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An Overview of UV-based Advanced Oxidation Processes for Drinking Water Treatment

Five Frequently Asked Questions About UV-Safety

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IUVA’s Web Page: www.IUVA.org
By now you should have ‘viewed’ the first Issue of IUVA News in electronic form. I would very much appreciate feedback on how you liked it (as well as this Issue 2).

The IUVA Web Site continues to evolve. Here are some of the changes:

The UV Buyer’s Guide has been “automated” (this is the most popular page on the web site, other than the Home page). If you are a manufacturer or distributor of UV products or a service provider, you can enter your listings, edit or update them and pay online for the charges. Go to http://www.iuva.org/public/buyersguide2.php and click on “CLICK HERE NOW”.

Encourage your friends and colleagues to join IUVA – it is easy to do online with a credit card – go to http://www.iuva.org/mbr/mbrapp.php.

I continue to update the UV references and UV patents in the Member Zone. If you see that I am missing references, please send them to me (jim.bolton@iuva.org). Also make sure that your UV references are listed by sending me your publications list.

I am creating a “What is UV?” page to be placed under the ‘UV Information’ tab on the Home page. If you have some ideas as to what should go onto that page, I would be pleased to hear from you.

The Organizing Committee for the World UV/Ozone Congress will meet in San Antonio on 11 June. This exciting event will take place at the Hyatt Century Plaza Hotel in Los Angeles, CA 25 – 30 August 2007. We are planning to have several ‘Mini-Symposia’, each organized by a specialist in that field. If you have any thoughts as to a Symposium Topic and a possible organizer, please let me know.

We continue to receive high quality articles, as this issue demonstrates. If you would like to write an article, or can recommend someone who should write an article for IUVA News, please let me know (jimbolton@iuva.org) and I’ll send you the “Instructions to Authors”.

Hope that you all enjoyed the first e-version of IUVA News recently. We received a lot of positive feedback, and we have to congratulate Jim Bolton for his excellent work. Having said that we managed the transition from print to electronic format, we are coming closer to the point where we have to decide about another even more difficult decision about the future of IUVA, which is the time after Jim Bolton’s retirement. The EOC has set a goal to have that decision done shortly after our next board meeting in San Antonio this year since we have to have some time to manage the transition after a decision has been made.

The options are: (1) collaboration with another association without losing our identity and (2) staying completely separate which would require a succession plan for Jim. Both ways are not easy and we are still in the evaluation phase. I would like to encourage you to participate in that important process. Please give me your input, questions or comments (Andreas.kolch@itt.com). We do not want to miss any voice here.

Other than that I am happy to say, that our conference in 2007 has been set up so far, that we are entering the detailed planning process. We will shortly have a program committee in place waiting to solicit your contributions.

Our new Manufacturers’ Council operates now under the first Chair, Bertrand Dussert, and the Awards Committee will shortly start under the supervision of Elliott Whitby. We have to thank both for their willingness to contribute and thus help giving us the structural add-on’s we need to better serve our member’s needs.

Budget and membership are well on track and we are not loosing any momentum in still offering strong workshop opportunities.

I hope that all of you make use of what is offered and enjoy being with IUVA and our activities. Please also join us through the important transition ahead for our association.

Andreas
The following are some of the more interesting items from the UV News page on the IUVA Web Site (http://iuva.org/public/uv_news.php). Some of these items have been provided by IUVA Board Member, Joan Oppenheimer, from MWH Applied Research Dept. in Pasadena, CA who has volunteered to help with selecting items for UV News. Thank you, Joan!

17 May 2006: LEDs move into the ultraviolet, PhysicsWeb
http://physicsweb.org/articles/news/10/5/10/1
Physicists in Japan have made a diode that emits light at the shortest wavelength ever. The device, made by Yoshitaka Taniyasu and colleagues at NTT Basic Research Laboratories in Atsugi, is made from aluminum nitride and emits deep in the ultraviolet part of the spectrum at 210 nanometres (Nature 441 325). The work represents an important step towards the development of very low-wavelength light emitters that could find use in a wide variety of applications, including medicine, photolithography and to destroy bacteria in water...

BERKELEY, CA — Three University of California, Berkeley engineering students are working in impoverished areas of India, Sri Lanka and Mexico to help provide inexpensive drinking water to residents, according to a May 13 San Francisco Chronicle report.

In rural Baja California Sur and Sri Lanka, two doctoral students are installing ultraviolet tubes to disinfect drinking water in household barrels; another student is working with female community leaders in Bombay, India, to improve drinking water quality through the use of a $5 filter, the report said...

28 April 2006: MI plant switches from chlorine to UV, WaterTech Online.
WYANDOTTE, MI — The Downriver Wastewater Treatment Facility has stopped using chlorine gas to treat wastewater and replaced it with an ultraviolet (UV) process, according to an April 28 news report in the Detroit News (http://www.detnews.com/apps/pbcs.dll/article?AID=/20060428/METRO01/604280374/1003/METRO).

The Wyandotte, MI-based treatment plant is one of 284 chemical facilities in 47 states, named in a report released this week, that have reduced the danger of a chlorine gas release by switching to less hazardous processes, the report said...

19 April 2006: First New Jersey public UV treatment facility, WaterTech Online.
PHILLIPSBURG, NJ — The state’s first public water treatment facility using ultraviolet light (UV) disinfection technology is up and running in Lopatcong Township, serving 10,600 Aqua New Jersey Inc. customers in four townships, according to a March 24 Aqua America press release.

The $2.6 million treatment facility is capable of treating 10.5 million gallons per day, using the UV treatment as an added level of disinfection in the chlorination process, the release said...

The following are some of the more interesting items from the UV Industry Announcements page on the IUVA Web Site (http://www.iuva.org/public/uv_industry_announcements).

30 May 2006: Philips promotes a lamp with the power to purify water Royal Philips Electronics (AEX: PHI, NYSE: PHG) – has launched a major promotional campaign aimed at the purification of water with its products and knowledge of ultraviolet lamps. At a time of rising populations and fast-increasing demand for water, 1.2 billion people around the world still have no access to safe drinking water supplies. Easy-to-install water purification systems with ultraviolet light offer a cost effective solution for providing safe water...

... Philips makes UV water purification possible with a range of special lamps, ballasts and sleeves that are suitable to build into filter units. The easy-to-use, easy-to-install technology promises to free communities from the threat of water borne diseases, caused by micro-organisms such as bacteria and viruses. Philips offers solutions for different markets covering different preferences and installation possibilities for residential and municipal drinking water, waste water, industrial water, swimming pools and other leisure facilities...

Contact Nicole Brekelmans (nicole.brekelman@philips.com)

17 May 2006: 360° field-of-view UV-C Detector, Gigahertz-Optik, Inc.
The low drift solid-state ROD-360-UV18 Detector has been developed by Gigahertz-Optik specifically for the measurement of effective ultraviolet germicidal irradiance (UVGI) applied in air and water sterilization applications employing low and medium pressure Hg or pulsed Xenon lamps. Since it receives impinging UV signal over a full 360°, more like the subject target of irradiation, it provides a better gauge of UV dose or fluence than the standard planar detector...

Contact Bob Angelo (b.angelo@gigahertz-optik.com)

4 March 2006: Market Launch New ITT WEDECO UV-Series “Spektron”, WEDECO/ITT Industries. http://www.wedeco.com/ (Click on Public Relations/Latest Press Releases) For more than 12 years, WEDECO AG as a leading UV manufacturer has been providing the municipal drinking water market with UV systems certified according to stringent Central European requirements (German DVGW W-294 and Austrian M-5871). WEDECO’s new UV product line “Spektron”, has been specifically designed for this market application. Employing the most up-to-date development methods, a specific focus has been on optimizing the combination of UV light intensity field and retention time distribution. The net result is an extremely energy-efficient UV series, which is designed for a wide range of UV transmittances (i.e., a broad range of water qualities). In comparison to conventional UV systems using low pressure lamps, the efficiency has been increased up to 30%. UV systems using medium pressure lamps require even 4 times more energy for the identical performance! ...

5 December 2005: Trojan Technologies and Aquafine Corporation Partner in Industrial UV
VALÉNCIA, CA – It was announced today that Aquafine Corporation, a leading manufacturer of ultraviolet equipment for industrial applications, will operate as a strategic business unit of Trojan Technologies. Trojan Technologies designs, manufactures and sells UV systems for municipal wastewater and drinking facilities. Aquafine will continue to operate in its current location, focusing on their strong experience in Industrial Commercial (I/C) business and fully integrate the current I/C business of Trojan in their Valencia facility. All I/C processes from sales to order fulfillment, product engineering to manufacturing, shipment to service (including aftermarket) will in time fully reside within Aquafine. This combination of Trojan and Aquafine will create a unique position in the marketplace, offering the best in technology, innovative design offerings and leading edge research, backed by their mutual focus on the highest quality customer support...
Dear Members,

We have changed over to a new server and web company for our web site. In doing so, there have been some changes to the login for the Member Zone. Please see the explanation below that applies to you.

**I have been a member since before April 1, 2006**

Your userid and password have not changed. You can still log into the Member Zone the same way you did before with your membership number as your password and the userid we gave you. These are both printed on your membership card.

**I am a new member since April 1, 2006**

When you signed up online you were given a userid, and you created your own password. These are what you will use to log into the Member Zone. Your userid is printed on your membership card along with your Membership #. Please note your Membership number is not your password. You created your password and only you know what it is.

**The following information applies to all members.**

All members can change their password for login by going into their member profile from the Member Zone. Please write down your password and keep it in a safe place. In the new system we cannot see your password to tell you what it is. We can only reset a password by typing into the system what you tell us. Passwords are encrypted for your protection.

Please keep your membership card in a safe place as you will still need your membership number to register online for any workshops or conferences. If you do not put in your membership number you will be charged the regular rate for registration and will not receive the member discount.

If you have any questions on the new login or any questions regarding your membership please contact me at the number below or by email to Kathy.Harvey@iuva.org.

Yours truly,

Kathy Harvey
IUVA Office Manager
Tel: 519-632-8190

**New Email Addresses:** The email addresses for Jim Bolton and Kathy Harvey have been changed to jim.bolton@iuva.org and kathy.harvey@iuva.org, respectively, to avoid problems with excessive SPAM. Please note these changed email addresses.

