IUVA NEWS

ISSN 1528-2017
Volume 7/ No. 1 March 2005

ISSUE THEME

Detailed Program for the 3rd International Congress on Ultraviolet Technologies

Whistler Conference Center

Round House Lodge

Come to Whistler, BC for the UV Congress 24-27 May

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Articles on UV Air Treatment and Aquatic Photochemistry

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Printed by Quality Color
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Editor in Chief: Dr. James R. Bolton

IUVA News (print version) (ISSN 1528-2017) is published quarterly by the International Ultraviolet Association, Inc. (IUVA) and is provided free to IUVA Members.

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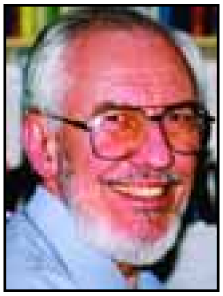

EDITORIAL

JIM BOLTON

Editor-in-Chief

This is the start of my second year as Editor in Chief of IUVA News. This Issue is very important because it contains, as a "pull-out" Section, the Detailed Program of the 3rd International Congress on Ultraviolet Technologies to be held 24-37 May in Whistler, BC, site of the 2010 Winter Olympics. There will be over 120 papers presented, a great UV Workshop, four exciting Plenary Speakers and an Exhibit Hall full of the newest and best UV equipment. This is the "Event of the Year" for anyone interested in ultraviolet applications. We have made registration very easy as an online process on the IUVA Web Site (www.iuva.org) to start the process. Plan to make this a family holiday as well. We have arranged the dates so that the Victoria Day Canadian long weekend is the weekend before the Congress and the Memorial Day long weekend in the US is the weekend after the Congress.

I am pleased to announce the appointment of **Yvaine Schulz** of 123 Admin, LLC in Colorado as IUVA News Manager. Yvaine is now responsible for ad sales and administration and the production and distribution of IUVA News. I will continue to be the Editor in Chief, responsible for all editorial content.

MESSAGE FROM THE PRESIDENT

BUSY, BUSY, BUSY.

BOB HULSEY

As so many things have happened since my last message, I thought it best to take a minute or two of your time to go beyond the world of UV. As I prepare to turn this corner of the News over to Andreas Kolch when he becomes IUVA President in May at our World Congress, my mind naturally turns to the issue of change. Just think of the changes over the last few months, some good, some with terrible consequences: the U.S. presidential election is over, the Israelis and Palestinians are talking again, the Kyoto protocol went into effect, and the tsunami took over 150,000 lives in Asia and Africa. All of these were far-reaching events that will continue to affect the lives of millions of people around the world for many years to come.

In the last two weeks, there have been events on a much smaller scale that cause one to reflect on the impact they have on the world around them. The vote I cast on Election Day was one of millions and didn't change its outcome; yet I still voted. Being friends with both Jews and Arabs doesn't alter the course of Middle East politics but it still illustrates that people can get along. Turning off lights in my house doesn't shut down an antiquated power plant, but it does save energy. Finally, my small gift to aid the tsunami victims doesn't change what happened, but I hope it will help rebuild some of the devastation. All of these acts are small, but are done in the hope that they will contribute to a much larger cause.

Along these lines, there are events that result in a huge impact on a smaller scale. One of these was the tragedy that claimed the life of a fellow water treatment professional. Geetha Angara, a lead chemist at the Little Falls Water Treatment Plant, lost her life on Tuesday, February 8th, while doing what she loved - providing safe drinking water to over 800,000 people. Geetha was a very peaceful person, but also a very dedicated and driven scientist. She was a catch all to those around her for any question related to process chemistry; her interest in water treatment was passionate. Having known Geetha, it seems cruel that she was taken from us so early. My heart goes out to her family, friends, and coworkers as they deal with this personal tragedy. This event has left a hole in the hearts of those around her. It can be filled only by the knowledge that she made an impact on many lives through her positive attitude, her smile, and her dedication to her work. These traits result in a legacy that will not be forgotten.

In the last few days, I was reminded of another great loss but was also given hope that good works live beyond any one person. Many of you will recall the passing of Dr. Gordon Finch in January of 2000. He was one of the leading researchers in the use of ozone and UV technology to inactivate *Cryptosporidium*, and his loss was felt deeply in the water treatment community. But the results of his good work live on. The research he was involved in is still being carried on at the University of Alberta and by those whose lives he touched through his teachings and collaborative research. I am happy to report that Dr. Chuck Haas, who was deeply involved in the original research, has continued to work on this subject and that his students are building on the strong foundation that Gordon provided to advance the scientific design of disinfection processes and systems.

