Features

Yikes! What the UVDGM Does Not Address

Calculating UV Dose for UV/AOP Reactors

UV Treatment: A Solution for Small Community Water Supplies?

IUVA World Congress Hotel in Vancouver, British Columbia, Canada

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all SUEZ brands are now one
Ozonia and 40 other water and waste experts have joined forces to become SUEZ.
On five continents, SUEZ supports towns and industries in the circular economy to maintain, optimize and secure the resources essential for our future.
Through the Ozonia product line, SUEZ provides chemical-free ozone and UV based advanced technologies to purify, clean, and protect water resources.
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To Boldly Go…… to Vancouver!

It’s World Congress Time! I am happy to report that IUV A is in full swing preparing for the IUV A World Congress in Vancouver from Jan. 31 to Feb. 3, 2016. The core team of organizers is busy receiving abstracts and developing the program as I write. Given everything that we do at IUV A, the World Congress is a time to hear and see and feel the energy of all the amazing activities our membership and affiliated colleagues are doing in the UV space. It’s a time to relax and visit with close colleagues, meet new professionals and make some friends. Vancouver will be an amazing place to come together. Winter in this city is a great time to visit. While it’s relatively mild in the city, the beautiful mountains of Whistler are close by and deserve a visit. The city has a rich ethnic heritage and has something for everyone, from beautiful nature and coast line to parks, restaurants and music – it is easily one of my favorite cities and consistently ranked in the top 5 of the worlds most livable cities.

I am also excited to be coming to Canada for the World Congress. As many of you know, Canada is a hotbed of UV activity. Many of the original players in the UV area started out in Canada. UV manufacturing has a strong foothold in the Canadian economy. This has grown hand in hand with the excellent cadre of researchers from universities across the country who have a serious focus in UV fundamentals and applications. I would venture to say that as a technology, UV has shaped Canada’s research and development landscape and made quite a few careers in the process. I know many of you! I hope we have some time to celebrate the Canadian contribution to the UV field and recognize the efforts, failures, and successes of those entrepreneurs who helped set the stage for an organization such as IUV A.

Lastly, I am excited to report a new relationship that IUV A has ventured into that will greatly enhance our administrative base. We have signed a contract with RadTech to support IUV A administrative needs. It has been a great experience getting to know the players at RadTech during our negotiations, and there are many synergies we feel will benefit IUV A through this relationship. While we will keep our same mission and programs and direction, we can now do so with a solid base and system of support that will better streamline our efforts and those of all the volunteers that work with IUV A. We will introduce the admin team at a later date, but you will certainly get to meet them at the Vancouver World Congress.

I hope your fall is starting out well and look forward to seeing your abstracts start to funnel in to fuel another great IUV A World Congress.

Best regards,
Karl Linden, Ph.D.
IUV A President
Professor of Environmental Engineering, University of Colorado-Boulder, USA

A Message
From the Editor-In-Chief

This is my second issue of IUV A News after being called back to be the editor-in-chief. I must say that I am enjoying the task, especially the opportunity to reconnect with old friends and make new friends. I hope you enjoy the articles I have selected – they are worth a good read. IUV A News is your quarterly ultraviolet magazine, so please take some time to read it through, and don’t forget the ads. The ads make it possible to publish IUV A News, so please support our advertisers. If you are an executive in a UV company, I encourage you to advertise in IUV A News. Send me an email at editorinchief@iuva.org and I’ll send you the IUV A News Media Kit.

Also note that IUV A News is willing to publish short Application Notes (e.g., see the one in this issue) highlighting interesting applications of a UV company’s technology.

Our readers might be interested to know about the profile of IUV A News readers. The job profile is UV company employees (40%), consultants (14%), academic (11%), utility employees (8%), research institutes (4%), government employees (2%) and other (20%). IUV A members come from all over the world with 60% from North America, 26% from Europe, the Middle East and Africa, and 10% from the Far East.
Clean water is a matter of trust.

UV radiation is a reliable way to disinfect water and eliminate harmful substances. That applies to treating drinking water – the essence of life – and waste water alike.

UV lamps from Heraeus Noblelight are particularly efficient and thus stand out due to their very low energy consumption. Our lamps offer this recognized standard of quality throughout their long service life. Heraeus UV lamps combine exceptional reliability with cost-effectiveness.

Each of our UV lamps is tailored to the specific requirements of our customers.

Interested in UV solutions for water treatment? Contact us at: hng-uv@heraeus.com

www.heraeus-noblelight.com
Aquionics Names Dan Shaver Regional Sales Manager for Canada and Western US

Aquionics has appointed Dan Shaver its industrial regional sales manager. In his new role, Shaver will provide service and support to customers in industrial markets, such as food and beverage, pharmaceutical and microelectronics.

Fujian Newland EnTech Co., Ltd. has won a bidding project for wastewater ultraviolet disinfection for the wastewater treatment projects of phase I, phase II, and phase III in the Qige WWTP in China Hangzhou city. The total wastewater flow rate is 1.56 million tons/day (peak) (1.56 billion m3/day or 5,900 MGD). The effluent quality should meet the China Standard of first class A (fecal coliform ≤ 1000 MPN/L, GB18918-2002). The design index of T254 is ≥ 45%, and with 7680 UV lamps equipped. The total power consumption of UV lamps is about 2457 kW. Especially, vertical modules of UV lamps were widely applied for this project. For further details, see http://www.newlanduv.com/news_info.asp?id=408.

Seoul Viosys to Produce UV LEDs for Sterilization

Seoul Viosys is moving to expand its ultraviolet light-emitting diode (UV LED)-making technology in the sterilization sector. The Seoul Semiconductor affiliate said Tuesday that it has strengthened its partnership with U.S.-based UV LED maker Sensor Electronics Technology (SETi) to commercialize “Violeds,” which Viosys says is key to developing UV LEDs to be used for sterilization.

Nikkiso is offering deep UV LEDs that it claims to be the highest in power, the highest in wall plug efficiency and the longest lifetime in the industry.

RayVio Announces Expansion of UV LED Manufacturing Capacity

RayVio Corporation, a developer of deep ultraviolet (UV) LEDs and integrated solutions, announced today that they are expanding their international sales force, and manufacturing capacity. The facility expansion at the original site is scheduled to be complete by year-end. RayVio’s current Silicon Valley headquarters houses their wafer growth, chip fabrication, packaging and test R&D and proto-typing capability. The expansion of this facility will enable RayVio to reduce cycle time and produce in excess of two million LED units annually through the installation of additional manufacturing and test equipment. Combined with its contract manufacturing strategy, RayVio is poised to keep pace with the increasing demand of the fast growing deep UV LED market.

Gigahertz-Optik announces an Integrated Filter Wheel for Dark Current Subtraction and Expanded Measurement Range. This system allows fast and accurate spectral photometric, radiometric and colorimetric measurements utilizing unique optical design and innovative technology. See http://bit.ly/1URnfWs.

AquiSense Technologies announces the unveiling of PearlAquaTM, the world’s first UV-C LED production product for water disinfection. This system utilizes state of the art UV-C LEDs into a unique, compact design, without the use of chemicals or mercury-based UV lamps. These LEDs also allow for instant, full-intensity power on start-up, unlimited cycling, and remote start/stop. PearlAqua can be used in a range of applications, including life sciences, medical devices, transportation, and commercial water. Standing 4 inches (103 mm) high, the compact PearlAqua can be seamlessly integrated into water treatment systems, providing maximum water security.