**Upcoming IUVA-sponsored Conferences and Workshops**

25-30 August 2007: World UV/Ozone Congress, Hyatt Century Plaza Hotel, Los Angeles, CA – A Call for Papers will be issued soon.

As always, comments on the web site are most welcome – send either to Jim Bolton (jim.bolton@iuva.org) or the Webmaster Kevin Wright (ask@iuva.org).

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**APPLICATION NOTES**

*Editor: UV companies are welcome to submit “Application Notes” for this column. Send to jim.bolton@iuva.org.*

**Micro-Flow Imaging™ (MFI™) – A New Benchmark in Particulate Analysis**

From Brightwell Technologies Inc., Ottawa, ON, Canada (www.brightwelltech.com).

It is well known that the log reductions of active pathogen concentration obtained by UV disinfection are linked to the particulate characteristics in samples being irradiated. Specifically, it has been observed that pathogens can be enmeshed and shielded within larger particulates. This leads to a non-linear and, ultimately, saturated UV dose-inactivation response. Shielding effects depend on the size, shape and optical density of particles. At a particle population level, the distribution of these parameters depends, in turn, on the source water characteristics and pre-treatment prior to irradiation.

MFI™ instruments (Brightwell Technologies) provide a comprehensive measurement of particle populations for UV disinfection studies. MFI™ operates by capturing images of particles suspended in a flowing liquid. These images are analyzed, and a database is produced consisting of particle count, size, transparency, perimeter, area and circularity. The database can be interrogated to produce parameter distributions, scatter plots and isolate images of particle populations of interest. Particle concentrations are determined absolutely.

When compared with traditional particle counting technologies, MFI™ has a number of unique advantages for UV applications:

- **Comprehensive Characterization of Parameters Relevant to UV Shielding:** In addition to particle size (expressed as ECD), particle shape and optical intensity (an indictor of absorbance) are also highly influential with respect to UV shielding. MFI™ provides these additional parameters.

- **Accuracy and Material Independence:** Unlike light scattering or obscuration devices, MFI™ measurements are insensitive to particle material. Since typical samples contain a range of materials, this assists in obtaining consistent and understandable results.

- **Direct Observation:** During analysis, frames are displayed at a rate of one per second. This provides immediate visual feedback on the nature of a particle population. Software assisted filtering saves particle images meeting user-defined characteristics.

- **High Sensitivity:** The sensitivity of MFI™ for detecting and sizing small particles exceeds that of particle counters. This feature, along with the capability for time dependent measurement studies, is important for aggregation / meshing / flocculation studies.

- **Speed and Convenience:** MFI™ analyzers are easy to operate and provide complete analysis of a 1mL sample in less than 5 min.

MFI™ analysis provides a new level of insight for understanding the impact of source water particle populations and pre-treatment protocols on UV disinfection performance. Researchers and engineers are making increasing use of this technology for process development and UV reactor validation.

For further information, contact Sean Russell (srussell@brightwelltech.com).

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**UVC Emitters™ Stop Mold, Enhance Indoor Air Quality (IAQ) in Minnesota Office Building**


At Medicine Lake Properties, a commercial building in Plymouth, Minnesota, mold-related IAQ problems were causing problems in an office suite used by a medical company for administrative and light laboratory work. Management firm JGM Properties, Inc. (Bloomington, Minnesota) found that UVC Emitters™ from Steril-Aire, Inc. provided a highly effective solution.

“We started by tearing out sections of walls to expose the concrete block underneath, but we did not find any evidence of mold,” explains Randy Remer, construction supervisor at JGM. “We also cleaned the carpeting, but that did nothing to eliminate the mildew odors. The tenant tried using ionizing-type air cleaners and dehumidifiers in the space, but the portable air cleaning units generated a smell of static electricity.”

Remer called in their mechanical contracting firm, Egan Companies (Brooklyn Park, Minnesota), to evaluate the situation. “After further investigation, we determined that the mold was growing in the interior plenums and circulating through the ventilation system,” says Remer…. “Our project manager, Bruce Strandberg, suggested that we use ultraviolet UVC lamps in the air handling units to eliminate both surface mold and airborne mold spores.”

Egan installed Steril-Aire’s multi-patented UVC Emitters in the two air handlers serving the medical office suite. Prior to installation, Strandberg took microbial Petri dish samples from the coil surfaces to measure the level of mold contamination. Approximately a month later, follow-up samples showed a dramatic decline in mold levels. “Within just a few weeks, we found that the UVC lamps got rid of the mold and the associated mildew odors,” states Remer. “We have had no recurrence of the problem, even in the most humid weather.”

As an added benefit, Remer has eliminated annual spring cleaning of air conditioning coils. “The continuous germicidal action of the lamps keeps contaminants from building up on coil surfaces, so chemical cleaning has become unnecessary. We hope to incorporate UVC into new air handlers as we replace them, so that we can enjoy further maintenance savings. We anticipate that the UVC will save energy and possibly increase air handler life as well, since the units won’t have to work as hard.” Last but not least, the use of UVC has helped to achieve tenant satisfaction and peace of mind.

For further information, contact Roger Stamper (sales@steril-aire.com).
QUESTION: I would like to know your definition for UV intensity reading. What is exactly this reading? (from Fernando Maldonado)

ANSWER: The ‘UV intensity’ is also called ‘UV irradiance’. It is defined as the UV power (in watts) incident on a small area dA, divided by that area. Thus the units in SI terms are W/m². However, in North America, the units are usually mW/cm². 1 mW/cm² = 10 W/m².

The UV intensity (or irradiance) is a measure of the ‘brightness’ of the lamp at a given distance away. Close to the lamp (at a distance much less than the lamp length), the UV intensity falls off linearly with the inverse of the distance; however, at distances much greater than the lamp length, the UV intensity falls off as the inverse square of the distance from the lamp.

Often UV lamps are rated according to the irradiance (UV intensity) at 1 m from the lamp.

The UV intensity (I prefer the term ‘irradiance’) is related to the fluence or UV dose, since the fluence (UV dose) is the product of the average irradiance and the exposure time in seconds.

QUESTION: I am currently evaluating UV-B levels in Little Rock Arkansas and was wondering if you had any data that would help me with this evaluation. I have noticed that our UV levels are considered moderate to high for about 9 months out of the year—how is UV-B specific radiation related to this over-all number? Where can I find index’s for adequate amounts of UV-B for vitamin D production or comparisons of this area to that of more southern and northern latitudes? (from Amanda Wray)

ANSWER: You can obtain information about the spectral distribution of sunlight from the National Renewable Energy Laboratory – see http://rredc.nrel.gov/solar/spectra/am1.5/, which is the “Standard Air Mass 1.5” solar spectrum that is used to provide an ‘average’ solar spectrum at the earth’s surface. You can also obtain the Air Mass Zero spectrum (http://rredc.nrel.gov/solar/spectra/am0/), which is the solar spectrum just outside the earth’s atmosphere. The UVA portion is that lying between 315 and 400 nm.

You might also be interested in the “UV Index”, which is described at http://www.cpc.ncep.noaa.gov/products/stratosphere/uv_index/uv_information.shtml.

QUESTION: I bet you don’t get too many questions from textile artists! I’m currently researching a book on Cyanotypes on Fabric (an alternative photographic process which relies on UV to expose the prints, in case you haven’t come across cyanotypes before). Many sources of UV light have been suggested in various publications, namely:

- the sun
- incandescent lights
- mercury discharge lamps
- black lights
- UV tubes as insect attractors or in aquariums
- domestic sun bed facial sun lamp arc lights fluorescent lights quartz-halogen lamps

I’ve been reading up on UV light and have come across references to UVA/B/C with their respective wavelengths and according to the ‘bible’ on cyanotyping the ideal wavelength is 320-400 nm with a peak output around 365 nm. Therefore I wondered if you would have time to comment on the various UV sources in terms of which would be most effective and safest to use in a domestic environment for this purpose. I have to admit, I don’t even know what some of them are - for instance I haven’t come across a mercury discharge lamp or an arc light before… (from Ruth Brown)

ANSWER: Thank you for your query. UV lamps that emit around 365 nm are called “black lights”. They are fluorescent lamps with a fluorescent phosphor that emits at around 365 nm. They are basically standard fluorescent tubes with a special phosphor.

I typed in “black lights” to Google and got lots of hits - here’s one: http://wolfstone.halloweenhost.com/TechBase/blltip_BlackLightTips.html#wavelength.
**QUESTION:** I am attempting to settle a dispute between some friends.

Does the moon reflect UV rays? And if it does is it possible to get a ‘moon tan’ at night – even if we are talking at an extremely small level of damage to the skin.

Any info you have here would be great! (from Anthony Clark)

**ANSWER:** Yes, I think that the moon would reflect some UV; however, you must realize that the overall irradiance of the moon at the Earth’s surface is only about 1/millionth that of the sun. So you would have to stay in moonlight a million times longer to get a tan as compared to the time to get a tan in sunlight – I don’t think anyone would be willing to wait that long!

**QUESTION:** I work in an indoor miniature golf that is solely lit by black lights – it is a ‘glow in the dark’ miniature golf place.

Anyway, will the black lights hurt my eyes or skin? (from Kevin Earley)

**ANSWER:** These “black lights” almost certainly emit at around 365 nm (in the UVA region). This range of wavelengths will not hurt your skin (other than inducing a slight tan if you get exposed too long). If you are worried about your eyes, wear glasses (or sunglasses) - almost all such devices block wavelengths below about 400 nm.

**QUESTION** (and **ANSWER**): On the IUVA FAQ page, it is mentioned that 185 nm light can actually produce ozone. Does the ozone formation only occur if emissions escape the reactor? (from Jason Kim)

No the ozone is formed in the air around the UV lamp, and if this air is then exhausted into a room the ozone will enter the room.

Can ozone be formed in the water?

No, the 185 nm light is absorbed (within a few micrometers) by water to form hydroxyl radicals.

However, 254 nm UV light is used for ozone decomposition. If all lamps that produce 185 nm UV through the synthetic quartz also produce wavelengths above it, including 254 nm, can the ozone creation/deconstruction effects cancel?

It is true that the 254 nm UV will destroy ozone, so there is a kind of dynamic formation and destruction; however, if air is flowing through past the lamp, the ozone will largely escape before it is destroyed.