Hot UV News

The following are some of the more interesting items from the UV News page on the IUVA Web Site (**https://secure.nelixstore.com/iuva/public/uv_news.htm**).

10 FEBRUARY 2005: Megola Announces Completion of Acquisition of UV Innovations Inc. (**http://www.primezone.com/newsroom/?d=72454**),PrimeZone Media Network

CORUNNA, Ontario, -- Megola Inc. (**www.megola.com**) (OTCBB:MGOA), a leading solution provider in physical water treatment, microbiological control, wastewater treatment and air purification, announced that it has completed its acquisition of UV Innovations Inc. (UVI). The acquisition gives Megola exclusive rights to all of UVI's intellectual property, including its commercial and residential lines of ultraviolet (UV) air and water disinfection units, which will compliment Megola's existing air and water treatment products…

11 JANUARY 2005: Malcolm Pirnie to Acquire McGuire Environmental Consultants **(http://www.wateronline.com/content/news/article.asp?docid=381f366c-86a2-4751-8f62-91dcbd5cb39a),** Water Online

White Plains, NY -- Malcolm Pirnie has signed a letter of intent to acquire the California-based firm of McGuire Environmental Consultants, Inc. (MEC). According to an announcement today by William P. Dee, P.E., DEE, Pirnie's president and CEO, the three principals of MEC - Michael McGuire, Edward Means, and Michael MacPhee - as well as all of the staff will join Malcolm Pirnie. The transaction is expected to be completed in the first quarter of 2005…

DECEMBER 2004*: *Giardia Outbreak In Norway, Health Stream (**http://www.waterquality.crc.org.au/hsarch/HS36b.htm**)

A waterborne outbreak of giardiasis with over 1,000 laboratory-confirmed cases has occurred in the town of Bergen, Norway. The outbreak appears to have begun in late August with case numbers gradually increasing over several weeks, but public health investigations did not identify the water supply as the probable source until early November…

…A water treatment plant with filtration and **UV disinfection** had already been commissioned for the affected water supply before the outbreak occurred. A temporary **UV plant** has now been installed to provide additional disinfection capacity for the supply while the new plant is being built.

UV Industry News

The following are some of the more interesting items from the UV Industry Announcements page on the IUVA Web Site (**https://secure.nelixstore.com/iuva/public/uv_industry_announcements.htm**).

25 January 2005: Cities of Winnipeg and Calgary Select Trojan UV for Environmentally Friendly Wastewater Equipment(**http://www.trojanuv.com/en/homeframe.htm**)
Trojan Technologies announced today that both the cities of Winnipeg, Manitoba and Calgary, Alberta have selected its **ultraviolet (UV) disinfection** equipment to treat the cities' wastewater before being released into nearby rivers and lakes. Trojan's **UV systems** use an environmentally-friendly ultraviolet disinfection process that destroys water-borne pathogens without the use of chemicals, such as chlorine…

13 JANUARY 2005: Steril-Aire Sues Dust Free for Patent Infringement.
Burbank, CA - Steril-Aire (R) Inc. (http://www.steril-aire.com/), which manufactures a line of patented "UVC Emitters (TM)" for mold and microbial control, today announced that it has filed suit against Dust Free (R) for infringement of U.S. Patent Numbers 5,334,347; 5,817,276; 6,245,293; 6,267,924; 6,280,686; 6,313,470; and 6,627,000. This series of patents involves the application of **UVC devices** for coil and drain pan irradiation in HVAC systems, where they are used for mold, microbial and indoor air quality control. The lawsuit was filed on January 7, 2005 in the U.S. District Court for the Central District of California…

26 January 2005: Dust Free Responds to the Steril-Air Press Release (**http://mail.nelix.com/newwebmail/Download.aspx?MessageID=B0013548331.MSG&ID=1235**).
Royse City, TX.- In response to the patent infringement complaint filed against Dust Free by Steril-Aire, Dust Free will be filing counter claims alleging that Steril Aire's UV/coil irradiation patent claims are invalid and not infringed. The counter claim further alleges that Steril-Aire failed to comply with its duty of candor towards the Patent Office and, for this reason, Sterile Aire's patents are unenforceable. Gregg Burnett, CEO of Dust Free, had this comment regarding the complaint. "We believe that the motivation for the complaint was to intimidate Dust Free into a license agreement that would have required Dust Free to pay substantial royalties in order to avoid legal costs in defending ourselves. It has always been Dust Free's policy to provide our customers the best product at the lowest possible price - so we intend to aggressively prove the invalidity of the patents in question."…