Protecting Public Health with Xylem’s Wedeco Spektron UV System

Xylem has expanded its Wedeco Spektron UV range to include two new models, the Spektron 2000e and Spektron 4000e. These models expand the Wedeco Spektron UV series to 14 available systems. The systems are most suitable for municipal drinking water treatment plants with a maximum flow capacity of more than 4,000 m³/h (26 MGD). 99.99% of all pathogens, including chlorine-resistant Cryptosporidium and Giardia, can be rendered harmless in a fraction of a second. They feature the latest low-pressure, high-power 600W Ecoray lamp technology, reducing lamp count by up to 60%, minimizing maintenance, and lowering energy costs. Extensive tests have been run based on USEPA’s UVDGM that demonstrate the performance efficiency of these UV systems and attractiveness over medium pressure UV systems. Communities in France, Germany, UK and Singapore are installing Wedeco Spektron UV systems to help provide safe water and efficient protection of public health.
to meet these requirements. The unique 600W Ecoray UV lamps are installed inclined at 45°, resulting in both excellent performance and ease of maintenance. The sensor-controlled OptiDose control monitors operating conditions in real time adjusting the energy consumption to the minimum needed to meet dosing requirements. With growing wastewater disinfection needs around the globe, the Duron UV system is proving to be an excellent choice to replace costly and inefficient medium pressure UV systems. A municipality in Ohio had a payback time of less than five years. The Wedeco Duron system has been thoroughly tested by a third party to allow for best-fit sizing with continuous performance monitoring.

**Fresh Water Systems, Inc.** (https://www.freshwatersystems.com/), one of the largest independent providers of water filtration systems in the US, has launched multiple initiatives designed to increase awareness about the effectiveness and efficiency of treating household water with ultraviolet, or UV, disinfection. These initiatives include a series of original informational videos about UV made in conjunction with Viqua, a leading manufacturer of UV systems for whom FWS is a major distributor. Another part of the promotion is a UV facts quiz with valuable gift cards as prizes.

**VIQUA’s LightWise Technology** – A Smart Solution To A Common Problem (http://bit.ly/1M7lhiy). VIQUA, the world’s leading manufacturer of residential ultraviolet (UV) water disinfection systems, recently officially introduced its new LightWise technology. LightWise technology is featured in the VIQUA PRO series – the PRO10, PRO20 and PRO30 – for light commercial applications. An industry first, LightWise allows the system’s electronic controller to automatically reduce lamp power during periods of no water flow. By adjusting the lamp power, water temperature is maintained below 40°C (104°F), and the rate of sleeve fouling is consequently reduced by as much as 60%. This can more than double the amount of time between sleeve cleaning cycles.

**Xenex Signs Agreement with HealthTrust:** Germ-Zapping Robots™ Added to the HealthTrust Portfolio (http://bit.ly/1iqzyNY). Xenex Disinfection Services today announced it has signed a national contract with HealthTrustSM, a leading group purchasing and total cost management organization that serves 1,350 acute care facilities nationwide. The contract, which covers Xenex Germ-Zapping Robots™, became effective June 1, 2015. Xenex’s pulsed xenon Full Spectrum™ ultraviolet (UV) room disinfection solution reduces the bacterial load in hospitals that is often associated with an increased risk for health care-associated infections (HAIs). The robot pulses intense UV light covering the entire UV spectrum, destroying viruses, bacteria and bacterial spores in a five-minute disinfection cycle.
**Application Note**

**Power Supplies for Ballast Water Treatment Systems that Save Space and Energy**

Since the International Maritime Organization (IMO) Ballast Water Management (BWM) Convention has specified the requirements for ballast water treatment, much engineering effort has been initiated. The establishment of BWM systems on existing and new vessels has been a major challenge.

For marine applications, a Ballast Water System must be a sophisticate with the smallest possible footprint. A compact design of all components is absolutely necessary to fit into the available environment, such as a power supply cabinet.

To optimize the electric power supply and to minimize its footprint, UV-Technik has developed its Multi-Lamp-Controller MLC-Rack (see photo). This modular electronic ballast is powered by a three-phase mains supply and is designed to operate up to 60 UVC low-pressure lamps.

The unit is equipped with an integral PFC stage to guarantee energy-saving and highly efficient operation of the UVC lamps with a power factor of more than 96%. Thanks to an Ethernet interface and its GL-approval, the MLC-Rack is perfectly made for Ballast Water Treatment Systems and can monitor all relevant operational conditions of the UV installation.

In addition to electronic ballasts, UV-Technik is specialized in the production of suitable low and medium pressure UV lamps for water treatment purposes. Quartz sleeves, as well as UV sensors, are also available.

For more details regarding the different components, please refer to www.hoenlegroup.com.

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you’re going to claim that your ultraviolet light product can “kill 99.9% of germs and bacteria in 10 seconds or less” or eradicate disease-spreading fungus and drug-resistant MRSA, then you should have the science to back these claims up. The Federal Trade Commission has announced settlements, totaling around $1.29 million, against two companies that marketed ultraviolet lights as “disinfectant” devices that could kill various pathogens. Angels Sales, Inc., are the folks behind the shUVee, an ultraviolet light device that, as far back as 2011, was advertised as a germ-killing shoe deodorizer.

**UV System Helps St. Mary’s Protect Patients** against infection (http://bit.ly/1ii62C). As drug-resistant strains of bacteria and viruses continue to arise, St. Mary’s Health Care System is taking steps to help protect patients from infection. The Athens hospital is the first in northeast Georgia to use powerful ultraviolet radiation to sterilize surgical suites, isolation rooms and other areas of the hospital. Ultraviolet light is the same kind of light that causes sunburns and skin cancer. Just as UV damages the DNA inside human cells, it also damages the DNA inside germs. This damage makes it impossible for germs to reproduce. By combining the Clorox OptimumUV system with traditional deep cleaning and disinfection, St. Mary’s is able to eliminate more than 99.9% of drug-resistant organisms on surfaces, says Doug Blomberg, RN, infection prevention and control manager.
Proposed Testing Protocol for Measurement of UV-C LED Lamp Output

Prepared by Jennifer Pagan and Oliver Lawal, of AquiSense Technologies, 7000 Houston Road #45, Florence, KY 41042 USA, on behalf of an IUVA Manufacturer’s Council working group (see chart).

Abstract

For many years the measurement of UV Low Pressure mercury-based lamps was not standardized, resulting in an inability to benchmark lamp performance within the industry. The International Ultraviolet Association, operating through a working group of the Manufacturers Council, published a testing protocol for the measurement of low-pressure lamp output intensity. This protocol has enabled agreement on lamp testing methods and reporting that enables greater transparency to system designers, regulators, researchers and end users. UV-C Light Emitting Diode (LED) technology has developed over the past decade to the point of commercialization for water, air and surface disinfection applications. However, much like the former situation with Low Pressure lamps, there are no commonly agreed upon or accepted methods for the determination of UV-C LED output.

This paper will describe a new IUVA initiative, undertaken by a working group of the IUVA Manufacturers Council to present a consistent methodology for the determination and benchmarking of UV-C output from LEDs. The protocol can be used for testing and comparing different UV-C LED lamps, to compare testing results from different laboratories and to compare operation under different ambient conditions. The protocol will accommodate both single device and multiple device lamps, showing emission spectra (i.e. power and wavelength) as well as absolute optical output power. The testing protocol will not cover angular distribution, aging, or mounting configuration. It is not intended for general manufacturing quality control or quality assurance testing.

The testing protocol will be in a similar format to the IUVA low pressure lamp method and, as such, will include descriptions of the following areas:

- Safety
- Measurement equipment
- Measurement conditions
- Measurement procedure
- Calibration
- Reporting

The mechanism used to refine and validate the protocol will also follow the precedent set by the IUVA low pressure lamp method, i.e. round robin testing will occur at various industry laboratories given in the chart and consisting of UV LED manufacturers, UV system manufacturers and research institutions, using the same UV LED lamp, same UV radiometer and sensor and each laboratory’s internal spectral measurement equipment. The results will be compiled by a third party and anonymously reported. After each complete round of testing, the results will be evaluated to seek an understanding for any variations between laboratories. As such, the protocol will be refined before final IUVA approval and publication.