If I need a 185 nm lamp, how can I prevent the formation of ozone?

Use a nitrogen atmosphere around the lamp; ozone is only produced by the absorption of the 185 nm light by oxygen in the air.

**QUESTION:** I work for a company developing a UV source for biodecontamination applications. We’re trying to gain a better understanding of the attenuation and losses we should experience in air. Will there be significant attenuation at 265 nm? If there is, I’d like to find out if there are published absorption coefficients for 265 nm radiation in air. Would you please let me know where I could look these up if they exist. Also, do these absorption coefficients account for all scattering mechanisms (Rayleigh, etc.) which occur for 265 nm radiation? (from Jim Smith)

**ANSWER:** Unless there are specific contaminants in the air, none of the components of air [N₂ (78%), O₂ (21%) or Ar(1%)] absorbs UV above 190 nm. So you are safe at 265 nm – you can assume that the transmittance of air is 100%.

Scattering is another matter. The degree of scattering depends on the concentration of particles and whether the particles have a diameter much less than the wavelength of the light (then the scattering is inversely proportional to the 5th power of the wavelength –this is why sunsets are “red” and the sky is “blue”). If the diameter is much larger than the wavelength of the light (here the scattering is independent of wavelength – that is why clouds are “white”).

**QUESTION** (and **ANSWERS**): I doing a project using UVC lamp in disinfecting air in consumer product. What types of material can I use for its cover to shield away harmful UVC ray. Can I use plastic or metal? Will there be any degradation of the material under UV ray? Please advise. (from Jiansheng)

Any kind of plastic will block UVC (i.e., 254 nm) light. Unless the UV intensity is very high and the exposure time is very long, you need not worry about degradation of the plastic.

In common air-disinfection, air is passed through the UVC rays for disinfection. On the other hand, if part of the air that has not been passed through yet (or coming from the outside), the air may still contain germs that can multiply.

It is important to assure good mixing as the air passes through the reactor. This is sometimes done by placing baffles along the air path.
As some of bacteria have generation times of less than 30 min, problems may arise if the bacteria keep increasing in number while we try to disinfect them. The air that has been disinfected will be infected again. The question is how fast must we disinfect the air, so as to be faster than the germs in multiplying.

Once a bacterium receives the minimum UV dose (i.e., about 40 mJ/cm²), it no longer can replicate. Also the usual transit time through the UV reactor is seconds (not minutes), so multiplication of bacteria as the air passes through is not an issue.

**QUESTION (and ANSWERS):** Is it true that typical UV doses used for drinking water disinfection would not be effective for the treatment of adenoviruses? (from Natasha)

It is true that adenovirus is probably the most resistant pathogen to UV disinfection. Whereas, a UV dose of 40 mJ/cm² is sufficient to achieve more than 4 logs inactivation of almost all pathogens (bacteria, viruses and protozoa), it appears that adenovirus requires a UV dose of more than 200 mJ/cm² to achieve even 3 logs inactivation. However, adenovirus is extremely sensitive to chlorine, so a small chlorine dose (1-2 mg/L) prior to the water entering the distribution system would provide complete protection against adenovirus.

Is possible the microbial repair after UV light-induced DNA damage (photoreactivation and dark-repair) if we use UV lamps that emit in the range 240-290 nm?

Photoreactivation is activated by light in the wavelength range 350-450 nm. In most drinking water systems, the water never is exposed to such light after UV disinfection, so photoreactivation is not a problem. This is of concern for UV disinfection of wastewater, where the water is discharged into a river where is can be exposed to sunlight. There is some evidence that medium pressure UV light (240-290 nm spectral range) may suppress photoreactivation, whereas low pressure UV light (monochromatic at 254 nm) does not suppress photoreactivation.

**QUESTION:** They say that UV-C radiation is blocked by the atmosphere. Would the atmosphere become transparent to UV-C without ozone layer? (from Csaba Purszki)

**ANSWER:** The sun’s rays with wavelengths less than 300 nm are blocked by absorption by the ozone in the stratosphere. This is why there is so much concern about the reduction in ozone levels caused by ozone depleting compounds (e.g., chlorofluoro hydrocarbons from freon gases) escaping into the atmosphere.

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</table>

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ABSTRACT

When deciding on reclaimed water disinfection technology, cost is frequently the primary factor. Reclaimed water regulations, which specify ultraviolet light (UV) and chlorine dose, inadvertently drive cost-based decisions toward chlorination. Chlorine disinfection requirements are based on dated information; do not reflect the current understanding of chlorine chemistry; and may not meet pathogen disinfection standards at the regulated doses, depending on a range of water quality parameters. Unlike chlorine regulations, regulated UV dose targets meet indicator organism and pathogen disinfection targets, including those for viruses (5 logs of inactivation of enteric viruses using a poliovirus model) and protozoa. What is required in the industry is an understanding of the differences in pathogen disinfection of UV and chlorine at the regulated dose levels. The end result would be a comparison of technologies that result in an equivalent low level of pathogen disinfection, and thus, an equivalent level of public health protection.

Key Words: UV, ultraviolet light, chlorine, pathogens, disinfection, reclaimed water.

INTRODUCTION

For wastewater disinfection, the primary drivers for technology selection are worker and public safety, cost, and the ability to meet indicator organism (bacterial) requirements. Reducing effluent toxicity (including disinfection by-products (DBPs)) and pathogen disinfection, while often listed in utility mission statements or goals, rarely govern disinfection process selection. If worker and public safety is an issue (related to the use of chlorine gas), most utilities will convert to sodium hypochlorite, and some will convert to ultraviolet light (UV) disinfection. If cost is the primary driver, and pathogen disinfection is not, chlorine will repeatedly be the disinfection technology of choice.

For reclaimed water disinfection, the disinfectant selection process becomes more complex. Some reclaimed water producers have stringent DBP requirements. If this is the case, UV or other non-chlorine technologies will be selected, regardless of cost. For certain reclaimed water providers, pathogen disinfection is of primary concern, not simply indicator organism destruction. In these cases, UV disinfection will be the technology of choice. Still, DBPs and pathogen disinfection rarely guide reclaimed water disinfection technology selection; cost remains the primary driver.

Though the intent of reclaimed water quality (or the disinfection barrier) regulations is pathogen inactivation, the framework of the regulations do allow for chlorine systems to be designed to a lower level of pathogen disinfection than the requirements for UV. It should be noted that regulated chlorine levels are intended as the minimum allowable levels for disinfection. Because of the common use of the minimum regulated dosing and contacting requirements, the costs for UV disinfection of reclaimed water are consistently higher than the costs for chlorine disinfection. The result is that the regulations are driving the selection and implementation of a technology with potentially inferior pathogen disinfection ability. This paper argues that reclaimed water quality regulations must incorporate the real differences in disinfection performance between chlorine and alternative disinfectants (particularly UV). An even more progressive approach, not detailed in this paper, is to examine the impact of integration of disinfection technology into the existing process train, that is, review the overall treatment process performance to meet regulatory disinfection objectives.
Reclaimed Water Regulations

For reclaimed water intended for potential public contact applications, most states have strict coliform limits, with the underlying assumption that the destruction of the indicator organism results in the destruction of various pathogens of concern. Traditionally, coliforms have been a useful, though not perfect, surrogate indicator of process performance. Meeting the coliform standard consistently is an indication of a well-run wastewater treatment plant. Some states, including California, set chlorine disinfection and UV dose requirements. Others, like Florida, have sliding chlorine dose requirements based on influent fecal coliform concentrations and are now recommending the high UV dose requirements utilized in California.

Table 1. Overview of Reclaimed Water Requirements for Several States

<table>
<thead>
<tr>
<th>State</th>
<th>Bacteria</th>
<th>Virus/Protozoa</th>
<th>Required Chlorine Ct</th>
<th>Required UV Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA “Tertiary Recycled”</td>
<td>2.2 MPN/100mL Total Coliform</td>
<td>5-log inactivation/kill virus expected, pathogen free water.</td>
<td>450 mg-min/L</td>
<td>100 mJ/cm², post media filter</td>
</tr>
<tr>
<td>TX “Type I Reclaimed”</td>
<td>20 CFU/100mL Fecal Coliform</td>
<td>No standard</td>
<td>&gt;100 mg-min/L (Dietrich et al. 2003)</td>
<td>No standard, potential UV dose needed &gt;25 mJ/cm²</td>
</tr>
<tr>
<td>FL “High Level Disinfection”</td>
<td>ND Fecal Coliform per 100mL</td>
<td>Pathogen free water expected</td>
<td>&gt;10,000 fecal/100 mL – 120 mg-min/L</td>
<td>CA standards acceptable, lesser doses not approved at this time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;10,000 fecal/100 mL – 40 mg-min/L</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;1,000 fecal/100 mL – 25 mg-min/L</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Florida Reuse Pathogen Guidelines (from FDEP 2003)

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Units</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giardia</td>
<td>Viable Cysts/100L</td>
<td>1.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Cryptosporidium</td>
<td>Viable Oocysts/100L</td>
<td>5.8</td>
<td>22</td>
</tr>
<tr>
<td>Enterovirus</td>
<td>PFU/100L</td>
<td>0.044</td>
<td>0.165</td>
</tr>
</tbody>
</table>

UV DISINFECTION PERFORMANCE

UV disinfection of reclaimed water is well proven in the industry and in the literature. Cosman and Wright (2000) summarized the dose/response literature for various microorganisms and pathogens of concern, clearly showing that UV disinfection meets reclaimed water disinfection pathogen standards at regulated dose values. The key water quality issue that can impact UV disinfection performance is the existence of particle-associated organisms. Coliform organisms frequently become embedded in particulate matter, partially or wholly protecting them from the UV light (Parker and Darby 1995, Emerick et al. 1999, WERF 1996). These publications indicate that particles larger than 10 μm in size can shield microorganisms from disinfection by UV light.

