collimated Beam protocol Mixing/Location of sampling ports Hydraulics & Set-up of test facility		Pirnie Pirnie Pirnie Pirnie	Malley Malley Malley Malley
Review 3rd party personnel Qualifications		City of Albany/ Pirnie	
Instrument Calibration ▪ Flow Meter ▪ UVT Instruments ▪ Ammeter			Malley
UV Sensor Calibration			GE
Verify Instrument & Lamp Serial Numbers			Malley
Operating Equipment	Trojan		
Recording System Parameters ▪ Power Settings ▪ Lamp Output ▪ UV Sensors ▪ Flow Meter ▪ UVT ▪ Turbidity ▪ Dose	Trojan		
Track & Verify Organism Stock Numbers	Trojan		Malley
Injection of Organisms & LSA	Trojan		
Sample Collection	Trojan		
Sample Custody & Transport	Trojan		Malley
Sample Analysis			GAP
Collimated Beam Test			GAP
Receive Results	Trojan (from Malley)	Pirnie	Malley
Analyze Data	Trojan		

Check/Verify Calculations	Trojan	Pirnie	Malley
Write Report	Trojan		
Confirm Accuracy of Conclusions		Pirnie	Malley
Provide Validation Approval			Malley

3. Quality Assurance and Quality Control

Flow measurements will be analyzed to ensure the range of flow during a run remained within +/-5% of the mean.

Replicate absorbance measurements will be analyzed to assess the overall precision in sampling and measurement and ensure the range of absorbance during a run remained within +/-5% of the mean. Systemic differences between the inlet and outlet would be an indication of incomplete mixing at the inlet of the reactor.

The lamp current measurements and power levels recorded will be analyzed to assess the lamp stability over the course of the testing.

3.1 Mixing Test

Flow will be established at the lowest rate to be validated (2 MGD) and injection of absorbance modifier (instant coffee) will be set to establish an absorbance higher (lower UVT) than is to be validated. Adequate time will be allowed to establish steady state and samples will be taken at the upstream and downstream sampling ports, simultaneously but at 1-minute intervals. Absorbance measurements (at 254 nm) of replicates and between the inlet and outlet sampling ports must be maintained over a range of +/- 5% of the mean absorbance to verify adequate mixing and to proceed with validation testing.

3.2 Microbiological Controls

Microbiological trip controls, both for stocks and diluted batches, will be compared with expected values to indicate whether or not there were problems either with storage or transport of the microbiological samples.

On day 1, a control trial will be run initially and samples collected to determine the background concentration of MS-2 in the influent water (Reactor blanks). A final run will be a control trial to determine that background counts has not changed and that no adherence to sample tubing has occurred.

Three samples will be enumerated for each run for both the upstream and downstream sampling positions. Three counts will be used to calculate an arithmetic mean, the standard deviation and Student's t-statistic of the inlet and outlet sample counts. The log residuals of the counts will be used to evaluate the overall sampling precision of the data.

During microbial analysis, GAP will incorporate Method Blanks into their analysis procedure (sterilized reagent grade water that undergoes the challenge microorganism assay procedure) to verify that the microbial concentration is non-detectable.

3.2 Determination of Log Reduction Measurement Sensitivity

One reactor test will be performed with zero germicidal input, i.e. with all lamps off, but with injection organisms. It is expected that counts from the inlet and the outlet will be the same, or that no log reductions of microorganisms occur across the de-powered reactor. Any measured difference, which could be an increase or decrease from inlet to outlet, is a measure of the ability to determine log reductions for the system. The challenge microorganism concentrations in both inlet and outlet samples should be the same at a 90% confidence level.

3.3 Determination of UVT Modifier Sensitivity

Comparison of the inlet microbe counts between runs at comparable flows and microbe injection rates, but with and without absorbance modifier, will serve as a test of sensitivity of MS-2 to the modifier. The dose delivery, sensor readings, and dose predictions will be compared for the two water absorbance spectra (with and without coffee). This will allow us to quantify the safety factors associated with testing with water that is different from that naturally occurring at site. Please refer to table B-4 in the UVDGM.

3.4 UV Sensors

Sensor calibration checks will be performed using the reference sensor at the beginning of the testing to assess sensor stability.

