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Abstracts

Sponsored by:

National Water Research Institute

and

NWRI Corporate Associates

in collaboration with

California Department of Health Services

Foreword

UV 2000: A TECHNICAL SYMPOSIUM was organized to focus on the most pressing issues facing those in the water and wastewater industry who want to utilize ultraviolet (UV) technology. The symposium provided a forum to examine the major science and engineering events that have occurred since the 1993 California Wastewater Reclamation Guidelines were published by the National Water Research Institute (NWRI).

Sponsored by the NWRI Corporate Associates, in collaboration with the California Department of Health Services, the 2-day symposium offered the opportunity to exchange ideas and experiences between those representing academic research, water utilities, technical service providers, and regulatory communities.

The extended abstracts presented in this document were the contributions of the conference speakers. Abstracts were edited only when obvious errors were detected or when printing requirements necessitated alteration. The opinions expressed within the abstracts are those of individual authors and do not necessarily reflect those of the sponsors.

NWRI gratefully acknowledges the efforts of all those involved with planning, organizing, and presenting the conference. NWRI also extends special thanks to the conference speakers and panelists, whose expertise provided valuable insight into UV technology.

Ronald B. Linsky
Executive Director, National Water Research Institute

Conference Planning Committee

We are indebted to the following individuals, whose tireless efforts over the past few months helped make this conference a success.

- Conference Chair

  RONALD LINSKY

  National Water Research Institute

- Technical Program Chair

  FRED SOROUSHIAN, P.E.

  CH2M Hill

- *Committee Members*

  JAMES CROOK, Ph.D., *Black & Veatch*

  THOMAS HARGY, *Clancy Environmental Consultants, Inc.*

  ROBERT HULTQUIST, *California Department of Health Services*

  BOB LAFRENZ, Ph.D., *Innovatech, Inc.*

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  JOAN OPPENHEIMER, *Montgomery Watson*

  DOUG OWEN, *Malcolm Pirnie, Inc.*

  REY RODRIGUEZ, *H_2O R^2 Consultants, Inc.*

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UV Disinfection: An Overview of its Applications and Cost Effectiveness for Water and Wastewater Treatment

James R. Bolton, Ph.D., International Ultraviolet Association

Introduction

- UV light has been used to inactivate microorganisms in contaminated waters since the early 1900s.
- UV is now being considered by the U.S. Environmental Protection Agency (EPA) as an allowed (or even "Best Available Technology") for the Stage 2 M/DBP Surface Water Disinfection Regulations.
- UV inactivates *Cryptosporidium* and *Giardia* at low UV Doses.
- UV produces no significant disinfection by-products (DBPs) and is quite inexpensive.
- UV is widely used to disinfect the effluents from wastewater (sewage) treatment plants.
- As yet, no large UV systems in operation for drinking water treatment and no certification regulations.

Types of UV Lamps

- Low-pressure mercury lamps
- Monochromatic (254 nm); efficiency 35 to 40 percent
- Low power (40 to 80 W per lamp)
- Long lifetime (8,000 to 12,000 h)
- High-output, low-pressure mercury amalgam lamps
- Monochromatic (254 nm); efficiency 30 to 35 percent
- Higher power (100 to 200 W per lamp)
- Long lifetime (8,000 to 12,000 h)
- Medium-pressure mercury lamps
- Broadband emission; efficiency 10 to 15 percent in the germicidal (230 to 300 nm) region
- High power (1 to 25 kW per lamp)
- Medium lifetime (3,000 to 5,000 h)
- Xenon flashlamps

Correspondence should be addressed to:
International Ultraviolet Association
P.O. Box 1110, Ayr, Ontario, Canada N0B 1E0
Phone: (519) 741-6283 Fax: (519) 632-8941 Email: jbolton@iuva.org
or President, Bolton Photosciences, Inc.
92 Main Street, Ayr, Ontario, Canada N0B 1E0
Phone: (519) 741-6283 Fax: (519) 632-8941 E-mail: jbolton@boltonuv.com

- Broadband (blackbody) emitters; efficiency 5 to 10 percent in the germicidal (230 to 300 nm) region
- Medium average power (1 to 5 kW)
- Lower lifetime (<2,000 h)

Mechanism of UV Disinfection

- UV photons are absorbed by the DNA in bacteria and protozoa and by either DNA or RNA in viruses.
- Photochemistry involves forming covalent dimers from two adjacent thymines (in DNA) or uracils (in RNA).
- The UV lesions in the DNA or RNA disrupt the replication process so that the organism cannot reproduce. Microorganisms that cannot reproduce cannot cause disease.

Defense mechanisms against UV

- Photoreactivation
- Activated by near UV and visible light
- Involves an enzyme that splits the thymine dimer
- Dark reactivation
- Nucleotide excision repair
- Recombination
- Repair genes
- All reactivation processes can be overcome by applying a sufficient UV Dose

Germicidal wavelengths

- Drinking water absorbs strongly below 230 nm; DNA absorbance is very small above 300 nm.
- Define effective "germicidal" wavelength range as 230 to 300 nm.
- Not all photons are equally effective; best effectiveness is at about 260 nm.

Definitions

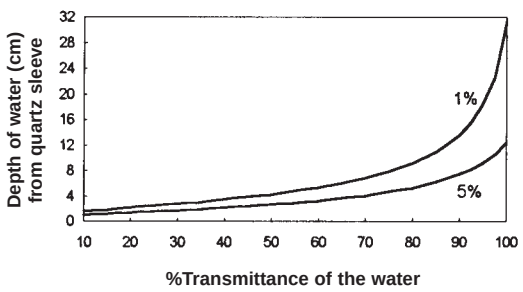
- *UV Irradiance (E)* (W/m^2 or mW/cm^2) is the total radiant *power* of all germicidal wavelengths incident from all forward directions onto an infinitesimally small area d*A*, divided by d*A*.
- *UV Fluence Rate (E′)* (W/m^2 or mW/cm^2) is the total radiant *power* of all germicidal wavelengths incident from all directions on an infinitesimally small sphere of cross-sectional area d*A*, divided by d*A*.
- *UV Fluence or UV Dose (H′)* (J/m^2 or mJ/cm^2) is the total radiant *energy* of all germicidal wavelengths incident from all directions on an infinitesimally small sphere of cross-sectional area d*A*, divided by d*A*. It is the UV Fluence Rate multiplied by the exposure time(s).
- *Germicidal UV Fluence or UV Dose* (J/m^2 or mJ/cm^2) — the UV Fluence (UV Dose) weighted by the relative absorbance of DNA with a weighting factor of 1.00 at 254 nm.

Collimated Beam Tests

- Important to establish the UV sensitivity of each pathogen.
- Use a collimated beam with either a low-pressure (254 nm) or medium-pressure (broad-band) UV lamp.
- Measure UV irradiance accurately with a UV radiometer.
- Determine *average* UV irradiance in the water sample.
- UV Fluence (UV Dose) is then the average UV irradiance times the exposure time(s).
- UV sensitivity of pathogens (4 logs inactivation) varies from 100 to 300 J/m^2 or 10 to 30 mJ/cm^2 (bacteria and protozoa) to 200 to 400 J/m^2 or 20 to 40 mJ/cm^2 (viruses).

Factors affecting UV disinfection

- *Percent transmittance (%T)* of the water — probably the most important factor — higher *%T* means lower power to achieve the same UV Fluence (UV Dose). The lower the *%T* the shorter the distance that UV can penetrate into the water (see figure on right).



- *Total Suspended Solids (TSS)* — microorganisms can "hide" behind solids and, thus, not be exposed to the UV.
- *Reactor hydraulic mixing* — must not have any "bypass" that would allow microorganisms to pass through the reactor with little UV exposure.

UV Fluence (UV Dose) in a UV reactor

- UV fluence rate varies markedly throughout a UV reactor, so a *single* UV sensor *cannot* be used to monitor the UV fluence (UV Dose).
- A mathematical model, based on the multiple point source summation approximation, of the UV fluence rate distribution in the reactor can be used to calculate the theoretical maximum *average UV fluence rate*. For drinking water applications, the model must take account of reflection and refraction at the quartz/water interface.
- The theoretical maximum *UV Fluence (UV Dose)* is then the average UV fluence rate times the hydraulic retention time(s) (reactor volume/flow rate).
- The actual applied UV Fluence (UV Dose) will always be less than the theoretical maximum due to imperfect radial mixing in the reactor. Detailed computational fluid dynamic analysis is required to assess the mixing characteristics of a given reactor.

Validation of UV Fluence (UV Dose)

- Very difficult to check instrumentally.
- Calculation (using a mathematical model) of the UV fluence rate at a UV sensor position.
- *Actinometry* to assess the UV fluence (UV Dose) at various positions in the reactor. An actinometer is a photochemical reaction of known quantum yield.
- *Biodosimetry* to determine the effective UV Fluence (UV Dose) for a given reactor and flow rate. This involves challenging the reactor with a surrogate (e.g., *bacillus subtilis* or

MS2 colliphage) of known UV sensitivity. This generates what is called a *Reduction Equivalent UV Dose*.

German/Austrian UV disinfection regulations

- All UV disinfection equipment must be capable of delivering a UV fluence (UV dose) of at least 400 J/m^2 (40 mJ/cm^2).
- These are "performance-based" regulations, since the UV fluence (UV dose) is related to an equivalent log reduction of the surrogate microorganism (e.g., *bacillus subtilis*).
- UV disinfection equipment must be certified by a UV Testing Laboratory using biodosimetry under "worst case" conditions.

Figure-of-merit for UV disinfection reactors

- The efficacy of a UV disinfection reactor depends on several factors:
    - *%T* and turbidity of the water
    - Hydraulic mixing efficiency
    - Lamp efficiency for germicidal wavelengths
    - Reactor design
- Suggest a *Figure-of-merit: Electrical Energy Disinfection* (E_{ED}^{400}) *Factor* defined as the total electrical energy (kWh) per 1,000 m^3 required to deliver a UV Fluence (UV Dose) of at least 400 J/m^2 or 40 mJ/cm^2 in a given UV reactor. For example, if a certain UV reactor requires 1 kW per mgd (million gallons per day) to achieve a UV Fluence (UV Dose) of 400 J/m^2 or 40 mJ/cm^2, then the E_{ED}^{400} would be 6.34 kWh per 1,000 m^3.

Operating costs

- A major component of the operating cost is the cost of electricity. For drinking water, the electrical energy cost varies from $0.50 to $2.00 per 1,000 m^3 ($0.002 to $0.008 per 1,000 gallons). For wastewater treatment, the costs are much higher due to the higher UV absorbance and turbidity of the water. Electrical energy costs vary from $3.00 to $12.00 per 1,000 m^3 ($0.012 to $0.048 per 1,000 gallons).
- In addition, there are other operating costs, such as lamp replacements and quartz cleaning (where this is not automatic) which, in total, can double the operating costs.

Conclusions

- It is important to have a clear picture of concepts and definitions in UV disinfection.
- UV fluence rate (and, hence, UV fluence or UV dose) measurements must be carried out with considerable care.
- Mathematical models can allow an estimate of the maximum UV fluence (UV dose) in a reactor, but biodosimetry or a computational fluid dynamic analysis is required to assess the true UV fluence (UV dose) for given reactor conditions.
- Regulators should not only set a UV fluence (UV dose) limit, but also should specify the method by which the UV fluence (UV dose) is to be calculated. Germany and Austria have made considerable progress in establishing UV disinfection regulations.

The History of UV Disinfection in the Last 20 Years

Gary Hunter, Black & Veatch

Introduction

During the past 20 years, the implementation of UV disinfection systems has been impacted by numerous regulatory changes, many of which were aimed at alternative disinfection systems that benefited the implementation of UV. These regulatory changes — as well as process changes and system design changes — have made it possible to apply UV disinfection over a wide range of conditions and have resulted in rapid growth in the use of UV systems in the United States. A review of some of the key historical transitions in the UV industry follows.

Regulatory Changes

During the early part of the 1980s, UV disinfection gained popularity as a result of funding of Innovative and Alternative (I/A) technologies by the United States Environmental Protection Agency (EPA). I/A funding allowed new technologies to be implemented at wastewater treatment facilities with the option for complete replacement if the technology failed to achieve compliance with NPDES permit requirements. Despite a number of failures, UV technology gained limited state regulatory acceptance during the 1980s. In some cases, these failures resulted in many state agencies delaying acceptance of UV disinfection until the mid to late 1990s.

In California, testing for compliance with Title 22 requirements was conducted during the early 1990s. Results of this testing[1,2] indicated that UV disinfection systems can achieve the coliform limits established by Title 22.

Other regulatory requirements that have impacted the growth of UV systems in the U.S. include Aquatic Toxicity, Uniform Fire Code, and OSHA risk management plans (RMP). The incorporation of aquatic toxicity limits into NPDES permits made it necessary for many communities to dechlorinate the wastewater effluent before it was discharged into the receiving stream. In 1988,[3] the Uniform Fire Code began to impact facilities that were undergoing expansion by requiring the installation of chlorine scrubbers as protection against the accidental release of chlorine gas. In 1999, facilities using more than 1,000 pounds of chlorine were required by OSHA[4] to develop and implement a RMP for use in the event of the accidental release of chlorine. Both the Uniform Fire Code and the RMP requirements have increased the interest in the use of UV for disinfecting wastewater.

Process Changes

Several authors have suggested criteria for the design of UV systems disinfecting wastewater. The National Water Research Institute (NWRI) has suggested guidelines for the use of UV for water reclamation facilities.[5] These guidelines have been adopted by a number of states as standards for the design of UV systems for reclamation facilities.

Dynamic modeling has become a key parameter in the design of UV disinfection systems.[6,7] The results of the modeling runs are leading to improvements in the hydraulic design of the UV reactors. Dose determination has also been refined during the last 20 years from the Multiple Point Source Summation Approximation to a model that uses an infinite number of point sources for the determination of UV dose.[8]

Correspondence should be addressed to:
Black & Veatch, 8400 Ward Parkway, Kansas City, MO 64114
(913) 458-3602 Fax: (913) 458-3730 E-mail: huntergl@bv.com

On-line sensor measurements of both transmissivity and intensity have presented a challenge rather than provided reliable results. In one study,[8] the results from six sensors were found to be inaccurate. An additional survey completed as part of the same study found that 80 percent of the sensors used in operating systems in the northeastern part of the U.S. had failed.

Testing of UV disinfection systems using a bioassay approach was suggested in 1983.[9] Over the past 20 years, testing has become more an art than a science, resulting in disagreement among professionals regarding the correct methodology for determining correct test results.[10]

System Design

Several changes have occurred since the 1980 vintage UV systems were installed at wastewater treatment facilities. Most notable of these changes has been the preference for open channel systems. Most UV systems installed in 1980 were enclosed reactors that did not allow easy access for cleaning the quartz sleeves. In some cases, enclosed space entry permits were required before treatment plant operators were allowed access for cleaning. Cleaning generally consisted of manually wiping the quartz sleeves. These systems were replaced during the mid-1980s with open channel designs in either the horizontal or vertical alignment. In 1980, almost all UV systems being used to disinfect wastewater used low-pressure mercury vapor lamps. This type of lamp still is used in smaller UV systems.

In the mid 1990s, UV disinfection systems with medium pressure lamps were introduced into the wastewater market. Medium-pressure systems produce a high-intensity, broad band spectrum of light, reducing the number of lamps needed for disinfection over the traditional low-pressure systems. Since these systems offer self-cleaning as a standard feature they have become popular with wastewater treatment operations staffs.

By the late 1990s, two additional types of UV systems appeared on the wastewater market: the first, low-pressure, high intensity UV systems (which basically used a higher wattage low-pressure lamp) and the second, pulsed UV. The low-pressure, high intensity typically require a lower number of traditional low pressure lamps and greater number of lamps when compared to medium-pressure UV systems.[11] These lamps are offered in either a vertical or horizontal alignment. The low-pressure, high intensity systems are also equipped with self-cleaning mechanisms. Testing has indicated that these systems may provide some energy savings over the traditional low pressure and medium pressure systems.[12] Pulsed UV systems[13] convert an alternating current to direct current and store the electrical charge in a capacitor. The energy is then released through a high-speed switch in plasma to generate intense radiation and UV light. The pulsed radiation is approximately 20,000 times more intense than sunlight at sea level.

Applications

UV disinfection has enjoyed a long history of use in the wastewater industry in the U.S. UV systems have been designed to treat stormwater,[14] combined sewer overflows,[15,16] wastewater effluent for reuse and, most recently, potable water systems.[17,18] One of the most promising advancements is the use of UV for disinfecting potable water. A number of researchers have found that UV can inactivate *Giardia Lamblia* and *Cryptosporidium*, known parasites at doses of 15 to 20 MJ/cm^2.[19,20]

Growth of Industry

In 1984, there were only a handful of UV systems being used in the U.S. to disinfect wastewater.[21] Very few of these systems had a design capacity greater than 5 mgd. At the end of 1999, the total number of installed UV systems treating wastewater exceeded 500. The average design capacity of these systems exceeded 20 mgd. Two of the largest systems, both exceeding 100 mgd, are located in Canada.[22,23]

Conclusion

UV disinfection systems have progressed a long way since 1980. Both equipment and process design approaches have undergone radical changes. These changes have resulted in a multiplicity of UV lamps and system configurations being implemented at treatment facilities. Regulatory impacts to other disinfection methods have brought about a resurgence in the acceptance of UV by the wastewater industry. This resurgence will enable UV disinfection to continue to gain popularity at a very rapid rate over the next several years.

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The Evolution of the Current Knowledge Base for UV Disinfection

George Tchobanoglous, Ph.D., University of California, Davis

This abstract is unavailable. Please contact the speaker at the address below for further information.

Correspondence should be addressed to:

Dept. of Civil and Environmental Engineering, University of California, Davis
662 Diego Place, Davis, CA 95616
(530) 752-1440 Fax: (530) 753-6365 E-mail: gtchobanoglous@ucdavis.edu

Key Technical Issues within the Water Utility Setting

UV Disinfection Technology Applied to a 100-mgd Groundwater Replenishment System

Greg Leslie, Ph.D., Orange County Water District

This abstract is unavailable. Please contact the speaker at the address below for further information.

Correspondence should be addressed to:

Orange County Water District, 10500 Ellis Avenue, Fountain Valley, CA 92728
(714) 378-3218 Fax: (714) 378-3373 E-mail: gleslie@ocwd.com

UV Technology Research Activities Within a Large Utility Environment

Jill Wicke and Brad Coffey, Metropolitan Water District of Southern California

Large utilities face unique challenges when implementing new technologies for drinking water treatment. This paper focuses on some of the technical, financial, and regulatory challenges which must be overcome before UV light can supplement or replace the use of chlorine or ozone.

Most disinfectants and oxidants used in drinking water treatment offer multiple benefits. Chlorine may be used to disinfect pathogenic bacteria and viruses, oxidize reduced iron and manganese, improve particle removal by pre-oxidation, and control algae growth. Ozone offers the same advantages, but can also inactivate *Cryptosporidium* oocysts, reduce taste-and-odor compounds (e.g., geosmin produced by algae), and organic micropollutants (e.g., chlorinated solvents, gasoline additives, and pesticides). Typically, the chlorine or ozone dosages required to achieve these objectives do not differ by more than a factor of two or three. Thus, a single application of chlorine or ozone often achieves multiple disinfection/oxidation goals.

Unfortunately, water utilities in California may have difficulty meeting pending U.S. Environmental Projection Agency (EPA) regulations for disinfection byproducts (DBPs) with traditional chlorine disinfection systems. Furthermore, switching to ozone to meet these regulations may be too costly for some utilities or may be limited by the formation of bromate, an ozonation DBP.

The understanding of UV disinfection — and its potential replacement of chlorine or ozone — is receiving increased attention in the drinking water industry. Treatment using UV light may provide another option for utilities to comply with the upcoming regulations. Potential benefits of UV technologies include a significant level of microbial disinfection, a low operating cost, and the minimal formation of DBPs.

The establishment of UV as a new disinfectant against *Cryptosporidium* oocysts first required consideration of three fundamental features: (1) biological plausibility, (2) efficacy, and (3) dose response. The concept of plausibility required a sound biological hypothesis to support UV's mode of action. Towards this end, researchers have established a mechanism through which UV photons react with intracellular DNA and prevent replication.[1] Researchers have also demonstrated significant reduction of *Cryptosporidium* infectivity following UV treatment compared to experiment controls.[2,3] The final area of investigation required the establishment of a dose-response relationship between the applied UV dose and the inactivation of *Cryptosporidium* oocysts. This important relationship confirmed both the mode of action and the efficacy of inactivation. The dose-response curve also established the minimum UV dose needed for design. These data have only recently become available.[4]

In addition to these scientific goals, large utilities must consider unique technical, financial, and regulatory constraints when developing and implementing new technologies. Though the effects of UV light on *Cryptosporidium* are now demonstrated, a number of issues must be addressed before a full-scale process can be implemented. Even greater concern arises when UV is considered as a replacement for ozone or chlorine.

Technical constraints include hydraulic performance, reactor verification, reliability, and redundancy. Because UV contacts the water for a short period of time (less than one minute), the reactor design must ensure that all of the water is adequately exposed to UV light. The

Correspondence should be addressed to:

Metropolitan Water District of Southern California, P.O. Box 54153, Los Angeles, CA 90054-0153
(213) 217-63606 Fax: (213) 217-6110 E-mail: jwicke@mwd.dst.ca.us

vast size of full-scale treatment plants (often exceeding 500 million gallons per day), combined with limited headloss for mixing, presents unique technical challenges to the designer. Finally, the short reaction time with UV increases the need for reliable and redundant units so that operators can respond to process upsets.

Financial constraints include ensuring a reasonable return on investment for the UV technology prior to designing full-scale units. The selection of treatment objectives becomes crucial to predicting the UV system costs. Figure 1 shows that the required UV dose may range by one-thousand fold depending on the treatment objective. Compared to ozone or chlorine treatment (with a two or three-fold dosage range), UV treatment may be contaminant specific. A second financial constraint that utilities face is the desire to minimize stranded costs of investment. That is, UV must remain compatible with other treatment processes at the plant. A third financial constraint for large utilities is to ensure that a number of potential vendors can supply the UV systems. Robust market competition and public-private partnerships must be encouraged to minimize the retrofit cost.

Finally, regulatory considerations include (1) any potential compromise with other treatment objectives, (2) the reduced ability to monitor performance, and (3) the time required to deploy new treatment technologies. Though both chlorine and ozone can achieve multiple water quality benefits within a narrow dosage range, UV is emerging as a single contaminant application. Also unlike chlorine or ozone, UV leaves no residual disinfectant following UV exposure. Thus, on-line monitoring devices must be developed that can measure the transferred UV dose. Without a well-documented and scientifically-sound dose measurement method, it is nearly impossible for water utilities to implement UV technologies without excessive factors of safety built into the UV dose. Finally, deployment of UV technology may take more than 10 years for large utilities. This deployment window may exceed the timelines for drinking water standards now under development.

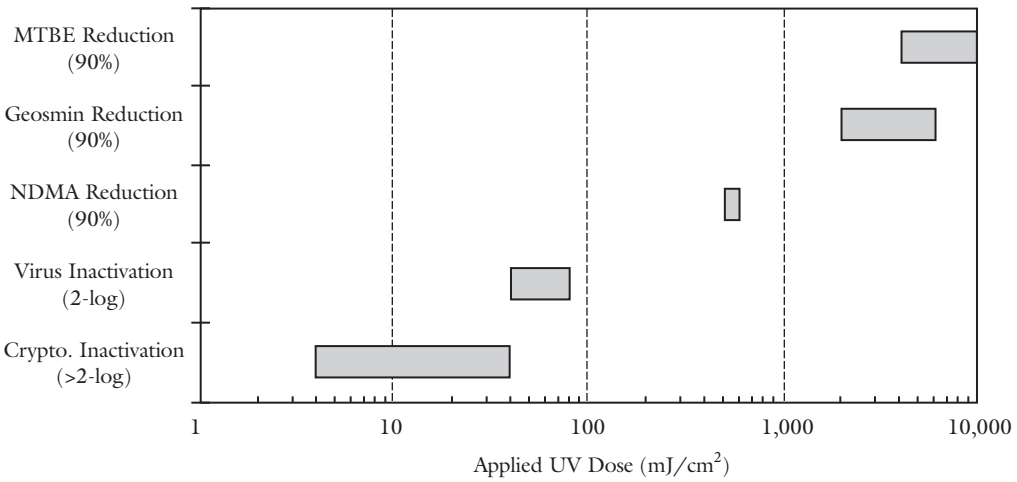

Figure 1. Summary of treatment effectiveness for UV light in drinking water.

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Can UV Technology Meet Regulatory Issues at the State and Federal Levels?

Reclaimed Water: The California Experience

Richard H. Sakaji, Ph.D., P.E., California Department of Health Services

It has been over 6 years since the National Water Research Institute (NWRI) published the "UV Disinfection Guidelines for Wastewater Reclamation in California and UV Disinfection Research Needs Identification" (1993). Based on the recommendation of the NWRI expert advisory panel that assembled these guidelines, the Department has accepted and allowed the use of UV disinfection in water recycling applications. In part, these guidelines have facilitated the approval of UV disinfection for specific water recycling applications by setting minimum design requirements for UV disinfection systems.

The NWRI guidelines allow for the use of low-pressure, low-intensity UV lamp technology with a horizontal lamp orientation (lamps set parallel to the flow direction) in an open channel. The Department, without any further testing, accepts UV technology conforming to the NWRI guidelines. The Department's current practice is to review the design of UV systems conforming to the guidelines for use in water recycling applications, assuming the UV technology meets the minimum design requirements set forth in the UV disinfection guidelines. The application of the technology is "approved" when the facility receives its permit to begin operation. UV systems that do not conform to the NWRI guidelines must demonstrate their ability to provide an equal level of disinfection performance.

To date, the guidelines have served as a template for the design and construction of several UV disinfection facilities throughout the state. The State Water Resources Control Board's (SWRCB) database on municipal wastewater treatment plants was scanned in an attempt to determine the number of wastewater treatment plants (WWTP) using UV.[1] The SWRCB reports about 830 WWTP plants in the state. Their database includes information on 710 of these plants. Of this subset, 12 are using UV disinfection, but not necessarily in conjunction with water recycling. The quality of water being treated by UV comes from a variety of biological oxidation systems, oxidation ditches, activated sludge, extended aeration storage ponds, a duckweed system, aerated lagoons, and trickling filters. As noted, this database is not complete and there are at least two major facilities using UV for water recycling that do not appear in the survey summary.

The NWRI UV disinfection guidelines have served the Department and the industry well for a number of years; however, based on the results of pilot testing and advent of new UV technology, it may be time to revise and update the guidelines so that they may reflect the current state of the knowledge. If possible, the guidelines should be expanded to cover closed pipe systems, pulsed UV, low-pressure high intensity UV, and medium-pressure UV technology. Based on research conducted to date, it may not be possible to establish design and installation guidelines for all these systems. This means that some UV systems will still need to demonstrate their disinfection effectiveness. Standardized testing protocols should be established as part of the guidelines in an effort to provide a uniform set of testing conditions that any UV technology can use to demonstrate disinfection equivalency and efficacy.