News from IUVA

WINNERS OF THE MEMBER-GET-A-MEMBER DRIVE

The year long contest has finally come to a close. We are very pleased to announce that the winner of the Member-Get-A-Member drive is ***Mr. Gerry Kolasser***. He will receive free registration to the Third International Congress on Ultraviolet Technologies in Whistler this May. Congratulations Mr. Kolasser! Our two runners up are **Phillippe Boileau** and Past IUVA Preseident, **Jennifer Clancy**. They will both receive one year free individual membership to the IUVA. Congratulations to all of you on a successful membership drive.

NEWS FROM THE UV AIR TREATMENT GROUP

The following new committee officers were appointed at the 2nd Annual Air Treatment Conference held at Penn State on 10 December 2004: Chair: **Wladyslaw Kowalski**, Chair-Elect: **Chuck Dunn**, Secretary: **Mary Clancy**, Treasurer: **John Putnam**. The committee reviewed and discussed two draft documents, "Draft Guideline for the Design and Installation of UVGI Air Treatment Systems," and "Draft Standard for the Testing and Commissioning of UVGI Air Treatment Systems." These documents can be downloaded from the UV Air Treatment Page in the Member Zone of the IUVA Web Site (**https://secure.nelixstore.com/iuva/member/atgroup.asp**). Comments from IUVA members are due by 1 April 2005. It was decided at the conference to subdivide these documents, after which the new documents, with member comments incorporated, will be reissued to IUVA members for a further round of review before releasing them for public comment.

Recently at the ASHRAE Winter meeting in Orlando, Florida, the ASHRAE Technical Affairs Committee unanimously approved a UV Task Group (TG2.UVAS), to be chaired by **Chuck Dunn** of Lumalier. Other officers of this group include **Meredith Stines** of American Ultraviolet as Vice-Chair, and **John Putnam** from Environmental Dynamics as Secretary. TG 2.UVAS is concerned with all aspects of equipment and systems that utilize ultraviolet germicidal irradiation (UVGI) to destroy or deactivate chemical and/or biological air and surface contaminants in HVAC systems and indoor spaces, including, but not limited to, effectiveness, safety, maintenance, and economics. Look for news and more information on this group's activities in IUVA News and the UV Air Treatment Page on the IUVA Web Site.

MEMBERSHIP INFORMATION

Now you can join the International Ultraviolet Association (IUVA) online! Visit **www.iuva.org** and click on the membership tab at the top of the page. There you will have access to information on the different categories of membership, membership benefits and online membership application. To join click the membership application button and fill out the form. To pay by check, simply print the completed form and send it in with your check. To pay by credit card click the payment button at the bottom of the page. Make sure you return to the IUVA site after your payment has been processed to complete the application. Please note that past issues of the IUVA News have had an application form printed in them. This form is no longer valid and should not be used when applying for membership.

IUVA GENERAL ASSEMBLY – NOTICE OF MEETING

The **Third IUVA General Assembly** will take place at 5:00 pm, Wednesday, 25 May 2005 in the Telus Conference Center, Whistler, BC, Canada. All IUVA Members in good standing are eligible to attend and vote. Non-Members may attend but may not vote. One of the principal items on the Agenda (see below) is the Election of the Members of the International Board of Directors. The Nominating Committee will present a slate of Nominees; however, any Member (with a Seconder) is entitled to present additional nominee(s) from the floor. The IUVA Bylaws are available for viewing at **http://www.iuva.org/public/bylaws.htm**.

IUVA GENERAL ASSEMBLY – AGENDA

1. Call to Order by the International President
2. Determination of a quorum.
3. Adoption of the Minutes of the Third General Assembly of 10 July 2003.
4. Reports
   a) International President - Bob Hulsey
   b) Executive Director - Jim Bolton
   c) International Treasurer - Chris Schulz
5. Report of the Nominating Committee and Election of the Members of the International Board of Directors
6. Amendments to the Bylaws (if any)
7. Installation of the new International President and his Address
8. Other business
9. Adjournment

NEW CORPORATE MEMBERS

IUVA is pleased to announce the following new Corporate Members - Welcome!