4. Data Analysis

4.1 UV Dose Calibration Curves

(Brian – UVDGM suggests averaging the zero doses). Except for zero dose samples, replicates will be treated as separate values, not combined into means. The log inactivation for each applied dose delivered by the collimated beam will be calculated as:

Log inactivation = log (No/N)
Where No = average concentration of the challenge microorganism in the zero dose aliquots
And where N = challenge microorganism concentration in an aliquot of sample

The response-dose of the MS2 will be plotted log inactivation versus calculated dose and a best-fit least squares regression will be performed on each set of collimated beam data (with and without coffee) to determine the calibration equations. Equation coefficients obtained from the regression analysis should be significant at the 95% confidence level and data should be randomly distributed about the regression line and independent of dose.

Coefficients may be checked for significance based on the R-squared value for the fit of the regression line and the p-statistic for each coefficient.

Random difference between measured and predicted dose-values, as a function of log inactivation, will be determined at the 80% confidence level. Calibration datasets (generated with and without coffee) may be combined if the regression coefficients generated by each regression analysis are the same at the 95 percent confidence level.

4.2 Delivered Dose Calculations

For each test condition, the Reduction Equivalent Dose (RED) will be calculated based on the arithmetic mean (and the lower 90 percent confidence interval, for internal Trojan use) as recommended in the June 2003 draft USEPA UV Guidance Manual.

Three (3) inlet and three (3) outlet samples will be taken for each bioassay point.
The arithmetic mean (Arithmetic_inlet) and the standard deviation (SD_inlet) of the three (3) inlet sample counts will be calculated.
The arithmetic mean (Arithmetic_outlet) and the standard deviation (SD_outlet) of the three (3) outlet sample counts will be calculated.

The RED will be calculated from the log inactivation using the calibration regression equation describing the response-dose curve of MS-2 as:

The pooled variance will be calculated as follows using the Student's t-value for n=3 and 80% confidence (three samples):

pooled variance (or % uncertainty of the log inactivation through the reactor; U_{in}) = [(t_inlet * SD_inlet)^2/(n_inlet) + (t_outlet * SD_outlet)^2/(n_outlet)]$^{0.5}$ * 100%

The percent measurement uncertainty of the RED will be calculated to include the variance of log inactivation through the reactor (U_{in}), the variance determined for the response-dose regression analysis (U_{DR}) and the uncertainty of the dose calculation for the collimated beam (U_D) as:

$U_{RED} = (U_{in} + U_{DR} + U_D)$

Arithmetic description of U_{in} is above, description of % uncertainty of the collimated beam is in section 4.1, and variability, as percent uncertainty, of the calculated calibration dose that is not captured within U_{DR} but attributable to variability of the radiometer and calculation of the Petri factor is calculated as:

U_D = (uncertainty of the radiometer^2 + measurement uncertainty of the Petri factor^2)$^{0.5}$

A safety factor analysis incorporating all forms of bias and random uncertainty will be calculated as described in the June 2003 Draft EPA UVDGM.

4.3 Delivered Dose vs. Predicted Dose

For each test condition, the RED (as calculated above) will be compared with the Predicted Dose from the control system. For each test condition the Predicted Dose will be divided by the RED to arrive at a ratio. The "worst case" ratio (i.e. the largest value) will then be used as the adjustment factor and will be applied to the Target dose in the controls software for on-site operation.

Target Dose = adjustment factor * 40 mJ/cm2

5.0 Documentation

5.1 Pre-Validation Documentation

The following documentation describing the system to be tested will be provided to the UV Experts in advance of the testing. This information will also form part of the final report.

Technical descriptions & dimensions of all internal components:
- Lamps
- Sleeves
- Sensors

Reactor inlet/outlet hydraulic specifications including:
- Length of straight pipe
- Pipe diameter
- Pipe bends

Lamp specification:
- Lamp manufacturer & product number
- Length from electrode to electrode
- Spectral output after 100 hr burn-in
- Spectral output at end of lamp life (3000 hours)

Sleeve specification:
- Sleeve material
- UV transmittance from 200 to 400 nm
- Length
- Thickness

Specifications for sensor & reference sensor:
- Manufacturer & product number
- Acceptance angle

- Working range
- Calibration factor
- Spectral response
- Linearity
- Temperature stability
- Long-term stability
- Environmental requirements
- Measurement uncertainty

Specifications for UV intensity sensor port:

- Dimensions & tolerances
- Positioning relative to UV lamps

Specification for UV intensity sensor Sleeves:

- Material
- Thickness
- UV transmittance from 200 to 400 nm

Technical description of algorithm used to determine compliance including:

- Use of intensity sensors
- Signal processing
- Calculations
- Low dose alarms & safeguards

Calibration Certificates for all measuring devices used during validation:

- flowmeter
- multimeters
- IL Radiometer
- Cary 50

5.2 Final Report

The final validation report will be written by Trojan Technologies Inc.. The report will be reviewed and the accuracy of the conclusions certified by the UV Expert, Dr. James P Malley, Jr.