Participants in Protocol Testing

<table>
<thead>
<tr>
<th>Participants in Protocol Testing</th>
<th>Contacts</th>
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- Dr. JJ Kim
- Tim Bettles
- Gordon Knight
- Jin Chang
- Karl Linden
- Fariborz Tagipour
- Anders Ruland
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Pentair Environmental Systems offers leading-edge equipment, accessories and water technology solutions across all industries including UV disinfection. A customer-centric approach to our SafeGuard UV Systems™ delivers solutions that can be tailor engineered. Offering design flexibility, a myriad of configurations, multiple options and over 30 models to choose from, Pentair Environmental Systems has the right UV to fit your application. Reliable, operator-friendly systems robustly constructed for a long service life.

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• Single-End UV lamp and quartz sleeve access for easy servicing.

• Choice of Inlet/Outlet port styles.

• Power supply is 50/60 Hz capable.
Dates Set for 2016 IUVA World Congress
The 2016 IUVA World Congress, set for Jan. 31-Feb. 3 in Vancouver, British Columbia, Canada, continues a long series of successful congresses organized worldwide by the IUVA to provide an international forum on recent advancements in technology and research addressing the environmental, health, and treatment process challenges of today, as well as to discuss the current trends in UV regulations and new applications.

Call for Abstracts!
The focus of this conference is to present the recent advancements in technology and research addressing the environmental and treatment process challenges of today, as well as to discuss the current trends in UV regulations and technology. A full list of suggested topics is at http://www.worldcongress2015.org/abstracts. The deadline for abstracts has been extended until Oct. 16. The abstracts need to be submitted through an Abstract Submittal Form located on the conference website at www.worldcongress2015.org.

Online Guest Room Reservations
IUVA has reserved guest rooms at a special conference rate at the Fairmont Vancouver Hotel. A link to the reservation system is on the conference website at www.worldcongress2015.org.

Award Nominations
The following awards will be presented at the World Congress. A one-page (maximum) submission is required by Nov. 1, explaining how the nomination meets the brief of the award. Both nominations and self-nominations are acceptable. Submissions must be emailed to Michael Templeton at m.templeton@imperial.ac.uk, who will reply to confirm receipt. Each submission will be reviewed independently by at least three members of the IUVA Awards Committee. All nominations will be kept confidential, and only the recipients will be announced (no runners-up).

• Lifetime Achievement Award
• UV Engineering Project of the Year
• UV Light Award for Volunteer Recognition
• UV Young Professional Award
• Best Paper Awards
• UV Product Innovation Award
• Green UV Award

Call for IUVA President-Elect Nominations
The IUVA is seeking nominations for the next IUVA international president. The next presidential term will run from the World Congress in January 2016 thru the World Congress in 2017. The president-elect will serve on the IUVA Executive Operating Committee (EOC) beginning in January 2016 and will continue as immediate past-president on the EOC until the 2021 World Congress. Refer to the board bylaws for more information on the president’s responsibilities.

Each candidate who has an interest in running for president-elect should send a short CV and a statement including background and vision on leading the IUVA.

Nominations Sought for Regional VP
The IUVA also is seeking nominations to serve for a two-year (renewable) term as regional vice president. The overall role of the regional VP is to:

1. Develop a detailed strategic direction for the IUVA in the region.
2. Plan concrete activities that work toward this strategic direction for the region.
3. Spread the IUVA brand within the region as much as possible, with the aim of expanding IUVA membership numbers and corporate members in the region.
Specific responsibilities include:
1. Participate in monthly IUVA Executive Organizing Committee and quarterly board meetings and provide feedback on IUVA documents and policies.
2. Lead the organization of IUVA events in the region, with support from the wider IUVA team. A minimum of two events in the region per year is desirable.
3. Promote IUVA at related conferences and events in the region as much as possible.

Nominations will be accepted until Oct. 31. Nominations are to be emailed to Bram Martijn, Nominations Committee Chair (bmartijn@pwntechnologies.nl) and must conform to the following guidelines:
• Nominee must be an IUVA member
• Nominee must have experience serving on the IUVA board for a minimum of one term
• Self-nomination permitted

Upon receipt of nominations, the Nominations Committee will review all nominees to ensure eligibility and confirm nomination, and pass the nominees to EOC for final review and inclusion on an electronic ballot.
Register now for the

2016 World Congress

Jan. 31-Feb. 3 • Vancouver, British Columbia, Canada

Fairmont Vancouver Hotel

This event aims to provide an international forum on advancements in UV technology and research.

Learn more at www.worldcongress2015.org.
Yikes! What the UVDGM Does Not Address on UV Disinfection

Harold Wright, Mark Heath and Jeff Bandy  
Carollo Engineers, 12592 W. Explorer Dr., Suite 200, Boise, ID 83713-1596  
Contact: Harold Wright (hwright@carollo.com)

This paper was presented at the IUVA World Congress on Ultra-violet Technologies held in Paris, France, in 2011.

The USEPA UV Disinfection Guidance Manual (UVDGM) provides guidance for the design, validation and operation of UV systems in the United States for disinfection under the Long Term 2 Enhanced Surface water Treatment Rule. The UVDGM was prepared over six years with drafts released in 2001 and 2003 and a final version released in 2006 (USEPA, 2006). The preparation of the UVDGM was challenged by the limited experience in the US with full scale UV system implementation and validation. During the drafting of the UVDGM and over the course of a decade of full-scale experience, there has been considerable evolution in the understanding of UV disinfection. This paper describes eight issues not fully addressed by the UVDGM that impact UV dose delivery and monitoring by installed systems. Solutions to each issue are proposed.

1. The collimated beam UV dose calculation does not account for UV light reflected from the walls of the vessel.

During UV validation testing, the UV dose response curve of the microbe is used to relate the log inactivation measured through the UV reactor to a UV dose value referred to as the Reduction Equivalent Dose (RED). The UV dose response of microbe is typically measured using a collimated beam apparatus, whereby a stirred microbial suspension is exposed to UV light at 254 nm emitted by a low-pressure mercury lamp. The UVDGM specifies that the UV dose delivered to the sample is calculated using:

$$D = I_0 \times P_f \times \left(1 - R\right) \times \frac{L}{d + L} \times \frac{1 - 10^{-ad}}{Ad \ln(10)}$$  [1]

where $D$ is the UV dose, $I_0$ is the UV intensity measured using a radiometer at a location corresponding to the center of the surface of the sample, $P_f$ is the Petri factor defined as the ratio of the UV intensity measured at the center of the sample surface to the average intensity measured across the sample surface, $1 - R$ is the reflection factor, where $R$ is the reflection of UV light at 253.7 nm at the air-surface interface (typically $R = 0.025$), $L/(d + L)$ is the divergence factor where $L$ is the distance (cm) from the lamp centerline to the sample surface and $d$ is the sample depth (cm), and $(1 - 10^{-ad})/[a d \ln(10)]$ is the absorbance factor where $a$ is the absorption coefficient (cm$^{-1}$) at 253.7 nm of the suspension. (For reference, see the Low Pressure Collimated Beam Protocol published in the Summer 2015 issue of *IUVA News*.)