Trane, Inc. (O1), La Crosse, WI (**www.trane.com**)

eta plus electronic gmbh & co kg (O2), Nuertingen Germany (**www.eta-uv.com**)

S.I.T.A. SRL (O2), Genoa, Italy (**www.sitauv.com**)

Letter to the Editor

From **David Free**, Principal, DF Consultants, Korschenbroich, Germany

Knowing that you will probably be having an IUVA executive meeting at the Whistler convention, I thought it might be appropriate and of interest to raise the following ad hoc comments maybe to include in the discussions there, and maybe possibly for some action.

The efforts that have been put in to launch and progress IUVA to date are laudable and superb, and you deserve heartiest congratulations. However, maybe now could be the time for a pause for reflection and a review of status. In this context, at a recent meeting with some UV business colleagues in the informal chitchat that ensued, the subject of IUVA came up. We at the cutting edge on the business side of the UV industry welcome and are grateful for IUVA. It is a breath of fresh air in our business, but the consensus was that IUVA is heavily or almost totally focused on the technical and scientific side of UV, with virtually no content of interest or direct help to the UV corporate business community. There is almost no UV focused finance, business development, trend, economist, marketing, legal or patent, media issues, investment considerations, etc. of interest to the UV corporate executive. Perhaps this is only to be expected when nearly all of the IUVA Executive come from the UV scientific, technical and academic community, with those that do come from the private sector again coming from the research or technical side of their organizations.

The consensus was that IUVA has become a low key extension of the UV sector in such a publication as 'Photochemistry and Photobiolog', and caters primarily only to the "techies." It was even mooted by some of the UV company executives present, that IUVA was one dimensional and had become "boring." To us on both sides of the UV industry spectrum, technical and business, the technical side will always be of interest and never "boring." However, I for one, along with some of the other UV business oriented colleagues, would welcome a broader base from IUVA mixing equally both the technical and business sides of UV business, if that is possible and fits the terms of reference. Maybe it has always been the intent to primarily focus on the technical side (after all this is your own background), and if so then the above comments are misplaced, but many of my colleagues had hoped that there be an equal mix of the technical and business in IUVA, and something in IUVA for all. We all agreed that it would be nice to have some content of help and interest to the business side of UV, such as for example WC&P International projects on the water treatment side.

Understanding that it is your prerogative to direct IUVA in any direction you wish, I leave these comments with you. If they are inappropriate and I am out of line, I apologize. Selfishly, for me it would be nice to have IUVA as it is broaden its scope, but if you decide not, perhaps there is room for a separate organization, maybe under the IUVA umbrella, to deal with UV business issues.

Trust the comments are of interest. Keep up the good work.

Editor: I circulated this letter to members of the Executive Committee and the Editorial Board. Bob Hulsey, IUVA President, has summarized some of the responses I received. I would welcome more discussion and will publish further responses in the next issue of IUVA News.

We like being the tech portion of the UV world - where researchers can get together and talk a bit more freely about what they are doing to improve UV systems.

Even the techies are still interested in the business side, it shouldn't take over the entire organization bent but without manufacturers actually selling their equipment, we all go away.

There is a limit placed on us because of our not-for-profit status. Even then, market information is part of the education process

We are already addressing some of these points, such as patents, the UV Buyers Guide, and some business data; perhaps we need to highlight that portion of our work more.

The bottom line is - if the information described is of interest, we need volunteers to take part in gathering it and putting it into words and numbers. Again, he we can serve that need through topical groups or just task forces on certain subjects.

Editor's Response: I welcome Dr. Free's letter, since I am sure this will open up considerable discussion. The IUVA Bylaws allow for the formation of "Topical Groups." If some members of the UV industry would like to take the initiative, it would be great to form a "UV Industry Topical Group" that could focus on the areas that Dr. Free and his colleagues would like to see developed. I would be happy to facilitate the process. We already have a "UV Air Treatment Topical Group," and they have their own page in the Member Zone. We could easily add another page for this new Topical Group.

Application Note

Editor: This is the first of a series that I am starting of interesting "UV Applications" from the UV Industry. I would welcome further contributions of about the same length as the one below.

Disinfection of Wounds with a UV Lamp (the V-254 lamp) from Bob Johnson of MedFaxx, Inc. (www.medfaxxinc.com)

What happened before we had the current antibiotics we use for most infectious diseases? How did we treat infections prior to penicillin? The short and simple answer is the use of ultraviolet C-range, 254 nm hand held lamps, such as our V-254 lamp. Prior to 1971, the U.S. military utilized a lamp that physical therapists carried around to shine into wound cavities, bed sores, and other pathogen infected dermatological conditions. One of the nice aspects of this treatment was there exists no known pathogen, whether bacteria, spore, mold or virus that has ever been able to mutate to adapt to this form of eradication. One of the benefits of the V-254 is that there has been no development of what we now call "super bugs."