The final report will contain the following information as a minimum.

- Size of reactor in terms of flow – maximum capacity as tested
- Required minimum inlet and outlet conditions – Hydraulic conditions of test
- Orientation of lamps with respect to flow – reactor description
- Number of UV lamps – reactor description
- Lamp characteristics (type, electrical power consumption, spectral output – lamp info provided for above)
- Number & location of UV Intensity sensors
- Monitoring and controls approach
- Confirmation that UV Intensity sensors are appropriate for the controls strategy
- Safety features to ensure water disinfection
- Microbe dose response
- Table of challenge results (flowrate, UVT, dose calculated, log inactivation, dose equivalent delivered)
- Interpolation of bioassay results (curves that show the interpolation in between bioassay points)
- Measurement uncertainties associated with on-line & reference UV Intensity sensors (safety factors that should be applied)
- Correction factors (or discussion surrounding) polychromatic issues (water spectra, water absorbance, lamp aging)
- Identity and qualifications of personnel involved in test (UV Expert)
- UV Reactor specifications
- UV intensity sensor specifications & calibration certificate
- Description of physical test set-up
- Summary of QA/QC procedures
- Materials & methods employed during the test
- Complete results (raw data & analysis performed)

APPENDIX B

Excerpt from "Fouling of Quartz Surfaces in Potable Water Ultraviolet Disinfection Reactors"

Since water chemistry demonstrated slight variations over the experiment period, three mineral speciation and solubility models were created: one based on a water chemistry profile developed by averaging the available parameters, one model where minimum values of each water chemistry parameter were used (except temperature, where the maximum observed value was used to force the highest solubility for minerals not subject to inverse solubility), and one model where the highest reported chemical concentrations were used (and the lowest reported water temperature).

The water chemistry data from the Metropolitan Water District experiments was of particular interest since aluminum was detected in solution at concentrations greater than the detection limit. This is important because of the low solubility of many aluminum-containing minerals. From the saturation index modeling that was performed (see Table 6.6), supersaturation of $Al(OH)_3$, $Al_4(OH)_{10}SO_4$, and AlOOH was identified. However, the highest observed aluminum surface concentration (in lamp #2) was very low: 0.033 $mmol/m^2$. While these results represent only a single long-term experimentation location for which aluminum concentrations were above the detection limit (and therefore for which this phenomenon was observable), they indicate that the rate of formation for aluminum-containing foulant materials may be slow when compared to other foulant components. Because of its implications with respect to coagulant selection, further examination of this topic in waters with high aluminum concentration would be beneficial.

6.4. City of Albany, New York

A single experiment was conducted at Albany, New York utilizing an eight lamp UV Swift MP reactor, similar to the reactor pictured in Figure 6.12. This reactor utilizes MP lamps that are oriented perpendicular to water flow through the reactor. During 28 days of experimentation, lamp sleeve wiping was disabled as water flowed through the reactor. This UV disinfection installation is unique in that water flows through the reactors in opposite directions at different times of the day as a storage reservoir is utilized and

Table 6.8. Mineral saturation indices for water used in the Albany Fouling experiment.

Mineral	Formula	Saturation Index
Calcite	$CaCO_3$	-1.172
Ferrihydrite	$Fe(OH)_3$	2.995
Ferrihydrite (aged)	$Fe(OH)_3$	4.116
Lepidocrocite	FeOOH	5.435
Magnesioferrite	$MgFe_2O_4$	5.521
Goethite	FeOOH	5.946
$Fe(OH)_{2.7}Cl_{.3}$	$Fe(OH)_{2.7}Cl_{.3}$	6.738
Maghemite	Fe_2O_3	7.226
Magnetite	Fe_3O_4	9.495
Hematite	Fe_2O_3	14.245

Modeling of mineral saturation indicated that several iron containing, and one magnesium containing mineral species were present in solution in excess of saturation. Calcite, however, was below saturation in the bulk water used in the experiments, indicating that calcium should not be a major component in the sleeve fouling matrix based on the mineral species identified by the model. Digestion analyses of sleeves removed from the reactor after two weeks run contrary to this finding, as shown in Figure 6.13, where for sleeves #1 and #2 calcium surface concentrations were 0.13 mmol/m^2 and 0.32 mmol/m^2, respectively, compared to 0.03 mmol/m^2 and 0.02 mmol/m^2 for sleeves #3 and #4. Calcium concentrations in the sleeves removed from the reactor after four weeks of operation were very low; the average calcium concentration for the four lamp sleeves was 0.02 mmol/m^2, accounting for, on average, only 9.0% the foulant that was detected. The sleeves used in these experiments were new, having never been installed in a UV reactor prior to the experiments, and so one possible explanation for the difficult to explain discrepancies in calcium concentrations within the two week sleeves and between the two week and four week sleeves could be material on the sleeves prior to experimentation, or impurities resulting from the sleeve removal, packing, and shipping process. Accumulation of iron on the lamp sleeves was more predictable: iron concentrations for the two week experiment were 0.09, 0.09, 0.08, and 0.08 mmol/m^2 and