CHLORINE DISINFECTION PERFORMANCE

Chlorine, like UV, is effective for the disinfection of bacteria, both in free and combined form. Like UV, chlorine disinfection is impacted by the existence of particle-associated organisms. Also like UV disinfection, chlorine disinfection performance is impacted by the chemical nature of the water. Of substantial note, however, is that the chemical impact of wastewater quality to UV is directly compensated for during UV design and operation through the incorporation of ultraviolet light transmittance (UVT) data, whereas there is no current monitoring or method to adjust chlorine doses based on the chemical nature of wastewater, since the basis for compliance is a total chlorine residual. Dietrich et al. (2003) presented definitive dose/response data showing two phase disinfection kinetics with rapid kill of total coliform (likely non-particle
associated) at low Ct values followed by a dramatically less effective kill of the remaining particle-associated organisms (a classic “tailing” effect). Further, Dietrich et al. (2003) presented evidence that chlorine disinfection is not accurately measured by Ct, as higher dose/shorter contact time Ct values provide better disinfection than lower dose/higher contact time Ct values. Sung (1974) studied the impact of a range of wastewater organics on chlorine disinfection potential and reported that most of the organics studied (studied compounds include carbohydrates, proteins, carboxylic acids, tannins, lignins, detergents, and other compounds) “react with chlorine to form chloro-organic compounds,” titrating as chlorine residual “yet were found to have little or no bactericidal (bactericidal) potential.” Essentially, standard Ct values, relying on the determination of a total chlorine residual without an understanding of what species make up the chlorine residual, do not result in predictable chlorine disinfection performance.

For disinfection of pathogens, chlorine performance is equally, if not more, variable. Free chlorine is a rapid and effective viral disinfectant in wastewater, as indicated by Figure 1, with 5-log reduction of MS2 at a Ct of less than 60 mg-min/L (well below the Ct required by the State of California for reclaimed water, but above some standards set by the State of Florida). The use of MS2 as a conservative surrogate for poliovirus was proven in Cooper et al. (2000). Note the tested water in Figure 1 was a high quality wastewater, nitrified and filtered with a chlorine demand of 1.5 mg/L. The existence of ammonia in moderate concentrations and/or the presence of a high level of organics will result in a combined residual with measurably worse disinfection potential, as shown below.

The EPA differentiates between the efficacy of combined chlorine and free chlorine (for drinking water disinfection). The EPA Guidance Manual (USEPA 1999) indicates that a Ct of up to 1000 mg-min/L is required to achieve 4-log virus reduction, using chloramines. Recent research (Cooper et al. 2000) substantiates the Surface Water Treatment Rule conclusions, showing minimal viral disinfection by chloraminated wastewater, even though the tested water was microfilter effluent (0.2 μm pore size) with a chlorine demand less than 1 mg/L (Figure 2 and Figure 3, indicating required Ct values of >1500 mg-min/L and from >300 to 1500 mg-min/L for 5-log kills of MS2 and poliovirus, respectively, in some cases well beyond the Ct requirements of any state). Additional new free chlorine data from this author, not published in Cooper et al. (2000), is shown in Figure 2 to underscore the impact of ammonia on chlorine disinfection performance.
The use of chlorine for reclaimed water disinfection raises concerns, in light of recent FDEP protozoan treatment goals (FDEP 2003) and the research and publications by Slifko (e.g., Slifko et. al. 2004), which show numerous detections of Giardia and Cryptosporidium (some viable) in reclaimed water effluents (in most cases with chlorine as the disinfectant).

The USEPA (1999) specifies that drinking water treatment engineers should only anticipate significant Giardia kill with free chlorine (3-log kill at a Ct of ~50 mg-min/L, depending on temperature and pH), as combined chlorine requires a Ct of >1,000 mg-min/L for an equivalent level of treatment.

Regarding Cryptosporidium kill, research has shown little to no disinfection by either free or combined chlorination (see USEPA 2006). It should be noted that USEPA 1999 is for drinking water treatment, and not for wastewater, which would be expected to have higher chlorine demand, due to wastewater and organics. As a result, CT values for wastewater will likely be measurably higher for the same disinfection result.

**SUMMARY**

The work discussed above, along with findings from other previous research, has resulted in heightened concern about the added health risk associated with the use of chlorine disinfection of reclaimed water when compared to other proven disinfectants, including UV. A WateReuse Foundation sponsored research investigation, titled “Pathogen Inactivation through Wastewater Reclamation,” is underway to address this concern.

If the target for reclaimed water disinfection is pathogen reduction, then the technology-specific regulated dose targets must be evaluated as to their relative ability to produce “pathogen-free” water at each treatment location. Only with this understanding can two technologies, such as chlorine and UV, be properly compared to each other. Each process may have different controlling factors, but the end product should generally pose the same degree of risk to the user or consumer. In total, performance, and not solely cost, should be a primary driver in disinfection process selection.

Comment: We know that not all pathogens are present at the same concentration throughout the year. The problem is that their appearance is not predictable and our monitoring systems are not adequate to provide a quick enough response. Therefore, a treatment barrier is erected to reduce or inactivate pathogen loads that may occur infrequently. Given the source of recycled water, the California Department of Health Services feels it is prudent to erect multiple barriers to reduce and minimize public exposure to these pathogens.

**REFERENCES**


WERF. 1996. Water Environment Research Foundation Project 96-CTS-3 99
An Overview of UV-based Advanced Oxidation Processes for Drinking Water Treatment

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ABSTRACT
This paper begins by presenting the regulatory interest behind the growth of UV-based Advanced Oxidation Processes (AOPs). The main focus of the paper will be a detailed look at the use of four UV-based AOPs (direct photolysis, UV/H\textsubscript{2}O\textsubscript{2}, UV/O\textsubscript{3}, and UV/TiO\textsubscript{2} photocatalysis) in drinking water applications. For each treatment technology, the following are considered: (1) the general mechanism by which it achieves contaminant removal, (2) factors affecting its performance, (3) some relevant recent literature and research projects, and (4) some current commercial activities.

Keywords: Ultraviolet radiation; advanced oxidation process; photocatalysis; photooxidation; drinking water.

INTRODUCTION
The practice of UV disinfection of water dates back to the early twentieth century. More recently, UV has begun to replace chlorine as a primary disinfectant (Oliver and Carey 1976) largely due to the fact that it has been demonstrated to be more effective at inactivating Cryptosporidium parvum and Giardia lamblia (Bukhari et al. 1999; Craik et al. 2001). With the increased use of UV in drinking water treatment plants, much attention has been placed on developing UV-based advanced oxidation processes (AOP) for the removal of taste and odor compounds, micropollutants, or natural organic matter (NOM) from raw drinking water (Parsons and Byrne 2004).

An AOP typically involves the formation of hydroxyl radicals (•OH) that carry out the oxidation and degradation of target species. For UV-based AOPs this involves the addition of an oxidant or catalyst (e.g. O\textsubscript{3}, H\textsubscript{2}O\textsubscript{2}, TiO\textsubscript{2}) that UV photolyses or activates leading to the formation of •OH radicals (Bolton and Cater 2004; Legrini et al. 1993).

UV-based AOPs date back to as early as 1899 when Bach (1899) observed the photolysis of carbonic acid. Much of the early work focused on the principles and theory behind photooxidation (i.e. quantum yields, reaction pathways). Currently, the main focus is on the full-scale application of AOPs, including reactor design and optimization. In the following, we present the drinking water regulations that have spurred the current interest in AOPs and discuss the current state of direct photolysis, UV/H\textsubscript{2}O\textsubscript{2}, UV/O\textsubscript{3}, and UV/TiO\textsubscript{2} photocatalysis in research and commercial drinking water applications.

REGULATORY INTEREST
Environmental and health organizations place strict regulations on the maximum allowable concentration (MAC) of a number of organic chemicals in potable water to protect consumer safety. Table 1 summarizes the water quality guidelines of the United States Environmental Protection Agency (USEPA), Health Canada, the European Union (EU), and the World Health Organization (WHO) for selected contaminants whose removal by AOPs has been studied.

A certain class of halogenated derivates, namely disinfection by-products (DBPs), trihalomethanes (THMs) and haloacetic acids (HAAs), enter the potable water via reaction between chlorine and NOM. UV-based AOPs are capable of reducing the concentration of NOM while also achieving primary disinfection. Thus, the reduced chlorine demand for maintaining a residual in the distribution system leads to an overall decrease in the formation of DBPs.

N-nitrosodimethylamine (NDMA) is a nitrosamine that is not currently regulated by national regulatory agencies. However, localized agencies such as the Ontario Ministry of Environment and the State of California have set drinking water guidelines of 0.009 ppb and 0.002 ppb NDMA, respectively. Because of its low molecular weight, low volatility, and poor adsorption characteristics, conventional treatment processes such as membranes, air stripping, and granular activated carbon (GAC) do not adequately remove NDMA. In addition, NDMA is not readily biodegradable so biological treatments are ineffective. Recently, much research has focused on the removal of NDMA (Mitch et al. 2003) and commercial AOPs exist specifically for the removal of NDMA from drinking water.
Another contaminant for which much attention has been focussed on its removal (Deeb et al. 2003) and is not currently regulated by national regulatory agencies is methyl tertiary-butyl ether (MTBE). MTBE is not efficiently treated by activated carbon or air stripping since it is highly soluble in water and has a low Henry’s law constant, 0.022 at 25 degrees Celsius (Squillace et al. 1998). In addition, biodegradation of MTBE under aerobic and anaerobic conditions is slow. Low levels of MTBE can make drinking water supplies undrinkable due to its turpentine-like taste and odour that are detectable at low taste and odour detection thresholds (Water Quality Branch 2001). Present data shows that MTBE is potentially carcinogenic but more research is necessary to determine concentration thresholds.

Taste and odor (T&O) are arguably the most important characteristics of drinking water, since they are the most tangible for the consumer. Geosmin and 2-methylisoborneol (MIB), compounds commonly found in drinking water reservoirs with high algal bloom activity, are often the source of earthy and musty odors present in drinking water. Typically, powdered activated carbon (PAC), ozonation, or GAC filtration is implemented for geosmin and MIB control. However, T&O episodes are variable depending on the season and climate, therefore treatment is only required on an as-needed basis. An alternative is the UV/H₂O₂ AOP (Koratgere et al. 2005; Linden et al. 2004; Paradis et al. 2005). During a T&O event, a drinking water facility equipped with a UV system designed for disinfection and T&O treatment can switch from “Disinfection-Only” mode to “Disinfection + T&O control” mode by energizing additional UV lamps and dosing H₂O₂ upstream of the reactors, potentially resulting in significant cost savings (Royce et al. 2005).