In the years since the NWRI guidelines were first published, demonstration of this equivalent performance has raised several issues surrounding the manner in which nonconforming UV systems are tested and accepted. Although the NWRI Guidelines stated that the rationale for setting a minimum UV dose of 140 mWs/cm2 was to achieve a 4-log inactivation of poliovirus, collimated beam tests have shown that UV doses less than 100 mWs/cm^2 are required for 4 logs of poliovirus inactivation. Due to issues regarding the economics and logistics of using poliovirus for testing the efficacy of UV systems, the industry and their consultants lobbied for an alternative surrogate. The Department has allowed the use of a

Correspondence should be addressed to:

California Department of Health Services, 2151 Berkeley Way, Room 449, Berkeley, CA 94704
(510) 849-5050 Fax: (510) 540-2181 E-mail: rsakaji@dhs.ca.gov

surrogate test organism (MS-2 bacteriophage) that may be more resistant to UV than poliovirus. Complicating this issue is the fact that polioviruses may not be the most UV disinfection resistant human viral pathogen. What then, is the targeted level of disinfection? Will a target of 4-log virus inactivation be appropriate and, if so, what organism will be used to establish a target dose?

Aside from the minimum design dose, the NWRI Guidelines also set minimum requirements to ensure proper hydraulic performance within the open channel reactor. One has to ask whether or not these criteria are adequate for open channel UV systems with higher flow velocities (e.g., medium-pressure UV). However, similar criteria need to be developed for closed pipe UV systems as well.

Recent work conducted by the University of California, Davis suggests that units should be evaluated by hydraulically isolating the banks. This will greatly aid the design engineer and may address questions regarding the sizing and scale-up of these systems. Currently, UV systems are tested as a whole and the potential synergistic impact of placement of the individual banks (that are not hydraulically independent of each other) has not been adequately evaluated. This may be one reason the relationship between the collimated beam dose-response curve and the continuous-flow system test appears to differ. Some might argue that the pathogen growth conditions, harvesting procedures, handling practices, and seeding protocols are not adequately standardized, leading to differences between dose response curves. Others will argue that a far more important source of variability may be the hydraulic flow condition that establishes a pathogen's flow path through the UV reactor.

Once the technologies are accepted by the Department, the competitive nature of the UV business takes over as the manufacturers move into full-scale design. At this point the Department relies heavily on the experience and the expertise of the utilities and their design consultants to ensure UV systems are designed, constructed, and operated to meet the objectives of the disinfection process, not just the compliance standard.

However, when the systems are scaled-up and the idea is to be cost competitive with the other manufacturers, the goal becomes to process more water at the lowest cost. This might entail increasing the lamp spacing, using fewer bulbs, and increasing the rated flow capacities, all of which will impact the cost of the system by decreasing lamp replacement or initial capital costs. But if we test UV systems with two or four lamps, will there be sufficient information on which to base a system design? Will we get the degree of expected performance on the full-scale system? Will errors or shortcomings not observed at pilot-scale manifest themselves at full-scale?

With only one notable exception, UV equipment gets installed without additional performance testing with respect to the pathogen that may have controlled the design of the system. At this point, a great deal of reliance is placed on the compliance standard to provide the regulators and the utilities with an indication that the system is functioning properly. Generally, there is no formal commissioning study to verify all around performance of the system and any performance standard written into a contract will probably be coliform-based. There are good logistical reasons for not conducting commissioning studies using viruses: where are you going to find enough phage to seed a 100 MGD plant?

Nevertheless, given the information coming from piloting these UV systems and from some anecdotal field data, one of the major concerns is whether or not the UV systems currently being installed are achieving the microbiological water quality objectives set forth in the NWRI guidelines. Since the development and publication of the NWRI UV guidelines, this Department, in conjunction with several manufacturers, consultants, and utilities, have observed anomalies in UV performance that bring into question the universal application of the current guidelines in their present format.

Two UV systems, one in Northern and one in Southern California, have reported or documented problems with meeting their coliform discharge requirements. One other facility located in Northern California has conducted commissioning tests and found that their UV system was not achieving a 4-log inactivation of MS-2 bacteriophage. What we don't know

is whether these are problems associated with the start-up of these facilities or whether these will become chronic long-term problems.

While one must remember the treatment objectives when defining treatment performance, one must also remember the limitations associated with the compliance programs so that regulations do not exclude "new" or "innovative" technologies, like UV, from consideration. We also do not want the regulation and compliance standards to become so removed from the specific treatment issue(s) that they focus on performance without clearly remembering the reason "why" the regulatory standard was developed.

The issues raised in this short paper are significant enough to warrant revising the NWRI UV disinfection guidelines. Information and protocols discussed at this conference can be used to revise specific sections of the guidelines. However, the information collected to date may be limited to specific technologies and not appropriately used on different UV technologies. This will require establishing standardized testing protocols so that the performance of UV systems are all tested under similar circumstances. We must also closely examine the UV technology to determine if there are certain elements that should be incorporated into regulation at this date.

Acknowledgements

The ideas in this paper are the result of months of discussion between UV manufacturers, university professors, consultants, and utilities. Many of these individuals are present at the symposium and have extended abstracts included in this document, and I would like to gratefully acknowledge their contributions to this paper.

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UV Disinfection: Florida's Perspective

David W. York, Ph.D., P.E., and Elsa A. Potts, P.E.,
Florida Department of Environmental Protection

This paper examines issues related to the permitting and use of UV irradiation for wastewater disinfection in Florida. Issues related to high-level disinfection and reuse applications are highlighted.

Disinfection Requirements

As shown in Table 1, Florida defines five disinfection levels for various water reuse and effluent disposal options in state rules governing domestic wastewater management[1] and water reuse.[2] Of most interest are the basic disinfection requirements, which apply to most surface water discharges and many land application and reuse projects, and high-level disinfection requirements, which apply to some of the most popular reuse activities in Florida (irrigation of residential properties, areas accessible to the public, and edible crops). These rules include relatively detailed design and performance requirements for chlorination systems. Fecal coliforms are used as the indicator organism in the definitions of most disinfection levels.

Table 1. Florida's Disinfection Requirements

Disinfection Level	Requirements	Applications
Low Level (a)	2,400 fecal coliforms/ 100 mL (maximum)	Pretreatment requirement for overland flow systems
Basic (a)	200 fecal coliforms/ 100 mL (annual average)	Most surface water discharges & land application systems
Intermediate (a)	14 fecal coliforms/ 100 mL (annual average)	Discharges tributary to shellfishing waters
High-Level (a)	Fecal coliforms: 75 % of observations less than detection Maximum: 25 fecal coliforms/100 mL TSS < 5.0 mg/L before disinfection Filters & chemical feed required	Public access reuse systems & edible crop irrigation {projects permitted under Part III of Chapter 62-610[2]}
Full Treatment (b)	Total coliforms less than detection	Indirect potable reuse & ground water recharge

Notes: (a) Defined in Chapter 62-600, F.A.C.[1]
(b) Required by Chapter 62-610, F.A.C.[2] Criteria reflect the basic provisions of the drinking water standards.

Florida's disinfection rules[1] note that chlorination offers several disadvantages and encourage alternative disinfection systems. However, no design standards are included for alternative disinfection systems. The fecal coliform requirements apply to any disinfection system —

Correspondence should be addressed to:
Florida Department Environmental Protection
2600 Blair Stone Road - MS #3536, Tallahassee, FL 32399-2400
(850) 921-9495 Fax: (850) 414-9031 E-mail: elsa.potts@dep.state.fl..us

regardless of the disinfectant used. The result is that any proposal for UV disinfection is evaluated by the Florida Department of Environmental Protection (DEP) on a case-by-case basis. This generally yields a lower level of certainty (or, at least, a perception of reduced certainty) that a permit will be issued for a UV system than would be encountered if the utility had proposed a chlorination system. It is believed that this contributes significantly to the relatively small number of UV installations in Florida.

High-level Disinfection Concerns

Florida's high-level disinfection criteria date back to experimental virus removal work done by Dr. Flora Mae Wellings[3] in support of St. Petersburg's landmark reuse project. She determined that the high-level disinfection criteria were sufficient to ensure production of reclaimed water that was essentially pathogen free. Subsequent analyses for virus in reclaimed water has demonstrated the ability of the high-level disinfection criteria to produce reclaimed water that is essentially virus free.[4-7]

The original impetus for the inclusion of filtration as part of the high-level disinfection system was for conditioning the water to maximize the effectiveness of the disinfectant for virus inactivation.[7] As the interest in the protozoan pathogens has increased, filtration also has been shown to remove protozoan pathogens.[7-8]

The DEP has concluded that chlorination systems designed and operated to meet the high-level disinfection requirements produces reclaimed water that is "essentially pathogen free" and is safe for the intended, non-potable reuse activities.

Florida does not have extensive experience with UV and other alternative disinfection systems, particularly for high-level disinfection applications. From the public health perspective, the fundamental question that the DEP has directed at UV and other alternative disinfection systems has been:

> If the alternative disinfection system is designed and operated to meet the fecal coliform and total suspended solids (TSS) limits for high-level disinfection, will the reclaimed water be of the same (or better) quality from a pathogen standpoint as reclaimed water that has been chlorinated and meets the fecal coliform and TSS standards?

As a result, the DEP had been reluctant to permit UV or other alternative disinfection systems for high-level disinfection applications without pilot studies or other pathogen data to answer this fundamental question.[9]

For UV systems, the lack of a measurable residual also entered into the DEP's historical reluctance to permit UV for high-level disinfection applications. Florida's reuse rules require continuous monitoring for disinfectant residual and turbidity as a means for controlling the high-level disinfection system to ensure that only acceptable quality reclaimed water is delivered to the reuse system.

Interest in UV Disinfection

Interest in alternative disinfection systems (primarily UV) has been growing in Florida since about 1990. Because of the emphasis on reuse in Florida, much of this interest has focused on high-level disinfection applications. In discussions with several of the major manufacturers of UV equipment in the early 1990s, the DEP noted its concern for pathogen data to support the use of UV for high-level disinfection applications. While UV equipment manufacturers and suppliers noted their interest in conducting studies needed to justify UV for high-level disinfection applications, no studies were completed and no data was provided to support UV for high-level disinfection.

Looking at the possibility of doing its own research, the DEP was successful in funding a literature review of alternative disinfection systems (UV and ozonation), which was envisioned as being the possible first phase of a possible multipart study designed to support

alternative disinfection systems. This literature review[10] identified the UV guidelines published by the National Water Research Institute (NWRI)[11] as providing a pathogen basis for UV disinfection criteria that would meet or exceed Florida's high-level disinfection requirements.

As noted in the following section, the DEP concluded that the NWRI guidelines provide reasonable assurances that a UV system will be designed, operated, and monitored in a manner that will ensure production of high-quality reclaimed water that will have a pathogen content less than or equal to a reclaimed water treated by chlorination.

Regulatory Framework for UV Disinfection

Currently, UV systems can be readily permitted in Florida for projects involving low level, basic, and intermediate disinfection. These facilities must be designed and operated to meet the fecal coliform performance standards established in Chapter 62-600, F.A.C.[1] Given that the state does not have design criteria for UV systems contained in our rules, each project will be evaluated on its own merits.

For high-level disinfection applications, UV can be permitted in Florida using either of the following two approaches:

1. The design, operation, and monitoring of the UV system must comply with all requirements of the NWRI guidelines for UV disinfection.[11] Filtration and chemical feed facilities must be provided. The fecal coliform and TSS performance criteria for high-level disinfection must be met.

2. Proposals for UV systems that do not comply with the full NWRI guidelines must be supported with pilot studies that include pathogen data (enterovirus, *Giardia*, and *Cryptosporidium*) justifying the design and operation parameters. The intent is to demonstrate that the UV system will produce reclaimed water that meets the performance standards for fecal coliforms and has a pathogen content no greater than what is anticipated from a chlorination system. Filtration and chemical feed facilities must be provided. The fecal coliform and TSS performance criteria for high-level disinfection must be met.

In both cases, all rule requirements related to the reuse system must be met.

UV Experience

While there is growing interest in UV disinfection, chlorination remains the overwhelming choice among domestic wastewater utilities in Florida. Of approximately 3,000 permitted domestic wastewater treatment facilities, only 21 currently employ UV. Of these, 16 are designed to meet basic disinfection requirements, 1 meets intermediate disinfection, and 4 provide high-level disinfection. Of the four high-level disinfection systems permitted in Florida, two were designed to meet the full requirements of the NWRI guidelines, one was supported by pilot- and full-scale testing, and one features UV with a complete chlorination system running in series.

Future Needs and Direction

The DEP anticipates that interest in UV disinfection will increase significantly over the next decade. In order to facilitate implementation of UV systems in Florida, the DEP would like to see the following activities accomplished:

1. Develop internal guidance on permitting of UV systems in Florida. This would include development of templates for standard permit conditions for a range of UV applications.

2. Update the NWRI UV guidelines to address a wider range of disinfection applications and technologies. It is recommended that UV guidelines be developed to meet the disinfec-

tion levels included in EPA's *Guidelines for Water Reuse*,[12] which are similar to Florida's requirements.

3. Develop detailed design and performance criteria for UV (including dose requirements) in Florida's domestic wastewater rules. Ideally, these rules would be based on updated NWRI guidelines (assuming the guidelines are updated to reflect EPA's *Guidelines for Water Reuse*).

4. Incorporate rule requirements governing UV applications into *Permit Builder* — DEP's expert system that aids DEP permitting engineers in the development of standardized permit conditions for domestic wastewater and water reuse facilities.

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Drinking Water Treatment: The Federal Experience

Daniel C. Schmelling, United States Environmental Protection Agency, Washington, DC.

Overview

The focus of this presentation is the status of UV radiation as a compliance technology for federal drinking water disinfection requirements. It begins with an overview of how UV is addressed in current regulations. This includes the Surface Water Treatment Rule, the Stage 1 Microbial and Disinfection Byproducts rules, and associated compliance guidance documents. The presentation then addresses current thinking on the role of UV in upcoming drinking water regulations, specifically the Ground Water Rule and the Stage 2 Microbial and Disinfection Byproducts rules.

Surface Water Treatment Rule

The Surface Water Treatment Rule (SWTR), promulgated in 1989, established primary disinfection requirements that currently apply to all public water systems (PWS), which use surface water or ground water under the direct influence of surface water.[1] These requirements include the removal and/or inactivation of at least 99.9 percent (3 log) of *Giardia lamblia* cysts and 99.99 percent (4 log) of viruses. The SWTR also requires systems to either provide filtration that achieves specified effluent turbidity levels or to meet certain criteria for the avoidance of filtration. In addition, systems must maintain a disinfectant concentration of at least 0.2 mg/L in water entering the distribution system.

The SWTR contains CT tables which specify the product of disinfectant concentration and contact time necessary to achieve 3 log inactivation of G. lamblia. Tables are provided for the following disinfectants: chlorine, chloramines, chlorine dioxide, and ozone. The SWTR does not address UV, although UV is discussed in the Guidance Manual for the SWTR,[2] as described below. However, under the SWTR, systems may use disinfection strategies other than those specified in the rule if the system demonstrates to the state that the system is achieving the required level of inactivation. This provision currently applies to UV. (Note that most states have primary enforcement responsibility for drinking water regulations.)

For systems using chemical disinfectants, the SWTR stipulates analytical methods and monitoring protocols for measuring the residual disinfectant and calculating the level of inactivation the system achieves. The SWTR also contains requirements that address the disinfection system. These state that the disinfection system must either have redundant components with automatic start-up to ensure that disinfectant application is maintained continuously, or employ automatic shut-off of delivery of water to the distribution system whenever the disinfectant concentration drops below a specified level. It is expected that analogous requirements would apply to the use of UV.

Guidance Manual to the SWTR

The Guidance Manual for the SWTR provides CT tables for 2 to 4 log inactivation of viruses and 0.5 to 3 log inactivation of *G. lamblia* using the disinfectants listed in the SWTR. In regard to UV disinfection, the Guidance Manual specifies CT (irradiance x time) values for virus inactivation of 21 and 36 mJ/cm^2 for 2 and 3 log, respectively. These CT values are based on studies by Sobsey[3] on inactivation of Hepatitis A virus (HAV), and were derived by applying a safety factor of 3 to the HAV data. Doses were based on HAV because this virus has been established as an important cause of waterborne disease. Also, CT values for HAV

Correspondence should be addressed to:
Office of Ground Water and Drinking Water, U.S. Environmental Protection Agency
401 M St., SW (MC 4607), Washington, DC 20460
(202) 260-1439 Fax: (202) 401-6135 E-mail: schmelling.dan@epa.gov

are higher than those for other viruses that were evaluated at that time, such as poliovirus 1 and simian rotavirus.[4] EPA expects that in future regulations, UV doses for virus inactivation will be based on the most resistant virus that is of public health significance in drinking water.

CT values for the inactivation of *G. lamblia* by UV are not included in the Guidance Manual for the SWTR. The Guidance Manual concludes that UV appears to be very ineffective for *Giardia* cyst inactivation, and that there is not sufficient data to determine the doses needed to inactivate 0.5 to 3.0 logs of cysts. This conclusion is based on studies by Rice and Hoff[5] and Carlson et al.[6] Both studies indicate that *Giardia* cysts are extremely resistant to inactivation by UV, with doses greater than 60 mJ/cm^2 achieving less than 1 log inactivation. It should be noted, though, that both of these studies used excystation to measure inactivation. Recent work indicates that excystation is not an accurate technique for assessing UV disinfection of protozoa,[7] and that protozoa like *Giardia* may be inactivated at relatively low doses of UV. Consequently, the conclusions of the Guidance Manual regarding UV inactivation of *Giardia* are expected to be revised in the future.

Stage 1 Microbial and Disinfection Byproducts Rules

The Stage 1 Disinfectants and Disinfection Byproducts Rule (Stage 1 DBPR) and the Interim Enhanced Surface Water Treatment Rule (IESWTR)[1] were promulgated in 1998. The Stage 1 DBPR established new or more restrictive maximum contaminant levels for certain disinfection byproducts (DBPs), such as total trihalomethanes, haloacetic acids, chlorite, and bromate. There are additional provisions as well, such as a treatment technique requirement for removal of total organic carbon. The IESWTR modified the SWTR by requiring PWS that filter to remove 2 logs *Cryptosporidium*. Compliance with this requirement is demonstrated by meeting more stringent effluent turbidity standards. Note, though, that the IESWTR does not require any PWS to inactivate *Cryptosporidium*.

Neither the Stage 1 DBPR nor the IESWTR addressed UV disinfection. Consequently, the status of UV was left unchanged from that described above for the SWTR. However, UV was considered in two guidance manuals that were developed by EPA along with the Stage 1 rules in order to assist systems in complying with drinking water disinfection requirements. These manuals are the Small *System Compliance Technology List for the Surface Water Treatment Rule and Total Coliform Rule* (TCR),[8] which has a short section on UV, and the *Alternative Disinfectants and Oxidants Guidance Manual*,[9] which contains a full chapter on UV. Both manuals revise and augment the Guidance Manual to the SWTR in several ways concerning UV disinfection.

For viruses, neither the *Small System Compliance Technology List* nor the *Alternative Disinfectants and Oxidants Guidance Manual* recommends a single UV dose for a specified level of inactivation. Rather, both manuals identify a range of doses which go up to 140 mJ/cm^2 for inactivation of 4 log viruses. These higher doses are based on consideration of more resistant viruses, such as rotavirus, and bacteriophage MS-2. For protozoa, both manuals describe UV as being capable of inactivating *Giardia* and *Cryptosporidium*. Unfortunately, the manuals contain protozoa inactivation data only from studies which used excystation as the viability assay. Based on these data, both manuals state that protozoa require a much higher UV dose than that needed to inactivate other pathogens. However, as indicated above, recent studies suggest that this finding is inaccurate. The *Alternative Disinfectants and Oxidants Guidance Manual* also has sections on generation of UV, monitoring UV systems, operational considerations, and UV disinfection byproducts.

Ground Water Rule

EPA is currently developing a regulation to address microbial risk from ground water sources that are used for drinking water. The ground water rule will specify appropriate use of disinfection and encourage the use of alternative approaches, including best management practices and control of contamination at its source. EPA is working with stakeholders to

develop a proposed Ground Water Rule in Spring 2000, and a final rule by Winter 2000. The statutory deadline for the Ground Water Rule is May 2002.

In a draft proposed ground water rule that was available to the public in Summer 1999, EPA proposed that ground water sources would be subject to an assessment of microbial risk. Those systems which were determined to be at risk for fecal contamination would be required to either eliminate the contamination, switch to an alternative source, or treat the ground water to achieve 4-log virus inactivation. The draft proposed rule recognized UV as a treatment technology which could be used to meet a virus inactivation requirement. The draft rule proposed that for systems using UV, the state would determine the irradiance level necessary to achieve 4-log virus inactivation. The system would then be required to continuously monitor for and maintain the irradiance level prescribed by the state.

Stage 2 Microbial and Disinfection Byproducts Rules

EPA is currently working with stakeholders to develop a Stage 2 Disinfectants and Disinfection Byproducts Rule (DBPR) and a Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). These rules will enhance and refine the public health protection stemming from the Stage 1 Microbial and Disinfection Byproducts rules. The Stage 2 DBPR will address the public health risks associated with chemical byproducts formed through disinfection of drinking water and the LT2ESWTR will focus on risks from microbial pathogens, specifically *Cryptosporidium*. Both rules are scheduled to be proposed in Spring, 2001 and finalized in May, 2002.

UV has the potential to be a significant compliance technology for these rules. UV does not form halogenated disinfection by-products and appears to be highly efficient at inactivating *Cryptosporidium*, which is resistant to most chemical disinfectants. However, the lack of experience in the United States with UV disinfection of drinking water causes uncertainty regarding the extent to which PWS could rely on this technology to perform effectively and reliably.

There are significant remaining issues related to the use of UV to inactivate pathogens in drinking water. These include: dose-response relationships for Giardia and Cryptosporidium, the relative performance of different types of UV lamps, reactor design and scale-up, performance monitoring and process control, and solution matrix effects. However, there is currently a very high level of interest in UV among the water treatment industry, and a great deal of research is both planned and ongoing. Consequently, it is reasonable to anticipate that many of these questions will be sufficiently resolved during the next several years to permit the routine use of UV in drinking water.

EPA anticipates that the Stage 2 Microbial and Disinfection Byproducts rules will allow for the use of UV for inactivation of viruses, *Giardia*, and, if required, *Cryptosporidium*. As part of this projected outcome, EPA would expect to provide CT (IT) tables for regulated pathogens. Unresolved issues related to the development of such tables include: the definition of UV dose, appropriate safety factors, and the virus upon which the virus inactivation dose would be based. It would also be necessary to assess the application of dose-response data to unfiltered water. For regulatory approval of UV, EPA would also expect to develop appropriate protocols for verification of disinfection performance, although these are as yet unresolved.

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Drinking Water Treatment: Application of UV for Disinfection of Drinking Water and Surface Water Supplies

Robert Hultquist, P.E., California Department of Health Services

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Correspondence should be addressed to:

California Department of Health Services, P.O. Box 942732, Sacramento, CA 94234-7320
(916) 323-6111 Fax: (916) 323-1382 E-mail: bhultqui@dhs.ca.gov

The Status of UV Technology in Europe

Oluf Hoyer, DVGW Test Laboratory for UV-Systems (Germany)

Terms (according to IEC ISO and IUPAC)

Irradiance	(unidirectional on a plane)	W/m^2
Fluence Rate	(omnidirectional on a point)	W/m^2
Intensity	use only for qualitative description!	
Radiant Exposure	(unidirectional on a plane)	Ws/m^2 or J/m^2
Fluence	(omnidirectional on a point)	Ws/m^2 or J/m^2
Dose	Absorbed radiation causing biological effect (Dose is less or equal to radiant exposure)	Ws/m^2 or J/m^2
Reduction Equivalent Dose - RED	Dose determined by biodsimetric tests	Ws/m^2 or J/m^2
Spectral Attenuation Coefficient - SAC		m-1

Development of UV Disinfection — Historic Background

In Europe, especially in Germany and Austria, disinfection with UV radiation in the range of 240 to 290 nm is becoming a more and more accepted alternative to conventional chemical disinfection. It is an interesting fact that application of chlorine and UV radiation for drinking water disinfection appeared almost simultaneously in the first decade of the 20th century and, therefore, UV disinfection is not a recent invention.

It took about three decades from the discovery of microbial inactivation with UV light from the sun by Downes and Blunt in 1878 via the invention of the mercury arc by Cooper-Hewitt in 1901, and the "Original Hanau" (Quartz-Burner as the first intensive UV source by Küch in 1906) to the construction of first full-scale UV disinfection apparatus by Henri and co-workers that went into operation at Marseille (France) on August 18, 1910. It was used to disinfect prefiltered water from the river Durance at a flow of 25 m^3/h with an energy consumption of 660 Wh, and achieved a more than 3 log reduction of *E. coli*. Problems with the ignition of the Hg arc that afforded tilting of the lamps and the simultaneous rise of chlorine disinfection as a simple and cheap alternative ruled UV out. There remained merely some niches for UV application in the production of pharmaceutics, food, and beverages. With the invention of the neon tubes in the 1940s, low-pressure Hg lamps became available for UV disinfection, but were only used for small capacity disinfection units for water in public transport vehicles and in small water supplies.

There were many attempts to promulgate UV disinfection, but the problems with control for proper operation and effectiveness were not solved. However, the discovery of harmful by-products from chemical disinfectants in the 1970s supported the search for alternatives and promoted disinfection with UV-radiation in the range of 240 to 290 nm regained interest as an alternative to conventional chemical disinfection. In the early 1980s, the German Professor Günther Schenck (Max-Planck-Institute for Radiation Chemistry) and Professor Heinz Bernhardt (Association of Drinking Water Reservoirs, ATT) took the initiative to promote research on fundamentals for a safe, large-scale application of UV disinfection in drinking water treatment.

Correspondence should be addressed to:
Washnbachtalsperrenverband and DVGW Test Lab for UV-Devices
Konprinzenstr.13, Siegburg, D53721 Germany
49-2241-128-372 Fax: 49-2241-128-376 E-mail: o.hoyer@t-online.de

They launched a joint research project under the auspices of ATT, lasting from 1987 to 1993. It received financial support from the German federal government and from four manufacturers. Involved were eight German and Austrian research institutes and it was advised by a panel of 12 experts. The results stated UV disinfection to be safe with a more than 4-log inactivation of drinking water relevant bacteria and viruses at radiant exposures above 400 J/m^2 (40 mJ/cm^2) also considering photo reactivation. Excess irradiation of surface water with natural organic matter (NOM) up to some 10 kJ/m^2 (which is far beyond normal application for disinfection) showed no changes in molecular weight, mutagenicity and bacterial aftergrowth (lab and 1 m^3 model tank experiments). Irradiation experiments with chlorinated hydrocarbons and pesticides showed the need of very high UV-doses beyond normal application to cause photochemical changes in the concentration of these trace contaminants. Solely, the formation of nitrite from nitrate by UV radiation may cause problems, especially with medium-pressure lamps and high nitrate concentrations. Interference from deposits of Fe and Mn were studied as well as lamp ageing and colored water.

The investigations made obvious that it is impossible to calculate performance of UV disinfectors solely from physical data. Hydraulic movement and field of irradiation are extremely complex, especially with units for high throughput, and can only be approximated by model calculations. Actinometric measurements in the system can only quantify UV input, but are given no information on the radiation field. The only means to verify performance is to take microorganisms with known UV susceptibility (ideally, 4-log inactivation at 400 J/m^2). This technique is called biodosimetry. *E. Coli* ATCC11229 and spores of *B. subtilis* ATCC 6633 were used to determine the reduction equivalent dose, simulating the worst case conditions of operation.