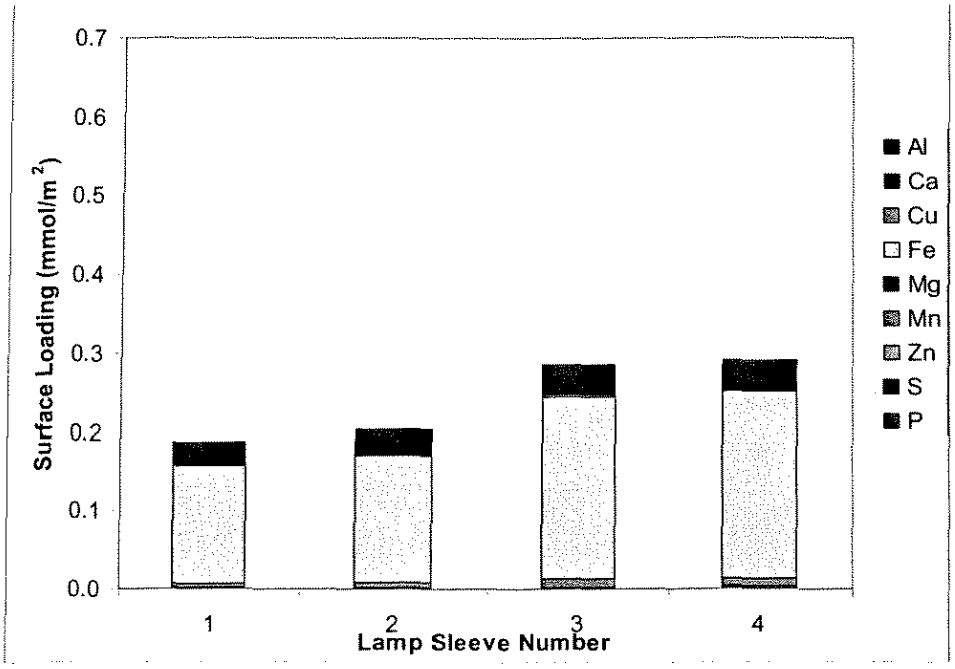

Figure 6.14 Lamp sleeve digestions from Albany fouling experiment: four weeks.

Table 6.9 Relative metals quantities and uptake ratios for UV sleeves for the Albany, New York fouling experiments.

Metal	Water % (molar basis)	2- Week UV Sleeve Foulant % (molar basis)	2-Week UV Sleeve Uptake Ratio	4-Week UV Sleeve Foulant % (molar basis)	4-Week UV Sleeve Uptake Ratio
Al	0.48%	4.59%	9.58	5.75%	12.01
Ca	84.00%	34.64%	0.41	9.11%	0.11
Fe	0.06%	44.47%	749.92	80.76%	1361.82
Mg	15.47%	12.84%	0.83	0.00%	0.00
Mn	0.00%	2.82%	Note B	3.57%	Note B
Zn	0.00%	0.64%	Note B	0.81%	Note B
	100.00%	**100.00%**		**100.00%**	

Note A: Element concentrations were below the detection limit for both water and sleeve foulant digestion samples.
Note B: Element concentrations were below the detection limit for foulant digestion sample.

The experiments in Albany, New York had aluminum in solution at concentrations greater than the detection limit, and this again permitted a calculation of the uptake ratio for this potentially important metal. As shown in Table 6.9, aluminum had an uptake ratio