The standard dose calculation does not take into account the impact of the reflection of UV light from the side walls of the glass vessel containing the suspension (Figure 1). The reflected light increases the UV dose delivered to the suspension. Figure 2 shows the UV dose-response of T1UV phage measured with and without these effects. In this example, reflection off the walls of the glass irradiation vessels (8.54 cm across, 4.9 cm tall) caused a 12% error when determining the UV dose-response.

Estimations suggest that this error could exceed 20%, depending on the size of the irradiation vessel. The error is minimized by using a vessel height that does not significantly exceed the suspension depth.

Figure 1. Reflection of UV light from the side walls of the dish into the microbial suspension increases the UV dose delivered by the collimated beam apparatus.
2. Defining the zero dose calculation using a fit to the UV dose-response curve can bias the relationship between log inactivated and RED.

The UV dose-response curve, measured using the collimated beam apparatus, defines the relation between UV dose, calculated using Equation 1, and log inactivation of the microbe. Typically, the concentration of the microbes is measured as a function of UV dose, typically at 6 or 8 discrete UV dose levels. The UVDGM recommends that the log inactivation with the UV dose-response curve is calculated as:

\[ \log I = \log N_0 - \log N \]  \hspace{1cm} [2]

where \( \log I \) is the log inactivation, \( \log N \) is the logarithm of the concentration of the microbes remaining after exposure to a known UV dose, and \( \log N_0 \) is the logarithm of the concentration of the microbes with zero dose. The UVDGM recommends that the value of \( \log N_0 \) should be defined using regression analysis as the y-intercept of a mathematical fit to \( \log N \) versus UV dose. For example, the UV dose-response of MS2 phage is often fit using a polynomial function:

\[ \log N = A + B \times D + C \times D^2 \] \hspace{1cm} [3]

and \( \log N_0 \) is therefore defined as the value \( A \).

An alternate approach to the UVDGM recommendation is to define \( \log N_0 \) as the average of the log concentrations measured with a zero UV dose. Figure 3 compares the UV dose-response curve of MS2 phage obtained using these approaches. The value of \( \log N_0 \) calculated using the fit was 5.94 whereas the \( \log N_0 \) value calculated as the average of the measured log concentrations was 6.03. As shown, the RED that would be predicted for a given log inactivation through the reactor would depend on which approach was used to analyze the collimated beam data. In many cases, the bias with the UVDGM approach is random. However, there are validations where the UVDGM approach results in a notable bias that increases the RED assigned to the UV reactor. This bias is eliminated if the \( \log N_0 \) is calculated as the average of the measured log concentrations obtained with a zero dose. It is recommended that validation data be inspected for this bias. If the bias is presented, the data should be reanalyzed to eliminate the bias.

3. MS2 is not a good surrogate for Cryptosporidium at wavelengths below 240 nm.

Section D.4.1 of the 2006 UVDGM (USEPA, 2006) describes approaches for evaluating the action spectra of the test microbes used for validation. Ideally, the action spectra of the test microbes should match that of the target pathogen. The UVDGM states that the relative impact of the action spectra can be assessed by calculating the germicidal output of the UV lamps using:

\[ P_G = \sum_{\lambda=200nm}^{320} P(\lambda)G(\lambda)\Delta\lambda \] \hspace{1cm} [4]

where \( P_G \) is the germicidal output of the lamps, \( P(\lambda) \) is the UV output of the lamp as a function of the wavelength \( \lambda \), and \( G(\lambda) \) is the action spectra of the microbe. The UVDGM states that the ratio of the germicidal output of the UV lamps calculated using the action spectra of MS2 to that calculated using the action spectra of Cryptosporidium is 1.04. While the 2006 UVDGM
does not provide details on the action spectra and lamp output used to determine this ratio, the 2003 draft UVDGM did (EPA 815-D-03-007). This ratio was determined using the MS2 action spectra from 225 to 320 nm as shown in Figure F.9 of the 2003 draft UVDGM and lamp output data given in Figure F.12 of the 2003 UVDGM. The UV output of the lamp used to calculate this ratio had negligible output below 240 nm. In contrast, MP lamps used today by UV vendors have significant output at wavelengths down to 200 nm. Furthermore, UV reactors are using synthetic quartz sleeves that transmit low wavelength UV light.

Figure 4 compares the action spectra of MS2 and Cryptosporidium. The Cryptosporidium action spectra data was measured by Linden et al. (2001) and is provided in Figure 2.9 of the 2006 UVDGM (USEPA, 2006). The MS2 action data was measured by Rauth (1965) and is provided in Figure D.8 of the 2006 UVDGM. Below 240 nm, the action spectra data shows that MS2 phage is much more sensitive to UV light than is Cryptosporidium. If the MP UV lamp used during validation emits UV light below 240 nm, the REDs measured using MS2 overstate Cryptosporidium inactivation credit. The magnitude of the differences will depend on the UVT spectra of the quartz sleeves housing the lamp and the UVT spectra of the water used during validation.

**Figure 4.** Comparison of the action spectra of MS2 and Cryptosporidium shows large differences below 240 nm.

4. While UV light at wavelengths below 240 nm can have a big impact on UV dose delivery, current UV sensor technologies used by medium-pressure systems do not respond to those wavelengths. While Cryptosporidium is less sensitive to UV light at wavelengths below 240 nm than MS2 phage, adenovirus is much more sensitive. As indicated in Figure 2.9 of the UVDGM (USEPA, 2006), the ratio of the action of adenovirus to that of MS2 at 230 nm is approximately a factor of 5.3, while the ratio of the action of MS2 to that of Cryptosporidium is approximately a factor of 2.1. If a UV lamp emits UV light at wavelengths below 240 nm, the inactivation of adenovirus will be greater than indicated by MS2 REDs, by a factor of two or more.

However, this performance benefit only applies if the water does not absorb the UV light at those wavelengths (Petri et al., 2009). Lamps and sleeves may also preferentially age and foul at lower wavelengths, reducing the benefits (Wright et al., 2007). If the UV sensors do not respond to wavelengths below 240 nm (example shown in Figure 5), the UV dose monitoring system will not capture these affects. Instead, the UV dose monitoring algorithm will indicate an MS2 dose greater than is actually delivered to the water.

One solution for this issue would be to validate UV systems using Type 219 quartz sleeves, which block UV light below 240 nm. Alternatively, the UV system needs to monitor the UV output of the lamps and the UVT of the water below 240 nm and include those parameters as inputs to the UV dose monitoring algorithm.

**Figure 5.** Comparison of the spectral response of UV sensors to the action spectra of adenovirus, MS2 phage and Cryptosporidium.

5. **Empirical UV dose algorithms can provide poor interpolation of UV dose if they use the wrong functional relationship between UV dose and the dependent variables.**

The UVDGM states that validation data can be analyzed to define a UV dose monitoring equation that expresses RED as a function of flow rate, UV absorbance of the water, UV sensor readings, and banks of lamps, if applicable. The UVDGM (USEPA, 2006) states that the following empirical equation provides a good fit to validation data:
where RED is the Reduction Equivalent Dose, UVA is the UV absorbance of the water, Q is the flow rate through the UV reactor, B is the number of banks of operating lamps, and \( S/S_0 \) is the relative lamp output calculated as the measured UV intensity (S) divided by the UV intensity \( (S_0) \) predicted for new lamps operating at 100% ballast power in new and clean quartz sleeves and being monitored by a calibrated UV sensor through a new, clean UV sensor port window. With MP UV systems, the UV sensor equation used to predict \( S_0 \) has the form:

\[
S = 10^4 \times \exp \left( B \times UVT \right) \times P^C
\]  

where \( UVT \) is the UV transmittance of the water, \( P \) is the ballast power setting, and \( A, B \) and \( C \) are constants obtained by fitting the equation to validation data. With LPHO UV systems, the UV sensor equations typically has the form:

\[
S = 10^4 \times \exp \left( B \times UVT \right) \times \exp \left( \frac{C}{P} \right)
\]