The final gap to close was to establish a control and monitoring concept for UV devices that maintain the conditions tested by biodosimetry during operation. This concept includes control of the electrical status of every lamp and monitoring of water quality and UV-input by a removable UV sensor placed in a sensor port with a quartz window and calibrated to irradiance in W/m^2 at 253,7 nm. All UV sensors must have a uniform optical characteristic and need a standardised and reproducible calibration procedure. It is necessary to allow control of the system's sensor function on site, which is possible by replacing it with a hand-held reference sensor and comparing the values. The deviation must be acceptable, otherwise the system sensor has to be replaced and recalibrated.

Based on these results, ONorm M5873 and DVGW Standard W 294 were prepared and released in 1996-1997. These standards define properties of UV systems for drinking water disinfection and describe the testing and monitoring procedures. With the release of the standards, testing facilities were established in Vienna (≤400 m^3/h) and Bonn (≤3.000 m^3/h), which allow biodosimetric tests under selected operation conditions.

Up to now, tests in Austria predominantly have covered smaller UV-systems while, in Germany, UV-systems between 400 and 2500 m^3/h have prevailed.

Successfully tested UV system may be certified by the DVGW or ÖVGW. Besides the biodosimetric tests UV sensors, command control and support documentation are validated to commit with the standard.

The German DVGW Standard W 294

DVGW Standard W 294 describes a validation/certification process involving four areas:

- Support documentation
- UV sensors
- Command and control
- Biodosimetric performance test.

Documentation

Support documentation supplied by the manufacturer on assembly and installation, operation and maintenance (O&M), cleaning procedures, UV lamps, sleeves, and sensors is examined.

- **UV lamp** documentation must include the lamp type, electrical operation, and UV spectral output. With UV disinfection systems using polychromatic lamps, documentation must show that UV radiation below 240 nm penetrating the water does not exceed two percent of the radiation between 240 and 290 nm.
- **Sleeve** documentation must include the sleeve material, dimensions, and UV transmittance spectrum.
- **Sensor documentation** must include the sensor's operating range in W/m^2, spectral selectivity, measurement uncertainty, linearity, temperature and long-term stability, and recalibration requirements.

Standardized Irradiance Measurement – Sensor Concept

A UV reactor must have at least one on-line sensor. On-line UV sensors must provide continuous monitoring of UV lamp output with measurements verifiable using a reference sensor. The size and properties of on-line and reference sensors are defined in detail. Most important is an nearly identical view angle with all sensors. A sensor port with defined physical dimensions and a quartz window is also described.

If the on-line sensor provides a UV irradiance measurement that deviates from the reference sensor measurement by more than the measurement uncertainty, the on-line sensor must be either cleaned, recalibrated, or replaced. Sensors must be tested and recalibrated within 15 months.

The distance between the sensor window and the lamp being monitored must be chosen by the manufacturer to provide a similar sensitivity to changes in UV lamp output and changes in the UV absorbance of the water (see explanation below).

On-line Command and Control

The UV disinfection system's on-line command and control continuously monitors water flow rate and UV sensor output, and responds to ensure UV dose delivery is maintained during system operation. UV dose delivery is ensured when the UV sensor indicates an irradiance above a setpoint.

The setpoint is defined as the sensor reading required to achieve the objective dose delivery as determined using biodosimetry plus the sensor's measurement uncertainty. The on-line command and control system must respond to lamp failure and low sensor output by activating safety devices and triggering alarms.

Challenge Test

German drinking water disinfection practice requires a 4-log inactivation of waterborne pathogens that is achieved using a UV dose of 40 mJ/cm^2. Ideally, the UV disinfection system should be challenged using a microbe that demonstrates a 4-log inactivation at a dose of 40 mJ/cm^2. Lacking such a microbe, Standard W 294 requires UV systems be challenged using two microbes – *Bacillus subtilis* spores and *E. coli*. *B. subtilis* inactivation is used to demonstrate a dose of 40 mJ/cm^2 while *E. coli* inactivation, followed by photoreactivation, is used to demonstrate a 4 log inactivation (see Figure 1).

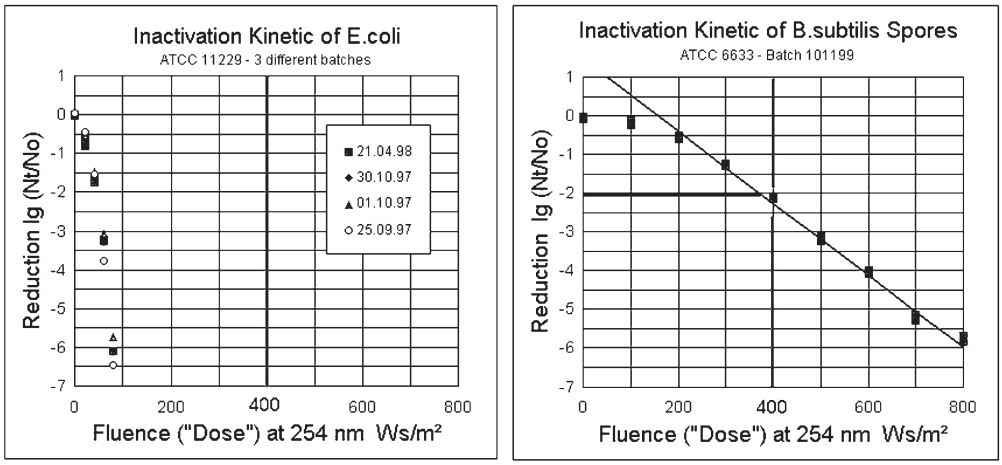

Figure 1. *E.coli* is no suitable organism to test for 400 J/m^2, but *B. subtilis* spores are.

Recent findings demonstrate the beneficial effect of the shoulder of the inactivation kinetic curve of *B. subtilis* spores that give sufficient safe results without *E. coli* challenge (see below).

The challenge test involves seeding the challenge microbe into the UV disinfection unit and measuring the inactivation achieved by the reactor (see Figure. 2). Static mixers are used upstream and downstream of the unit to ensure that seeded microbes are properly mixed and that microbial samples are represented. Challenge tests are performed at the minimum and maximum flow through UV unit with the UV sensor reading at the setpoint.

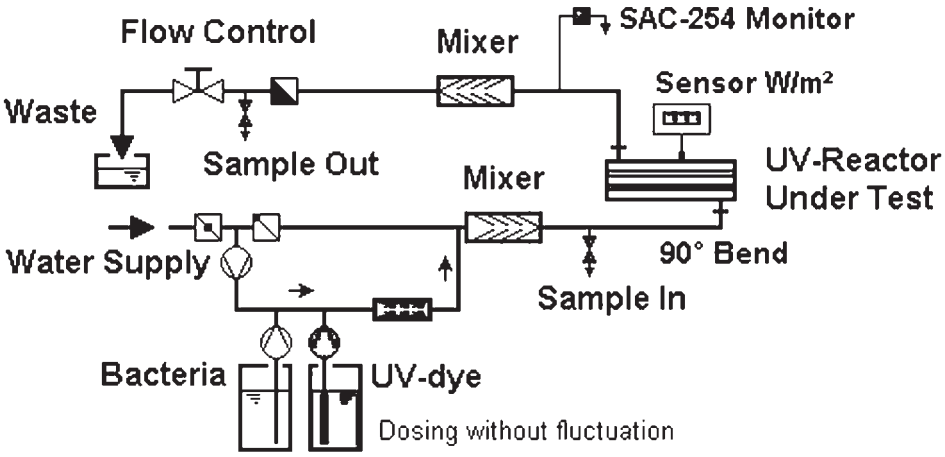

Figure 2. Test facility for UV-Systems acc. to DVGWW 294.

To determine the setpoint value of the UV sensor, UV lamp intensity is reduced to the level expected at the end of its useful service life (e.g., 70 percent) and UV absorbance of the water is adjusted to the maximum value for operation (e.g., 8 m^{-1}) (see Figure 3).

For the challenge the setpoint is achieved using two methods:

- By lowering the lamp output with low UV absorbance the water (≤1,0 m^{-1}).
- By increasing the water UV absorbance with the lamps at maximum output.

A UV dose equivalent is assigned to the UV reactor by comparing the inactivation achieved by the reactor to a UV dose-response curve for the challenge microbe obtained using a laboratory irradiation apparatus. In this collimated beam apparatus, the inactivation of a challenge microbe is measured as a function of applied UV dose under controlled laboratory conditions.

In the German standard, the laboratory irradiation apparatus (a low-pressure mercury arc lamp) is used as the standard source. Furthermore, the microbial suspension irradiated must not be stirred and must be sampled from the center of the suspension using a small volume.

All tests are performed at a facility capable of evaluating sensors, performing challenge tests, and evaluating one-line command and control strategies. Validated UV disinfection systems are certified with a registration number and a period of validity.

Some Details

A 4-log-reduction requires a 99.99 percent homogeneous UV radiant exposure of 400 J/m^2 to all water volume elements passing the UV system and depends on radiation field and flow pattern. The optical path and intensity are influenced from diffraction through the quartz glass sleeves, reflectance from glass and steel walls, and absorbance of the water. The complex intensity pattern may be modelled, but cannot be calculated from physical measurement. Superimposed to the radiation field is the pattern of hydraulic movement. Ideally, complete mixing should be achieved, but the real intensity pattern and hydraulics may cause severe mismatch between calculation and reality.

A performance of 400 J/m^2 and a 4 lg-reduction has to be verified by biodosimetric testing of prototypes using suspensions of germs with a known UV susceptibility. The UV susceptibility is determined with inactivation kinetic in a standardized laboratory apparatus with Hg low-pressure lamps at 253.7 nm. The standard organism are *B. subtilis* spores and the radiant exposure is adjusted in steps of 100 J/m^2 between 0 and 800 J/m^2 (see Figure 1). The kinetic shows a shoulder curve with already no effect below 100 J/m^2, followed by a semi-logarithmic linear slope above 200 J/m^2. As partial deficiencies in fluence cause no inactivation when below 100 J/m^2, shoulder curve kinetic enhances the detection of partial insufficient fluence (see Figure 3).

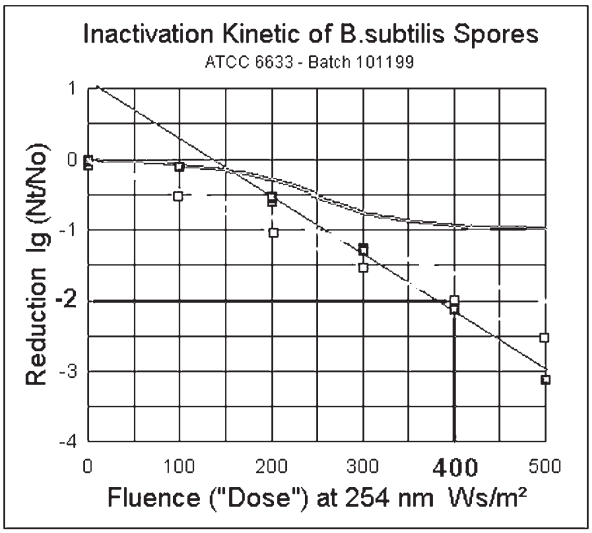

Figure 3. "Shoulder-Curve Kinetic" is more sensitive to detect hydraulic and irradiance deficiencies than is "Linear Kinetic" because fractions obtaining "Doses" below 100 J/m^2 are not inactivated and contribute fully to lower lg-reduction results. Example: 10 percent receives less than 100 J/m^2.

On its way passing a UV-unit, each water volume element, which may carry a micro-organism, must collect sufficient UV-radiation so that the integral of the differential product of irradiance dE_0 over time dt sums up to a radiant exposure $H = \int dE_0 \times dt$ of at least 400 J/m^2. It is obvious that inhomogenities of flow pattern and radiation field have strong effects on the disinfection result. Already a mismatch of 0.1 percent may cause insufficient disinfection to only 99.90 percent instead of 99.99 percent inactivation, as required.

As linear increase of UV radiant exposure causes logarithmic decrease in numbers of survivant micro-organisms (see Figure 1), survivors in a portion of insufficiently irradiated water will dominate the result while partial super-irradiated portions have no survivors and cannot compensate for non-sufficiently irradiated portions with surviving organisms.

The field of radiation around the tubular mercury lamps mounted in sleeves from UV-transparent quartz glass depends on optical geometry (intensity decreases with distance according approximately to the reciprocal value of the radial distance d) and on the spectral absorption coefficient at 254 nm (SAC-254) of the water (according to Beer's law)

$E_d \sim E_1 \times (r_1 / (r_1+d)) \times 10^{-SAK\text{-}254 \times d}$.

It is obvious that an increasing number of UV-lamps makes the field of radiation and hydraulics more complex. Furthermore, it is apparent that the sensor does not record only the longest light path but a continuum of paths of different length. Figure 4 shows in a simplified model with a sensor position in 3 cm distance from the sleeve and a setpoint of 20 W/m^2 good for a SAC of 8 m^{-1} and lamp fouling to 70 percent must be tested in two ways.

- First, by lowering the lamp output to 43 percent and with low UV absorbance of the water (SAC = 1,0 m^{-1}) to obtain a reading of 20 W/m^2. The irradiance between sleeve and sensor position is lower compared to SAC of 8 m^{-1} and 70 percent lamp intensity and higher at greater distances.

- Second, by increasing the water UV absorbance (SAC = 13 m^{-1}) with the lamp at maximum output to obtain again a reading of 20 W/m^2. Now, the irradiance between sleeve and sensor position is higher compared to SAC of 8 m^{-1} and 70 percent lamp intensity, but lower at greater distances.

With well-designed UV reactors and well-chosen sensor position, the second setting gives a lower RED compared with the first setting.

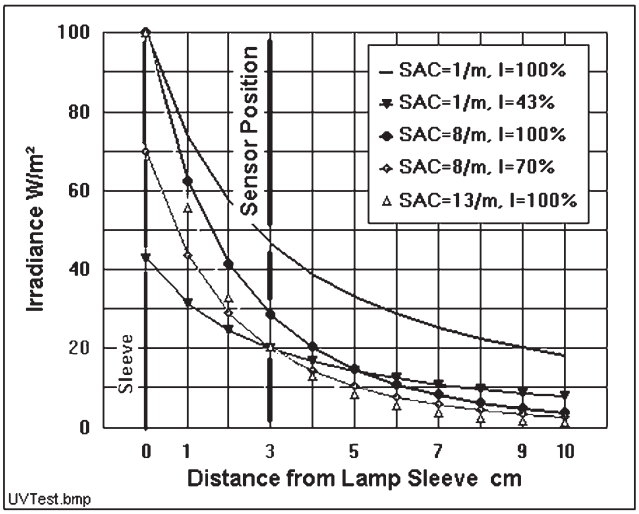

Figure 4. Diagram to explain why a UV-System — example: setpoint 20W/m^2 good for SAC = 8/m and 70 percent lamp intensity — must be tested with two settings. In this case, ▼ SAC = 1/m, I = 43 percent. △ SAC = 13/m, I = 100 percent.

Conclusions

- UV-systems that comply to the German DVGW Standard W 294 will be suitable for reliable use in water works as a substitute for chemical disinfectants.

- With progress in testing experience, details of procedures and requirements may change.

- Especially when applied to multi-wavelength UV sources sensor properties may need redefinition.
- The present concept normalises UV susceptibility to radiant exposure of monochromatic radiation at 253.7 nm, which is easily available. This concept insures that UV sources with emission of other wavelengths (but also of microbicidal effect) are equally evaluated.
- International cooperation on the standardisation of equipment, performance, and testing of UV systems is a desirable aim to focus on.

Acknowledgements

Some parts of the text are related to a compilation on the W 294 standard by H. B. Wright and Y. A.Lawryshyn, which eased my English writing and is gratefully acknowledged.

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Research, Information, and Data Needs

Knowledge Gaps: What is Required for Reliable UV Application?

Fred Soroushian, P.E., CH2M Hill

Advances in UV technology, more efficient lamps, and more reliable equipment are increasing the popularity of UV disinfection. These advances have resulted in commercial application of UV for water treatment in pharmaceutical, food, and electronic industries and for municipal water and wastewater disinfection.

Determining the efficiency of UV technologies requires recognition that it is a combination of UV system (lamp technology and output spectra, lamp age, reactor hydraulics), water quality parameters, and microorganism's action spectra/repair capabilities and their state of aggregation (free or particle associated) that determines the efficiency of the UV systems and DBP formation. Today, there is not a single model that can reliably predict how the interaction of these parameters impacts the UV dose and performance of UV systems. Therefore, the need exists for a simple standardized technology validation approach that integrates the complex variables of UV disinfection into a simple output that can be readily measured to assess the performance of UV systems. To achieve this objective and assess the performance and reliability of UV systems, the following major issues need to be addressed:

- Protocol for establishing UV dose and validating UV systems performance and scale-up.
- Target pathogens and surrogate microorganisms.
- Microorganism response spectra and repair mechanisms.
- UV by-products and associated disinfection by-products.
- Performance monitoring requirements and instruments.

The following presents these significant UV disinfection issues in greater detail.

Protocol for Establishing UV Dose and Validating UV Systems Performance and Scale-up

In addition to the low-pressure low-intensity systems, which are widely used, other technologies such as low-pressure high-intensity, medium-pressure high-intensity, pulsed UV, and excimer systems are being proposed for use in water and wastewater disinfection. There are significant differences in power input, intensity output, lamp arc length, power supply, and reactor configuration among these technologies. In addition, UV manufacturers use different methods for estimating effective germicidal intensity for polychromatic lamps and for calculating UV dose within the reactor, which further complicates establishing the performance of these systems.

The measurement of UV dose in a nonidealized, continuous-flow UV reactor is complicated by the complex flow patterns, contact time distribution within the reactor, and variations in chemical and physical water quality parameters (Severin, et al., 1983a,b, Qualls et al., 1985). For measurement of UV dose in bench-scale and pilot-scale systems, two approaches have been used: (1) to use actinometric methods, either chemical or biological actinometers (Linden and Darbey, 1997; and Qualls et al., 1989) or (2) to measure UV intensity and retention time distribution with results substantiated by actinometry (Soroushian et al., 1999). Although these methods may be satisfactory for bench-scale dose verification, neither of these approaches alone would be completely satisfactory for dose measurement in a

Correspondence should be addressed to:
CH2M Hill, 3 Hutton Centre Drive, Suite 200, Santa Ana, CA 92707
(714) 429-2000 E-mail: fsoroush@CH2M.com

continuous-flow reactor. Therefore, the process modeling of a continuous-flow reactor based on a combination of mathematical modeling, biological or chemical actinometry, and laboratory measurements using collimated beam is the most valuable tool for characterizing the UV disinfection efficiency for the commercially available UV systems. Because, currently there is not a single protocol for determination of the applied UV dose in a nonideal reactor with polychromatic lamps, a standardized protocol for measurement of UV dose and validation of reactor performance is necessary.

Target Pathogens and Surrogate Microorganisms

The UV inactivation of bacterial pathogens indicates that 3-log inactivation can be achieved with doses of less than 10 mWs/cm^2 (Rosesslerand Severin, 1996). The pathogenic viruses that can cause waterborne outbreaks are more resistant. For example, the required dose for 3-log inactivation of viruses would range from 23 to 50 mWs/cm^2 for poliovirus, reovirus, Coxsackie virus, echorvirus, and *bacillus subtilis* spores to 55 to 65 mWs/cm^2 for coliphage MS2. The adenovirus is most resistant requiring a dose of 80 to 90 mWs/cm^2 (Rosessler and Severin, 1996). Recent studies indicate that UV is more effective than chemical disinfectants for the inactivation of protozoa. Three-log inactivation of *Cryptosporidium* required a UV dose of less than 10 mWs/cm.^{2}

Kallenbach et al. (1989) made an interesting observation concerning the relative resistance of viruses. They noted that viruses with high molecular weight, double-stranded DNA or RNA were easier to inactivate than those with low molecular weight, double-stranded genomes. This was similarly true for single-stranded viruses. However, viruses with double-stranded genomes are less susceptible than those with single-stranded genomes.

Pathogens of concern and emerging pathogens were summarized at recent EPA-sponsored workshops. *Viborio cholerae, Salmonella typhi,* shigella, mycobacteria, and campylobacter were listed as pathogenic bacteria. Poliovirus, Coxsackie virus, Norwalk agent, echovirus, rotavirus, and Hepatitis A virus were listed as pathogenic virus. *Cryptosporidium* and *Giardia* were listed as pathogenic protozoa. *Mycobacterium avium* is an emerging pathogen of high priority and helicobactor, Norwalk, calicivirus, cyclospora, microporidium, and toxin-producing algae are emerging medium-priority pathogens. However, little is known about the effectiveness of UV light against many of the emerging waterborne pathogens. These include *Helicobacter pyroli*, *Mycobacterium avium*, astrovirus, calciviruses, Norwalk virus, picobirnavirus, and picotrirnavirus.

Because of the problems associated with handling of pathogens and the difficulties in their production and assay, surrogates are used for pilot-scale testing. The surrogates, as discussed previously, include coliphage MS2, *Bacillus subtilus*, and *Giardia muris.* Coliphage MS2 is the most commonly used surrogate microorganism. *Bacillus subtilus* is also used as a virus indicator in UV disinfection studies. For *Giardia muris* is a surrogate for protozoa.

Recent unpublished work has suggested that the age of MS-2 coliphage after production may effect its resistance to inactivation by UV light (Gerba, unpublished). Although the growth state of bacteria is known to effect UV light resistance (bacteria are more susceptible to UV light in the log phase of growth), no studies have been done to assess impact of holding conditions on virus susceptibility (temperature, in the presence of organic matter, pH). Such information is critical to accurately assess virus inactivation.

Microorganisms Response Spectra and Repair Mechanisms

Currently, the basic knowledge regarding UV wavelength-specific inactivation and repair of pathogens is deficient. Meulemans (1986) defined an effective UV dose obtained by summing the dose contribution of each wavelength weighted by the germicidal action spectra of the irradiated microbe. However, the wavelength-specific information regarding microbial responses to UV irradiation is limited. Therefore, it is not currently possible to apply more fundamental (wavelength-specific) approach for dose calculation.

DNA/RNA damage caused by UV disinfection can be reversed by microbial repair mechanisms. Exposure of microorganism to visible light shortly after UV irradiation activates enzymes that reverse pyrimidine dimers created by UV (photoreactivation). Even in the absence of light, enzyme systems excise and rebuild sections of damaged nucleic acid (dark repair). Some but not all bacteria are capable of photorepair and dark repair mechanisms. The ability to undertake repair is also a function of the UV dose with less repair observed with greater UV doses. The photorepair ability of a microorganism is also reduced if, after UV radiation, the sample is kept in the dark for a period of time prior to exposure to visible light (Groocock, 1984). Although viruses cannot repair themselves, they may utilize the enzymes within host cells to undertake repair.

UV By-products and Associated Disinfection By-products

Compared to chemical disinfectants, UV is considered to form minimal disinfection by-products. Malley et al. (1995) did not find any significant DBP in groundwaters or coagulated and filtered surface waters exposed to UV doses of 60 to 200 mWs/cm^2. Low levels of formaldehydes were produced in highly colored waters, and BDOC levels were increased in untreated surface waters.

The combination of UV and chlorine did not significantly change THM production and HAA concentrations (Zheng et al., 1999) even at doses as high as 4,000 mWs/cm^2. Von Sonnlag (1992) demonstrated that UV can result in the formation of nitrite. The pulsed UV was reported to result in very little change in THM and HAA formation and small production of formaldehyde, nitrite, and AOC next to the lamp (Mofidi, 1998). Study of by-product formation for medium-pressure, high-intensity lamps in secondary and tertiary-treated wastewater confirmed that there were no appreciable differences in concentrations of volatile and semivolatile organic compounds and THMs between untreated and UV irradiated waters, but there were small increases in aldehydes (Soroushian et al., 1997). Small increases in formaldehyde, acetaldehyde, and glyoxal and a 2-log reduction in 8 to 16 carbon hydrocarbons with UV doses of up to 150 mWs/cm^2 with low-pressure UV system were reported by Awad et al., (1993).

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UV Process Modeling Based on the Dose Distribution Approach: Application and Scale-Up Issues

Ernest R. Blatchley III, Ph.D., P.E., Purdue University

Background

UV irradiation has developed into a legitimate alternative for disinfection of many media, including wastewater effluents (for direct discharge or reuse), potable water, air, surgical equipment, surfaces, and clean rooms.[1] While the frequency with which UV irradiation is chosen in disinfection applications is increasing, the methods used to design these systems remain relatively crude, thereby leading to final designs that are quite conservative, at least as compared to other disinfection process alternatives. This situation is particularly acute in systems used to disinfect aqueous media, where process dynamics and large treatment volumes create a demanding design scenario. Though a number of factors have contributed to the current situation, the deficiencies that exist in the design process for these systems appear to be largely associated with the characteristics of the available models and the empirical methods used in their development, implementation, and interpretation.

The deficiencies of traditional models used in the design of UV systems can be traced to the assumptions used in their development. While it is true that all models represent a simplification of reality, the assumptions made in these models have been shown in recent years to be without justification. The specific assumptions that lead to failure of these models are unique to each model, but generally are traceable to the point in model development at which empiricism is included in the model.

Dose Distribution Model

The concept of the dose distribution was introduced by Blatchley and Hunt.[2] The model acknowledges the fact that the strong gradients in the intensity (I) and turbulent velocity (V) fields that characterize continuous-flow UV systems dictate that these systems will deliver a (broad) distribution of doses, and that process dynamics cannot be accurately estimated based on a single-valued representation of UV dose. In particular, the dose estimates based on the product of the spatial average of the radiation intensity within the irradiated zone and mean hydraulic detention time within the irradiated zone ($I_{avg}\ \theta$) and biodosimetry were shown to be incapable of being used in developing accurate estimates of process performance for the general case. It should be pointed out that these simplified approaches have merit for application to simple systems (e.g., collimated-beam batch reactors) and continuous-flow systems, where the extent of microbial inactivation is minimal (i.e., <1-1.5 $\log_{10}$ units of inactivation).

The dose distribution model is based on the integration of model simulations and experimental measurements to provide accurate representations of the physico/chemical phenomena that are believed to govern process dynamics in UV systems. In effect, a component approach is used to develop the model, with integration of model components being used to develop process simulations. The specific requirements of each component are described in detail in publications by Chiu et al.[3,4] and Lyn et al.[5] Figure 1 provides a schematic representation of the model components and the methods that have been used (to date) to represent each. Abridged descriptions of each model component and their integration are provided below.