The actual treatment is generally less than 60 seconds with the lamp held approximately 1 inch from the wound surface. The cost is the minimal price of electricity for a 4 watt bulb. One of the more difficult concepts to explain today is that most educated health practitioners do not realize that the V-254 can also be used for systemic infections, for example bacteria, such as staph, that can be systemic yet the treatment can destroy the staph by repeated exposure to the open wound area. This is possible due to the colonization aspect of the bacteria, which after treatment, results in the accumulation of the bacteria in the treated area and over repeated treatments rids the body of the infection until the immune system can regain control and overwhelm the infectious agent.

Unfortunately, in the U.S. the health care system does not reward cost efficiencies and the old treatment has not caught on due to reimbursement issues. In third world countries, the implications are great to help stop the spread of infectious agents for those unable to afford drugs and/or adequate health care. In the longer term, UV treatment addresses the issue of the stopping of the proliferation of drug resistant pathogens which require continual development of new, more powerful drugs. Drug reactions are curtailed by this form of treatment, and in our society drug associated reactions are becoming more costly in dollars and lost lives.

UV FAQ's

Editor: I often get questions about UV. I have collected the Questions and Answers in the UVFAQ's page on the IUVA Web Site (http://www.iuva.org/public/faqs.htm). The following are some of the more interesting items.

QUESTION: *I am a research student, and I am working on UV treatment for air pollutants. Would you please tell and guide me as to how to calculate the UV dose for air pollution treatment?*

ANSWER: This is a very complex issue. First, you have to be able to calculate the fluence rate (irradiance) distribution within the UV reactor. This requires a sophisticated computer program. Then you must carry out a volume average of the fluence rate (irradiance) over the entire reactor. The residence time of the air in the reactor is given by: volume/(flow rate). The fluence (UV dose) is then the product of the average fluence rate and the residence time.

This calculated UV dose is a "theoretical maximum" because it assumes that the air is perfectly mixed (in a radial sense) as it passes through the reactor. This is usually not the case, so the actual fluence (UV dose) will be less than the theoretical maximum.

One can experimentally measure UV dose by using biodosimetry. Here a (non-pathogenic) microorganism is infected into the air upstream of the UV reactor and allowed to thoroughly mix in the air stream. Samples are taken of the upstream and downstream air (after mixing). These are then compared with a laboratory (determined using a collimated beam apparatus) fluence (UV dose)-response curve, where the fluences (UV doses) are accurately known.

QUESTION: *What is the difference between a blacklight and a bluelight?*

ANSWER: A "blacklight" is a fluorescent light tube that emits at about 365 nm - this is just below the wavelengths that humans can see, but it is absorbed by most pigments in clothes so that they "fluorescence." This is the effect seen in many bars and discos.

I'm not sure what you mean by a "bluelight" - perhaps you means "germicidal" low-pressure mercury lamp. They do glow "blue," but most of their output is at 254 nm, so DO NOT look directly at such a lamp when it is operating. These lamps are used in air and water disinfection, since the 254 nm light is absorbed by DNA in bacteria and viruses causing their inactivation.

LIGHT AND ENVIRONMENTAL CHEMISTRY: Influence of Changing Solar UV Radiation on Aquatic Photoreactions

RICHARD G. ZEPP

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ABSTRACT

Solar radiation provides the primary driving force for the biogeochemical cycles upon which life and climate depend. Recent studies have demonstrated that the absorption of solar radiation, especially in the ultraviolet spectral region, results in photochemical reactions that can have significant effects on the environmental cycling of carbon, oxygen, sulfur, and various trace metals in the environment. Other research has shown that photoreactions help cleanse the environment of the waste materials derived from human activities. Selected current research results on the photochemical reactions in aquatic environments are discussed here. Aquatic photoreactions considered include: photoinduced changes in the optical properties of dissolved organic matter; formation of greenhouse and chemically important trace gases; conversion of refractory organic matter, organic nitrogen and metals to biologically available compounds (and vice versa); and changes in the redox state of the upper ocean and freshwaters through formation of reactive oxygen species and changes in transition metal speciation.