The UVDGM (USEPA, 2006) states that the exact form of the UV dose monitoring equation will depend on the reactor and the functional relations between the RED and each variable. One approach for identifying the functional relations is to plot RED against one variable holding the others constant. For example, as shown in Figure 6, at a fixed UVA and bank configuration, RED can be expressed as a function of a combined variable \( (S/S_0)/Q \) using:

\[
RED = a' \times \left( \frac{S}{S_0} \right)^{b'} Q
\]

where \( a' \) and \( b' \) are constants obtained from regression analysis. The values of \( a' \) and \( b' \) vary as a function of UVA. The relation between \( a' \) and UVA can be expressed as:

\[
a' = 10^4 \times UVA^b
\]

while the relation between \( b' \) and UVA is expressed as:

\[
b' = C + d \times UVA + e \times UVA^2
\]
Equation 10 accounts for the curvature in the relation between RED and \((S/S_0)/Q\), which increases at lower UVT. The curvature reflects the impact of the UV dose distribution on the RED. At high UVTs, the UV dose distribution is narrow and the relation is almost linear (i.e. \(b' \rightarrow 1.0\)). At low UVTs, the UV dose distribution is relatively wide, and the relation shows significant curvature (i.e. \(b' < 1\)).

\[
RED = 10^a \times UVA^b \times \left( \frac{S}{S_0} \right)^{c+dUVA+eUVA^2} \times \left( \frac{Q}{Q} \right)^{f+gUVA+hUVA^2} \times Banks^{i+jUVA+kUVA^2} [14]
\]

Typically, the impact of \(Banks\) on RED is independent of the impact of the combined variable \((S/S_0)/Q\), and these terms cannot be combined.

The overall approach described in Equations 8 to 14 leads to a UV dose equation that is functionally different from Equation 5 given in the UVDGM (USEPA, 2006). Both equations can be fitted to validation data with relatively high R-squared values; however, Equation 11 (or Equation 14 if the reactor validation includes banks) always provides a higher R-squared value. Typically, all the terms of Equation 5 are statistically significant, whereas most if not all of the terms of Equation 11 (or Equation 14) are statistically significant. However, because Equation 5 does not account for dependence of the curvature of RED vs. \((S/S_0)/Q\) on UVT, Equation 5 can provide biased predictions of UV reactor performance by as much as 25 or 30%. Given the potential for such errors, validation reports should provide a rationale for the equations used to fit the biodosimetry data, showing that the functional relations used are appropriate for the underlying data and demonstrating that the coefficients are statistically significant.

6. The optimal UV sensor location for UV intensity setpoint monitoring can result in significant under-dosing.

The UVDGM (USEPA, 2006) specifies two approaches for UV dose monitoring: the calculated dose approach (see Equation 5) and the UV intensity setpoint approach. The UV intensity setpoint approach is also specified by the German DVGW and Austrian ONORM UV disinfection rules.

With the UV intensity setpoint approach, the UV reactor delivers a specified UV dose when the UV sensor reading is equal to or greater than an alarm setpoint value that is defined as a function of flow rate. The UVDGM, DVGW and ONORM protocols specify that the UV intensity setpoint approach should be validated using two test conditions. With the first test condition, the reactor operates at the maximum ballast power (typically 100%) and a decreased UVT until the UV sensor reads at the alarm level. With the second test condition, the reactor operates at the maximum UVT (typically 98%), and the lamp power is lowered until the UV sensor reads at the alarm level. The RED measured under these conditions depends on the placement of the UV sensor relative to the lamps. If the UV sensor is located relatively close to the lamps, the RED measured with the first test condition will be lower than that measured with the second test condition. If the UV sensor is located relatively far from the lamps, the RED measured with the second test condition will be lower than that
measured with the first test condition. At some intermediate UV sensor location, the REDs measured with the two test conditions will have the same value. The UVDGM, DVGW and ONORM protocols state that the UV reactor is rated based on the lowest RED measured with the two test conditions. As such, UV vendors are motivated to locate their UV sensors at the intermediate position where the two REDs have a similar value.

An underlying assumption with the two test conditions is that at UVT and ballast power combinations that result in UV sensor readings at the setpoint value, the RED will have a value that lies between the two values measured with test conditions 1 and 2. However, as shown in Figure 7, this assumption does not hold true. Figure 7 shows a plot of RED as a function of UV sensor reading divided by the flow rate observed during UV reactor validation. As shown, the relationships at low UVT (70%) and high UVT (97%) overlap such that an RED of 40 mJ/cm² is associated with an $S/Q$ of 220 mW/cm² per mgd. However, at UVT values between 70% and 97%, the REDs associated with an $S/Q$ of 220 mW/cm² per mgd range from 40 down to 24 mJ/cm². This issue is addressed if the UV intensity setpoint validation includes a third test point at an intermediate UVT.

![Figure 7. Relationship between RED and UV sensor reading divided by flow rate shows that UV intensity setpoint validation should include test points at intermediate UVT values.](image)

7. The UVT measured during validation with LSA as a UV absorber is strongly impacted by the wavelength accuracy of the spectrophotometer.

Figures 8a and 8b show the UVT spectra of validation test waters adjusted using LSA. Because the LSA spectrum has a significant slope at 254 nm, a 1 nm wavelength error with a spectrophotometer (the wavelength accuracy of many commercial spectrophotometers) will cause a significant error measuring UVT at 254 nm. For example, the UVT at 253, 254 and 255 nm with the spectra shown in Figure 8 is 81.3%, 82.3% and 83.1%, respectively. While the impact appears small over a 1 cm path length in water, the differences are significant over the longer path lengths that occur within a UV reactor, and these errors have a significant impact on the accuracy of RED predictions by the UV dose monitoring algorithm. The errors are eliminated by using a UV photometer equipped with a LP lamp to...
measure the UVT during validation, since the wavelength of the UV output from the LP lamps is fixed at 253.7 nm.

8. A 2 percent UVT monitoring error with UV system operation can cause large UV dose monitoring errors at high UVTs.

The UVDGM (USEPA, 2006) states that the accuracy of the online UVT monitor should be checked at least weekly by comparison of the online UVT measurements to UVT measurements using a bench-top spectrophotometer. The UVDGM states that the online UVT monitor must not deviate by more than two percent UVT from the spectrophotometer measurements.

The UVDGM does not discuss the magnitude of the RED error than can occur with a 2% UVT monitor error. The RED error, however, can be calculated using the UV dose monitoring equation provided in the validation report. Typically, the UVT monitor error impacts the accuracy of UV dose monitoring in two ways. First, the UVT monitor error impacts the UVA (or UVT) used in the UV dose monitoring equations (see Equations 11 or 14). Secondly, the UVT monitor error impacts the value of $S_0$ used to calculate the ratio $S/S_0$ (see Equations 6 and 7). The impact of the UVT monitor on the value of $S/S0$ depends on the location of the UV sensor relative to the lamps, and is greater when the UV sensor is relatively far from the lamps.

As an example, Figure 9 shows the RED error as a function of true UVT where the online UVT meter read 2% greater than the true UVT. With this particular UV reactor, the error in the calculated RED varies with UVT and ranges from 9 to -42%. These errors can lead to significant under- or overdosing by the reactor and can be minimized by specifying tighter criteria for UVT monitor accuracy.

Summary

This paper describes eight issues not fully addressed by the UVDGM that impact UV dose delivery and monitoring by installed UV systems. The impact ranges from a few percent to as much as 50%. Currently, there is no formal mechanism for addressing issues with the UVDGM and future updates of the UVDGM are not anticipated at this time. It is recommended that IUVA develop a working group of stakeholders to address issues with the UVDGM and provide communications on these issues and their solutions.