Correspondence should be addressed to:
Purdue University, School of Civil Engineering, West Lafayette, IN 47907-1284
(765) 494-0316 Fax: (765) 496-1107 E-mail: blatch@ecn.purdue.edu

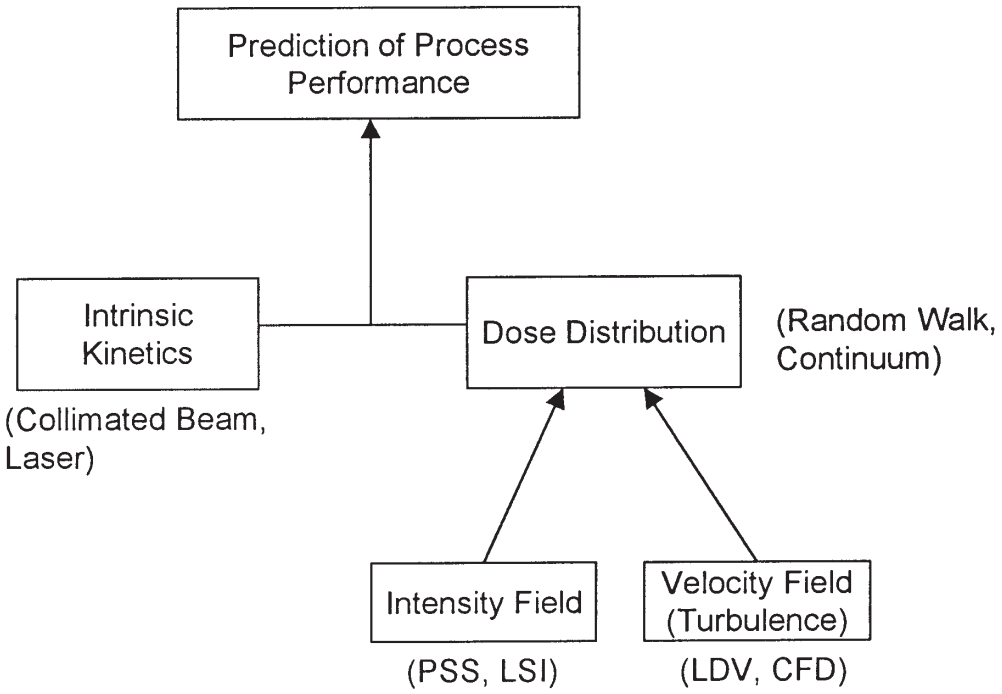

Figure 1. Schematic representation of dose distribution model components. Parenthetical entries refer to methods that have been used to measure or model each component. Arrows indicate the direction of information flow and integration in developing estimates of process performance.

Intensity (I) Field

A number of numerical tools have been developed to provide detailed representations of the I field. The most basic of these is the point-source summation (PSS) technique, first presented by Jacob and Dranoff.[6] In this technique, the cylindrical geometry of the excited mercury vapor in a lamp is modeled as a co-linear set of point sources, all of equal output power. The I field around each hypothetical point source may be represented by accounting for the effects of dissipation (dilution in space) and absorbance (through the Beer-Lambert law). The I field in the entire system is assumed to be represented by the sum of all point source contributions. Blatchley[7] developed a continuous version of this model, the so-called line-source integration (LSI) model. The LSI model incorporates the same assumptions as those used in the PSS approach, but accomplishes the simulation through integration of (differential) point source contributions. Both models provide reasonable representations of the three-dimensional I field in UV systems; however, these models in their current form do not account for some of the factors that are known to affect the I field. In particular, the true cylindrical geometry of the source, as well as the effects of reflection and refraction, are all ignored. In general, these phenomena are likely to have their most significant effect on the local estimates of I in the near-field (i.e., close to the source). At present, efforts are being made to incorporate these effects into numerical models of the I field, but as of this publication, no such model had become available for general use. Fortunately, process behavior in UV systems appears to be limited by trajectories that tend to be relatively distant from the source. As such, the limitations in I field models that are in current use do not appear to represent a serious problem in modeling of process dynamics in continuous-flow UV systems.

Velocity Field

In all but the most extreme cases, the fluid mechanical behavior in continuous-flow UV systems demonstrates the characteristics of turbulence. Therefore, it is necessary for model

component(s) used to represent the velocity field to account for the turbulence characteristics. To date, a number of experimental and numerical techniques have been used to accomplish this goal. Among experimental techniques, laser Doppler velocimetry (LDV) has been used to provide detailed information regarding the mean and turbulence characteristics of the flow.[3,4] The data from these measurements provides detailed and accurate representations of the flow characteristics and may be used as benchmark data against which other representations of the flow field may be compared. Unfortunately, this method is labor intensive and probably not practical for general applications. As such, it is evident that other techniques should be employed.

The family of techniques that has shown the greatest promise for representing the turbulent velocity field in UV disinfection systems is computational fluid dynamics (CFD). In recent years, CFD software and computational hardware have evolved to the point where commercially available packages are available to conduct these simulations on high-end PCs and workstations. However, these simulations are non-trivial to conduct, and should be conducted with intimate involvement of people with specific CFD expertise. For simple reactor geometries, CFD simulations have been shown to be capable of closing on reliable representations of fluid mechanical behavior. As reactor geometry becomes more complex (e.g., through the incorporation of intra-array mixing elements), these simulations become more difficult to conduct. Under all circumstances, CFD simulations should be accompanied by reliable data from physical models and/or pilot-scale systems to provide confirmation of the ability of the model to accurately simulate the flow field and its characteristics. CFD simulations have been conducted on several existing reactor geometries for the purpose of defining process behavior.[5, 8-11]

Intrinsic Kinetics

The third elementary component of UV system process behavior is an expression to describe the intrinsic kinetics of the reaction of interest. Such an expression will describe the dose-response behavior of the microorganism and physiological endpoint (e.g., inactivation) that are relevant to the specific treatment objectives of the system. Mathematical representations of intrinsic kinetics (dose-response) behavior are most easily obtained by analysis of data from systems that are capable of delivering a single, quantifiable UV dose. Though many reactor configurations are capable of accomplishing this objective, the simplest and most commonly used system for these purposes is a shallow, well-mixed batch reactor subjected to collimated UV radiation. Properly designed collimators will deliver radiation at a uniform intensity that can be easily and accurately measured by radiometry, or other techniques.[7] Observed microbiological responses are fit to an appropriate mathematical model using regression techniques for purposes of providing an estimate of expected response (as a function of dose) as well as response variability.

Dose Distribution

The dose distribution delivered by a UV system is governed by the I and V fields. As such, models used to predict the dose distribution must incorporate an algorithm for integrating these system characteristics. Though a continuum approach to this integration may be appropriate,[5] the most intuitive approach developed to date is based on simulations of discrete particle trajectories.[3,4,12] For each trajectory, the UV dose is calculated according to the following expression:

$$D = \int_0^{\tau} I(t)\, dt$$

where,

D = UV dose received by particle (mJ/cm^2)

τ = particle residence time within irradiated zone (s)

I(t) = intensity history corresponding to particle trajectory (mW/cm^2)

t = time (s).

Several algorithms have been developed to accomplish this integration, or an analogous summation. Chiu et al.[3,4] and Lin and Blatchley[12] used random-walk models to simulate particle trajectories in a turbulent flow field. These models yielded simulated particle trajectories that were consistent with the known (measured) physical behavior of the flows in the systems they were designed to simulate.

Prediction of Process Performance

Estimates of reactor efficacy require proper integration of the predicted dose distribution and dose-response behavior. This is accomplished through an algorithm that is mathematically analogous to the segregated-flow model.[13] For systems in which microbial inactivation (i.e., loss of viability) is the treatment objective and endpoint by which efficacy is measured, the governing relationship is[3]:

$$\Phi_{out} = \int_0^{\infty} \Phi_{batch}(D)\, E(D)\, dD$$

where,

Φ_{out} = fraction of organisms that retain viability following irradiation

$\Phi_{batch}(D)$ = fraction of organisms that retain viability in a batch reactor at dose D

$E(D)$ = dose distribution function (cm^2/mJ)

D = UV dose (mJ/cm^2).

When compared against process performance data collected from continuous-flow systems, this model has been shown to provide accurate estimates of process performance.[3,4] The ability of the dose distribution model to provide accurate predictions of process dynamics is taken as an indication of the ability of the model and its elementary components to provide accurate representations of the fundamental physical phenomena that govern reactor dynamics. Separate evaluations of component behavior support this assertion.

Other Factors that Affect the Dose Distribution

The dose distribution delivered by a continuous-flow UV disinfection system is dynamic. The model components described above explicitly account for variations in the dose distribution (and process efficacy) that are associated with changes in hydraulic loading, the transmittance characteristics of the fluid being treated, and changes in the intrinsic kinetics of inactivation. It is clear that these factors are critical to the performance of the system; however, these terms do not explicitly incorporate all other factors that could affect the dose distribution.

Current models assume that the lamps in a system yield constant UV output power. However, measurements of lamp output power under operating conditions indicate variability on the order of 20 percent.[7] Moreover, the measured output of these lamps may be substantially different than the estimated values provided by the manufacturer. Lamp output is also known to demonstrate strong variations as a function of lamp age. In models applied to date, these effects are generally ignored. While it is impractical to expect to have access to real-time data regarding (actual) UV lamp output power for all lamps in a system, it is plausible for these effects to be incorporated into a modeling approach using a stochastic approach.

Another factor that is often ignored in process models is the effect of lamp jacket fouling on the I field. Fouling materials, which tend be largely inorganic in nature, can lead to rapid changes in the I field and in process performance.[14-17] These materials, which can be extremely effective at absorbing UV radiation, are characterized by strong temporal and spatial patterns of accumulation. For systems where fouling is significant, these effects should be incorporated into the process model.

A further issue of concern regarding the dose distribution is the behavior of systems that employ polychromatic UV sources. Many new system designs rely on these polychromatic sources because of their compact size relative to the UV power emitted. Unfortunately, the designs of these systems have implicitly assumed that photons in the UV range are of equal or, at least, similar effectiveness relative to microbial inactivation. At present, the validity of this assumption is unclear. Conceptually, the dose distribution model could be applied to polychromatic systems, though no model has yet been developed to accomplish this objective.

Model Application for Full-scale System Design

The design of full-scale UV systems does not follow a rigidly defined protocol. The specific mechanisms by which final designs are developed are quite varied. The models that have been used for the purpose of developing final designs are highly empirical and conservative. Even in cases where modeling is used as a component in the design process, designs are likely to rely heavily on extrapolation of test results from pilot-scale tests. In general, the designs that have resulted from these procedures have yielded systems that perform reliably; however, in most cases, this reliability is linked to the fact that the systems are grossly overdesigned (i.e., inefficient).

The dose distribution modeling approach has been shown to be effective for predicting process performance and, therefore, represents a tool that may be used for development of systems that reliably and efficiently meet treatment objectives. In fact, the dose distribution model has been used as a tool for improving the performance of UV systems through modifications of reactor geometry.[4,9]

It is likely that pilot testing will be retained as a tool to be used in the design of UV systems for the foreseeable future. The results of such tests provide important information regarding the performance of UV systems at a particular site, usually based on pilot-scale prototypes that are geometrically similar to their full-scale analogs. As such, they represent a valuable source of data that may be used to validate model predictions. If a model can be demonstrated to have the ability to yield accurate predictions of process performance in a pilot-scale system, it is reasonable to expect that an analogous model could be developed to predict the performance of a geometrically and dynamically similar full-scale system. Under these conditions, the model could be used to assess the performance of full-scale designs.

In extrapolating model predictions based for a pilot-scale system to a full-scale analog, it is important to recognize the limitations of the model and physical characteristics that may change in the scale-up process. In all UV systems investigated to date, regions of the reactor have been identified that tend to yield low-dose trajectories.[3,4,6,12,18] For most systems, these areas tend to be relatively close to the reactor walls. Microorganisms (particles) that enter these areas of the reactor are far more likely to retain viability in the treated water than are microorganisms that enter the system in areas that are relatively distant from the walls.

In pilot-scale systems, the ratio of near-wall to non-near-wall reactor volume is likely to be larger than in full-scale systems, because full-scale systems normally employ lamp modules (or banks) that house larger numbers of lamps than their pilot-scale analogs. Based on this argument, one would expect a full-scale system to perform better than a pilot-scale system, if all other attributes of the system were equivalent. However, full-scale and pilot-scale systems may also operate at different approach velocities, even when comparable ratios of hydraulic loading to lamp number are used in both systems. In general, high approach velocities will tend to yield relatively narrow dose distributions.[18] In many systems, these two factors (ratio of near-wall:central volume ratio and approach velocity) will counteract each other in translating from pilot-scale to full-scale; therefore, it is impossible to make a priori statements regarding the relative performance of pilot-scale and full-scale systems. Quantitative predictions of full-scale performance require detailed modeling of the anticipated full-scale system. It is not reasonable to expect pilot-scale data to translate to full-scale, or even represent a conservative estimate of full-scale system performance.

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UV Dose Verification Using Chemical Actinometry and Biodosimetry Methods

Karl G. Linden, Ph.D., Duke University

Introduction

Verifying the delivery of UV dose within a reactor at full-scale is one of the challenges to ensuring proper and continuous disinfection is being achieved. Although a number of mathematical models have been developed for estimating the average UV dose or the dose distribution within a reactor under various conditions, modeling alone does not provide total assurance that a given design dose is actually being delivered under field conditions. A physical manifestation of actual dose delivery would provide an indication of UV dose within a reactor and help to validate model predictions. The selection of a particular UV dose indicator is key to gaining valuable insights.

The first question to ask is "What do we really want to know about a reactor?" Ultimately, we want to know how well it performs at inactivating pathogenic microorganisms. So, perhaps, the best challenge for verification is to seed the reactor flow with a pathogen and measure the disinfection efficacy. In this case, we would not be interested in the particular UV dose delivered, just verifying that the reactor was doing its intended job. But there are a number of organisms that we would like to know about and to test them all at full scale is not practical. Furthermore, we are not able to optimize reactor performance by performing such tests, as we would not necessarily know if our reactor design is overly conservative from the results. If we could relate the inactivation of an organism of some interest to a scaleable parameter such as UV dose, then we could gain some valuable information on reactor performance as well as disinfection efficacy. If we had information on the UV dose-response for other pathogens of interest we could then determine the extent of inactivation that could be expected under the given conditions. The approach of utilizing the inactivation of a single organism at reactor scale to provide an average value for the UV dose provided in a reactor is referred to as biodosimetry (also called a bioassay or biological actinometry). There are many considerations that need to be taken into account when designing and evaluating the biodosimetry approach for UV dose validation. A discussion of these is presented below.

A second approach to validating UV dose in a reactor is one employing UV light reactive chemicals. The first law of photochemistry states that only absorbed radiation can produce a chemical change. Utilizing this principal, a number of chemicals absorb UV radiation in the wavelength range of interest. In chemicals suitable for radiation measurement, this absorption of radiation energy causes some measurable chemical change. The extent of the chemical change can be correlated to the amount of energy (photons) absorbed providing a measure of absorbed UV dose. This photochemically based approach is referred to as chemical actinometry. There are many important factors that need to be considered and understood in choosing and utilizing a chemical actinometer. These factors are discussed in detail below.

Biodosimetry

Use of a microbiological response as an indicator of UV dose was reported by Qualls and Johnson.[1] Since this time the method, termed a "bioassay," has been in use as a means to measure the UV dose within a reactor. The bioassay method appears well suited for estimation of effective germicidal UV output from any UV system. Because it is a biologically based test, it provides a measure of effective germicidal dose — the dose necessary for a desired germicidal effect — and can be calibrated using a collimated beam low-pressure UV

Correspondence should be addressed to:
Duke University, Department of Civil and Environmental Engineering, Box 90287, Durham, NC 27708-0287
(919) 660-5196 Fax: (919) 660-5219 E-mail: kglinden@duke.edu

system where the germicidal dose can be estimated confidently. In a strict sense, biodosimetry goes beyond use of an organism to verify the performance of a reactor. Biodosimetry is a means to put an actual value on the average UV dose delivered by a reactor under specified conditions. A principal drawback with use of a bioassay is that the results must be presented in terms of the most probable result with an associated confidence interval. Unless a large number of replicate samples are analyzed with extreme care, the confidence interval associated with microorganism enumeration can be quite large. In addition, the bioassay approach is relatively time consuming and potentially expensive compared to alternative methods of estimating UV dose.

Biodosimetry Test

In the bioassay approach, the relationship between UV dose and log survival of a challenge organism is first developed using a collimated beam low-pressure UV system where dose can be determined accurately using a calibrated radiometer, traceable to NIST standards. Then the log survival of the challenge organism in a system where dose is unknown (such as at full scale) is measured and the UV dose is back calculated from the low-pressure dose response curve. This approach is illustrated in Figure 1.

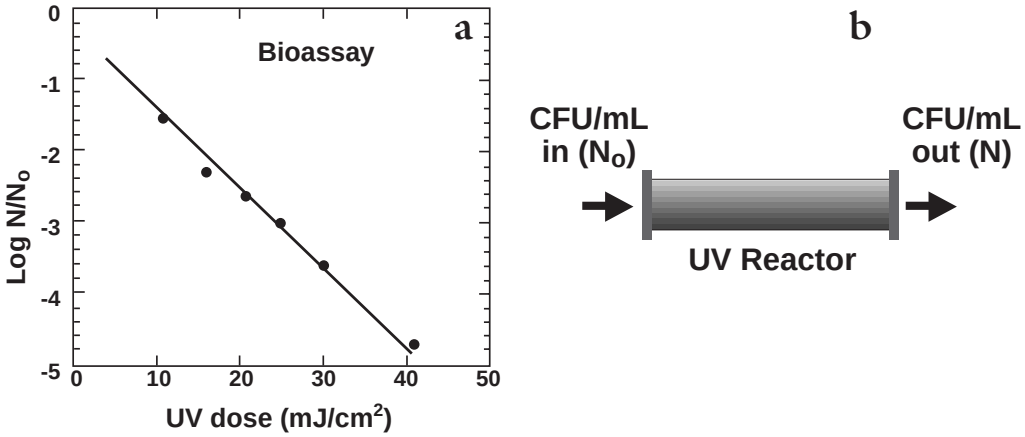

Figure 1. Schematic of a biodosimetry test. (a) A relationship between applied UV dose and log survival of the challenge organism is developed under controlled laboratory conditions — measurement of UV dose is traceable back to NIST standards. (b) Challenge organism is seeded into UV reactor. The log of the ratio of surviving organisms to initial organisms is calculated and a reactor UV dose is determined from the plot in (a).

Typically, the initial relationship between UV dose and survival of the challenge organism (UV dose-response curve) is performed using a low-pressure, mercury vapor lamp encased in a collimated beam apparatus. Low-pressure, mercury vapor lamps emit virtually monochromatic radiation (at 253.7 nm) in the UV range. A collimated beam apparatus is illustrated in Figure 2. UV irradiance incident on the sample in the petri dish can be measured using a detector and radiometer. The average irradiance within the liquid sample can be determined taking into account UV absorbance and the depth of sample.[2] The UV dose is calculated by multiplying the average irradiance by the exposure time and is most often expressed in units of mJ/cm^2 or J/m^2. Caution needs to be taken in following strict procedures to obtain accurate and confident results.

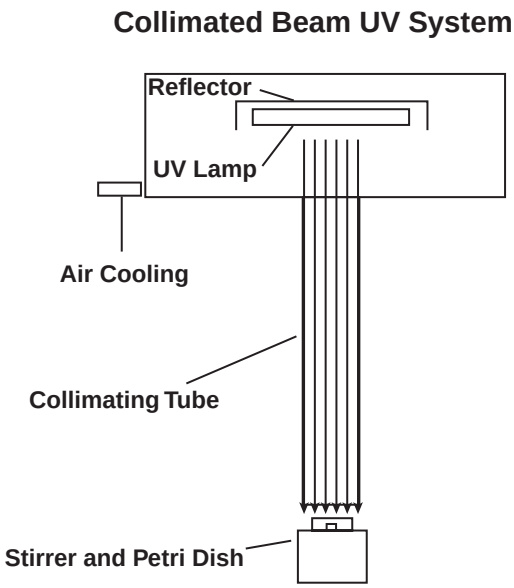

Figure 2. Collimated beam UV apparatus used on the bench scale to develop standardized dose-response data for microorganisms.

Cautions when Using Biodosimetry for Reactor Validation

A number of cautions must be issued and reviewed when evaluating results from biodosimetry to arrive at a UV dose for a reactor. By its nature, the test only provides a measure of the average UV dose supplied by the reactor under the given set of conditions. In actuality, there is a distribution of doses that any given population of microorganisms will be exposed to during a disinfection event. The biodosimetry test does not provide any indication of this dose distribution. The choice of microorganism must be relevant to the dose range of interest. Ideally an organism that has a dose-response that straddles the dose range of interest should be chosen. For instance, if the dose range of interest is in the 30 to 40 mJ/cm^2 range, an organism that exhibits 2 to 3 log inactivation in this dose range should be chosen. Furthermore, with current methods, the biodosimetry test may take up to 2 days or more to complete. This time lag for results makes a biodosimetry approach to monitoring UV dose impractical.

When using the biodosimetry approach to estimate the UV dose in a reactor using lamps that emit polychromatic radiation, the results obtained must be reported and evaluated as a low-pressure equivalent UV dose. The dose response curve that is used to estimate the UV dose in the full-scale reactor was developed using a low-pressure monochromatic UV source; therefore, the dose must be reported as referenced back to the low-pressure source. Because not all UV wavelengths are equally germicidal, the actual effective germicidal dose from a polychromatic UV source is not easily calculated. Relating this relatively complex manifestation of dose back to a simple monochromatic basis has its benefits and drawbacks. One benefit is that all UV systems can be related back to their low-pressure UV lamp equivalent dose and, thus, be compared on this basis. One drawback is that the actual germicidal dose delivered in the polychromatic systems is not truly understood. The choice of organisms is also important when estimating UV dose in polychromatic UV systems. Some organisms may be more susceptible to energy from other germicidal wavelengths (such as 265 to 275 nm) as compared to UV 253.7 nm, and these wavelengths are often prominent in the emission spectra of the reactors using medium pressure UV lamps. In this case, the germicidal UV dose calculated using the biodosimetry approach described above might overestimate the actual UV dose necessary for a given inactivation. An evaluation of the action spectra (inactivation response of an organism at different UV wavelengths) of a challenge organism would be

beneficial when analyzing data from the biodosimetry approach used to determine dose with polychromatic UV lamps.

Chemical Methods

Chemical actinometry provides a direct quantifiable chemical measure of the total UV energy available in a UV system and is an easy, fast, accurate, and potentially low-cost method for determination of UV dose. It is a light-induced chemical process whereby UV photons, absorbed by a photosensitive chemical, induce a chemical change. This chemical change may be a photoreduction reaction (as in the case of potassium ferrioxalate actinometer), a photohydrate reaction (as in the case of uridine actinometer), or other measurable change in the parent chemical.

Chemical actinometry has been proposed as one means to measure UV dose in UV disinfection systems. Numerous chemical actinometers can be used to measure radiation from the wavelengths that cover the absorption spectrum of nucleic acids in the UV-B and UV-C regions.[3,4] However, many chemical actinometers also absorb energy from wavelengths outside of the germicidal range and the reported quantum yields (moles of chemical changed per Einstein of energy absorbed — Einsteins are a measure of moles of photons and can be related to UV irradiance through a conversion factor) are not constant over a wide wavelength range. Applications of actinometry to UV disinfection systems have primarily focused on determination of UV dose in systems employing low-pressure UV lamps. The monochromatic output of the low-pressure lamp has simplified the determination of the germicidal irradiance. Because the lamp does not emit appreciably at any other wavelength, any actinometer can be employed to measure the germicidal intensity. The polychromatic output of the medium pressure and pulsed UV lamps poses a unique challenge for actinometry applications. An ideal actinometer for quantifying the effective germicidal radiation of a polychromatic UV lamp should have the following characteristics[5]:

1) Absorb only germicidal radiation.
2) Absorbance spectrum similar to that of DNA.
3) Constant quantum yield throughout the germicidal wavelength range.
4) Knowledge of quantum yield for entire wavelength range of absorbance.
5) Easy to quantify using standard laboratory equipment.
6) Non-toxic for use in full-scale reactors discharging to natural water bodies.

Common Actinometers

The most widely used actinometer is potassium ferrioxalate, considered the "Gold Standard" of actinometers because its quantum yield has been well established and is relatively high (1.16 to 1.25). Potassium ferrioxalate absorbs radiation from 200 to 500 nm; thus, it measures radiation outside of the germicidal (230 to 300 nm) range. This fact makes the use of potassium ferrioxalate limited to low-pressure UV systems that emit principally monochromatic radiation in the germicidal range. Uridine is a compound that has many of the characteristics that would make an ideal actinometer and has been investigated for use with medium-pressure UV systems.[6] The uridine molecule contains uracil, a naturally occurring nucleobase, as its chromophore. The absorbance of potassium ferrioxalate and uridine, expressed as the absorbance relative to the peak absorption at 262 nm, is illustrated in Figure 3. Also illustrated in Figure 3 is the German DIN germicidal effectiveness curve, based on the action spectra of *E. coli*. The relative absorption spectrum of uridine is similar to that of the German DIN standard. The similarity between the *E. coli* action spectra as depicted in the German DIN standard and the uridine absorbance spectrum indicates that uridine may be a realistic surrogate for estimating effective germicidal UV dose. Because only absorbed radiation can produce a chemical change, the degradation of uridine is expected to have wavelength dependence similar to its absorbance spectrum. Thus, any chemical change (photo-

hydration) that occurs in uridine will be in proportion to the energy absorbed, which is appropriately weighted to reflect the relative germicidal effectiveness of each wavelength in the germicidal range. The presence of uridine can be monitored easily through spectrophotometric analysis of the compound absorption peak at 262 nm.

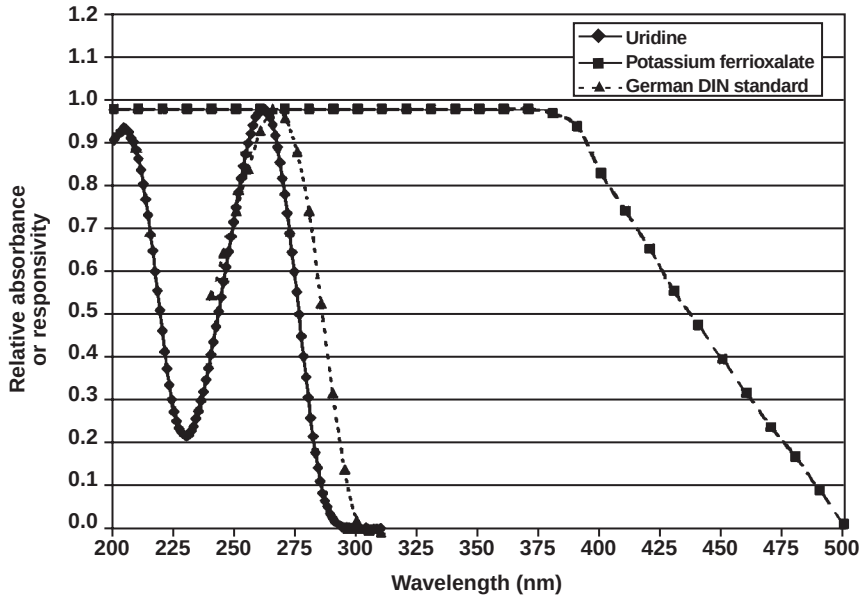

Figure 3. Absorbance spectra of uridine and potassium ferrioxalate, and responsivity of the German DIN Germicidal Standard.

Application of Chemical Actinometry for Reactor Scale Dose Validation

Because actinometers provide a direct measure of UV dose, they have great potential for use at reactor scale. Potassium ferrioxalate has been investigated for use at full-scale[7] and the dose results were comparable to those using a bioassay approach. One drawback to using actinometers is that a lot of chemical needs to be prepared if the actinometer is to be injected into the flow of the reactor. An alternate approach is to fix the actinometer solution at strategic points within a reactor[8] to determine UV irradiance in air using an iodide/iodate actinometer. This approach would provide a measure of UV irradiance within a reactor but would not account for reactor hydraulics. Application of actinometry for routine monitoring of UV irradiance or dose within a reactor has potential. Because actinometers provide nearly real-time results (subject to chemical reaction and monitoring) that can be often monitored spectrophotometrically, they could be applied for use in reactor irradiance or dose monitoring with the proper engineering ingenuity to apply the technology.