Conventional treatment technologies are limited in their ability to remove a wide variety of contaminants and each has its drawbacks. The main advantages AOPs hold over current technologies are:

1. They are not specific to any one contaminant, and
2. The target contaminant is permanently eliminated and not transported from water to another medium.

### Table 1: USEPA, Health Canada, EU, and WHO drinking water regulations

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Maximum Allowable Concentration (MAC) (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>USEPA&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Organic Chemicals</strong></td>
<td></td>
</tr>
<tr>
<td>Atrazine</td>
<td>3</td>
</tr>
<tr>
<td>Benzene</td>
<td>5</td>
</tr>
<tr>
<td>Benzo(a)pyrene</td>
<td>0.2</td>
</tr>
<tr>
<td>Carbofuran</td>
<td>40</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>100</td>
</tr>
<tr>
<td>1,2-Dichlorobenzene</td>
<td>600</td>
</tr>
<tr>
<td>1,4-Dichlorobenzene</td>
<td>75</td>
</tr>
<tr>
<td>2,4-D</td>
<td>70</td>
</tr>
<tr>
<td>1,2-Dichloroethane</td>
<td>5</td>
</tr>
<tr>
<td>1,1-Dichloroethylene</td>
<td>7</td>
</tr>
<tr>
<td>Dioxin (2,3,7,8-TCDD)</td>
<td>0.00003</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>700</td>
</tr>
<tr>
<td>Polychlorinated biphenyls</td>
<td>0.5</td>
</tr>
<tr>
<td>Pentachlorophenol</td>
<td>1</td>
</tr>
<tr>
<td>Tetrachloroethylene</td>
<td>5</td>
</tr>
<tr>
<td>Toluene</td>
<td>1000</td>
</tr>
<tr>
<td>2,4,5-T</td>
<td>n/a</td>
</tr>
<tr>
<td>1,1,1-Trichloroethane</td>
<td>200</td>
</tr>
<tr>
<td>Trichloroethylene (TCE)</td>
<td>5</td>
</tr>
<tr>
<td>Vinyl chloride</td>
<td>2</td>
</tr>
<tr>
<td>Xylenes (total)</td>
<td>10000</td>
</tr>
<tr>
<td><strong>Disinfection Byproducts</strong></td>
<td></td>
</tr>
<tr>
<td>Haloacetic acids (HAA)</td>
<td>60</td>
</tr>
<tr>
<td>Trihalomethanes (TTHM)</td>
<td>80</td>
</tr>
</tbody>
</table>

<sup>a</sup> – USEPA 2003; <sup>b</sup> – Health Canada 2004; <sup>c</sup> – European Union 1998; <sup>d</sup> – World Health Organization 2004
On the other hand, the disadvantages of AOPs are (Suty et al. 2004):

1. The water to be treated should have low bicarbonate/carbonate and natural organic matter (NOM) concentrations so that •OH radicals are reserved for the oxidation of organic contaminants,
2. The oxidation of some compounds may lead to the generation of more toxic by-products,
3. The oxidation by-products are generally more biodegradable so downstream treatment may be necessary to improve the biological stability of the water.

**UV PHOTOLYSIS**

Direct UV photolysis can provide effective removal of pollutants that exhibit large molar absorption coefficient and high quantum yields over the lamp’s emission spectrum (Stefan and Williamson 2004). For vacuum UV (VUV) irradiation (185 nm), •OH radicals can be produced by the photolysis of water (Gonzalez and Braun 1995). The degradation pathway by UV photolysis varies depending on the pollutant and water conditions. In general, homolytic bond scission is the predominant mechanism (Stefan 2004).

A number of factors affect the performance of process involving direct photolysis. As stated by the First Law of Photochemistry, such treatment can only be carried out if the target contaminant is able to absorb UV. Additionally, once absorbed, the energy must be greater than the energy of the weakest bond in the molecule to initiate a photochemical reaction (Bolton 2001). With these factors in consideration, the UV source must be carefully considered to ensure the spectrum emitted by the lamp is best suited for the application. Water quality may also contribute to the performance by way of indirect or sensitised photolysis as suggested by Stefan (2004). Photosensitisation involves the photolysis of NOM and nitrates to form reactive species, including •OH radicals, which encourage the degradation of pollutants.

**Commercial Application: Low- and medium-pressure UV systems for NDMA removal**

NDMA is effectively photolyzed by UV in the 200 nm to 260 nm range, thus eliminating the need for oxidant addition. Calgon Carbon’s Rayox™ system, featuring 20 kW medium-pressure UV lamps designed to emit UV in the 200 to 260 nm absorbance spectrum range have been installed in a number of applications for NDMA removal from drinking water sources (Lem 1999). Trojan’s TrojanUVPhox™ is a reactor based on low-pressure amalgam lamp technology emitting UV primarily at 254 nm. A recent study has shown that low-pressure UV is as effective as medium-pressure UV for the photolysis of NDMA (Sharpless and Linden 2003). Therefore, due to the significantly lower energy requirements and life-cycle costs, low-pressure lamp-based reactors are currently the technology of choice for NDMA removal applications.

**Table 2: 21st century studies involving UV direct photolysis of compounds found in drinking water**

<table>
<thead>
<tr>
<th>Compound</th>
<th>UV Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOM</td>
<td>VUV185, LPUV</td>
<td>Buchanan et al. 2004; Thomson et al. 2002a; Thomson et al. 2004</td>
</tr>
<tr>
<td></td>
<td>UVC</td>
<td>Thomson et al. 2002b</td>
</tr>
<tr>
<td></td>
<td>UVA, UVB, UVC</td>
<td>Parkinson et al. 2003</td>
</tr>
<tr>
<td></td>
<td>LPUV, MPUV, Pulsed-UV</td>
<td>Liu et al. 2002a</td>
</tr>
<tr>
<td></td>
<td>MPUV</td>
<td>Hofbauer and Andrews 2004</td>
</tr>
<tr>
<td>TCE</td>
<td>MPUV</td>
<td>Li et al. 2003</td>
</tr>
<tr>
<td>PAHs</td>
<td>UVA, UVB</td>
<td>Bertilsson and Widenfalk, 2002</td>
</tr>
<tr>
<td></td>
<td>Polychromatic</td>
<td>Fasnacht and Blough, 2002</td>
</tr>
<tr>
<td></td>
<td>LPUV, MPUV</td>
<td>Miller and Olejnik 2001</td>
</tr>
<tr>
<td>NDMA</td>
<td>MPUV</td>
<td>Stefan and Bolton 2002; Stefan et al. 2002</td>
</tr>
<tr>
<td></td>
<td>Pulsed-UV</td>
<td>Liang et al. 2003</td>
</tr>
<tr>
<td></td>
<td>LPUV, MPUV</td>
<td>Sharpless et al. 2003</td>
</tr>
<tr>
<td>Herbicides &amp; Pesticides</td>
<td>Various</td>
<td>Burrows et al. 2002; Koratgere et al. 2005; Linden et al. 2004</td>
</tr>
<tr>
<td></td>
<td>MPUV 250-750 nm</td>
<td>Kruithof et al. 2001; Sharpless et al. 2003; Zheng and Ye 2001</td>
</tr>
<tr>
<td></td>
<td>LPUV</td>
<td>Panadés et al. 2000</td>
</tr>
<tr>
<td></td>
<td>HPUV</td>
<td>Rayne et al. 2002</td>
</tr>
<tr>
<td>Phenols</td>
<td>MPUV</td>
<td>Benitez et al. 2002</td>
</tr>
<tr>
<td>Dioxins</td>
<td>MPUV</td>
<td>Esplugas et al. 2002</td>
</tr>
<tr>
<td>MIB &amp; geosmin</td>
<td>LPUV, MPUV</td>
<td>Konstantinov et al. 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Koratgere et al. 2005; Linden et al. 2004</td>
</tr>
</tbody>
</table>
Integrating Ozone and UV Disinfection Processes at the Greater Vancouver Water District's Coquitlam Source Installation (year) Parameter Value

First Nations reserve, ON, Canada (early 1990s)a Reactor Rayox™ Flow rate 270 GPM Influent NDMA concentration 100 ppt Effluent NDMA concentration <5 ppt Operating cost (USD) US$0.40/1000 gallons

Suburban Water, Covina, CA, USA (1999)b Reactor Rayox™ Flow rate 3,000 GPM Influent NDMA concentration 90 ppt Effluent NDMA concentration <2 ppt

California Domestic Water, El Monte, CA, USA (2004)c Reactor TrojanUVPhox™ Flow rate 14.4 MGD Influent NDMA concentration 200 ppt Effluent NDMA concentration <2 ppt

Alamitos Barrier recycled water project, CA, USA (2004)c Reactor TrojanUVPhox™ Flow rate 3 MGD Influent NDMA concentration 420 ppt Effluent NDMA concentration <10 ppt Operating cost (USD) US$0.06/1000 gallons

THE UV/H₂O₂ PROCESS

Based on the relevant literature available, UV/H₂O₂ is the most widely studied UV-based AOP for drinking water applications (Tuhkanen 2004; Stefan and Williamson 2004). The theory, kinetics, and mechanisms of oxidation are well understood (Tuhkanen 2004; Crittenden et al. 1999).