References


Calculating UV Dose for UV/AOP Reactors Using Dose/Log as a Water-Quality Metric

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Abstract
A method for scale up of UV/AOP reactors is outlined that uses bench scale testing to determine the UV dose required per log destruction ($D_L$) of a particular contaminant. This can then be used in CFD Modeling to size a full-scale UV reactor and to test the reactor in performance trials. Methods for calculating dose based on the path length distribution in a UV reactor are given.

Keywords: Advanced Oxidation; AOP; Pilot Testing; Scale up; CFD; Geosmin; MIB; Ultraviolet; UV; UV/Peroxide; UV/Chlorine; Direct photolysis; Dose per Log; $D_L$

Background
Traditional methods using Electrical Energy per Order ($E_{EO}$) (Bolton et al., 2001) to compare the performance of various full scale AOP technologies, while useful, are not effective in translating collimated beam or bench testing to full-scale. While most parameters that affect the $E_{EO}$ of a reactor (lamp output, lamp efficiency, path length) can be scaled up from laboratory scale to full-scale without much difficulty, Computational Fluid Dynamic modeling (CFD) is needed to predict the hydraulic or mixing efficiency of a flow-through UV reactor. This article describes a method that has been developed that uses bench-scale testing to determine the UV dose required per log destruction of a particular contaminant ($D_L$) and methods for calculating the dose applied.

UV dose for Medium Pressure (MP) UV/H_2O_2 reactors is defined as the integral, by wavelength, of the UV dose, weighted by the peroxide (or other photoactive reactant) absorption coefficient relative to its value at 254 nm (H_2O_2 weighted UV dose). This is similar to UV dose in disinfection reactors, which is weighted by the germicidal (DNA) absorption spectrum relative to that at 254 nm, or by the action spectra of specific microbes (germicidal dose). As in disinfection UV reactors, and unlike the $E_{EO}$, $D_L$ is independent of the lamp spectral output, the UV transmittance and the path length that UV traverses in a reactor. Unlike disinfection reactors, however, $D_L$ in AOP reactors is dependent on the H_2O_2 concentration and the scavenging potential of the water. Therefore tests must be performed on a representative sample of water at one or more H_2O_2 concentrations to determine the scavenging potential, or better still, if the contaminant(s) of concern are used in the bench testing, the $D_L$ of the contaminant. This can then be used in CFD modeling to determine the destruction of the contaminant at each point in the reactor, and hence the full-scale performance incorporating the hydraulic efficiency can be determined. This empirical method greatly simplifies the CFD modeling of an AOP reactor where otherwise the simultaneous chemical reactions would need to be modeled.

Calculation of Average Dose in a UV Reactor
The average UV dose imparted to water passing through a UV reactor or over time in a batch reactor can be calculated from the average irradiance in the reactor, the volume in the reactor and the flow rate. However, calculating the average irradiance is complex requiring the use of computer modeling, such as UVCalc (Bolton Photosciences Inc.), and has to be done at all UV transmittances of interest. In addition, issues of shading by adjacent quartz tubes and reflection of those same tubes and the reactor wall add complexity.

An alternate simpler technique to calculate UV dose has been developed based on the path length distribution of the photons, the radiant flux of UV entering the water and the UV transmittance of the water. The equation for this calculation can be derived from first principles, but in this derivation the well known collimated beam dose calculation equation will be used as a starting point. The principle of the collimated beam calculator is that the irradiance is integrated over the column of water that the UV passes through, taking into consideration the attenuation of the UV. The depth of this column of water ($d$) is the path length that the UV is afforded. Not all the UV penetrates through this column but this “path length” is the maximum distance that the UV can travel. The dose is calculated from this path length, the time of exposure and the absorbance of the water by the following equation:

$$ D = E_s P_t \left(1 - R\right) \frac{L}{(d + L)} \left(1 - 10^{-a_{254} d}\right) t $$

where:
- $D = \text{UV dose (mJ/cm}^2\text{)}$
- $E_s = \text{UV irradiance at the center of the surface where UV enters the water}$
- $P_t = \text{power transfer factor}$
- $L = \text{length of UV reactor}$
- $d = \text{path length (cm)}$
- $R = \text{reflectance}$
- $a_{254} = \text{absorbance at 254 nm}$
- $t = \text{time of exposure (s)}$

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\( P_f = \) the Petri Factor
\( R = \) Reflectance at the air water interface
\( L/(d + L) = \) Divergence Factor
\( d = \) depth of suspension (cm)
\( L = \) the distance (cm) from the surface of water to UV lamp
\( a_{254} = \) UV absorption coefficient \((\text{cm}^{-1})\) at 254 nm
\( t = \) Exposure time(s)

For a perfect collimated beam, the Petri factor and \( L/(d + L) = 1\), and if \( E_e \) is the UV irradiance entering the water, or \( E_e = E_s P_f (1 - R) \)

\[
D = E_e \left(1 - 10^{-a_{254}d}\right) \frac{t}{\ln(10)} \quad [2]
\]

Or, for \( P_e \) the total radiant power entering the water spread over area \( A \), \( E_e = P_e / A \)

\[
D = \frac{P_e}{A} \left(1 - 10^{-a_{254}d}\right) \frac{t}{\ln(10)} \quad [3]
\]

**Batch reactor**

For a batch reactor of Volume \( V = A \times d \),

\[
D = \frac{P_e}{V} \left(1 - 10^{-a_{254}d}\right) \frac{t}{a_{254} \ln(10)} \quad [4]
\]

Therefore the UV dose is a function of the radiant power entering the water, the path length, the volume, the exposure time and the UV absorption coefficient.

Note, as would be expected, the UV dose is independent of area \( A \) and only dependent on the distance that can be traveled or the path length \( (d) \) for any “column” of photons. If there are multiple path lengths in a non-uniform batch reactor:

\[
D = \sum_{d_i} \frac{PF_i}{V} \left(1 - 10^{-a_{254}d_i}\right) \frac{t}{a_{254} \ln(10)} \quad [5]
\]

where \( F_i \) is the fraction of UV with path length \( d_i \).

**Flow-through reactor**

For a flow-through reactor the Flow rate \( Q = \frac{\text{Volume}}{\text{Time}} \), therefore:

\[
D = \sum_{d_i} \frac{PF_i}{Q} \left(1 - 10^{-a_{254}d_i}\right) \frac{t}{a_{254} \ln(10)} \quad [6]
\]

However, caution must be used for the UV dose calculated for a flow-through reactor, as it does not include the hydraulic efficiency resulting from the UV dose distribution. CFD modeling should be used to determine the delivered dose or “Reduction Equivalent Dose”.

**Calculating path length**

The path length distribution in a UV reactor can be calculated from reactor geometry, where all the UV emits from the quartz in an arc approximately \(+/-\) 45 deg to the normal (the UV coming out of a quartz tube is limited to a \(+/-\) 45 degree angle due to internal reflection and refraction by the quartz tube). If the lamps are transverse to the flow a significant proportion of the UV shines up and down the pipe approaching the reactor. These much longer path lengths are only important at very high UV transmittance.

The graph shows UV dose vs. path length for a \( P_e F / V \) ratio of 1.

As can be seen, the UV dose is relatively independent of path length, especially at lower UVT’s (<90%T) and higher path lengths (> 20 cm). That is because substantially all the UV is gone by 20 cm at 90%T and so providing extra path length for it...
to traverse does not result in an additional UV dose contribution. Conversely, at very high UVT’s (>97%T) the UV can penetrate beyond 100 cm and consequently larger diameter reactors and the UV that shines up and down the inlet/outlet piping can add substantially to the UV dose. However, in general, an error in the calculated path length only impacts the UV dose provided by the UV that travels beyond the lower bound of this error, and this is small compared to the total UV dose calculated; therefore being very accurate in the determination of the path length distribution is usually not critical.