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Standardizing UV Equipment Performance Validation

Robert W. Emerick, Ph.D., P.E.[1], ECO:LOGIC Engineering
Fred Soroushian, P.E.[2], CH2M Hill
George Tchobanoglous, Ph.D., P.E.[3], University of California, Davis

Introduction

The testing protocol described herein is applicable to UV disinfection systems that do not conform to the requirements set forth in the document *UV Disinfection Guidelines for Wastewater Reclamation in California and UV Disinfection Research Needs Identification* (hereafter referred to as NWRI [1993]), published by the National Water Research Institute (NWRI). The additional study that must be conducted when using non-conforming UV disinfection systems is described in this document. The intent of this protocol is to provide a tool for regulators, consultants, and end users to provide a level of comfort that the validated technology will perform at full-scale facilities within the range of parameters used during the validation testing. All of the conditions specified in the "Protocol Details" must be fulfilled for adherence to this protocol. All data, statistical analyses, results, and schematics demonstrating compliance with this protocol are to be included in the Engineering Report as described in NWRI (1993) and its subsequent revisions.

This protocol addresses equipment dose application verification only. It does not provide design constraints that would ensure adequate or reliable operation. This protocol must be applied in conjunction with design constraints outlined in NWRI (1993) and its subsequent revisions. Separate testing should be conducted at any given site to ensure adequate dose delivery for additional site-specific pathogen indicators of concern (e.g., total coliform bacteria).

Definition of Non-conforming UV Disinfection Systems

This validation protocol is designed to demonstrate that a non-conforming UV disinfection system provides a degree of treatment and reliability at least equal to systems that have been shown to be acceptable to the regulatory agencies. Specifically, use of this testing protocol is required if the UV disinfection system deviates from that described in NWRI (1993) in the following manners:

1. Use of lamp orientations other than parallel to the direction of fluid flow.
2. Use of lamps other than low pressure/low intensity mercury arc lamps.
3. Systems that do not utilize open channel flow.
4. Systems intended for use on reclaimed wastewater that has a UV transmittance less than 55 percent (λ = 254 nm).
5. Use of fewer than three banks of lamps for UV dose application
6. When significant changes have been made to previously validated UV equipment.
7. Even when one manufacturer's technology appears equivalent to that of another manufacturer's equipment.

Correspondence should be addressed to:

1) ECO:LOGIC Engineering, 3005 Douglas Boulevard, Suite 200, Roseville, CA 95661
(916) 773-8100 Fax: (916) 773-8448 E-mail: ecologic@foothill.net

2) CH2M Hill, 3 Hutton Centre Drive, Suite 200, Santa Ana, CA 92707 (714) 429-2000 E-mail: fsoroush@CH2M.com

3) University of California, Davis, Dept. of Civil and Environmental Engineering, 662 Diego Place, Davis, CA 95616
(530) 752-1440 Fax: (530) 753-6365 E-mail: gtchobanoglous@ucdavis.edu

Performance Goal

Any UV disinfection system used as part of a wastewater reclamation treatment process must be capable of producing a UV dose with the same germicidal effect as the UV dose required by monochromatic UV light with a wavelength of 254 nm for achieving 4-log poliovirus inactivation. A default dose of 140 mJ/cm^2 can be used in the absence of poliovirus inactivation data. The equivalent UV dose must be delivered subject to the applicable wastewater transmittance measured at a wavelength of 254 nm. Systems will be approved for use only on wastewaters with a transmittance greater than that tested during pilot study. Note that for design, a transmittance of 55 percent is to be assumed for wastewater reclamation facilities unless six months of testing (including wet weather flows) has been conducted that supports use of a higher value. For transmittance values greater than 55 percent, a separate study must be conducted.

Applicable reduction factors for equipment aging and wear, lamp fouling, and cleaning efficiency can be found in NWRI (1993) and subsequent revisions. Systems will be approved for specific sites only when the operating conditions at the full-scale installation are expected to fall within the range over which the technology was validated previously.

UV Test Protocol

The following tests must be completed simultaneously on UV disinfection equipment that is similar to equipment that would be installed at full-scale facilities:

1. Determination of the dose-response relationship for MS2 coliphage in a collimated beam test apparatus.

2. Measurement of MS2 coliphage inactivation through the pilot-scale UV disinfection equipment under the range of conditions over which the technology is to be validated.

For the purpose of the testing protocol, pilot systems are to be designed as stated under the Section, "Set-up of Pilot Testing Equipment." All pilot systems must be operated with the same cleaning system and at the same lamp submergence that is to be used in the full-scale facilities.

Determination of Dose-response Relationship for MS2 Coliphage

A dose-response curve for MS2 coliphage must be generated by applying a collimated beam of UV light to a batch sample of disperse MS2 coliphage. Use of a polychromatic light source to generate the collimated beam of UV light is not acceptable even if a narrow band filter is used to isolate a relatively narrow region of the emission spectrum around 254 nm. The collimated beam apparatus must be designed according to the design guidelines in the Appendix. The radiometer used to measure intensity applied to the sample must have been calibrated within the last 12 months. The batch sample is to be drawn from the test water used for pilot-scale testing, thus having the same MS2 coliphage number concentration and chemical characteristics as the water passed through the pilot scale unit. Sufficient virus titer shall be added to the test water to achieve a minimum outfeed bacteriophage concentration of 10^2/mL. The UV light applied via the collimated beam must be generated from a low-pressure mercury vapor lamp (i.e., 254 nm light wavelength). At minimum, four doses shall be applied as part of the collimated beam test. The UV doses are to be chosen such that they bracket the performance observed as part of the pilot-scale testing and adequately illustrate the inactivation relationship of MS2 coliphage with respect to applied UV dose. An acceptable dose-response curve is linear (i.e., when virus are dispersed) with a correlation coefficient exceeding 0.95 for a linear regression through the log-inactivation data as a function of applied UV dose. There shall be no extrapolation beyond investigated doses.

Set-up of Pilot Testing Equipment

All banks of lamps that would be included in a full-scale system shall be in place, including redundant banks (if applicable). A minimum of two banks shall be used for UV dose application. For open channel systems, the maximum flowrate shall correspond to the flow-rate that results in a depth of flow over the top of the lamp equal to one-half of the lamp spacing measured from the centerline of the top lamps. Full-scale facilities shall use the same ballasts, energy usage, lamps, lamp-spacing, channel configurations, lamp submergence, cleaning system, etc. as the pilot-scale unit being tested. The only difference between full-scale facilities and pilot-scale facilities shall be the number of lamps and any channel cross-sectional sizing differences necessary to accommodate the different numbers of lamps. All additional parameters not specifically listed by this protocol but likely to impact specific UV disinfection equipment performance (e.g., wastewater temperature) must also be tested and its impact documented during the testing procedure.

Measurement of MS2 Coliphage Inactivation Through Pilot-scale Equipment

A test water containing MS2 coliphage shall be passed through the UV disinfection equipment. All banks of lamps that would be included in a full-scale system shall be in place, including redundant banks (if applicable), when such banks impact the hydraulic behavior of upstream banks. Pilot systems must be operated with the relevant components (e.g., lamps, sleeves, lamp spacing, and cleaning system) and operated under the range of conditions that are equal to (e.g., hydraulic loading rate per lamp) or worse than (e.g., lamp submergence profile, wastewater transmittance) that applicable to a full-scale facility.

Both the infeed and effluent MS2 coliphage concentrations shall be measured. Infeed concentrations shall be adjusted for any absorption or inactivation through the pilot unit independent of UV light application by passing the phage through the disinfection system with all of the UV banks (lamps) turned off. Effluent samples must be well mixed and represent the average of the effluent concentration from the reactor (e.g., as flowing over an effluent weir). For systems utilizing "closed" flow (e.g., filled pipe flow), samples shall be taken on the composite effluent exiting the reactor.

Because a minimum of two banks must be used for UV dose application, disinfection performance can be determined either for any two banks operating simultaneously or for each bank operating independently. However, all banks must be in place (i.e., present but turned off if not included in the analysis). Sufficient samples must be analyzed after each bank (or pair of banks) to demonstrate estimation of the mean virus log-removal to within 0.5 log with a confidence coefficient of 0.95. When attempting to assess the number of banks beyond which there are diminishing returns in achieving additional disinfection, or when attempting to assess differences in performance resulting from different operating conditions, analysis of variance techniques shall be used to demonstrate that the difference in log inactivation between any two banks (or pair of banks) is not statistically significant at the 95 percent level of confidence.

The total virus log-removal shall be calculated as the -log of the virus inactivation fraction,

$$-\log\left[\frac{N}{N_O}\right]$$

where N = number of surviving MS2 coliphage exiting the disinfection system with the lamps turned on, and

N_O = the number of MS2 coliphage exiting the disinfection system with all lamps turned off.

The inactivation fraction shall be calculated using the average (geometric based on lognormal statistics) calculated over all samples.

Testing shall be conducted at different flow rates to cover the range of range of dose application over which the manufacturer wishes the technology to be validated. At any given percent transmittance, testing shall be conducted at (1) the minimum manufacturer approved flowrate, (2) the maximum manufacturer approved flowrate that is also allowable as defined in sub-section 2 (i.e., "Set-up of Pilot Testing Equipment"), and (3) a minimum of two different intermediate flowrates. For systems using adjustable output ballasts, tests shall be repeated for the minimum ballast setting, the maximum ballast setting, and at least one intermediate ballast setting.

UV Dose Determination

Equivalent Dose Assignment

The equivalent applied UV dose in the pilot system shall be defined by comparison to the collimated beam test results. Results shall be reported in terms of flow/lamp to achieve a specified dose under critical conditions. The equivalent applied UV dose for the pilot system shall be assigned by comparing the average log inactivation observed upon passage through the pilot-scale UV disinfection system to the UV dose observed necessary for equivalent MS2 coliphage log inactivation in the collimated beam system. Such equivalent doses should be determined for all conditions (percent transmittance, flowrate) over which the technology is being validated. Applied UV doses may not be mathematically assigned to higher liquid transmittances or alternative lamp spacing arrangements (i.e., extrapolation). Interpolation between tested conditions is allowable.

Calculation of Per-lamp Applied UV Dose

A per-lamp applied UV dose shall be calculated as the ratio of applied equivalent UV dose to the number of lamps in the pilot-scale system at the tested flowrates and transmittances. Interpolation of performance between flowrates investigated will be permitted for a given transmittance. The per lamp dose shall be used to determine the number of lamps and banks in series necessary (i.e., the number of banks) in the full-scale system to achieve the requisite 4-log poliovirus inactivation.

Protocol Details

Definition of Third Party

Although this protocol lists the steps necessary for assignment of UV dose through a pilot-scale UV system, it cannot address all conditions likely to occur with situation specific applications of this testing protocol. Thus, a third party is defined as a licensed professional civil or chemical engineer registered to practice in the state of California who is properly experienced to exercise engineering judgment for the situation specific application of this protocol. All laboratory work is to be conducted by a laboratory approved by the California Department of Health Services for the conduct of this protocol. In circumstances where facilities do not exist to test adequately a pilot-scale UV disinfection system within the state of California, testing in another location by qualified personnel under the charge of a third party will be approved.

Propagation of MS2 Coliphage

Propagation of phage involves infection of a host bacterium whereby replication of phage occurs within the cell. Replication typically results in several orders of magnitude more phage being produced per cell infected. Propagation and enumeration of MS2 coliphage requires both the MS2 coliphage (ATTC No. 15597-B1) and its host bacterium, *Escherichia coli* (ATTC No. 15597). Both can be purchased in freeze-dried form from the American Type Culture Collection (phone: 1-800-638-6597, technical support 1-301-881-2600). Some universities also maintain collections. The American Type Culture Collection provides information for reviving freeze-dried cultures, instructions for obtaining a high titer of phage,

and media recipes for optimal phage multiplication. Titers of at least 10^{10} phage/mL are easily obtained, and titers with several higher orders of magnitude are possible with care. Information for MS2 coliphage propagation can be found in American Type Culture Collection (1992), Adams (1959), Davis and Sinsheimer (1963), and Davis and Sinsheimer (1964).

It is important to note that upon cell lysis and phage release, the cellular debris must be removed from the phage titer solution. Host bacteria cellular debris contains numerous adsorption sites for phage attachment and, if left in the stock solution, will result in phage becoming associated with the cellular debris, resulting in particle association. Association with the cellular debris will increase the resistance of MS2 coliphage to UV inactivation and prevent the occurrence of log-linear inactivation behavior. Centrifugation is *not sufficient* for the removal of cellular debris. Submicron filtration (e.g., <0.45 μm) following centrifugation must be used for complete debris removal.

Enumeration of MS2 Coliphage

A modified form of the Coliphage Detection Method (Method 9211D) outlined in Eaton et al. (1995) can be used to enumerate the concentration of MS2 coliphage. Modify the procedure by using *Escherchia coli*, ATCC No. 15597 as the host culture and use the growth media, top agar, and bottom agar as described by Davis and Sinsheimer (1963). Sufficient replicates (typically, three to four) for each dilution plating must be conducted such that the coefficient of variation (i.e., the sample standard deviation divided by the sample mean) for each sample is less than 0.3. The average value shall be used for data analysis.

Collimated Beam Apparatus and Testing

Dose application via a laboratory scale collimated beam is used for calibration of the applied UV dose in the pilot-scale facilities. The necessary UV dose, calculated as the product of exposure time and applied UV intensity, is obtained by maintaining a fixed UV intensity, measured with a radiometer, and varying the exposure time. Although numerous configurations of the collimated beam testing apparatus are possible, it is important that the collimating tube be long enough to ensure that light hitting the UV sensor of the radiometer (or test water sample) be perpendicular to the plane of the sensor (or water surface of the sample). UV intensity sensors can only record UV light normal to the sensor surface and, thus, any light not normal to the surface will not be measured by the sensor but will contribute to MS2 coliphage inactivation.

A simple collimated beam apparatus, as described and illustrated by Darby et al. (1995), is described below. The collimated beam apparatus necessary for generation of the log-survival vs. UV dose curve can be constructed by housing two low-pressure, mercury vapor lamps in copper pipe (50.8 mm ID). A tee extends approximately 15 tube diameters downward from the horizontal tube to achieve collimation of the UV light. The lamps are connected to a power supply via a transformer box and sockets. The intensity of UV light is measured at the point of application using a radiometer (International Light, Model IL1700, connected to International Light photomultiplier Model 400A with tube IL101; International Light is located in Newbury Port, MA). Ten milliliters of test water containing MS2 phage to be used for passage through the pilot-scale facilities are placed into a sterile petri dish (50 mm ID) containing a stir bar. The collimating tube is covered with an opaque sheet of cardboard, and the petri dish positioned approximately 10 mm from the end of the collimating tube. Mixing is initiated, the opaque sheet of cardboard removed, and the irradiation timer started simultaneously. After the sample is irradiated for the desired amount of time, the opaque sheet of cardboard is inserted between the collimating tube and the sample. Alternatively, an automatic shutter mechanism can be used for dose application. The number of MS2 coliphage in the irradiated sample is then enumerated. Repeat the process for all UV doses necessary.

Altering Wastewater Transmittance

Test water transmittance can be reduced by means of addition of brewed or instant coffee, PHBA, or other chemical. Roughly 1 part of medium strength coffee is necessary per 200 parts test water to achieve a 55 percent transmittance with brewed coffee.

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Research, Implementation, and Monitoring Requirements for Ultraviolet Light Treatment of Surface Water

Alex Mofidi and Brad Coffey, Metropolitan Water District of Southern California

Introduction

UV light has been used for decades in the United States to disinfect bacteria and viruses in treated wastewater. In addition, UV light has been used as a potable water disinfectant in Europe for several years. Due to recent discoveries that UV light can act as an excellent disinfectant for protozoa, this technology is gaining momentum in the U.S. potable water market as well. However, a number of concerns must be addressed before UV becomes well accepted to disinfect treated surface water. These concerns include: (1) the effectiveness of UV against protozoa; (2) the integration of UV disinfection within conventional treatment; and (3) the ability to monitor transferred UV dose to ensure adequate disinfection.

Research Needs

Many studies have shown that UV light inactivates bacteria and viruses; however, only recent studies have shown that UV light also inactivates protozoa. Prior to 1998, UV light was not demonstrated as an adequate disinfectant against protozoa.[1, 2] Recent data show that this premise was based on inadequate assay techniques, and protozoa may be easily disinfected by UV light.[3, 4] Before UV disinfection of protozoa can be fully understood, an establishment of biological plausibility (i.e., UV photons react with DNA to prevent infection), treatment efficacy (i.e., the comparison of UV treatment of protozoa versus experiment controls), and UV-dose response is needed.

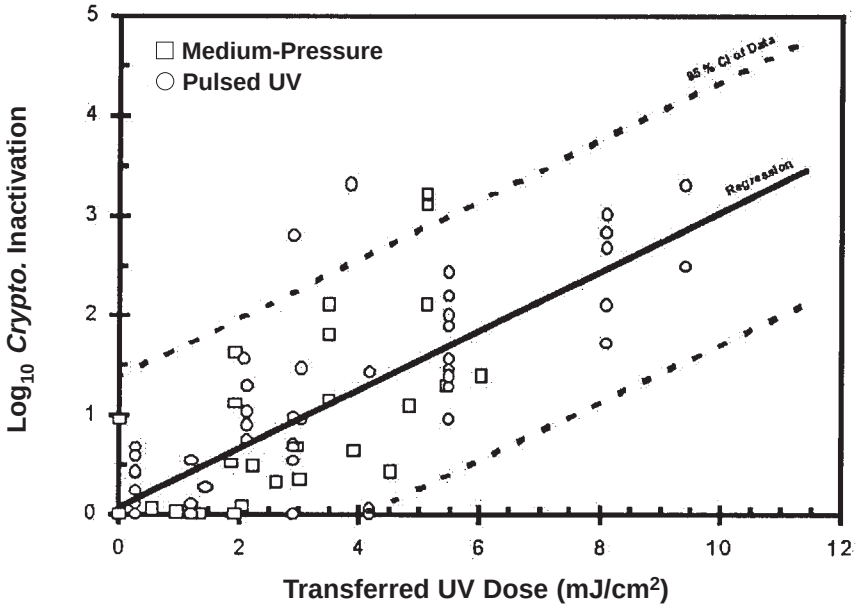
Combined with earlier research [1-4] that demonstrates biological plausibility and efficacy, a UV dose-response relationship established by Mofidi et al.[5] (see Figure 1) confirms the mode of action and the efficacy of protozoan inactivation. This dose-response relationship helps establish necessary doses to achieve a specified level of treatment. This research also provided evidence that inactivation is not influenced by UV irradiance (i.e., UV dose from continuous-wave UV provides disinfection similar to a UV dose applied with high-intensity, pulsed-UV light).

A number of lamp types (e.g., low-pressure, low-pressure high-output, medium-pressure, and pulsed UV) are available with different emission spectra and irradiance levels. Research is underway to equitably compare these lamps.[6,7]

Full-scale Challenges

Although there are several years of experience utilizing UV reactors in the wastewater industry, UV treatment of surface water brings challenges in terms of both scale and role as a disinfection process. First, there needs to be an understanding of how UV reactor design (and verification) can be made flexible enough to compliment both small (<5 mgd) and large (>100 mgd) systems. Large systems will be needed for drinking water and there currently exists no track record for their design or operation. Furthermore, in order to integrate UV disinfection with conventional treatment, UV reactors will need to be placed post-filtration as a secondary disinfectant. This placement selection is due to water quality needs where a low turbidity and UV light absorbing water is provided. A separate primary disinfectant/oxidant (such as free chlorine, chlorine dioxide, or ozone) is needed for preoxidation to assist

Correspondence should be addressed to:
Metropolitan Water District of Southern California, 700 Moreno Avenue, La Verne, CA 91750-3399
(909) 392-5463 Fax: (909) 392-5166 E-mail: amofidi@mwd.dst.ca.us



(Mofidi and Barbeau, et al., AWWA WQTC, 1999)

Figure 1. Bench-scale UV dose vs. *Cryptosporidium* response assayed by human cell culture infectivity.

particle removal[8] and to provide disinfection assurances to protect public health (e.g., in case of disinfection process failure, there is ample time for backup treatment strategies to be implemented prior to filtration).

Also, process monitoring for drinking water treatment differs dramatically from wastewater. For example, wastewater systems monitor UV performance using reductions in coliform density (a monthly geometric mean of coliform bacteria) whereas the presence of any coliforms causes alarm in drinking water treatment and can cause Surface Water Treatment Rule violations. Other biological surrogates suffer as a monitoring tool because of low densities (aerobic spores) and long analysis time (heterotrophic bacteria). This calls for the need to develop reliable monitoring tools for full-scale UV reactors.

Process Monitoring

UV reactors cannot be directly monitored by either a residual disinfectant or indirectly by changes in water quality characteristics. Thus, UV reactor manufacturers typically characterize UV reactor operation in two ways. First, reactor operation is validated by comparing reactor-seeded organism inactivation with bench-scale results (biodosimetry). Second, lamp operation is monitored for UV application (by detection of lamp current draw) and UV transfer (indirect measurement of light irradiance with different sensor technologies). This reactor monitoring does not provide a measure of transferred UV dose. It only provides a measure of irradiance at a single point and is blind to certain factors that influence transferred UV dose. Below are some brief examples of how pulsed and continuous-wave UV reactors are currently monitored for disinfection performance.

Pulsed UV Reactors

For pulsed systems, a combination of instruments are used to determine if the reactor is operating properly. Before a reactor is brought on-line, joulemeter measurements (measuring light dose contributed by both germicidal UV light and longer wavelengths) are made with and without a filter which blocks UV light. Calculating the difference between these readings determines the 190 to 300 nm UV dose at different distances from the lamp for each pulse. After joulemeter characterization and reactor biodosimetry, a light-sensitive photodiode

(made with semiconductors such as silicon carbide which absorb UV light[9]) mounted at the reactor wall (shown in Figure 2) qualitatively detects a combination of UV and visible light output in the pulsed-UV reactor. A drop in sensor readings would indicate either changes in water absorbance, fouling of the UV lamp's quartz sleeve, or a failure of the lamp. These sensors do not provide a quantitative measure of UV light and only are used to measure the light at a single point in the reactor for process alarm purposes. Characterization of pulsed-UV reactors is determined by combining the number of pulses applied per volume of water treated with biodosimetry and/or UV dose per pulse readings obtained from the joulemeter.

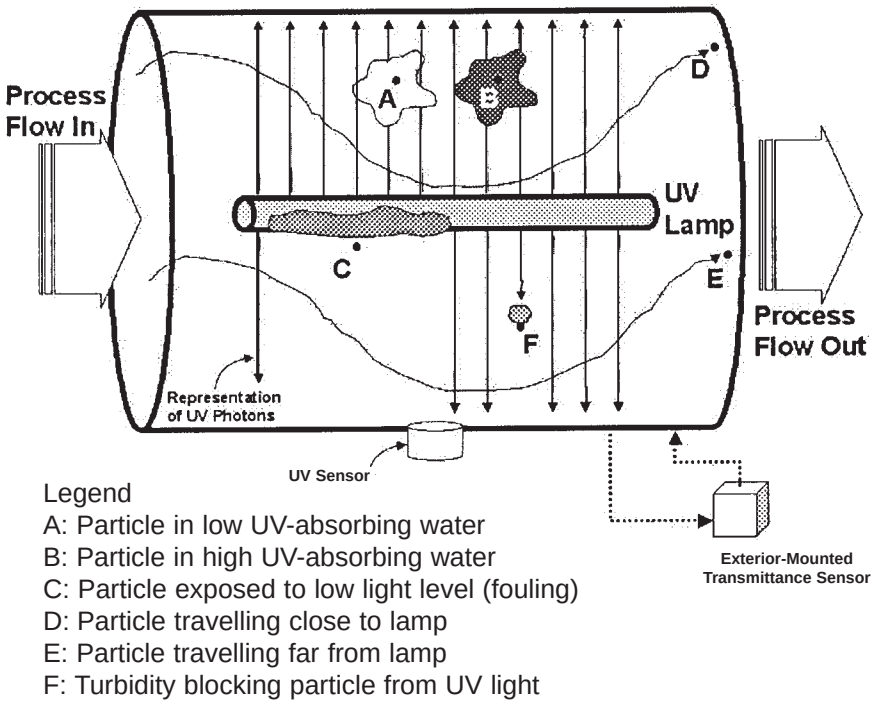


Figure 2. Water quality and process variables creating differences between applied and transferred UV dose.

Continuous-Wave UV Reactors

For continuous wave systems, there are numerous sensor configurations available. After reactor validation, sensors similar to that described above are either utilized alone to provide an ongoing measure of lamp irradiance or can be combined with a continuous measure of the process water's UV-light transmittance (process water can be pumped to a transmissivity probe, as illustrated in Figure 2). The combined readings are used for feedback control in reactors where the lamp intensity can be modulated. These readings are also used in conjunction with different lamp cleaning systems, whereby operators can be notified by a low-intensity alarm if the measured irradiance drops below a specified value. The transmissivity/sensor combination compensates for both water quality fluctuations and drops in UV irradiance (whether caused by the end-life of a lamp or by lamp fouling, which has overcome the cleaning system). However, there are still reported problems in these sensor designs because light measurement degrades over time due to both fouling and degradation of light detecting material.

The abilities of UV sensors used for either pulsed or continuous-wave lamp monitoring can be summarized by Figure 2. Sensors are able to detect some changes that will affect UV dose while other factors affecting UV dose remain undetected. As shown in Figure 2, sensors can detect the degradation of light intensity transferred through water due to variable water qualities (represented by the significant changes in the process water UV absorbance at

locations A and B) and lamp quartz sleeve fouling (location C). However, hydraulic changes (possibly induced by changes in plant flow) might alter particle trajectory and residence times through a reactor (illustrated by the travel routes D and E) and particles may also block UV light from reaching target organisms (location F). If particles do not pass directly between the lamp and the sensor, dissolved particle effects will remain undetected (sensor light acceptance levels are only ±15 percent, so sensors must face directly at a lamp to detect light). These last phenomenon, which significantly affect delivered UV dose, are not detectable by UV sensors. Because of this degradation, sensors are frequently calibrated using radiometers.

Summary and Conclusions

In summary, there are many benefits and concerns that arise with the desire to use UV for disinfection of drinking water. As research investigating protozoan disinfection continues, and scale-up issues are addressed, the most needed improvements remain in the area of UV dose monitoring techniques. It is possible that improvements could arise from a combination of computational fluid dynamics and UV sensors, providing a monitoring tool for conservatively assessing transferred UV dose.

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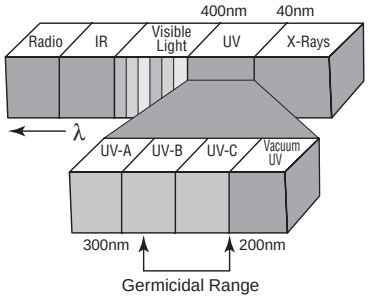
The Use of Ultraviolet Light for Inactivation of *Cryptosporidium* in Water

Thomas M. Hargy, Clancy Environmental Consultants, Inc.

•*Cryptosporidium* oocysts

- **Small size (4-6 μm)**
- **Ubiquitous occurrence**
- **Robust nature (resistant to chemical disinfectants)**

Electromagnetic Spectrum



UV Dose

$mJ/cm^2 = mW\ sec/cm^2$
$= 1000\ \mu W\ sec/cm^2$

What is typical UV dose?