The dominant pathway of •OH formation in UV/H₂O₂ AOPs is the photolysis of H₂O₂ (Baxendale and Willson 1957). At first glance (Reaction 1), this process looks highly efficient since one mole of H₂O₂ yields two moles of •OH. However, two main factors limit the efficiency of the process. First, the molar absorption coefficient of H₂O₂ at 254 nm is very low (ε 254 = 19.6 M⁻¹ cm⁻¹), so a high concentration of H₂O₂ is required to have sufficient •OH production. However, this leads to the second problem, that is H₂O₂ itself scavenges •OH radicals (Reaction 2). Therefore, high concentrations of H₂O₂ can reduce the effectiveness of the process (Wang et al. 2000; Wang et al. 1997; Ku et al. 1998).

\[
\text{(1)} \quad \text{H}_2\text{O}_2 + h\nu \rightarrow 2 \cdot\text{OH} \\
\text{(2)} \quad \cdot\text{OH} + \text{H}_2\text{O}_2 \rightarrow \text{HO}_2\cdot + \text{H}_2\text{O}
\]

**Table 3: Design parameters for UV photolysis installations for NDMA treatment**

<table>
<thead>
<tr>
<th>Installation (year)</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Nations reserve, ON, Canada (early 1990s)a</td>
<td>Reactor</td>
<td>Rayox™</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>270 GPM</td>
</tr>
<tr>
<td></td>
<td>Influent NDMA concentration</td>
<td>100 ppt</td>
</tr>
<tr>
<td></td>
<td>Effluent NDMA concentration</td>
<td>&lt;5 ppt</td>
</tr>
<tr>
<td></td>
<td>Operating cost (USD)</td>
<td>US$0.40/1000 gallons</td>
</tr>
<tr>
<td>Suburban Water, Covina, CA, USA (1999)b</td>
<td>Reactor</td>
<td>Rayox™</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>3,000 GPM</td>
</tr>
<tr>
<td></td>
<td>Influent NDMA concentration</td>
<td>90 ppt</td>
</tr>
<tr>
<td></td>
<td>Effluent NDMA concentration</td>
<td>&lt;2 ppt</td>
</tr>
<tr>
<td>California Domestic Water, El Monte, CA, USA (2004)c</td>
<td>Reactor</td>
<td>TrojanUVPhox™</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>14.4 MGD</td>
</tr>
<tr>
<td></td>
<td>Influent NDMA concentration</td>
<td>200 ppt</td>
</tr>
<tr>
<td></td>
<td>Effluent NDMA concentration</td>
<td>&lt;2 ppt</td>
</tr>
<tr>
<td>Alamitos Barrier recycled water project, CA, USA (2004)c</td>
<td>Reactor</td>
<td>TrojanUVPhox™</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>3 MGD</td>
</tr>
<tr>
<td></td>
<td>Influent NDMA concentration</td>
<td>420 ppt</td>
</tr>
<tr>
<td></td>
<td>Effluent NDMA concentration</td>
<td>&lt;10 ppt</td>
</tr>
<tr>
<td></td>
<td>Operating cost (USD)</td>
<td>US$0.06/1000 gallons</td>
</tr>
</tbody>
</table>

\(a\) - case study provided by Calgon Carbon Corporation 2005; \(b\) – Lem 1999; \(c\) - case studies provided by Trojan Technologies Inc. 2006

**Table 4: 21st century studies involving UV/H₂O₂ treatment of compound found in drinking water**

<table>
<thead>
<tr>
<th>Compound</th>
<th>UV Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOM</td>
<td>HPUV</td>
<td>Wang et al. 2000</td>
</tr>
<tr>
<td></td>
<td>VUV₁₈₅, UVC</td>
<td>Thomson et al. 2004</td>
</tr>
<tr>
<td></td>
<td>MPUV</td>
<td>Speitel et al. 2000; Hofbauer and Andrews 2004</td>
</tr>
<tr>
<td></td>
<td>UVC</td>
<td>Kleiser and Frimmel 2000; Parkinson et al. 2001</td>
</tr>
<tr>
<td></td>
<td>MPUV, LPUV, Pulsed-UV</td>
<td>Liu et al. 2002b</td>
</tr>
<tr>
<td></td>
<td>LPUV</td>
<td>Berube et al. 2004; Toor and Mohseni 2005</td>
</tr>
<tr>
<td>Phenols</td>
<td>MPUV</td>
<td>Esplugas et al. 2002</td>
</tr>
<tr>
<td></td>
<td>Polychromatic</td>
<td>Fasnacht and Blough 2002</td>
</tr>
<tr>
<td>NDMA</td>
<td>MPUV</td>
<td>Stefan and Bolton 2002</td>
</tr>
<tr>
<td></td>
<td>LPUV, MPUV</td>
<td>Sharpless et al. 2003</td>
</tr>
<tr>
<td>MTBE</td>
<td>LPUV, MPUV, PUV</td>
<td>Kavanaugh et al. 2003</td>
</tr>
<tr>
<td></td>
<td>MPUV</td>
<td>Cater et al. 2000; Stefan et al. 2000</td>
</tr>
<tr>
<td></td>
<td>LPUV</td>
<td>Chang and Young 2000</td>
</tr>
<tr>
<td></td>
<td>LPUV</td>
<td>Müller and Jekel 2001</td>
</tr>
<tr>
<td></td>
<td>HPUV</td>
<td>Benitez et al. 2002</td>
</tr>
<tr>
<td></td>
<td>LPUV, MPUV</td>
<td>Koratgere et al. 2005; Linden et al. 2004</td>
</tr>
<tr>
<td>MIB &amp; gesomin</td>
<td>LPUV, MPUV</td>
<td>Koratgere et al. 2005; Linden et al. 2004; Paradis et al. 2005; Royce et al. 2005</td>
</tr>
</tbody>
</table>
Commercial Products: TrojanUVPhox™ and TrojanUVSwift™ ECT

Trojan Technologies has a number of drinking water installations, treating a range of compounds, using the UV/H₂O₂ AOP. Depending on the application, either a TrojanUVPhox™, which implements low-pressure amalgam lamp technology, or a TrojanUVSwift™ ECT based on medium-pressure lamp technology is selected. H₂O₂ concentrations range from 1 to 15 ppm.

Included are two water reuse projects (Orange County Water District and West Basin Municipal Water District), a drinking water well protection application (Stockton), and several drinking water treatment plant installations (PWN Treatment Plant Andijk, City of Cornwall, La Puente Valley County Water District, Valley County Water District, and San Gabriel Valley Water District).

Table 5. Design parameters for Trojan’s UV/H₂O₂ installations

<table>
<thead>
<tr>
<th>Installation (year)</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange County Water District, CA, USA (2004)</td>
<td>Reactor Flow rate Target compounds Influent NDMA concentration Effluent NDMA concentration Design electrical energy per order (EE/O)</td>
<td>TrojanUVPhox™ 100 MGD peak NDMA; 1,4-dioxane 150 ppt 10 ppt &lt;0.20 kWh/1000 gallons/order</td>
</tr>
<tr>
<td>West Basin Municipal Water District, CA, USA (2005)</td>
<td>Reactor Flow rate Target compound Design influent NDMA concentration Target effluent NDMA concentration</td>
<td>TrojanUVPhox™ 12.5 MGD NDMA 100 ppt &lt;10 ppt</td>
</tr>
<tr>
<td>Stockton, CA, USA (2001)</td>
<td>Reactor Target compound</td>
<td>TrojanUVPhox™ 1,4-dioxane</td>
</tr>
<tr>
<td>The La Puente Valley County Water District, CA, USA (2002)</td>
<td>Flow rate Target compounds Influent NDMA concentration Effluent NDMA concentration Influent 1,4-dioxane concentration Effluent 1,4-dioxane concentration</td>
<td>TrojanUVPhox™ 3.6 MGD NDMA; 1,4-dioxane 1,500 ppt &lt;1 ppt 3.4 ppb &lt;0.5 ppb</td>
</tr>
<tr>
<td>PWN Treatment Plant Andijk, Netherlands (2004)</td>
<td>Reactor Flow rate Effluent micropollutant concentration</td>
<td>TrojanUVSwift™ ECT 25 MGD peak 80% reduction of influent micropollutant concentration</td>
</tr>
<tr>
<td>City of Cornwall, ON, Canada (2006)</td>
<td>Reactor Peak flow rate Target compounds Design influent geosmin concentration Target geosmin reduction</td>
<td>TrojanUVSwift™ ECT 26.4 MGD MIB &amp; geosmin 50 ppt &gt;1-log</td>
</tr>
<tr>
<td>Valley County Water District, CA, USA (2006)</td>
<td>Reactor Flow rate Target compounds Influent NDMA concentration Effluent NDMA concentration Influent 1,4-dioxane concentration Effluent 1,4-dioxane concentration</td>
<td>Trojan Low Pressure 11.2 MGD NDMA; 1,4-dioxane 3,000 ppt &lt;2 ppt &lt;0.5 ppb</td>
</tr>
<tr>
<td>San Gabriel Valley Water Company, CA, USA (2006)</td>
<td>Reactor Flow rate Target compounds Influent NDMA concentration Effluent NDMA concentration Effluent 1,4-dioxane concentration</td>
<td>TrojanUVPhox™ 11.2 MGD NDMA; 1,4-dioxane 700 ppt &lt;2 ppt &lt;0.5 ppb</td>
</tr>
</tbody>
</table>

\( a \) – case studies provided by Trojan Technologies Inc. 2006; \( b \) – Kruithof et al. 2005; \( c \) – Martin et al. 2005; \( d \) – Stefan et al. 2005; \( e \) – Williams et al. 2005; \( f \) – Royce et al. 2005; \( g \) – Paradis et al. 2005
In addition to the above-described Rayox™ installations used for direct photolysis of NDMA, Calgon has an application combining Rayox™ technology with hydrogen peroxide. Tetrachloroethylene (PCE), in the range of 0.5-4.5 ppb, was detected in the drinking water supply, from a groundwater source, for the Salt Lake City Department of Public Utilities. Although, this was below the USEPA's TCE MAC of 5 ppb, treatment was preferred. This was the first UV/H₂O₂ system for treating a public drinking water supply in North America.

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### Commercial Product: Calgon’s Rayox™ based UV/H₂O₂ systems

The oxidation potential of UV/O₃ AOPs with UV of 254 nm wavelength is high due to the high molar extinction coefficient of O₃ ($\varepsilon_{254} = 3300 \text{ M}^{-1} \text{ cm}^{-1}$) (Gottschalk et al. 2000). In addition, O₃ decays rapidly so the problem of residual concentrations in treated water is not of concern (Guittonneau et al. 1991). A great advantage of the UV/O₃ AOP is that it offers multiple barriers for contaminants in that both •OH and O₃ are available oxidants. A major drawback of the UV/O₃ AOP is, however, the requirement of O₃ production, generating high capital and operational costs. Additionally, as with all liquid phase O₃ processes, mass transfer limitations of O₃ into the liquid phase can severely decrease process efficiency and increase operating costs (Andreozzi et al. 1999). Another drawback of using O₃ arises when treating waters containing bromide, leading to the formation of bromate, a regulated carcinogenic byproduct.