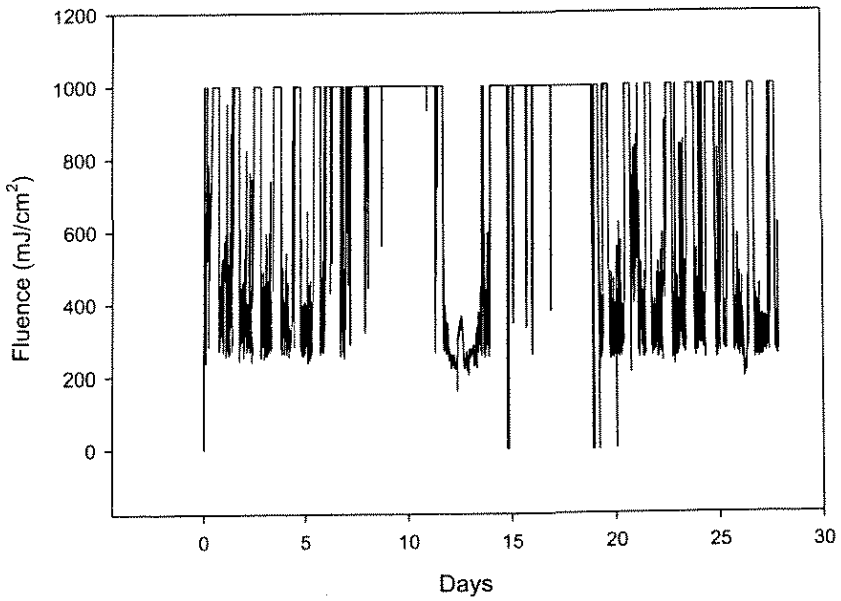

Figure 6.15 Fluence variation during the experiment at Albany, New York.

Flow through the reactor varied in magnitude from zero flow, during periods where flow direction changed, to a peak of 15 million gallons per day (mgd). The average of the absolute value of flow rate through the reactor was 2.54 mgd and the median flow rate was 2.49 mgd. Variation in flow rate through the reactor during the experiment is shown in Figure 6.16. A positive flow rate indicates flow leaving the UV plant, and a negative flow rate indicates water is entering the UV plant and filling the storage reservoir.

mJ/cm^2 – but is only a screened subset of data which represents common operating conditions which should yield constant fluences were there no fouling. Although there were many times during the experiment when these conditions were not satisfied and fluence was higher or lower than those values shown in Figure 6.17, this figure illustrates that fouling did reduce the transmittance of lamp sleeves in the reactor, and therefore reduced the efficacy of the disinfection reactor. The slope of the linear regression curve fit through the data in Figure 6.17 indicates that the reduction in reactor fluence was approximately 1.20 mJ/cm^2 per day, which represents a decrease of 10.7% over the 28 days of the experiment. While these results indicate that fouling did occur, the reductions in fluence that result from this fouling are, from a practical standpoint, unimportant in a reactor that is operating with such high fluences.

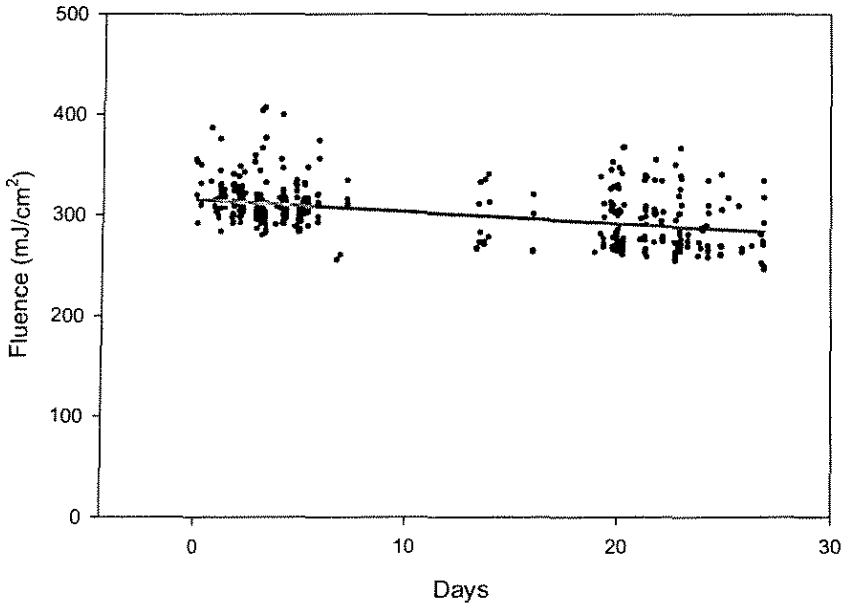

Figure 6.17 Decrease in reactor fluence at times when reactor flow rate is between 2.45 and 2.55 mgd and output power is at 60%.

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and Development Authority
17 Columbia Circle
Albany, New York 12203-6399

toll free: 1 (866) NYSERDA
local: (518) 862-1090
fax: (518) 862-1091

info@nyserda.org
www.nyserda.org

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Vincent A. DeIorio, Esq., Chairman
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