- **5 - 50 mJ/cm^2 effective (3-4+ log) against most bacteria, many viruses**
- **ANSI/NSF 55: 38 mJ/cm^2 for POE, 16 mJ/cm^2 for POU**
- **PA, NJ: 16 mJ/cm^2 for groundwater**
- **Norway: 16 mJ/cm^2 for drinking water**
- **Austria: 30 mJ/cm^2 for drinking water**

Prevailing assumptions about UV and *Cryptosporidium*

1. **UV not effective at inactivating *Cryptosporidium* at practical exposures**
2. ***in vitro* surrogate methods (excystation, vital dye stains) could be used to determine viability of *Cryptosporidium* oocysts following UV treatment**

Why we have lacked confidence in UV as a *Crypto* disinfectant

- **Inference from *Cryptosporidium's* resistance to chemical disinfectants**
- **Early UV-Crypto work inconclusive or misleading**

Correspondence should be addressed to:
Clancy Environmental Consultants, Inc., P.O. Box 314, St. Albans, VT 05478
(802) 527-2460

Inactivation of *Cryptosporidium* by Free Chlorine

- 80 mg/L chlorine, 90 min: 1.9 log
  Korich et al, 1990
- 1.6-2.1 mg/L, 120 min: no inactivation
  Liyange et al, 1997

Lorenzo-Lorenzo et al.
J. Parasitology 1993

- Assessed inactivation of *Crypto* by low pressure UV, using *in vivo* assay.
- Lacked clarity in experimental detail.
- Indicated >3 log inactivation, BUT: apparently 150 minute exposure required
- In fact, only 300 mJ/cm^2 (pers. comm. via A. Campbell).

Campbell et al.
Water Research, 1995

- Used DAPI/PI in CID under static conditions to assess oocyst inactivation.
- LP-UV dose was 8,700 mJ/cm^2.
- Achieved at least 3 log inactivation
- BUT: Reported only 2 to 3 log inactivation
- Discussed the need to follow this up with mouse infectivity.

Clancy et al.
JAWWA, 1998

- Conventional LP-UV dose was 180 mJ/cm^2.
- Reported no inactivation
- BUT: Used *in vitro* methods to assess oocyst inactivation

Finch et al.
AWWARF, 1997

- LP-UV dose was 41,000 mJ/cm^2.
- No inactivation indicated
- Used *in vivo* methods to assess oocyst inactivation
- BUT: UV applied through (UV opaque) glass bottle: IN Vitro!

AWWARF UV Project History

AWWARF RFP 282 -
"Innovative Electrotechnologies for the Inactivation of *Cryptosporidium*"

AWWARF RFP 395 -
"Comparative Study of Methods for Assessment of Viability and Infectivity of *Cryptosporidium* in the U.S. and U.K."

Cryptosporidium Testing under AWWARF 282

- first test: evaluate using excystation and vital dyes.
- Only if promising: second test using animal infectivity assay

Clancy, Hargy, Marshall, Dyksen
J. AWWA, 1998

Lamp Type	mJ/cm^2	Log Inactivation *In vitro*	Log Inactivation *In vivo*
Pulsed UV	1900	2.4	>3
Advanced UV	8700	>2	>4
Low Pressure	180	No inactivation indicated	????

Conventional UV Results

(Low Pressure, 180 mJ/cm^2)

- **No inactivation of oocysts observed using *in vitro* surrogates.**
- **Animal studies not warranted.**

AWWARF 395 Comparison

***In vitro* Surrogate Assays:**

Excystation, DAPI/PI, SYTO®9, SYTO®59

***In vivo* Assay:**

Mouse Infectivity using the Outbred CD-1 neonatal mouse model

In vitro Viability Surrogates

Maximized *in* vitro excystation: Release of sporozoites following suitable biochemical triggers.

DAPI/PI: Inclusion/exclusion of two fluorogenic vital dyes.

SYTO-9: Inclusion/exclusion of a single fluorogenic vital dye.

SYTO-59: Inclusion/exclusion of a single fluorogenic vital dye.

Mouse Infectivity Assays

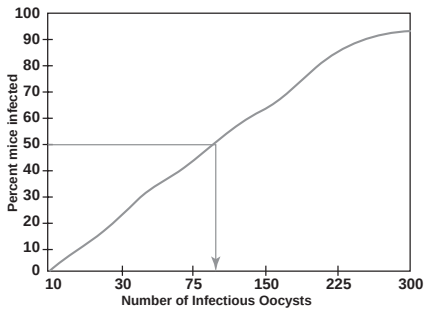
Infectivity determined by calculating percentage of CD-1 mice infected at each oocyst inoculum.

Dose response curves generated with oocyst inocula on X-axis and percentage infectivity on Y-axis.

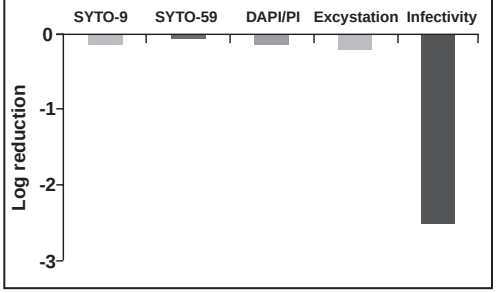
The ID_{50} determined as oocyst doses necessary for infection in 50% of the recipient mice population.

For each experiment, percentage infectivity determined and extrapolated on dose response curve to calculate number of infectious oocysts and log inactivation.

Infectious Dose Response Curve



Oocyst inactivation with 40 mJ/cm^2 pulsed UV, by in vitro assays and mouse infectivity



Calgon Carbon Corporation

- **Initial project examined inactivation of *C. parvum* oocysts in DI water using medium pressure UV.**
- **The goal: establish a dose response curve for oocyst inactivation using collimated beam studies.**
- **Used both *in vitro* surrogates and animal infectivity**

Collimated Beam Bench Scale Test Results

- **UV dose applied: 41 mJ/cm^2**
- **Animal infectivity: >4 log inactivation**
- **The *in vitro* surrogates: <0.5 log**

Demonstration Scale Project Calgon Carbon Sentinel®

- Tested under the NSF-ETV program
- Conducted at the Mannheim WTP in Kitchener, Ontario.
- Test unit: 111 L (29.4 gal) UV vertical reactor
- 6 x 1 kW medium pressure UV lamps mounted horizontally
- Excystation, DAPI/PI and animal infectivity were used for viability/infectivity assays.

Aquionics/Hanovia
Medium Pressure UV
Recreational (water park) water

UV Dose (mJ/cm^2)	Log Reduction of *Cryptosporidium*
10	>4.4
38	>4.5
95	>4.5

UV Dose required for 4 log inactivation

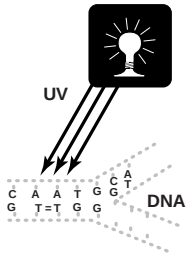
bacteria*: 3-15 mJ/cm^2 (low pressure UV)
viruses*: 30-80 mJ/cm^2 (low pressure UV)

Cryptosporidium:
Low pressure UV <10 mJ/cm^2
Medium Pressure UV: <10 mJ/cm^2

*Wilson, et al. 1993

Ultraviolet Radiation: Mechanism of Action

- Physical process
- Energy absorbed by DNA
- Dimer formation
- Inhibits replication



UV/*Crypto* Research Needs

- Effects of shielding of oocysts by matrices
- Better definition of *Crypto*/UV dose response
- Applicability of cell culture analysis (AWWARF has initiated research)

Demonstration scale UV
Log Inactivation of *Cryptosporidium*

UV Dose (mJ/cm^2)	Log Inactivation
20	3.9
69	>4
167	>4

Calgon Carbon: Follow-up Bench studies using Medium pressure UV

UV Dose (mJ/cm^2)	Log Reduction
3	1.9- 3.3
6	>4
9	3.7

Calgon Carbon: *Crypto* inactivation in Recycled Backwash Supernatant using Medium pressure UV

UV Dose (mJ/cm^2)	Log Reduction
3	>4.5
9	>4.5
27	>4.5
81	>4.5

WaterHealth International:
4 gpm system using low pressure UV

UV Dose (mJ/cm^2)	Log Reduction
100-130	>5.4

Comparison of UV Technologies for Pathogens Inactivation

Julia Norman, Orange County Water District

This abstract is unavailable. Please contact the speaker at the address below for further information.

Correspondence should be addressed to:
Orange County Water District, 10500 Ellis Avenue, Fountain Valley, CA 92728-8300
(714) 378-3319 Fax: (714) 378-3381 E-mail: jnorman@ocwd.com

The Impact of Particle Size and Upstream Treatment Processes on UV Disinfection Efficiency

Frank Loge, Ph.D., Washington State University

Coliform bacteria are the most widely used indicator of disinfection performance in the United States and their surviving numbers form the basis for most discharge permits. The dose of UV is calculated as the intensity of UV light in the bulk liquid medium multiplied by the exposure time. A typical plot of the concentration of coliform as a function of applied UV dose is illustrated in Figure 1. At low doses, the inactivation of coliform bacteria follows first-order kinetics. Deviations from first-order kinetics are commonly observed at moderate to high doses of the applied disinfectant, referred to as tailing, that are characterized by a reduced rate of inactivation with increasing values of the applied disinfectant.

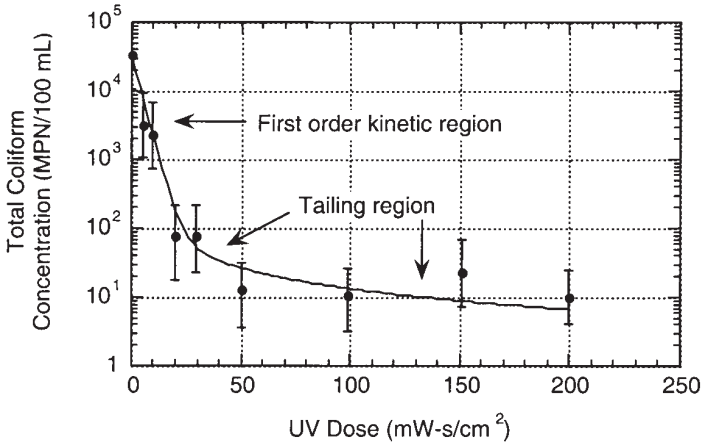


Figure 1. Typical response of coliform bacteria to UV light in a wastewater secondary effluent.

The tailing phenomenon apparent in both UV (Oliver and Cosgrove, 1975; Petrasek et al., 1980; Ho and Bohm, 1981; Qualls et al., 1983; Qualls et al., 1985a; Scheible, 1987; Cairns, 1993; Parker and Darby, 1995; Emerick et al., 1999a) and chlorination/dechlorination (Hejkal et al., 1979; LeChevallier et al., 1981; Ridgway and Olson, 1982; LeChevallier et al., 1984; Berman et al., 1988; LeChevallier et al., 1988) disinfection systems has been attributed to the association of targeted organisms (commonly coliform bacteria) with particles in the bulk liquid medium. The intensity of UV light or the concentration of a chemical disinfectant declines with increasing distance into particulate material. Consequently, the dose of disinfectant penetrating into particles is a function of particle size and is lower than the dose applied to the bulk liquid medium.

A technique was recently developed for measuring the UV absorbance and internal scattering characteristics of wastewater solids (Loge et al., 1999a). The absorbance of wastewater solids collected from six treatment plants are summarized in Table 1. Wastewater solids developed as part of the trickling filter and activated sludge processes were observed to be strictly absorbing, with light attenuation following the Beer-Lambert Law. The absorbance of the solids ranged from 3,300 to 569,000 cm-1. To put the particle absorbance values in perspective, the UV light in the bulk liquid medium would be attenuated by two orders of magnitude within the first 0.04 to 6 μm of wastewater solid material. Although UV light is highly absorbed by wastewater solids, light penetrates into wastewater particles (solid plus liquid) as evident in the continued reduction of surviving organisms in the tailing region of

Correspondence should be addressed to:
Washington State University, Dept. of Civil and Environmental Engineering
P.O. Box 642910, Pullman, WA 99164-2910
(509) 335-3227 Fax: (509) 335-7632 E-mail: floge@wsu.edu

any log-survival versus dose curve (see Figure 1). However, there are likely regions within particles (dependent on porosity) that receive none of the UV light applied in the bulk liquid medium.

Table 1.
Absorbance of Wastewater Solids Collected from Selected Wastewater Treatment Processes

Name of WWTP	Process[a]	Absorbance[b] of wastewater solid material per cm	Absorbance[b] (transmittance) of bulk liquid medium per cm
Sacramento Regional, CA	AS with pure oxygen	74,300	0.152 (70%)
San Jose, CA	Air AS	15,200	0.118 (76%)
San Jose, CA	AS with bio N	10,700	0.145 (72 %)
Frankenmuth, MI	AS with bio N/bio P	54,200	0.118 (76 %)
City of Port Huron, MI	AS with chem P	569,000	0.159 (69%)
Mt View Sanitary District, CA	Trickling filter	3,300	0.164 (69 %)

[a] Definition of abbreviations: AS = activated sludge; bio N = biological nitrogen removal; bio P = biological phosphorous removal; Chem P = chemical phosphorous removal.
[b] Measured at a wavelength of 254 nm.

Because most disinfection systems operate in the tailing region, the performance of a disinfection system is highly dependent on the number of particles with associated coliform bacteria. Various empirical UV disinfection models have been developed to describe the response of coliform bacteria associated with wastewater particles (Severin, 1984a,b; Qualls and Johnson, 1985b; Scheible, 1987; USEPA, 1986; WPCF, 1986; Cairns et al., 1993; Loge et al., 1996). An empirical modeling approach was necessary due to the inability to directly enumerate the particles with associated coliform. A technique was recently developed for enumerating the number of particles with associated coliform using a 16S rRNA oligonucleotide probe specific to the family Enterobacteriaceae (Loge et al., 1999b), and the technique formed the basis for developing a theoretical disinfection model (Emerick et al., 1999b). The model, developed to describe both the first order and tailing regions of a dose-response curve, has the following functional form:

$$N(D) = N_f e^{-kD} + \frac{N_P}{kD}\left(1 - e^{-kD}\right)$$

Where $N(D)$ = number of surviving coliform bacteria after applied dose D.

N_f = total number of non-particle associated coliform bacteria enumerated prior to the application of the disinfectant.

N_P = total number of particles greater than a critical particle size, enumerated prior to the application of the disinfectant, that contain one or more coliform.

k = inactivation rate coefficient of coliform.

D = dose of the disinfectant applied in the bulk liquid medium.

To date, the model has been extensively applied to UV disinfection systems (Emerick et al., 1999a,b) but has not been applied to chemical disinfection systems (e.g., chlorine or ozone). The fit of the model to experimental data collected from a UV disinfection system is illustrated in Figure 2. At relatively low values of UV dose (e.g., less than 30 mW(s/cm^2), the first term in Equation 1 dominates the overall expression and the response of coliform

bacteria follows first order kinetics (labeled 1 in Figure 2). The inactivation of organisms in this region is attributed to free-swimming or non-particle associated organisms. At moderate to high values of UV dose (e.g., greater than 30 mW(s/cm^2), the second term in Equation 1 dominates the overall expression (labeled 2 in Figure 2). The inactivation of organisms in this region is attributed to organisms associated with particulate material.

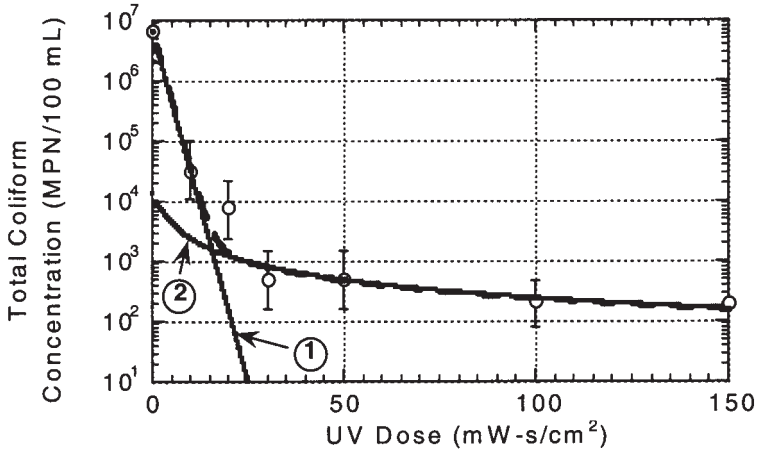


Figure 2. Graphical representation of the UV disinfection model developed to describe both the first order kinetic and tailing regions.

As we begin to short circuit the hydrologic cycle and reuse water on a more frequent basis, we must insure that the water quality standards developed in the U.S. for assessing the biological quality of post-disinfected water provide adequate protection to public health. The model presented in Equation 1 provides two principal insights into developing such standards. First, a critical particle size appears to govern the inactivation of targeted organisms in the tailing region. The critical particle size is defined as the size such that all particles greater than this size are equally likely in shielding an associated organism from an applied disinfectant. Particles smaller than the critical particle size are incapable of shielding associated organisms from the applied disinfectant and, consequently, are not of concern from a disinfection standpoint. Although the model does not provide an explicit estimate of the dose reaching targeted organisms associated with particulate material (e.g., the dose, D, in Equation 1 is the dose applied in the bulk liquid medium), the model can be used to estimate the critical particle size impacting the performance of a disinfectant. The variable N_p in Equation 1 is the sum of all particles greater than the critical particle size that contain one or more associated organisms of interest. The critical particle size impacting the inactivation of coliform bacteria with UV light in wastewater secondary effluents is 10 µm (Emerick et al., 1999a). To date, no study has been conducted to evaluate the critical particle size impacting the performance of other disinfectants.

The second principal insight provided by Equation 1 into developing standards for assessing the biological quality of post-disinfected effluents is that the concentration of coliform in the tailing region reflects the concentration of particles with associated coliform, not the actual number of organisms (e.g., Np is the sum of all particles greater than the critical particle size that contain one or more associated organisms). Consequently, for coliform to be a suitable indicator of the inactivation of other targeted organisms (e.g., bacterial and viral pathogens), the other targeted organisms of interest would have to be associated at roughly the same frequency and in the same location within particles as coliform bacteria. If these two conditions are not met, coliform bacteria are not good indicators of the inactivation of other targeted organisms associated with particles.

One method of assessing the biological quality of post-disinfected waters would be to develop an understanding of the relationship between the association of pathogens and indicator organisms with particulate material. Given that the rate of association of an organism with

particulate material is dependent on the concentration of organisms in suspension (e.g., first order with respect to the concentration of organisms and particles in suspension), any relationship between the association of pathogens and an indicator organism with particulate material would be temporal and site specific. Therefore, any method of assessing health risks based on the survival of organisms in post-disinfected waters must focus on the survival of specific pathogens. This approach would not be economically feasible to perform on a routine basis given the potentially broad array of emerging infectious diseases.

An alternative method of assessing the biological quality of post-disinfected waters would be to shift from monitoring the survival of selected pathogens and indicator organisms to a particle-based standard. With this approach, the dose of the applied disinfectant would be based on the frequency and distribution of particles in the effluent. All particles greater than a critical particle size would be treated as having equal potential to harbor one or more targeted organisms of interest. The dose would be modified to insure a specified level of penetration of the applied disinfectant (e.g., UV, chlorine, or ozone) throughout each of the particles greater than a critical particle size. Such an approach would eliminate the uncertainty associated with evaluating the biological quality of post-disinfected effluents. For example, the effluent standards of coliform bacteria for drinking water and reclaimed wastewater are often less than 2.2 MPN/100 mL (the detection limit of the multiple tube fermentation test). This standard provides no adequate indication of the health risks associated with the post-disinfected effluent. However, a particle-based standard developed to ensure complete penetration of the disinfectant throughout all particles greater than the critical particle size would result in a coliform concentration less than 2.2 MPN/100 mL, but would also provide adequate assurance the effluent would have no adverse public health impacts on the intended use. Additionally, unlike monitoring the occurrence of specific pathogens, a particle-based standard is economically feasible, even for small municipalities in the U.S. and developing countries that have limited funds for water quality monitoring. Overall, with this approach, a detailed understanding would have to be developed of (1) the critical particle size impacting the performance of various disinfectants and (2) the penetration of disinfectants into particles developed as part of engineered systems.

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Impact of Water Quality Parameters, Turbidity, and Transmittance on UV Disinfection Performance and By-product Formation

Joan Oppenheimer, Montgomery Watson

UV radiation in the wavelength region of 200 to 300 nanometers has clearly demonstrated germicidal properties and is broadly established in the food, beverage, and pharmaceutical manufacturing industries. In the United States, serious interest in applying UV disinfection technology to wastewater treatment facilities developed in the 1970s as chlorine disinfection failed to consistently meet increasing stringent disinfectant residual discharge standards and health and safety guidelines for the storage of hazardous chemicals. There was little motivation to apply this technology to potable water supplies because of the need to maintain a disinfectant residual throughout the distribution system. This situation changed with the discovery that chlorine and chloramines are relatively ineffective disinfectants for *Cryptosporidium*. Subsequent research to establish alternative disinfectants led to the discovery that UV radiation appears to inactivate *Cryptosporidium* at doses lower than those required for the inactivation of bacteria and viruses.

Water Quality Impacts on UV Inactivation Performance

The ability of UV radiation to inactivate microorganisms is dependent upon how well the radiation can penetrate through the organism's outer cellular material and induce photochemical damage to its nucleic acids. This is the innate inactivation dose requirement for each type of organism and the relative rates of inactivation as a function of radiation wavelength is referred to as the action spectrum for the organism. When the action spectrum and the UV lamp emission spectrum is well characterized, the dose needed to achieve a specified level of inactivation can be calculated. This dose requirement is then tempered by the extent to which the organisms are clumped together or shielded by partciulate material and by how well the radiation can travel through the water medium in which the organisms are suspended.

As shown in Figure 1, turbidity and suspended particulate matter can shield organisms from UV radiation in a number of ways: by adsorbing the UV radiation before it can reach the nucleic acid contained within the microorganism; by scattering the UV radiation away from the microorganism; or by shading the microorganism from the UV light. Water quality parameters might also influence dose to the extent that the water contributes to particle consolidation or particle solvation. Water quality parameters will also influence how well the radiation can travel from its emission point at the lamp surface to the organism. Pure water has an approximate transparency minimum of 180 nm and allows wavelengths in the 200 to 300 nm germicidal region to pass through unabsorbed. Certain water quality constituents, however, will absorb germicidal UV radiation and lower the effective dose that can reach the suspended microorganisms. Compounds capable of absorbing UV and visible radiation above 180 nm contain functional groups called chromophores that contain valence electrons with relatively low excitation energies. An abbreviated list of the types of organic and inorganic compounds that absorb light in the 200 to 300 nm region is provided in Table 1. Review of this list demonstrates that while many of these compounds are commonly present in raw water supplies, only compounds with large extinction coefficients will be capable of absorbing large amounts of radiation at the low concentrations at which these compounds are typically present in water. In drinking water sources, humic acids probably represent the most ubiquitous group of naturally occurring compounds with a high capacity to absorb UV light.

Correspondence should be addressed to:
Montgomery Watson, 301 N. Lake Avenue, Suite 600, Pasadena, CA 91101
(626) 568-6068 Fax: (626) 568-6052 E-mail: joan.oppenheimer@mw.com

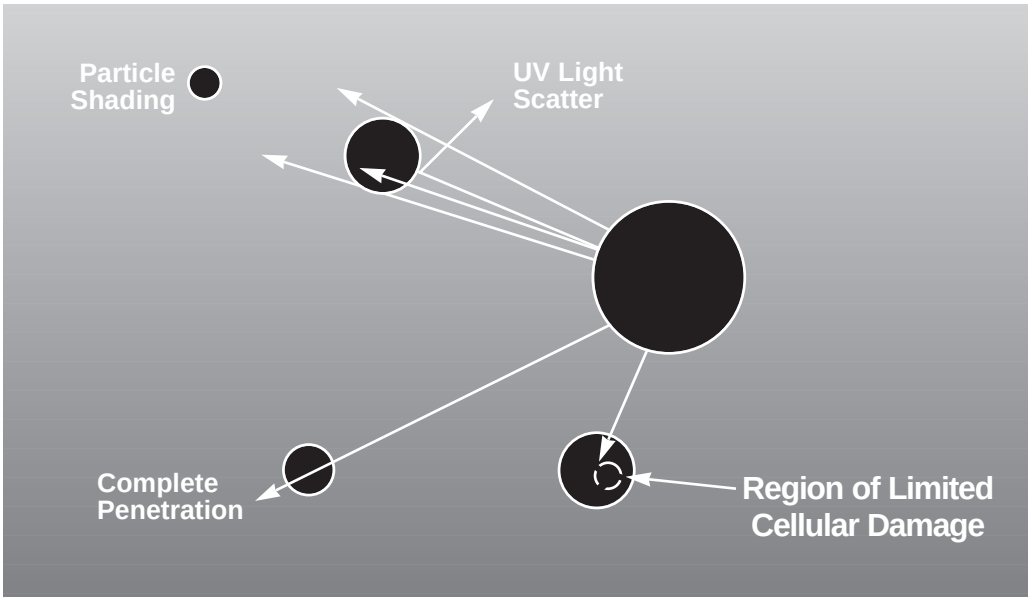

Figure 1. Impact of particles on UV light transmittance.

Source: Darby et al., 1995.

Table One.
Absorption Characteristics of Common Chromophores in the 200 to 300 nm Range

Chromophore	λ_{max} (nm)	ε_{max}
Alkyne	225	160
Carbonyl	280	16
Carboxyl	204	41
Amido	214	60
Nitro	280	22
Nitroso	300	100
Nitrate	270	12
Unsaturated conjugated ketone	219	3600
Benzene	204	7900
Toluene	207	7000
Chlorobenzene	210	7600
Phenol	211	6200
Phenolate ion	235	9400
Aniline	230	8600
Thiophenol	236	10,000
Napthalene	286	9300
Styrene	244	12,000

Source: Skoog and West, 1971.

In addition to adsorbing radiation, inorganic water quality constituents can interfere with radiation propagation by forming a coating on the surface of the quartz sleeve surrounding each UV lamp. Compounds that have been demonstrated to cause significant fouling include the cations of calcium, iron, and aluminum, and the anions of carbonate, sulfate, hydroxide, chloride, and phosphate. The presence of combinations of these compounds at concentrations approaching their solubility limits leads to precipitation fouling of the quartz due to the heat released by the UV lamps. While lamp fouling has been extensively studied for low-pressure lamps (Lin et al., 1999), additional studies are needed to determine the impact of the hotter medium-pressure lamps on fouling rates. Water temperature, while generally considered to have no impact on UV inactivation kinetics, appears to significantly impact fouling deposition reactions.

Disinfection By-products, Whole Effluent Toxicity, and Bacterial Regrowth

A number of studies have investigated the disinfection by-product content or whole effluent toxicity of water and wastewater disinfected with UV light at bench, pilot, and full-scale. A brief summary of some of these studies, provided in Table 2, reveals no major changes in the chromatographic scans of the waters before and after treatment with UV light even at doses significantly higher than those required for disinfection. These results, however, should be viewed in the context of the limitations inherent in these studies. First, the majority of these studies were performed in treated wastewater rather than potable source waters and, secondly, it is not possible to fully identify potentially harmful by-products with the type of chromatographic screening techniques employed. Therefore, it is important to augment these results with the investigation of whole effluent toxicity testing of UV irradiated waters. Such studies (Cairns et al., 1993; Kool et al., 1985; and Oppenheimer et al., 1997), while limited, have shown no evidence of toxicity for any of the UV irradiated waters.