---

### Table 6. Design parameters for the Calgon Rayox™ UV/H₂O₂ installation

<table>
<thead>
<tr>
<th>Installation (year)</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt Lake City Department of Public Utilities, UT, USA (1998)</td>
<td>Reactor</td>
<td>12 lamp tower (300 kW)</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>3000 gpm</td>
</tr>
<tr>
<td></td>
<td>Target compound</td>
<td>PCE</td>
</tr>
<tr>
<td></td>
<td>Influent PCE concentration</td>
<td>2.3 ppb average</td>
</tr>
<tr>
<td></td>
<td>Effluent PCE concentration</td>
<td>&lt;0.05 ppb</td>
</tr>
<tr>
<td></td>
<td>Operating and maintenance cost (USD)</td>
<td>US$0.15/1000 gal</td>
</tr>
</tbody>
</table>

*a - case study provided by Calgon Carbon Corporation 2005

---

### THE UV/O₃ PROCESS

The use of ozone in drinking water treatment applications involving disinfection, oxidation and removal of micropollutants, NOM, taste and odour compounds, and colour has been extensively reviewed (e.g. Camel and Bermond 1998; Langlais et al. 1991; Gottschalk et al. 2000; Graham 1999). Ozone has a high oxidation potential but it is selective and may not completely oxidize some species. Therefore, AOPs that combine O₃ with UV or H₂O₂ to enhance •OH production are often more effective than O₃ alone (Camel and Bermond 1998).

The O₃/UV AOP is initiated by the photolysis of O₃ by UV to form H₂O₂ and O₂ (Peyton 1988). •OH production is carried out by the reaction between O₃ and H₂O₂.

\[
3 \quad \text{O}_3 + 2 \text{H}_2\text{O} + \text{hv} \rightarrow \text{H}_2\text{O}_2 + \text{O}_2 + \text{O}_2
\]

\[
4 \quad 2 \text{O}_3 + \text{H}_2\text{O}_2 \rightarrow 2 \cdot \text{OH} + 3 \text{O}_2
\]

\[
5 \quad \text{H}_2\text{O}_2 + \text{hv} \rightarrow 2 \cdot \text{OH}
\]

---

### Table 7. 21st century studies involving UV/O₃ treatment of compounds found in drinking water

<table>
<thead>
<tr>
<th>Compound</th>
<th>UV Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIB &amp; geosmin</td>
<td>LPUV</td>
<td>Collivignarelli and Sorlini 2004</td>
</tr>
<tr>
<td>Herbicides &amp; Pesticides</td>
<td>LPUV</td>
<td>Collivignarelli and Sorlini 2004; Müller and Jekel 2001</td>
</tr>
<tr>
<td></td>
<td>UVC</td>
<td>Ma et al. 2002</td>
</tr>
<tr>
<td></td>
<td>HPUV</td>
<td>Benitez et al. 2002</td>
</tr>
<tr>
<td>MTBE</td>
<td>LPUV</td>
<td>Garoma and Gurol 2004; Graham et al. 2004</td>
</tr>
<tr>
<td>NOM</td>
<td>LPUV</td>
<td>Latioglu and Gurol 2003; Mischuk et al. 2003; Collivignarelli and Sorlini 2004; Berube et al. 2004; Chin and Berube 2005</td>
</tr>
<tr>
<td>THMs</td>
<td>UVC</td>
<td>Liu and Sun 2003</td>
</tr>
<tr>
<td>MTBE</td>
<td>LPUV</td>
<td>Ramakrishnan et al. 2004</td>
</tr>
<tr>
<td>Phenols</td>
<td>MPUV</td>
<td>Teo et al. 2003; Esplugas et al. 2002</td>
</tr>
</tbody>
</table>
**Commercial Activity: Development of UV/O₃ systems**

Commercial UV/O₃ AOP systems are being developed but no commercial applications currently exist for drinking water treatment. However, UV/O₃ systems have been applied for municipal wastewater treatment by Wedeco (Ternes et al. 2003) and Hydroxyl Systems (www.hydroxyl.com) offers UV/O₃ systems that disinfect and remove colour and odor from wastewaters.

**THE UV/TiO₂ PHOTOCATALYSIS PROCESS**

The ideal semiconductor photocatalyst for UV-based water purification should be chemically and biologically inert, easy to produce and use, and activated by UV (Mills and Lee 2004). The semiconductor that comes closest to meeting these criteria is titanium dioxide (TiO₂), the most studied semiconductor photocatalyst today (Bhatkhande et al. 2001).

TiO₂ is a semiconductor with a band gap energy of ~3.2-3.0 eV, so UV of wavelengths less than 400 nm can excite pairs of electrons and holes. The photogenerated electrons then react with O₂ to produce predominantly superoxide radical anions (•O₂⁻), and the photogenerated holes react with water to produce •OH. These two types of reactive radicals, along with other oxidants and radical species, work together to decompose organic compounds. The longer the photocatalyst film is illuminated with UV, the more organic material can be decomposed. The efficiency of most processes is low, typically <1% due to reflection and scattering losses and significant electron-hole recombination at light intensities typically found in photoreactors (Mills and Lee 2004; Fujishima et al. 2000; Hoffmann et al. 1995). Another drawback of the UV/TiO₂ AOP is the quantum yield of •OH is only about 4% (Sun and Bolton 1996).

The key advantage of the UV/TiO₂ AOP is that no chemical addition (e.g., O₃, H₂O₂) is required to generate •OH radicals. Additionally, studies have shown the ability of UV/TiO₂ processes to disinfect water (Zhang et al. 1994; Ireland et al. 1993; Matsunaga et al. 1995; Curtis et al. 2002; Dunlop et al. 2002; Otaki et al. 2000; Wist et al. 2002) and this topic was reviewed by Blake et al. (1999). Yet, the design of photocatalytic reactors for water treatment is still in development. Slurry-based reactors are common but require separation of the TiO₂ slurry from the water stream. More promising are reactors with TiO₂ coated surfaces, but certain engineering challenges must be overcome before these types of systems are commercially available.

**Table 8. 21st century studies involving UV/TiO₂ treatment of compounds found in drinking water**

<table>
<thead>
<tr>
<th>Compound</th>
<th>UV Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOM</td>
<td>MPUV</td>
<td>Palmer et al., 2002</td>
</tr>
<tr>
<td>Chlorinated benzaldehydes</td>
<td>max @ 365 nm</td>
<td>Bekbolet et al., 2002</td>
</tr>
<tr>
<td>Chlorinated benzaldehydes</td>
<td>max @ 365 nm</td>
<td>Kerc et al., 2004; 2003a; 2003b; Uyguner et al., 2004</td>
</tr>
<tr>
<td>Chlorinated benzaldehydes</td>
<td>300-400 nm</td>
<td>Gonenc and Bekbolet, 2001</td>
</tr>
<tr>
<td>Herbicides &amp; Pesticides</td>
<td>UVC</td>
<td>Bekbolet and Getoff, 2002</td>
</tr>
<tr>
<td>Phenol</td>
<td>MPUV</td>
<td>Hequet et al., 2001</td>
</tr>
<tr>
<td></td>
<td>Xenon arc lamp</td>
<td>Konstantinov et al., 2001</td>
</tr>
<tr>
<td></td>
<td>1000W Hg lamp</td>
<td>Daneshvar et al., 2004</td>
</tr>
<tr>
<td></td>
<td>sunlight</td>
<td>Toyoda et al., 2000</td>
</tr>
</tbody>
</table>

**Commercial Activity: Photocatalytic reactors for water treatment**

Mills and Lee (2004) included a table of companies that currently promote photocatalytic systems for water purification. The most note-worthy product is Purifics’ Photo-Cat™, a TiO₂ slurry-based photocatalytic reactor that Purifics claims is capable of treating water down to level exceeding drinking water standards as well as having a quarter of the operating and maintenance costs of other AOPs. However, Purifics is yet to install the Photo-Cat™ reactor for a drinking water application (private communication with T.P., Purifics ES Inc. 2006).

In Europe, much attention has been focused on the development of low-cost, fully autonomous water treatment systems for disinfection and removal of trace organic pollutants for use in remote locations and developing countries. Photocatalytic reactors driven by sunlight have emerged as the technology best suited for such applications (Galvez and Rodriguez 2002). Two groups, The Plataforma Solar de Almería (PSA), a dependency of the Center for Energy, Environment and Technological Research (CIEMAT) in Spain, and France’s Laboratoire d’Application de la Chimie à l’Environnement (LACE) are respectively overseeing two major projects, SOLWATER (www.psa.es/webeng/solwater) and AQUACAT (Chapelon and Herrmann 2004).
REFERENCES


Five Frequently Asked Questions About UV-Safety

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² Comité Européen de Normalisation (CEN), Technical Committee 169 “Light and Lighting” / Workgroup 8 “Photobiology
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ABSTRACT
Human UV exposure can lead to acute effects (skin: erythema; eyes: photokeratitis, photoconjunctivitis) and long term effects (skin: accelerated skin aging, basal cell carcinoma, squamous cell carcinoma, malignant melanoma; eyes: cataracts). The International Commission for Non-Ionizing Radiation Protection (ICNIRP) has published international recommendations for maximum UV-exposure levels. For the effective radiant exposure Heff (biologically weighted dose) the daily exposure (8 h) limit value is 30 J m⁻² with an additional requirement that the unweighted UVA dose H_UVA shall not exceed a daily exposure limit value of 10⁴ J m⁻². These ICNIRP UV-exposure limit values have been incorporated in a recently published European Union Directive on Optical Radiation exposure by artificial sources during work. Measurement and assessment methods are standardized by EN 14255-1. In response to a previous article in IUVA News [Wieringa and Vermeulen 2004], many questions related to UV safety were received by the IUVA which have been summarized here in five questions with associated short-form explanations.

DOES THE ICNIRP UV-HAZARD ACTION SPECTRUM APPLY TO SKIN ONLY, OR ALSO TO THE EYES ?

The ICNIRP UV-hazard spectral weighting function S(λ) takes the combined hazards for eyes and skin into account. Figure 1 shows the ICNIRP UV-hazard weighting function in combination with the absorption spectra of three important biological molecules.