Summing over 10 path length groupings, each representing 10% of the photons, is usually sufficient. One technique is to use the reactor geometry to obtain a rough estimate of the path lengths of the 10 (or more) groupings. CFD modeling can then be used to calculate the “mass average UV dose” of the water passing through the reactor at four or five different UVT’s. The equation above is then used to adjust the path lengths to obtain the best fit to the CFD model results. In this manner, the UV dose calculated by the equations will match the CFD results over all UVT’s, spectral distributions, etc.

**Polychromatic light**

The UV dose for Medium Pressure (MP) UV/H₂O₂ reactors is defined as the integral, by wavelength, of the dose, weighted by the H₂O₂ absorption coefficient relative to its value at 254 nm (H₂O₂ weighted UV dose). This is similar to UV dose in disinfection reactors, which is weighted by the germicidal (DNA) absorption spectrum (germicidal dose) or by the action spectra of specific microbes. As in disinfection UV reactors, Dₜ is independent of the lamp spectral output, the UV transmittance and the path length that UV traverses in a reactor. Therefore results from testing using a low-pressure (LP) lamp (254 nm) in a collimated beam or batch reactor can be used to scale up to a medium pressure (polychromatic) reactor and vice versa.

The UV dose for a batch reactor is therefore calculated by dividing the spectral output typically into 20 or 100 wavebands (5 nm or 1 nm intervals) and summing over all wavelengths

\[
D = \sum_{\lambda=200nm}^{300nm} \sum_{i} \frac{P_\lambda r_\lambda F_\lambda (1-10^{-a_\lambda d_i})}{a_\lambda \ln(10)} t \quad [7]
\]

where:

- \(P_\lambda\) is the total radiant power at waveband \(\lambda\) entering the water.
- \(r_\lambda\) is the relative absorption coefficient of the oxidant or photoactive species at wavelength \(\lambda\) to that at 254 nm. If the quantum yield varies with UV wavelength, then this factor should be multiplied by the relative quantum yield at wavelength \(\lambda\) to that at 254 nm.
- \(a_\lambda\) is absorption coefficient (cm⁻¹) of the water at wavelength \(\lambda\).

The wavelength range (200 to 300 nm above) should be sufficient to encompass the entire absorption band of the oxidant or photoactive species. The relative absorption coefficient is used because that determines the photons absorbed at wavelength \(\lambda\) relative to those absorbed at 254 nm and thereby converts the UV dose to a 254 nm equivalent dose (as is done for disinfection reactors).

The UV dose in a flow through reactor can be calculated by

\[
D = \sum_{\lambda=200nm}^{300nm} \sum_{i} \frac{P_\lambda r_\lambda F_\lambda (1-10^{-a_\lambda d_i})}{a_\lambda \ln(10)} \quad [8]
\]

**Bench test results**

The results from laboratory testing can be plotted as the log of
the contaminant concentration vs. the UV dose calculated by the above equations.

The inverse slope of the curves is calculated as the dose per log
or $D_L$ (mJ/cm²/log destruction). As can be seen, for first order
kinetics, the $D_L$ is independent of concentration.

**CFD Modeling to Predict Full-Scale Performance**

As mentioned earlier, the results from collimated beam or
“perfectly mixed” batch reactor testing do not include the
hydraulic inefficiency that results from the uneven UV dose
distribution in a full-scale reactor.

**Hydrogen Peroxide Weighted Dose**

For full-scale, UV Intensity modeling (UVI) is used to calculate
the hydrogen peroxide (or other photo-active species) weighted
UV dose in each of the meshed CFD cells (the UV reactor is
divided into approximately 3 million cells).

$$D_{H_2O_2} = \sum_{\lambda=200nm}^{300nm} E_{\lambda} r_{\lambda} t$$  \[9\]

where

$D_{H_2O_2}$ is the hydrogen peroxide (or other photoactive species)
weighted UV dose in the CFD cell

$E_{\lambda}$ is the total UV irradiance (fluence rate) at waveband $\lambda$ at the
CFD cell

$r_{\lambda}$ is the relative absorption coefficient of hydrogen peroxide
(or other photoactive species) at wavelength $\lambda$ to that at 254 nm

$t$ is residence time of the water in the CFD cell

The $D_L$ above (from the batch testing) is multiplied by the
hydrogen peroxide weighted UV dose in each CFD cell to
compute the destruction of the target contaminant in each mesh
cell, and hence in the reactor as a whole as the water passes
through. This way any hydraulic inefficiencies are accounted
for as the greater destruction in the higher intensity field close
to the UV lamps is mixed back with the lower destruction in
water further away from the UV lamps.

**Contaminant Destruction**

A typical CFD plot of the Geosmin destruction through the
reactor (Bircher et al., 2011) is shown below.

![Log geosmin destruction. Flow is from right to left.](image)

**Validation of Method for Scale-Up of AOP Reactors**

Validation testing has been performed using both the Sentinel
Chevron 48 inch reactor with 18 x 20 kW lamps and the 24
inch reactor with 9 x 10 kW lamps. The former was reported on
(Bircher et al., 2011) and showed that the $D_L$ obtained from batch
reactor tests on the same water as the full-scale tests can be used
in CFD modeling to accurately predict the full-scale performance.

**Direct UV Photolysis**

This approach can be used in direct photolysis (e.g., NDMA
destruction) with the absorption coefficient of the target substi-
tuted for that of hydrogen peroxide in all instances.

If the destruction of the contaminant is primarily by direct
photolysis (NDMA) then the $D_L$ is constant regardless of water
quality and hydrogen peroxide concentration and CFD alone
can be used to predict performance since $D_L$ is known.

**UV/ Chlorine**

The photolysis of chlorine is complicated by the fact that chlo-
rine in water dissociates into HClO and ClO⁻ depending on the
pH (pKₐ = 7.49). Both compounds absorb UV powerfully with
ClO⁻ showing particularly strong absorbance up to 350 nm.

As such, the output of medium pressure lamps between 280 and
320 nm can be used very efficiently owing to the typically low
background absorbance of waters at these wavelengths. In fact,
MP lamp systems would require similar total lamp power as
low pressure lamp systems at pH’s between 5.5 and 7 and less
This is in stark contrast to disinfection systems where MP systems typically require two to three times the total lamp power of LP systems.

However, ClO⁻ reacts very fast with the hydroxyl radicals, negating the higher absorption by ClO⁻ at high pH. The net result is that the UV/chlorine AOP is more efficient at pH < 6.5, where HClO is the predominant species.

Calculating UV dose with the UV/Chlorine AOP is done in the same way as with hydrogen peroxide except this very strong pH dependence must be considered; it must be summed for both chlorine species normalized for their respective quantum yields at 254 nm and the integration must be carried out to 360 nm.

Discussion

The hydrogen peroxide weighted UV dose per log inactivation ($D_L$) derived from empirical performance data generated from bench-scale testing can be used in CFD modeling to accurately predict the performance of full-scale UV AOP systems. Using this method, the performance of a full-scale system can be reliably predicted from bench-scale testing of a representative sample of water.

The $D_L$ water quality metric can be used to specify the performance requirements of UV AOP systems and then be checked in performance testing of the installed system, reducing the risk for both purchasers and suppliers of UV AOP systems.

$D_L$ is inversely proportional to the reaction rate constant with the hydroxyl radical for compounds that do not react signifi-
cantly to direct photolysis.