Table Two. Summary of DBP Studies Performed

Site	Lamp	UV Dose Range ($mw \cdot sec/cm^2$)	Analysis	Results
Oak Ridge	LP	13 – 61	Organic screen (LC) VOC (HEC/GC)	No major change
Elsinore	LP	188, 300, 2800	Organic screen (HPLC, GC/MS) VOC (EPA 5030/8260) Semi and non VOC (LC/MS)	No major change, Unidentified peak at 2800 dose
Goldbar	MP	70	VOC (GC/MS) Semi VOC (extraction GC/MS)	No major change Increase in acetone
Santa Rosa	MP	100, 200	VOC (EPA 8260) Semi VOC (EPA 8270) Carboxylic acid (EPA 300M) Chlorinated byroducts (EPA 551) HAA (EPA 552) Aldehydes (GC/ECD) Inorganic anions (EPA 300B)	Aldehydes increased with UV dose, Otherwise no major change.
Fairfield	LP, MP	150 – 898	Organic screen (HPLC, GC/MS)	No major change
Santa Rose	LP	150, 300	Organic screen (HPLC, GC/MS)	No major change
Vallejo	LP, MP	150 – 1138	Organic screen (HPLC, GC/MS)	No major change
Sacramento	LP, MP	144 – 903	Organic screen (HPLC, GC/MS)	No major change
Greenville	MP	60 – 80	Organic screen (HPLC, GC/MS)	No major change

Source: Linden, 1998

One study (Li et al, 1996) specifically investigating the effect of UV light on the characteristics and trihalomethane formation potential of commercial humic acid determined that UV irradiation does bring about photo-oxidation of humic materials in dilute solution with decarboxylation and de-coloring reaction as the probable major reactions occurring. While UV irradiation decreased the TOC concentration of the humic acid with irradiation time, the humic acids could not be completely decomposed and UV irradiation was shown to enhance the yield of THMs when it preceded chlorination. However, field studies (Malley et al., 1995) utilizing two surface waters known to produce significant levels of DBPs did not suggest that UV radiation significantly affected the rate of DBP formation under real-world conditions. Another area of interest is the potential for UV disinfection to promote bacterial regrowth due to the photolytic degradation of biogenic high molecular weight substances. A study by Hengesbach et al., 1993, demonstrated that UV irradiation does not enhance bacterial

regrowth of water as a result of formation of low-molecular weight material from the photo-oxidation of macromolecules. Additional studies are currently being performed to further investigate the impact of UV disinfection on bacterial regrowth and the formation of undesirable by-products.

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Review of National UV Research Programs

Los Angeles Department of Water and Power UV Research

Gary F. Stolarik, Los Angeles Department of Water and Power

Summary

The Los Angeles Department of Water and Power (LADWP) is examining UV light disinfection as a potential new tool to improve disinfection and meet upcoming regulations impacting its complex distribution system. Initially, LADWP pursued UV disinfection as part of a filtration avoidance alternative at large uncovered reservoirs subject to the Surface Water Treatment Rule (SWTR). Current plans to remove these reservoirs from service have not diminished other potential applications as LADWP develops strategies to comply with the Stage 2 Disinfectants and Disinfection Byproducts Rule (DBP Rule). The present UV study plans involve animal infectivity testing at bench scale, O&M and reactor evaluation at pilot scale, use of a raw water matrix with elevated turbidity, TOC and algae, and comparison testing of target organisms (*Cryptosporidium, Giardia,* and MS2 Coliphage) with another utility's source water. The UV study is a cooperative effort involving Montgomery Watson, Calgon Carbon Corporation, Oregon Health Sciences University, the National Sanitation Foundation, several water utilities practicing filtration avoidance under the SWTR, and LADWP. The California Department of Health Services, the United States Environmental Protection Agency, and a panel of experts in disinfection kinetics and reactor hydraulics will provide technical input and review.

Possible Applications for UV in Los Angeles

The first application of UV treatment suggested for Los Angeles, California was disinfecting water leaving LADWP's uncovered distribution system reservoirs. Los Angeles' primary water source originates 340 miles from the city and crosses major earthquake faults. To maintain a reliable water supply, significant storage has been designed into the distribution system. There are now 10 uncovered reservoirs in the LADWP distribution system. Four reservoirs that are unpaved and receive direct surface runoff have been classified as raw waters subject to the SWTR.

A filtration avoidance alternative including UV disinfection was proposed by community groups surrounding the SWTR reservoirs as a way to eliminate filtration facilities and reduce chemical use. It was suggested that the previously filtered water in the reservoirs would meet SWTR turbidity and coliform requirements, and that *Giardia* and virus inactivation targets could be achieved using UV on the reservoir outflow. Since UV is not an approved technology for *Giardia* inactivation under the SWTR and previous drinking water UV research involved filtered water, LADWP planned a bench and pilot study using UV on unfiltered water. Recently, the filtration avoidance alternative has been dropped in favor of a plan to permanently remove the four SWTR reservoirs from normal service.

Although the first proposed application of UV technology is no longer likely, some of the remaining six open reservoirs may benefit from a compact disinfection process like UV. LADWP is considering converting from chlorine to chloramines and other strategies to comply with the Stage 2 DBP Rule. UV treatment may be an efficient way to boost disinfection of water leaving open reservoirs if free chlorine treatment is discontinued.

Applications for UV technology may also be found at the 600-MGD Los Angeles Aqueduct Filtration Plant (LAAFP), located at the inlet to the distribution system. SWTR disinfection requirements are currently met with a combination of pre-ozonation and post-chlorination. Ozone contactor size and high bromide levels in the secondary supply will limit the use of

Correspondence should be addressed to:

Los Angeles Department of Water and Power, 1111 N. Hope Street, A-18, Los Angeles, CA 90012
(213) 367-3193 Fax: (213) 367-3297 E-mail: gary.stolarik@water.ladwp.com

higher ozone doses to meet any future *Cryptosporidium* inactivation requirements. UV treatment might also be used to provide an additional treatment barrier for the filter backwash water decanted from settling ponds and recycled to the plant inlet.

Los Angeles' Current UV Study

The current UV study is designed to determine if UV treatment is effective for *Cryptosporidium* and *Giardia* inactivation in unfiltered surface waters. The project was defined in early 1999 to quickly develop the data necessary to support an application for filtration avoidance at the uncovered SWTR reservoirs. LADWP was joined in the effort by the Unfiltered Regulatory Group, which includes the Portland Water Bureau, Seattle Public Utilities, Tacoma Public Utilities, San Francisco Public Utilities Commission, Massachusetts Water Resources Authority, New York City, Greater Vancouver Regional District (Vancouver, British Columbia, Canada), and Capital Regional District (Victoria, British Columbia, Canada). Montgomery Watson is coordinating the work under an agreement with LADWP. Calgon Carbon Corporation, Oregon Health Sciences University, and Mark Heath LLC are also participating. Recently the National Sanitation Foundation joined the project team to supplement the UV data they are collecting under their Environmental Technology Verification Program for Package Drinking Water Treatment Systems.

The project includes six phases: experimental plan development, three bench-scale studies, a 7-month pilot study, and final report preparation. The first series of bench tests will compare the effectiveness of low-pressure and medium-pressure UV technologies using one of the Unfiltered Regulatory Group utilities' raw water or Milli-Q water. *Cryptosporidium, Giardia,* and MS2 Coliphage inactivation will be measured in triplicate by animal infectivity testing at five UV doses and a control set with no UV exposure. Results of the first bench tests will be used to select the lamp to be used in the other two bench-scale studies. The second bench study will generate dose-response curves for the same three organisms on LADWP raw water. Again, five UV doses and a control will be used. MS2 Coliphage tests will be repeated using LADWP water with elevated turbidity, algae, and TOC concentrations. The final series of bench tests will determine the UV inactivation of the same three organisms using a natural water from one of the Unfiltered Regulatory Group utilities. Tests will be conducted at two different turbidities using five UV doses and a control for each test. The pilot study will evaluate O&M needs over 7 months and allow comparison of dose-response curves between the 200-gpm pilot facility and the collimated beam bench tests. An independent mathematical model will also be developed for the pilot unit based on reactor hydraulic characterization.

The pilot studies will be conducted at LAAFP using the Calgon Carbon Corporation Sentinel UV Disinfection System (see Figure 1). The Los Angeles Aqueduct will be the primary water source, but blends of this source and State Project Water will also be treated during the pilot study. The pilot unit will operate nearly continuously for 7 months to determine O&M needs. During normal operation, 200 gpm will be pumped from the LAAFP inlet, through the UV pilot unit, and back to LAAFP. Figure 2 is a schematic of the pilot UV facilities. The initial sampling schedule for UV influent and UV effluent is shown in Table 1. It is anticipated that sampling frequency can be reduced and either the influent or effluent location can be dropped for many of these parameters based on initial data. Tracer tests will be conducted early in the pilot study and seven monthly MS2 seeding tests will be conducted to evaluate performance of the unit over time. Temporary tanks will be used to prepare and collect the water spiked with MS2. *Giardia* and *Cryptosporidium* will only be studied in bench tests. The pilot unit is currently being installed at LAAFP. Pilot studies are scheduled to begin in March 2000 and run through October 2000.

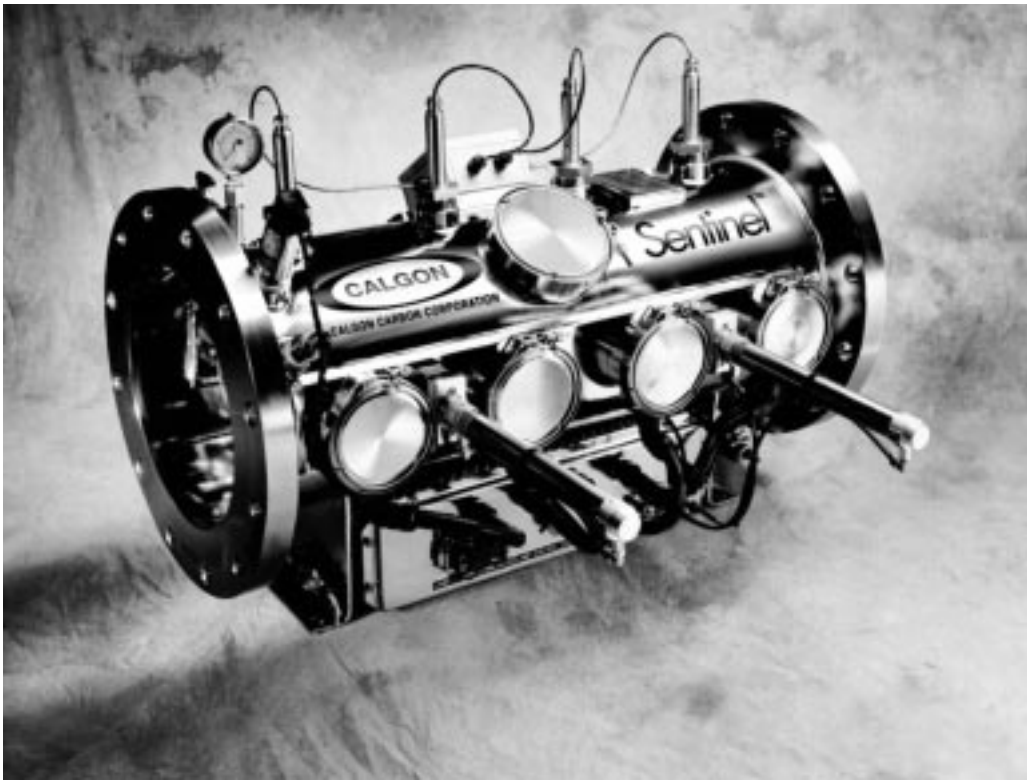

Figure 1. LADWP's Pilot Unit — a 4 x 1 kW UV Disinfection System — is to be evaluated for a 7-month period. Photo courtesy Calgon Carbon Corporation.

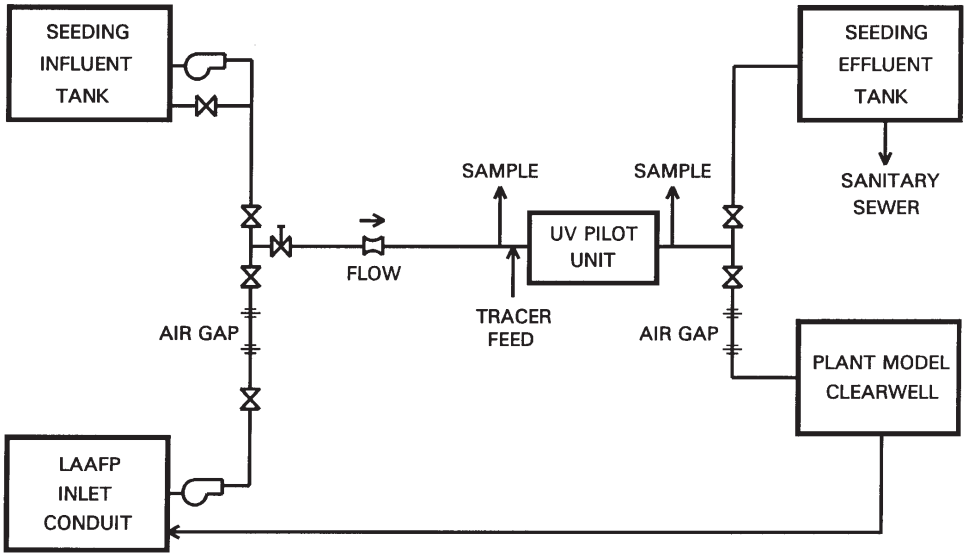

Figure 2. UV pilot study schematic.

Table 1. UV Pilot Study Sampling Schedule

Parameter	Samples per week
Temperature	5
pH	5
Total Alkalinity	2
Hardness	2
Total Organic Carbon	2
UV254 Absorbance	5
Turbidity	5
Algae Enumeration	1
True Color	2
Trihalomethanes	2
Haloacetic Acids	2
Aldehydes	2
Nitrate	2
Iron	2
Manganese	2
Aluminum	2
Total Coliforms	5
Heterotrophic Plate Count	5

EPRI MWW Program Research into UV Disinfection of Potable Water

Keith E. Carns, P.E., and John Murphy, EPRI Community Environmental Center

In 1993, the Electric Power Research Institute (EPRI) launched the Municipal Water and Wastewater (MWW) Program as a vehicle for member electric utilities to collaborate with their water and wastewater customers. Water and wastewater treatment accounts for about three percent of the United States electric use, so the electricity industry recognizes the importance of this market sector. Further, as populations rise and regulations stiffen, electricity use by the water and wastewater treatment industry is expected to increase by as much as 15 percent in the next 20 years.[1]

MWW Program

Initially, the MWW Program focused on energy efficiency and energy use in water and wastewater treatment plants. By the end of 1999, the Program had conducted hundreds of energy audits throughout the continental U.S. and Hawaii. However, the MWW Program has expanded its focus to include the wise use of all electrotechnologies in water and wastewater treatment.

This has lead to collaboration with numerous state, national, and international organizations, such as the International Ozone Association (IOA), American Water Works Association Research Foundation (AWWARF), Water Environment Research Foundation (WERF), and U.S. Environmental Protection Agency (EPA). Thus, by the end of 1999, the MWW Program had sponsored over 85 research and demonstration projects on topics as diverse as biological denitrification of nitrates and pulsed power treatment of anaerobically digested sludges.

Today, the Program places emphasis on three primary areas, including technology applications, desalination and water reuse, and small community systems. Activities in the technology applications area in the past have included the Ozone Efficiency Project, which was a multi-year effort to optimize the use of ozone in existing water treatment plants. That project demonstrated that water treatment plants could achieve anywhere from 15 to 40 percent savings in ozone generation costs through changes in the way it was generated and applied.

UV Technology Development

More recently, the technology applications group has focused on the use of UV in both water and wastewater treatment. In 1996, EPRI and AWWARF collaborated on an assessment of unique methods of inactivating *Cryptosporidium.* Recent outbreaks of this pathogen in potable water supplies, including the most notable incident in Milwaukee, Wisconsin in 1993, have raised the concern of public water suppliers and regulators. Unfortunately, conventional methods of treating water (in particular, chlorine) are ineffective against *Cryptosporidium.* This research project suggested that UV light under certain circumstances could inactivate *Cryptosporidium*.[2] Specifically, researchers found that pulsed UV was quite effective, but that low-pressure UV was effective only at very high dosages (>8000 J/cm^2). At that time, both systems tested were prototypes and not truly in production.

The EPRI/AWWARF study was the first indication in the U.S. that UV could effectively inactivate *Cryptosporidium*. Follow up research on a medium-pressure UV system demonstrated that UV inactivates *Cryptosporidium* at UV dosage levels easily achievable by existing

Correspondence should be addressed to:

EPRI Community Environmental Center, Municipal Water and Wastewater Program
Washington University, Campus Box 1150, Cupples 2, Rm 11, St. Louis, MO 63130
(314) 935-8598 Fax: (314) 935-8599 E-mail: kecarns@epri.com

systems. Bukhari et al. have shown that 2 to 4 log inactivation of *Cryptosporidium* is possible with UV dosages as low as 20 J/cm^2.[3]

During the same period, the EPA was conducting negotiations on the Groundwater Disinfection Rule (GDR). While specific requirements of the GDR are still unclear, it is clear that many water utilities currently not disinfecting their groundwater supplies will have to do so sometime before year 2005. Many purveyors of groundwater supplies are quite concerned about the effect of disinfection on the taste of their water, so they are looking for alternative disinfection methods. Thus, UV light has become one possibility.

Unfortunately, there has been little research into the full-scale use of UV for the disinfection of groundwater. This lack of information makes convincing regulatory officials to accept this method to meet GDR requirements a significant challenge. Thus, EPRI and AWWARF collaborated in sponsoring a full-scale demonstration of UV disinfection of groundwater.

Full-scale UV Demonstration

The full-scale demonstration was launched in August 1998 at two water utilities in Maine and Indiana. Trojan Technologies donated equipment and expertise in installing their units at South Berwick, Maine and Indianapolis, Indiana. A low-pressure system is in place and has been in operation continuously since September 1998. A medium-pressure system has been operated sporadically on a well operated by the Indianapolis Water Company. Results to date from these two sites are summarized below.

The unit in Maine has operated continuously since startup. Performance to date has been excellent and, in fact, has exceeded all expectations. The system has achieved disinfection goals and showed that levels of HPC bacteria can act as an adequate surrogate in assessing disinfection performance. The UV sensor installed in the unit has operated continuously for over 2,500 hours. Further, the operation of the system has shown that UV sensor readings can be used as an operational tool. Researchers have shown that when UV sensor readings drop below 75 percent transmittance, the UV quartz sleeves should be cleaned.

The demonstration has also shown that UV disinfection can be cost effective. Based on cumulative power use and water production figures, the water district is able to disinfect the water for about $ 0.007/1,000 gallons. This value is quite good considering the water district pays $ 0.11/kWh, which is high compared to other regions of the country.

The demonstration in Indiana has been more problematic. Initial start up problems included difficulties with the calibration of the UV sensor and pump problems at the test well. However, the most significant and challenging problem has been fouling of the quartz sleeves due to unanticipated levels of hardness and iron. In fact, fouling was initially so severe that the automatic cleaning systems were initiated after 15 minutes of operation. The UV sensor failed after 200 hours and the initial cleaning system installed was unable to control fouling.

After a series of modifications, engineers from Trojan started up the system in Indianapolis again in the summer of 1999. While no disinfection data is available, the researchers have been able to extend the time between cleaning cycles from 15 minutes to nearly 24 hours. Disinfection data from this system is expected in the spring of year 2000. These experiences demonstrate the need to carefully assess water quality prior to project initiation and the need for better UV sensors.

Both UV systems seem to have very low power usage costs and neither system has significantly affected distribution system regrowth as measured by AOC and BDOC. Thus, researchers are relatively confident that UV disinfection systems could be installed in existing groundwater systems with a minimum of additional construction and capital outlay.

Pulsed UV Development

The EPRI MWW Program also recently completed a 3-year program to develop a pulsed UV unit for disinfection of potable water. This development program, lead by Innovatech, Inc.

(San Diego, California), has resulted in a pulsed UV prototype. To date, the unit has proven effective against *Cryptosporidium* and other common waterborne pathogens. Additional research is underway to evaluate its use on wastewater. While no units are in operation at water plants in the U.S., there are a few installations in cruise ships and similar applications. A report is available describing the results of this developmental program.[4]

UV Research in California

In collaboration with Metropolitan Water District, Orange County Water District, and Southern California Edison, the California Energy Commission and MWW Program are sponsoring a number of UV demonstrations in California. These studies are evaluating the various UV technologies, including medium-pressure, low-pressure high intensity, and pulsed UV for both potable water and reclaimed water applications. In fact, results to date show that pulsed UV is quite effective in disinfecting water at a reasonable cost.[5] Complete results of this research will be reported in two workshops to be held in central California and San Diego, California in year 2000.

Future Emphasis

Results from the various EPRI research projects definitively show that UV light is a viable potable water disinfection alternative. However, additional research is needed to achieve regulatory approval. The problems encountered in Indianapolis suggest that both water quality and the type of UV lamp used are critical design parameters. The iron levels in the water in Indianapolis are very high (over 1.0 mg/L), so pretreatment may be necessary.

More research is needed to develop a UV sensor capable of measuring UV dose. Current sensors measure UV transmittance that is then converted to a dose. However, these sensors are prone to fouling and are merely surrogates for dosage. It would be ideal to have a sensor that can actually measure the UV energy put into the water. In addition, treatment chamber hydraulics should be assessed and optimized. New information suggests that this essential issue must be addressed. Finally, the impact of UV on other emerging pathogens, such as *Giardia*, is unclear. The impact must be quantified before this technology could be used on surface waters and some groundwater.

International UV Association

One significant step towards defining and addressing many of these issues is the recent formation of the International UV Association (IUVA). This professional organization is designed to advance the science and engineering of UV light and technology. It is patterned after the great success of the International Ozone Association, which has been doing the same thing for ozone technology for more than 25 years. This organization can serve as a forum for defining research needs and standardization of monitoring equipment. The MWW Program continues working with the IUVA and other parties to further the understanding of UV science and technology.

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A Review of UV Research at AWWARF

Albert L. Ilges, American Water Works Association Research Foundation (AWWARF)

The American Water Works Association Research Foundation (AWWARF) funded its first UV research project in 1992 to investigate if, and what, disinfection by-products are produced by UV disinfection, and if UV influences chemical post-disinfection by-product formation. Since then, a total of 10 research projects with budgets totaling $3,575,000 have been funded with an additional four projects and budgets totaling $1,325,000 currently being considered for funding. Several organizations have been partners in various projects and have helped to co-fund the research. A brief overview of each project is presented.

Project Title: Evaluation of the By-products Produced by the Treatment of Groundwaters with Ultraviolet Radiation (UV)

Principal Investigator: Dr. James P. Malley, Jr., University of New Hampshire

Objectives
To determine if UV causes disinfection by-products (DBPs) to be formed in surface- and groundwaters when followed with and without chemical post-disinfectants.

Approach
The study examined the effects of varying UV dose (60, 130, and 200 mW-sec/cm^2) on Simulated Distribution System Disinfection By-products (SDSDBPs), BODC, assimilable organic carbon (AOC) and hydrophobic-hydrophilic carbon fractions. Chlorine and chloramines were used as post-disinfectants and DBP formation rate was examined. Low-pressure UV lamps were used.

Results/Findings
UV irradiation did not produce significant concentrations of any DBP when used to treat groundwaters or treated (coagulation or filtration) surface waters. UV did not significantly affect the SDSDBPs formed by chlorine or chloramines or the BDOC of those waters. The total AOC was not significantly affected by UV irradiation.

Site-specific correlations between BDOC and P17-AOC were found. BDOC and NOX-AOC did not correlate well in any of the waters studied.

The combination of UV and post-disinfection with chloramines resulted in the lowest overall SDSDBP production for all waters tested. Varying the UV dosage from 60 to 200 mW-sec/cm^2 did not alter any of the previously stated conclusions.

Project Title: UV Inactivation of Viruses in Natural Waters

Principal Investigator: Dr. James P. Malley, Jr., University of New Hampshire

Objectives
This research determined the UV dose needed to kill certain human pathogenic viruses (polio, rotavirus, and hepatitis A) as well as the surrogate MS-2 virus in natural waters. Post-disinfection studies were designed to provide a side-by-side comparison of chlorine to chloramine for protection during distribution and regrowth control.

Approach
This project involved a field study, a field pipe-loop study, and lab work — all of which were conducted simultaneously. Two pilot facilities were designed and constructed to treat

Correspondence should be addressed to:
AWWA Research Foundation, 6666 W. Quincy Avenue, Denver, CO 80235
(303) 347-6128 Fax: (303) 730-0851 E-mail: ailges@awwarf.com

groundwater using a10 gpm pilot-scale UV system (Trojan Technologies, Ontario, Canada). The pilot plants were operated for 1 year and were repeatedly challenged with MS-2 to evaluate performance and confirm 4-log inactivation levels.

Results/Findings
Data from this study show clearly that UV is a viable means of disinfection when the pathogens of interest are viruses. Both pilot-scale systems achieved a 4-log inactivation of MS-2 at reasonable doses ranging from 64 to 93 mW-sec/cm^2.

Fouling of UV sleeves and sensors can cause system performance deterioration or indicate a problem when none exists. Waters containing high concentrations of fouling agents (iron, calcium hardness, or organics) may require pretreatment or, an automatic cleaning mechanism in the UV reactor. Long-term pilot studies helped determine the degree of fouling that can occur in any particular system.

Three pipe-loops (iron, PVC, and copper) were used to help evaluate UV's effects on bacterial regrowth in both the presence and absence of a secondary chemical disinfectant (chlorine or chloramine). Regrowth was evaluated using AOCs and pipe coupons analyzed for plate count bacteria. Results of the biofilm analysis showed counts in the pipe-loop receiving no chemical disinfectant to be about 10 times greater than the loops receiving chlorine or chloramine. This is significant because it suggests that a secondary disinfectant may be needed to suppress biofilm formation in distribution systems.

Lab studies showed that MS-2 was more resistant to UV than the human viral pathogens tested (poliovirus, HAV and rotavirus). Because MS-2 is more resistant and non-pathogenic, it can be used as a conservative performance indicator for UV systems. Providing a 4-log inactivation of MS-2 will ensure a 4-log or greater inactivation of poliovirus, HAV and rotavirus. Results did show variation in required doses needed to obtain a 4-log inactivation in different groundwater matrices. This variation can be attributed to interferences caused by groundwater constituents, however, attempts to correlate constituent concentrations to 4-log dose requirements generally yielded weak correlations. Required doses for inactivation in specific waters however can be determined relatively easily in the laboratory through bioassays.

Project Title: Full-Scale Implementation of UV Groundwater Disinfection Systems

Principal Investigator: Dr. James P. Malley, Jr., University of New Hampshire

Objectives
This research is developing full-scale information on UV disinfection of groundwater, which will aid the water industry in the selection, design, operation and regulation of full-scale UV systems.

Approach
Two groundwater utilities were selected. One utility used a conventional low-pressure UV system (Trojan Technologies, Ontario, Canada) to treat their 0.25 MGD well supply and the other utility used a medium-pressure system (Trojan Technologies, Ontario, Canada) to treat a 1 MGD well supply. The UV systems are commercially available systems and are being monitored for power usage, bacterial quality, human viruses, and MS-2 bacterio-phage challenges to determine UV performance. Various physical/chemical parameters are being monitored and quarterly samples are analyzed for DBPs before UV, after UV, and after UV and chlorine.