How do you calculate a biologically effective dose from a lamp spectrum?
Let’s suppose one has measured a lamp spectrum of interest at the considered position of exposure with a calibrated spectroradiometer equipped with cosine diffused input optics. Then one knows the physical spectral irradiance E(λ, t). Several different biological effects may result from the lamp’s irradiance, depending on which kind of tissue is exposed and for how long (and/or how often). The biological effects of UV radiation are strongly wavelength dependent. The efficiency of UV radiation to induce a certain biological effect can be described by a spectral weighting function. Multiplication of the spectral irradiance by the pertaining spectral weighting function, followed by integration over time gives the biological weighted dose Heff(λ). The ICNIRP UV-hazard spectral weighting function S(λ), which takes the combined hazards for eyes and skin into account, is thus applied via a simple calculation:

\[ H_{eff} = \int_{0}^{t} \int_{\lambda} \cdot E(\lambda, t) \cdot S(\lambda) \cdot d\lambda \cdot dt \] should be \( \leq 30 \text{ J m}^{-2} \)
per working day (8 h).

Figure 1: Top curve: ICNIRP UV-hazard weighting function for the combined risks for skin and eyes. Lower curves: three absorption spectra of important bio-molecules.
Source [Wieringa 2006].
where: $H_{\text{eff}}$ is the effective radiant exposure, that is, the radiant exposure spectrally weighted by $S(\lambda)$, expressed in joules per square meter [J m$^{-2}$]; $H_{\text{eff}}$ is only relevant in the range 180 to 400 nm.

$E_\lambda(\lambda, t)$ is the spectral irradiance or spectral power density, that is, the radiant power incident per unit area on a surface, expressed in watts per square meter per nanometer [W m$^{-2}$ nm$^{-1}$]; values of $E_\lambda(\lambda, t)$ come from measurements or may be provided (for a defined geometry) by the manufacturer of the equipment;

$S(\lambda)$ is a spectral weighting function taking into account the wavelength dependence of the health effects of UV radiation on eye and skin [dimensionless].

Figure 2 shows a lamp spectrum before and after application of the ICNIRP UV-hazard weighting function $S(\lambda)$.

For an ozone-free low pressure mercury UVC lamp, measurement data from a radiometer with a flat response spectrum can be used as an input value. Here the calculation is quite easy. Since there is only one emission line of biological significance at 254 nm, the unweighted value of a calibrated broadband meter may be simply multiplied with the corresponding value from Table 1 (which is 0.5). Thus, for a 254 nm lamp a maximum unweighted dose of 60 J m$^{-2}$ over 8 h is allowed (because it corresponds to a biologically effective dose of $0.5 \times 60 = 30$ J m$^{-2}$). As one can clearly see from Figure 1, this simple calculation by hand is not feasible with more complex spectra. Therefore, broadband UV-radiometers have been developed that closely match the ICNIRP UV-hazard function using a carefully designed filter/detector combination, thus offering direct readings of biologically effective irradiance $E_{\text{eff}}$. Sophisticated devices can be equipped with the possibility to integrate over time to measure $H_{\text{eff}}$. For dose measurements over prolonged exposure duration, the noise behavior and stability of the integrating function are crucial for accuracy.

If one measures UV with a broadband radiometer, one must know whether the radiometer has a flat response curve and measures the unweighted (physical) UV or that it has a biological response curve and thus measures the weighted (biological) UV. Note that, apart from the ICNIRP curve, there are several other weighting functions too (e.g. for erythema, for the beneficial effect of vitamin D production, or the CIE NMSC weighting function shown in Figure 3, etc.). To make it even more complicated, the response bandwidth may only partly cover the whole lamp output spectrum, and you have to be aware of this too!

Note that an additional requirement also applies, namely that the unweighted (i.e. physical) UVA dose $H_{\text{UVA}}$ shall not exceed a daily exposure limit value of 104 J m$^{-2}$:

$$[2] \quad H_{\text{UVA}} = \int_{0}^{t=400} \int_{\lambda=315}^{\lambda=400} E_{\lambda}(\lambda, t) \cdot d\lambda \cdot dt$$

where: $H_{\text{UVA}}$ is the radiant exposure, that is, the time and wavelength integral or sum of the irradiance within the UVA wavelength range 315 to 400 nm, expressed in joules per square meter [J m$^{-2}$]; $H_{\text{UVA}}$ is only relevant in the range 315 to 400 nm.

$E_{\lambda}(\lambda, t)$ is the spectral irradiance or spectral power density, i.e., the radiant power incident per unit area on a surface, expressed in watts per square meter per nanometer [W m$^{-2}$ nm$^{-1}$]; values of $E_{\lambda}(\lambda, t)$ come from measurements or may be provided (for a defined geometry) by the manufacturer of the equipment;
It is important to use consistent methods for Occupational Health and Safety related UV-measurements and their according assessment. In Europe, for UV safety measurements the standard EN 14255-1 “Ultraviolet radiation emitted by artificial sources in the workplace” applies. This standard describes how to perform measurements and assessments of personal exposures to artificial ultraviolet radiation sources within the wavelength band of 180 to 400 nm. The standard became effective in March 2005 and supports implementation of the recently released EU Directive about artificial optical radiation exposure by artificial sources in the workplace [EU 2006].

The Directive on Optical Radiation Safety applies for the whole EU, while at least the following countries are bound to implement EN 14255-1: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

### Table 1: UV exposure limits and general weighting factors

<table>
<thead>
<tr>
<th>λa / nm</th>
<th>ELa / J m⁻²</th>
<th>ELb / mJ cm⁻²</th>
<th>S(λ)a</th>
<th>ELc / λa / nm</th>
<th>ELd / J m⁻²</th>
<th>ELb / mJ cm⁻²</th>
<th>S(λ)b</th>
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a. Wavelengths chosen are representative; other values should be interpolated (see eqs. 3a-c).
b. Relative spectral effectiveness. This is the ICNIRP spectral weighting function S(λ) for determination of Heff and exposure limits.
c. Emission lines of a mercury discharge spectrum [ICNIRP 2004].
d. EL for a monochromatic source, but also limited by a dose-rate of 10 kW m⁻² (1 W cm⁻²) for durations greater than 1 s, as well in order to preclude thermal effects.

Values of S(λ) for wavelengths not listed in Table 1 may be interpolated with reasonable accuracy using the following three expressions which apply only from 210 – 400 nm [ICNIRP 2004]:

\[ S(\lambda) = \begin{cases} 
0.959^{(\lambda - 270)} & \text{for } 210 \leq \lambda \leq 270 \text{ nm} \\
1 - 0.36^* \left( \frac{\lambda - 270}{20} \right)^{1.64} & \text{for } 270 < \lambda \leq 300 \text{ nm} \\
0.3^*0.736^{(\lambda - 300)} + 10^{(2 - 0.0163 \lambda)} & \text{for } 300 < \lambda \leq 400 \text{ nm} 
\end{cases} \]
Yes, this is true. In skin, at 254 nm over 99% of the incoming radiation is absorbed in the first 100 μm where most cells will not replicate any more. This is very fortunate, because in this way only very few of the highly energetic UVC photons can reach the basal cell membrane where the new skin cells grow. Note, however, that absorption is a statistical process, which means that although only a very small fraction of the UVC photons may penetrate into living cells, the higher the irradiance at the surface becomes, the higher the absolute number of damaged cells. The longer the wavelength, the deeper UV radiation can penetrate the skin, but also the photons possess less energy to produce damage.

Broad-spectrum ultraviolet radiation (solar UV, as well as UV from sunbeds and sunlamps) is known to be a human carcinogen, based on sufficient evidence of carcinogenicity from studies in humans, which indicates a causal relationship between exposure to broad-spectrum ultraviolet radiation and human cancer. The separate spectral bands of UVA, UVB and UVC radiation are reasonably anticipated to be a human carcinogen based on limited evidence of carcinogenicity from studies in humans and sufficient evidence of carcinogenicity from studies in experimental animals, which indicates there is an increased incidence of malignant and/or a combination of malignant and benign tumors in multiple species of experimental animals [USDHHS 2002].

Skin cancer is caused by damage to cells that are able to reproduce themselves. These are located around the basal membrane, where some UVB and relatively much UVA can penetrate. This (along with the absorption spectra of biological molecules in Figure 1) explains the shape of the CIE non-melanoma skin cancer (NMSC) action spectrum as shown in Figure 3. Although the NMSC action spectrum indicates a rather low efficiency for UVA to induce skin cancer, it must be realized that the UVA irradiance of many lamp types is much higher than that within the UVB and/or UVC range.

Is UVC (e.g. 254 nm) strongly absorbed in the uppermost skin layer?

Yes, indeed strong absorption takes place immediately at the surface, but unlike the skin, the cornea is not covered by a relatively “insensitive” protective layer. Welder’s flash (or photokeratitis) is a well-known acute effect that easily occurs when eye protection is not worn during welding (even if welding only lasts a few seconds). Snow blindness is the same effect, but due to the lower irradiance values and comparably longer wavelengths in solar radiation, it requires a lot more exposure time. Chronic exposure to UVB and UVA over the years can cause cataracts (the eye lens forms a life-time “UV dosimeter”).

Figure 3. Non Melanoma Skin Cancer (NMSC) action spectrum issued by the International Commission on Illumination (CIE – Commission Internationale de l’Eclairage), which can be used to compare lamps for their long term effects regarding to skin cancer (except for melanoma). UVB radiation clearly is most efficient for the induction of non-melanoma skin cancers and UVC to a lesser extent. Note that, although less effective, UVA is not “harmless”.

Figure 4. Penetration in the eye for various spectral regions. Source: Dutch Health Council.
Are there any agreed UV-warning symbols?

The good news is that there are several symbols, the bad news is that they are not united. Some examples are shown in Figure 5a (origin IEC) and 5b (origin Comité Européen de Normalisation).

Symbols alone can sometimes be unclear. Additional warning texts, like shown in Figure 6, can be very helpful to inform workers and put the risk in proportion. Clear designation (e.g., on the floor) of safe zones where no protection is needed versus zones where eye (and in some cases even skin) protection is needed also can be very useful.

**Figure 6.** Instead of only applying a UV-warning symbol, an additional clear specification of maximum allowable unprotected exposure duration helps workers to judge the risk.

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**REFERENCES**


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INIRC/IRPA 1985. INIRC/IRPA Guidelines on limits of exposure to ultraviolet radiation of wavelength between 180nm and 400nm (incoherent radiation), Health Physics, 49(2): 331-340. [www.icnirp.net/downloads.htm](http://www.icnirp.net/downloads.htm)


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