Therefore, it can be measured for one compound or surrogate in a water matrix and then derived for all other compounds of interest, provided their individual reaction rate constant with ·OH is known. In addition, the impact of all hydroxyl scavengers in the tested water (such as carbonate/bicarbonate, TOC, H₂O₂, etc.) can be calculated, and from that, a $D_L$ can be specified having been adjusted for design water quality conditions.

This approach has benefits to all parties in an AOP purchase and installation.

\[
\text{References}
\]


UV Treatment: A Solution for Small Community Water Supplies?

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Introduction
In December 2014, the authors started an international collaborative research program entitled “Innovative UV Technologies for the Removal of Emerging Contaminants and Sustainable Water Supplies in Small Communities.” Drs. Oguma and Mohseni respectively serve as principal investigators (PIs) for the Japanese and Canadian teams in this three-year project, which is supported by the Japan Science and Technology Agency (JST) and the Natural Sciences and Engineering Research Council of Canada (NSERC).

Several institutions in both countries are participating in the project – Japanese team members come from the University of Tokyo, National Institute of Public Health and Hokkaido University, while the Canadian team includes experts from the University of British Columbia, École Polytechnique de Montréal and Dalhousie University. This research collaboration builds on the work of the RES’EAU-WaterNET Strategic Network in Canada, which is a multi-disciplinary program funded by NSERC with partners from industry, communities, government and NGOs, and which focuses on the development of affordable solutions to the drinking water challenges faced by small and rural and aboriginal communities (SRCs).

The need for, and potential utility of, such collaboration is illustrated in Figure 1. Japan and Canada share common challenges stemming from limitations in financial and human resources that hinder efforts to ensure the provision of safe drinking water in SRCs in an effective and sustainable manner. The use of UV, with its great potential for applications in small community settings, is growing in Japan following the enforcement of the UV disinfection guideline in 2007 (Figure 2). Canada’s extensive experience in the application of UV disinfection and advanced oxidation will be of great value to Japanese researchers and the communities they serve, as they strive to advance the use of UV technology in various applications. Meanwhile, North America has in recent years been facing the growing problem of eutrophication and harmful algal blooms in shallow lakes and reservoirs. On these matters, Japan’s deep expertise in algal bloom monitoring and the routine treatment of taste and odor (T&O) compounds in drinking water may be valuable for Canada. As such, the research strengths and expertise of both countries are complementary, leading to mutual benefit and a win-win relationship in collaboration. Team members of both countries have ongoing research projects focusing on UV-based technologies, which is a great accelerator to promote collaboration.

Challenges in Japan
According the Ministry of Health, Labor and Welfare (MHLW), over 95% of people in Japan having connection to a water supply are served by large public water utilities with populations of 5,001 or more. Meanwhile, based on the number of facilities, small public water supplies (about 6,100 facilities) and private water supplies (about 8,100 facilities) account for roughly 90%
of the total water supply systems in Japan. It should be noted that these statistics are for facilities serving a population of 101 or more; that is, those serving 100 people or less do not appear in the data. Our estimation suggests that over three million people in Japan are served by these “invisible” facilities.

Small water systems commonly use nearby streams or groundwater as the source, with chlorination. Over the past 30 years, water quality incidents in Japan with negative health impacts have mostly been associated with microbial contamination (Kishida et al., 2015). Waterborne diseases caused by pathogens in water have been reported almost every year for decades, and only 4% of such incidents occurred at large public water supply systems (serving pop. ≥5,001). Namely, the remaining portion of incidents leading to negative health impacts has occurred at small water systems, particularly at very small water supply systems serving a population of 100 or less. Hence, it is evident there is a clear and urgent social need in Japan for effective and robust water disinfection technologies that work reliably in small water settings.

The population in Japan has been decreasing since 2008 and the society has been aging very rapidly. These phenomena can have negative consequences on water utilities, such as a decrease in water sales revenue, lower economic efficiency arising from lower water demand density, limited human resources and less skillful engineers, and the presence of more sensitive customers. Moreover, climate change is an emerging threat to water utilities, and adaptation measures require additional cost. These difficulties are particularly hard for small water supply utilities with significant human and financial limitations.

**Challenges in Canada**

Approximately 80% of Canadians live in urban areas and enjoy a relatively stress-free relationship with their water supply and treatment systems. However, a multitude of factors make providing even basic services much more difficult for SRCs. In March 2015, the Council of Canadians (Council of Canadians, 2015) reported nearly 1838 water advisories in SRCs in Canada. This includes 169 advisories in 126 First Nations communities, out of nearly 600 First Nations communities across the country. These advisories are generally intended to be a precautionary measure in the public health tool kit, ensuring the public is protected from exposure to harmful waterborne pathogens. However, given that some advisories have been in place for years, it is apparent that they are used as substitute for proper disinfection and treatment.

While the risk of microbiological contamination is still a primary concern and the impetus for boil water advisories in many small and remote communities, disinfection by-products (DBPs), seasonal algal toxins and T&O compounds also pose significant risks to public health and represent major issues to overcome. Indeed, eutrophication of shallow lakes is a key emerging issue in Canada affecting the quality of drinking water sources of many SRCs. A combination of climate change, population growth and evolving land use activities have resulted in algal and cyanobacterial bloom occurrences, raising a serious concern for public health and safety due to the increased detection of cyanotoxins in the impacted waters. Tackling the issues of cyanotoxins and T&O compounds for small water systems can be quite challenging, given the fact that many such systems are at a comparative disadvantage due to their size (e.g., limited financial and human resources), and often due to their remote location.

**UV Technology as a Potential Solution**

Challenges in Japan and Canada clearly indicate the need to explore technologies suitable for small water systems in terms of reliability, robustness, feasibility and sustainability. The goals of this Japan-Canada research collaboration include, but are not limited to, the application of UV light emitting diodes (UV LEDs) for water disinfection at small facilities and/or point-of-use systems, as well as the UV-based advanced oxidation (UV-AOP) process for decomposing emerging micro pollutants, such as cyanotoxins and T&O compounds.

Such UV-based technologies will be evaluated in comparison with other relevant unit processes, such as chlorination (for disinfection) and ozone or activated carbon adsorption (for T&O control), and the final outcome will include technical data required for the design, implementation and operation of the technologies in small community settings.

**Past and Upcoming Activities**

This research collaboration was kicked off with a workshop at the University of Tokyo in January 2015, followed by a special session at the 10th International Symposium on Water Supply Technology in Kobe, Japan, in July 2015. At the Kobe symposium, more than 70 international participants from academia, industries and water utilities joined in the discussion and information sharing. Moreover, team members have joined site visits at small water systems in Japan and in Canada (Figure 3), resulting in a deeper understanding of the issues and opportunities at hand.

A special session on the application of UV in small water systems will be held at the IUVA World Congress 2016 in Vancouver. Needless to say, small water supply systems are of concern in many other countries. We are very much looking forward to having many international participants with diverse
backgrounds to share and bridge our knowledge for a better future for all nations facing similar challenges.

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References

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Figure 3. From left, visits to small water treatment systems in Japan (Yabu, Hyogo) and in Canada (Agassiz, British Columbia).
October
• RadTech Europe 2015, Oct. 13-15
  Prague, Czech Republic
  www.radtech-europe.com/events/radtech15
• UV LED 2015, Oct. 28-29
  Hilton Garden Inn, Troy, N.Y.
  www.uvled2015.com

January
• IUVA World Congress, Jan. 31-Feb. 3
  Vancouver, British Columbia, Canada
  www.worldcongress2015.org

May
• RadTech UV/EB Conference, May 16-18
  Hyatt Regency O’Hare, Rosemont, Ill.
  www.radtech2016.com

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