Results/Findings
The Indianapolis Water Company (IWC) medium-pressure UV pilot plant was officially started on August 10, 1998. During the first 6 weeks of operation, there were 4 weeks of successful run time and data collection. Operational problems encountered include (1) incorrect calibration of the intensity sensor during the first week of operation, (2) dose adjustment to account for lower flow than expected, (3) exceedingly frequent cleaning events due to lamp fouling, (4) a cleaning cycle drain failure, and (5) failure of the intensity sensor

during the fifth week of running. The lamp fouling and irregular sensor performance at IWC resulted, in part, from the combination of iron and manganese concentrations that are relatively high. The average influent concentrations of iron and manganese at IWC are 0.36 and 0.23 mg/l respectively. The installation at South Berwick, ME ran smoothly based on sensor reliability, effluent HPC counts, and operator observations. Neither UV system significantly affected AOC or BDOC.

Project Title: Inactivation of Pathogens by Innovative UV Technologies

Principal Investigator: Dr. James P. Malley, Jr., University of New Hampshire

Objectives
The goal of this project is to determine bacterial and viral inactivation efficiencies for several innovative UV technologies for use in treatment of both drinking water and treated wastewater.

Approach (from RFP)
A review of current research will be conducted and will focus on bacterial and viral pathogens. UV systems using low-pressure, medium-pressure, and pulsed UV lamps will be evaluated at high UV intensities with varying levels of UV dose to look for effects on microbial inactivation and disinfection by-product formation (e.g., simulated distribution system disinfection by-products [SDSDBP] tests).

Selection of pathogens and surrogates (NOTE: *Cryptosporidium* and *Giardia* are specifically excluded from this project except for the literature review) to be studied included considerations such as:

- Availability of analytical methodologies to determine viability or infectivity.
- Bacterial and viral pathogens found in groundwaters, surface waters, and wastewater treatment plant effluents.
- Emerging pathogens.

Initial inactivation screening studies will consider bench-scale experiments using synthetic waters under conditions that would allow for comparisons to existing inactivation data. The more resistant pathogens to each technology would be selected for bench-scale experiments in a well-defined, reproducible water matrix. The research should also investigate if bacterial repair occurs and determine if it is a function of the UV wavelength. Water quality parameters such as, but not limited to, total organic carbon, turbidity, iron, color, and UV-adsorbing materials should be considered in constructing the water quality matrix design. A selected number of pilot-scale experiments to verify bench-scale data representative of drinking waters and treated wastewaters should be part of the experimental design.

Measured UV doses will be verified using MS2 inactivation studies. Measured UV doses will also be assessed using actinometry in at least the bench-scale work and correlated to MS2 measurements. Control runs without UV being applied will be conducted to measure potential pathogen loss due to operational factors.

The final report will include cost evaluations, potential scale-up issues, and comparison of inactivation performance to that of low-pressure systems. For each lamp technology the effect of the spectrum and its intensity on the received UV dose should be studied to ascertain whether system parameters that are used for the low-pressure systems need to be altered.

Project Title: Removal of MTBE with Advanced Oxidation Processes

Principal Investigator: Dr. Michael C. Kavanaugh, Malcolm Pirnie, Inc.

Objectives
The goal of this project is to determine if advanced oxidation processes (AOPs) are technically and economically feasible treatment alternatives for removing methyl tertiary butyl ether (MTBE) from drinking water.

Approach (from RFP)
This project will evaluate several AOP technologies (e.g., UV/peroxide, ozone/UV, ozone/peroxide, titanium oxide, ultrasonic cavitation, and photocatalytic processes) and determine the MTBE removal effectiveness, design and operating factors, and capital and operating costs for each technology. Research at the bench-scale using laboratory waters will determine the feasibility of each technology. The most promising technologies will then be pilot-scale tested with representative ground and surface waters to determine engineering parameters and costs. A subset of studies should include groundwater and surface waters that contain typical levels of bromide. The research team will monitor parameters such as power used per quantity of water treated, operational problems, need for maintenance, and impacts of water quality on fouling. Experiments on each technology will include monitoring of oxidative by-products (e.g., commonly formed carboxylic acids, aldehydes, ketones, alcohols, and bromate). The research team will use adequate controls and analyses to account for losses of MTBE to components of a treatment system (i.e., volatilization or sorption losses). Levels of residual oxidants after treatment (i.e., residual peroxide levels) will be quantified. Other secondary impacts will also be addressed (i.e., disinfection credit is being considered for UV- or ozone-based AOPs).

The final report will outline the potential use of AOPs for MTBE removal and the optimal conditions for operating these technologies. In addition, capital and operating costs of each technology will be presented.

Project Title: Innovative Technologies to Oxidize Organic and Organoleptic Chemicals

Principal Investigator: Dr. Karl Linden, Duke University

Objectives
The primary goal of this project is to determine the effectiveness of various innovative UV technologies to oxidize organic chemicals such as volatile organic chemicals (VOCs), pesticides, herbicides, disinfection by-product (DBP) precursors, and taste-and-odor compounds. This project will focus on UV technologies already shown to inactivate protozoan pathogens.

Approach
This project will determine the effect of at least three different UV technologies under various operating conditions, alone and in combination with hydrogen peroxide, ozone, or ozone/hydrogen peroxide on a number of different organic chemicals at pilot scale. The selected UV systems will also have the capability of inactivating protozoan pathogens, such as *Cryptosporidium* and *Giardia,* using dosages financially feasible for drinking water utilities. The compounds to be examined will include, but are not be limited to: DBPs, DBP precursors, pesticides, herbicides, VOCs, and taste-and-odor compounds. DBP formation potential using chlorine and chloramines (after UV application) will also be determined with each UV system under various operating conditions. The researcher will determine the operating conditions and costs needed to remove unwanted organic chemicals and optimal conditions for minimizing the production of DBPs, DBP precursors, and taste-and-odor compounds. During pilot-plant operations, the researcher will record and report power usage and gallons treated on a daily basis.

The analytical measurements of UV dose delivered by the pilot plant during the project and how the quality of these data, such as verification of UV sensor readings with actual bioinactivation studies will be ensured. The final report will summarize the destruction and production of various organic compounds with several different innovative UV systems that are capable of inactivating protozoan pathogens. Operating conditions for maximizing total water quality and preliminary cost estimates for the applicable technologies will be proposed.

Project Title: Evaluation of Advanced UV Disinfection Systems for the Inactivation of *Cryptosporidium*

Principal Investigator: Dr. Gil Crozes, Carollo Engineers

Objectives
The objective of this study is to perform longer-term testing of UV systems to address implementation issues, evaluate feasibility, and develop design criteria. Key features of UV disinfection, membrane filtration, and ozonation will be organized into a decision-making tool to assist with identifying the optimal *Cryptosporidium* control strategy under site-specific water quality conditions.

Approach (from Robert Cushing's abstract)
The Sentinel™ unit from Calgon Carbon (Ontario, Canada) was in the system test matrix from project inception. As standard low-pressure technologies were shown to be effective for *Cryptosporidium* inactivation, the approach was modified to include low-pressure and low-pressure, high-output (LPHO) in the technology-screening matrix. A review of commercially available drinking water UV disinfection systems was conducted to select systems to test in conjunction with the Sentinel™. The main criteria for alternate UV system selection were differences in lamp type, lamp configuration, flow regime, cleaning technique, and UV sensor type and location. Two UV units manufactured by Ideal Horizons (Poultney, VT), the MDW-1 and MDW-HO, and one unit by PCI-Wedeco (Germany), the Series K, were selected. As shown in Table 1, these systems have significantly different design characteristics both in terms of hydraulics and UV lamp design and monitoring.

The Calgon system was mobilized to Neenah Water Utility and the Ideal Horizons systems were mobilized to the North Shore Water Commission (NSWC) for the first 6 months of operation (Phase 1). The PCI Wedeco unit was mobilized to Cudahy Water Utility and will remain at this location for the duration of the study. During Phase 1, the four units will operate continuously at each of these three locations. At the end of this period, the Calgon system will be moved to NSWC and the Ideal Horizons systems will be moved to Neenah and operated for another six months at the alternate location (Phase 2). The pilot plant-piping configuration is consistent among the sites. In each case, flow from the clearwell passes through an RPZ valve for backflow prevention and a butterfly valve for flow control and into the UV reactor(s). Injection ports for MS-2 and sodium bisulfite (labeled MS-2 and HSO_3^-, respectively), and sampling ports before and after the UV reactors, are provided. During standard operation (i.e. when not performing the MS-2 Challenges), the water exiting the UV reactor(s) flows back into the clearwell. During the MS-2Challenges the reactor is piped to waste.

Project Title: Disinfection Efficiency and Dose Measurement for Medium-pressure and Pulsed UV Disinfection Systems

Principal Investigator: Dr. Karl G. Linden, Duke University

Objectives
The goal of this research is to evaluate the disinfection effectiveness of high intensity polychromatic UV radiation from medium pressure- and pulsed-UV disinfection systems.

Approach
Initial tasks will develop methodologies that can be used to measure the effective germicidal UV dose from a polychromatic UV source. Once the germicidal dose can be accurately estimated from any given source, a fair comparison can be made of the ability of different types of UV systems to inactivate pathogens. Three methods of UV dose determination are being investigated and applied to medium-pressure and pulsed UV systems. The specific objectives of the research are to (1) develop and evaluate physical, chemical, and biological methods for calculating the effective germicidal dose of medium-pressure and pulsed UV irradiation, (2) establish a UV dose/log inactivation relationship for specific bacterial and viral indicators, (3) determine the extent of photoreactivation and dark repair of HPC bacteria following irradiation, and (4) compare the ability of the UV systems to inactivate *Cryptosporidium*.

Project Title: Application of KI Actinometry to UV Reactor Dosimetry

Principal Investigator: Dr. Ronald O. Rahn, University of Alabama at Birmingham

Objectives
The principal objectives of this research are (1) to characterize the newly discovered iodide/iodate actinometer system in terms of its applicability to UV disinfection of drinking water, and (2) to apply the actinometer to the problem of how to determine the distribution of radiant energy in a UV reactor employed for drinking water disinfection.

Approach
Three specific tasks will be undertaken to achieve the objectives: (1) establish appropriate methodologies that will allow iodide/iodate actinometry to be used as an industry standard for UV dosimetry with application to modeling studies and assessment of efficacy; (2) demonstrate the use of iodide/iodate actinometry for measuring the total germicidal output of a medium-pressure mercury lamp and to compare these results with manufactures' specifications; and (3) demonstrate how spherical actinometry can be used to measure the UV irradiance at various points in space within a UV reactor and to compare these results with theoretical calculations.

Project Title: Protocol for Designing and Conducting UV Disinfection Studies

Principal Investigator: TBD. Funding not yet approved.

Objectives
The results of this study will provide critical guidance on how UV disinfection studies should be accomplished. The protocol, in report format, would provide guidance on (1) selection of the pathogenic and surrogate microorganisms; (2) methods to assess inactivation; and (3) selection, design, operation, and scale of UV equipment to be tested based on full-scale needs.

Approach (from project description)
A protocol would be developed through a survey of the literature and the use of a workshop to identify the scope of issues and to make protocol recommendations. The protocol would cover such things as the design of bench-scale, pilot-scale, and demonstration-scale test of UV systems. Guidance would be provided in four specific areas: microbiology, collimated beam studies, continuous flow studies, and data analysis.

Project Title: Hydrodynamic Characterization of UV Reactors

Principal Investigator: TBD. Funding not yet approved.

Objectives
This project will develop a tool or protocol for evaluating the disinfection efficiency of UV reactors by predicting both the light irradiance distribution and the hydraulic residence time distribution so that microbial inactivation performance can be modeled.

Approach (from project description)
The initial phase of this research would evaluate the literature related to the hydraulic performance and design of reactors that could be used in drinking water UV applications. Precedence in wastewater and industrial applications would also be reviewed.

The study would combine computational fluid dynamics modeling and light irradiance distribution modeling to predict both the light irradiance distribution and the hydraulic residence time distribution in full-scale facilities. The model results should be capable of determining the minimum inactivation performance (minimum UV dose). Previously generated pilot-scale and full-scale data (if available) from well-characterized UV reactors should be employed for model calibration and verification. The researcher should determine and state in the proposal whether new experimental data would be generated as part of this project. Factors such as lamp orientation relative to water flow would be examined along with

the sensitivity of hydraulic design conditions. Changes in flow rates, baffles, valve fittings, appurtenances, and common header designs would also be considered.

The final report would document how to use the model to calibrate and validate pilot-scale data in order to produce accurate, full-scale microbial inactivation predictions. The application of the model as a design tool would be documented with examples at various plant capacities. The report would also state how use of the drinking water model differs from the other types of liquid streams (i.e., wastewater).

Project Title: *Cryptosporidium* Oocyst Repair Following Disinfection

Principal Investigator: TBD. Funding not yet approved.

Objectives
This project would investigate whether self-repair by *Cryptosporidium parvum* oocysts can occur following UV disinfection and, if so, evaluate the implications for use of UV technologies. The evaluation would include identification of possible repair mechanisms following UV treatment to determine the kinetics of reactivation and the impacts of post-disinfection storage times and environmental conditions during distribution.

Approach (from project description)
This project will use a cell culture methodology to evaluate *C. parvum* for self-repair mechanisms based on UV dose and a matrix of conditions typical of drinking water conditions. A limited number of duplicate experiments using an animal model to collaborate the cell culture results would also be conducted. One component of the project would be to investigate the kinetics of reactivation that allows oocysts to once again become infective. The general approach would involve exposing *C. parvum* oocysts to well-defined doses of UV light (e.g., using a collimated beam apparatus), measuring the extent of initial inactivation followed by monitoring of oocysts for changes in infectivity due to reactivation over time.

Factors that need to be considered in the research matrix include, but are not limited to:

- Different types of UV systems (e.g., low-pressure high-output; medium-pressure; pulsed UV).
- A range of UV doses (e.g., 5, 10, 20, 40, 80 mJcm-2).
- Various lengths of holding time following UV exposure (e.g., 0 to10 days).
- Light and dark reactivation conditions.
- Presence of post-UV chemical disinfectants, such as chlorine and monochloramine (if reactivation is found to occur).

The experiments will be designed to be reflective of full-scale water treatment conditions and realistic distribution system residence times. For conditions where reactivation is found to occur, the experimental study would also evaluate possible mechanisms and kinetics of reactivation.

The final report would document the ability of oocysts to self-repair following UV disinfection. If repair mechanisms are found to be present, the type of repair mechanism would be identified and the potential impacts of post-disinfection storage times on repair would be presented.

Project Title: Evaluating the Long-term Operational Reliability of Full-scale UV Disinfection Systems for Surface Water Treatment

Principal Investigator: Funding not yet approved.

Objectives
This demonstration project would evaluate the operational issues of UV disinfection by installing and operating two 1-MGD UV disinfection treatment systems. One unit would be

a low-pressure, high intensity UV technology and the other would be a medium-pressure technology. The project would examine and document the operational parameters, required maintenance, and quality of the water produced by each unit.

Approach (from TC proposal)
This project would conduct a demonstration project to evaluate the operational challenges associated with a full-scale UV system. The project includes procurement, installation, and 12-month operation of two 1-MGD UV treatment units at a surface water treatment plant that currently uses chlorine as the primary disinfectant. One of the UV units will be based in low-pressure high-intensity UV lamp technology and the other on medium-pressure UV lamp technology. While it is believed that these two technologies rely upon the same fundamental process of microbial inactivation, the difference in lamp intensity results in vastly different design and operational criteria. The water treatment operational staff will be responsible for the day-to-day operation of the UV units, implementation of the operations plan, documentation of operational parameters, and collection of water quality samples. A nationally recognized consulting firm will be responsible for the development of operations and monitoring plans, data analysis and reporting.

Lyonnaise des Eaux, France

Philippe Savoye, Lyonnaise des Eaux

This abstract is unavailable. Please contact the speaker at the address below for further information.

Correspondence should be addressed to:
Phone: 33 0 134 802 390 E-mail: Philippe.SAVOYE@lyonnaise-des-eaux.fr

Project Status: Application of UV Technology in Wisconsin

Robert S. Cushing, Ph.D., P.E., Erin D. Mackey, and Patrick C. White, Carollo Engineers[A]
James P. Malley, University of New Hampshire
Thomas Hargy, Clancy Environmental Consultants, Inc.[B]

Introduction

Protection against disinfectant resistant pathogens and, in particular, *Cryptosporidium* has become a critical issue for water purveyors. Proven treatment technologies currently available include membrane filtration and ozonation at elevated dosages. These two technologies, however, have some significant potential drawbacks. The cost of membrane filtration can be relatively high for waters with high fouling potential or when membranes are used as a polishing process after conventional treatment. Ozone requirements for *Cryptosporidium* inactivation can be much greater than doses currently typically applied, leading to high capital and operating costs and elevated levels of ozone byproducts.

To investigate new technologies, the American Waterworks Association Research Foundation (AWWARF) and the Electric Power Research Institute (EPRI) jointly funded a proof of concept study for electrotechnologies with potential application for *Cryptosporidium* inactivation (AWWARF/EPRI Draft Report, 1997). Most notable among the technologies evaluated were UV disinfection systems, pulsed UV technology,[1] and the *Cryptosporidium* Inactivation Device (CID). Subsequently, studies determined that medium-pressure UV light is effective for inactivation of *Cryptosporidium*.[2] Demonstration studies of medium-pressure UV carried out under the NSF/EPA ETV program showed that a UV dose of 19 mJ cm^{-2} provided 3.9 logs inactivation of *Cryptosporidium* oocysts. Studies have now confirmed that low-pressure UV is also effective for inactivation of *Cryptosporidium* at doses similar to that of medium-pressure systems. Experience with UV disinfection of conventionally treated surface waters is limited. Testing is needed to determine operability, reliability, and feasibility for such systems.

The overall objectives of this project are to evaluate long-term performance and feasibility and to develop a decision-making tool to assist utilities in selecting the most appropriate technology for providing protection against *Cryptosporidium*. To achieve these objectives, the following key questions are considered:

- What are the regulatory acceptance requirements?
- How durable are components?
- What are the maintenance requirements?
- What type of redundancy is required?
- Does the efficiency of inactivation decline over time? And, if so, what are the causes and solutions?
- How significant is lamp sleeve fouling over time? And, what are the impacts on disinfection, what are the foulants, and what are appropriate cleaning regimes?
- What are the precision, stability, and maintenance requirements for the UV sensors?
- How is dose confirmed?
- Is by-product formation an issue of concern, and how does system type and water quality impact by-product formation?

Correspondence should be addressed to:

(A) Carollo Engineers, 12426 W. Explorer Dr., Suite 200, Boise, ID 83713
(208) 376-2288 Fax: (208) 376-2251 E-mail: rcushing@carollo.com

(B) Clancy Environmental Consultants, Inc., P.O. Box 314, St. Albans, VT 05478 (802) 527-2460

- What is the inactivation effectiveness for other pathogens?
- Given the above constraints, what are the system design and operating parameters?
- How does UV disinfection compare with other options for *Cryptosporidium* removal/inactivation in terms of reliability, cost, and constructability?

Approach

UV Disinfection System Selection and Installation

The Sentinel™ unit from Calgon Carbon (Ontario, Canada) was in the system test matrix from project inception. As standard low-pressure technologies were shown to be effective for *Cryptosporidium* inactivation, the approach was modified to include low-pressure and low-pressure, high-output (LPHO) in the technology-screening matrix. A review of commercially available drinking water UV disinfection systems was conducted to select systems to test in conjunction with the Sentinel™. The main criteria for alternate UV system selection were differences in lamp type, lamp configuration, flow regime, cleaning technique, and UV sensor type and location. Two UV units manufactured by Ideal Horizons (Poultney, VT), the MDW-1 and MDW-HO, and one unit by PCI-Wedeco (Germany), the Series K, were selected. As shown in Table 1, these systems have significantly different design characteristics, both in terms of hydraulics and UV lamp design and monitoring.

Table 1. Attributes of Selected UV Systems

Manufacturer:	Calgon Carbon Corp.
System name:	Sentinel(tm)
Lamp type & number:	Medium pressure, 4
Lamp configuration:	In-line, perpendicular to flow
Hydraulic design:	Straight flow through
Internal diameter:	8 inches
Sensor types:	4 intensity sensors
Cleaner type:	Wire brushes, set on automatic timer
Manufacturer:	Ideal Horizons
System name:	MDW
Lamp type & number:	Low pressure, 12
Lamp configuration:	Radial, parallel to flow
Hydraulic design:	Flow enters from the top & exits at the bottom at right angles
Internal diameter:	6 inches
Sensor types:	Intensity and % transmittance
Cleaner type:	Wire brushes, set on automatic timer
Manufacturer:	Ideal Horizons
System name:	MDW-HO
Lamp type & number:	Low pressure-high output, 6
Lamp configuration:	Radial, parallel to flow
Hydraulic design:	Flow enters from the top & exits at the bottom at right angles
Internal diameter:	6 inches
Sensor types:	Irradiance and % transmittance
Cleaner type:	Wire brushes, set on automatic timer
Manufacturer:	PCI Wedeco
System name:	Series K
Lamp type & number:	Medium pressure, 4
Lamp configuration:	Side-by-side , perpendicular to flow
Hydraulic design:	Straight flow through
Internal diameter:	20 mm at inlet and outlet sloping to 500 mm at midpoint
Sensor types:	Intensity
Cleaner type:	Off-line chemical clean

The Calgon system was mobilized to Neenah Water Utility and the Ideal Horizons systems were mobilized to the North Shore Water Commission (NSWC) for the first six months of operation (Phase 1). The PCI Wedeco unit was mobilized to Cudahy Water Utility and will remain at this location for the duration of the study. During Phase 1, the four units will operate continuously at each of these three locations. At the end of this period, the Calgon system will be moved to NSWC and the Ideal Horizons systems will be moved to Neenah and operated for another six months at the alternate location (Phase 2).

The pilot plant piping configuration is consistent among the sites, and Figure 1 shows process flow diagram for the pilot systems. In each case, flow from the clearwell passes through an RPZ valve for backflow prevention and a butterfly valve for flow control and into the UV reactor(s). Injection ports for MS-2 and sodium bisulfite (labeled MS-2 and HSO3–, respectively), and sampling ports before and after the UV reactors, are provided. During standard operation (i.e. when not performing the MS-2 Challenges), the water exiting the UV reactor(s) flows back into the clearwell. During the MS-2Challenges the reactor is piped to waste.

Sampling and Analysis

Hardness, calcium, alkalinity, pH, temperature, and turbidity are monitored daily on-site. Water samples are collected and shipped weekly for TOC, UV absorbance scan, iron, and manganese analysis. The UV units are monitored for power consumption, UV irradiance/ intensity, lamp operation, cleaning frequency, and pressure drop across each unit daily.

Evaluation of the actual dose delivered will be established using MS-2 Challenges. Three MS-2 Challenges are tentatively planned for each phase at Neenah and NSWC and quarterly at Cudahy. These MS-2 inactivation studies will verify UV sensor output and UV dose during the course of each piloting phase.

Cryptosporidium Inactivation Studies

Live *Cryptosporidium* challenge studies will be performed on the Ideal Horizons MDW unit (low-pressure) and the Wedeco Series K unit (low-pressure, high-output). Note that the *Cryptosporidium* inactivation response has already been confirmed for the Calgon Carbon system during previous testing, so further testing is not deemed necessary for the Sentinel™ unit. The UV systems will be shipped to St. Albans, Vermont, where Clancy Environmental Consultants will be responsible for conducting the *Cryptosporidium* Challenge studies. MS-2 Challenges will be performed at the same time to benchmark the UV dose.

Project Status

The pilot systems are installed and have been operating for approximately one month. The first MS-2 Challenge has been completed; however, results are not yet available.

Acknowledgements

This project is being conducted under the American Water Works Research Foundation Tailored Collaboration program with funding provided by North Shore Water Commission, Energy Center of Wisconsin, and Electric Power Research Institute.

References

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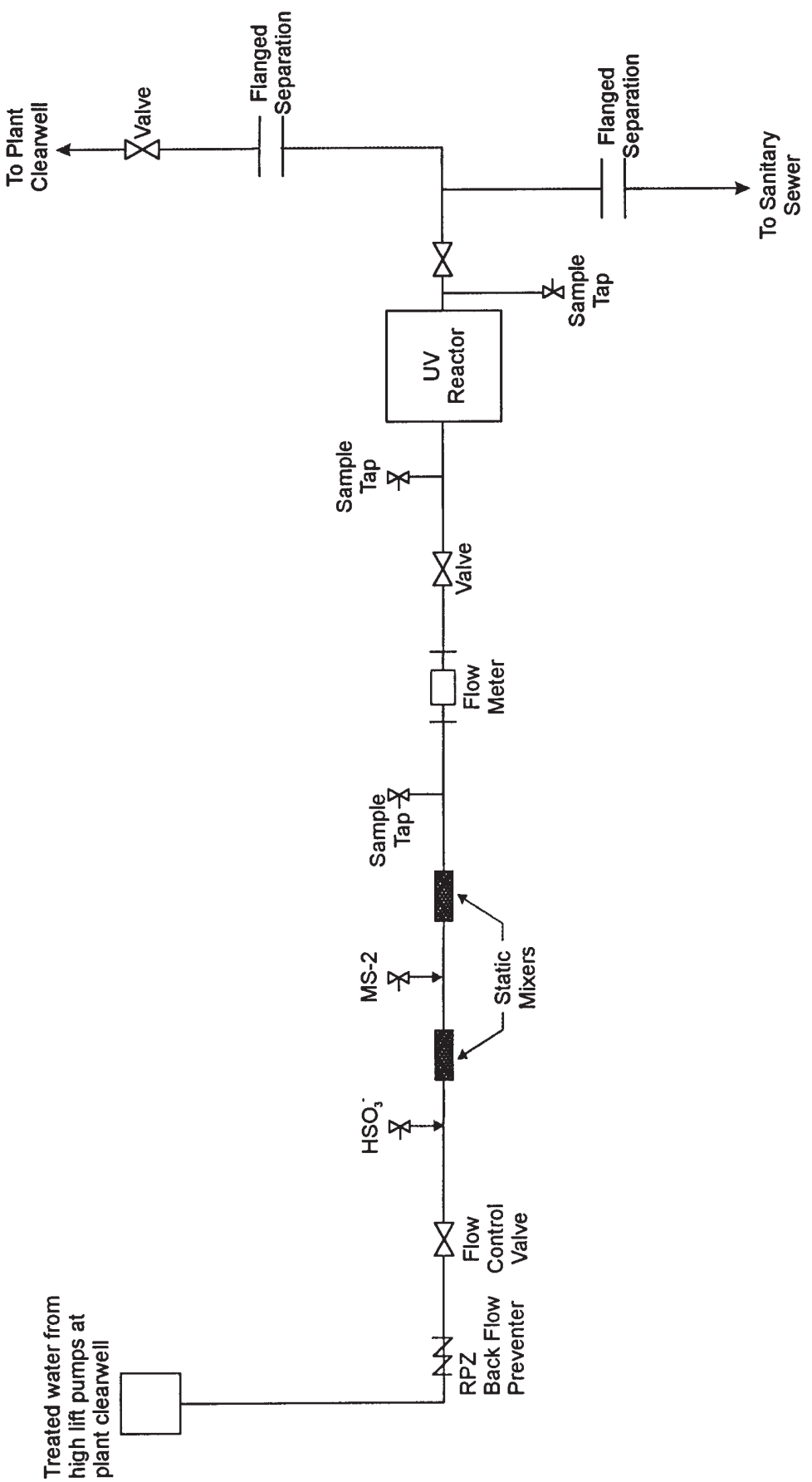

Figure 1. UV pilot system process flow diagram.