Keywords: aquatic photochemistry, CDOM, carbon, nitrogen, metals, ROS

INTRODUCTION

The origins of the field of photochemistry date back to a period in which sunlight was the only available light source for photochemical studies. For example, pioneering research was conducted at the turn of the 20th century in a photochemical laboratory located on the rooftops of the University of Bologna (Heindel and Pfau 1965; Balzani and Moggi 1990). In sunlight experiments at the Bologna laboratory, Ciamician conducted photochemical studies that laid the groundwork for organic photochemistry. With the advent of artificial light sources, the great bulk of photochemical studies during the middle part of the 1900s no longer used sunlight due to its variable intensity and polychromatic nature.

Interest in sunlight-induced photoreactions in the environment has been rekindled since the 1960s through the emergence of various environmental problems. First, it was recognized that photoreactions play an important role in smog formation (Leighton 1961), stratospheric ozone depletion (Rowland and Molina 1975), acid rain (Calvert et al. 1985), and the cleansing of the aquatic and terrestrial environment of the waste materials derived from human activities (Zafiriou et al. 1984). Second, recent studies indicate that photoreactions in aquatic environments have significant effects on the cycling of carbon, oxygen, sulfur, and various trace metals that are biologically important (Moran and Zepp 2000; Mopper and Kieber 2002; Zepp 2003).

Aquatic photoreactions that are strongly influenced by ultraviolet radiation include: formation of greenhouse and chemically important trace gases [carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), dimethylsulfide (DMS), carbonyl sulfide (COS)]) (Erickson et al. 2000); conversion of organically bound nitrogen to biologically available inorganic N (Bronk 2002); conversion of refractory organic matter to biologically available organic compounds (Moran and Zepp 1997; Mopper and Kieber 2002); photoinduced changes in the optical properties of dissolved organic matter (Frimmel 1998; Nelson et al. 1998; Blough and Del Vecchio 2002; Osburn and Morris 2003; Whitehead and de Mora 2004); and changes in the redox state of the upper ocean and freshwaters through formation of peroxides and changes in transition metal speciation (Sulzberger et al. 1990; Emmenegger et al. 2000; Kieber et al. 2003; Zepp 2003). Direct photoreactions of pollutants are also usually primarily initiated through absorption of UV radiation.

Interest in aquatic photochemistry has been stimulated in part by declines in stratospheric ozone over the past two decades that have resulted in increases in solar UV-B radiation (280–315 nm) reaching the Earth's surface

(Madronich et al. 1998). Current projections indicate that return of the ozone layer thickness to pre-1980s levels may not occur for another 50 years.

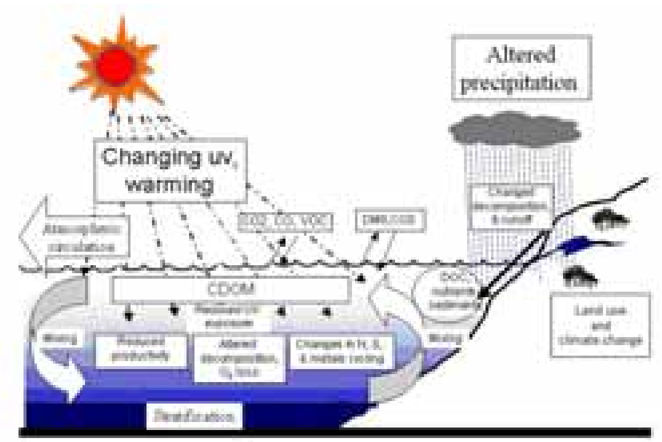

Figure 1. Interactions of aquatic photoreactions with changing UV and climate.

Aquatic photoreactions are sensitive to other factors that affect underwater UV exposure such as UV light attenuation in the water, mixing and stratification (Williamson et al. 1996; Vodacek et al. 1997; Nelson et al. 1998; Blough and Del Vecchio 2002; Del Vecchio and Blough 2002; Johannessen et al. 2003; Leavitt et al. 2003; Zepp 2003). Underwater UV exposure is thus sensitive to global changes in climate, land use and other human activities that affect aquatic transport, composition and optical properties. These effects are changing the UV-A (315-400 nm) as well as the UV-B (280-315 nm) spectral region so the discussions here include aquatic photochemical effects that are influenced by the entire solar UV spectrum (280-400 nm).

PHOTOREACTIONS OF ORGANIC MATTER

A significant portion of the photochemistry that occurs in aquatic environments is associated with the colored component of dissolved organic matter, referred to as CDOM (Williamson et al. 1996; Vodacek et al. 1997; Nelson et al. 1998; Blough and Del Vecchio 2002; Del Vecchio and Blough 2002; Johannessen et al. 2003; Leavitt et al. 2003; Zepp 2003). CDOM, which is a mixture of lignocellulose-derived polyelectrolytes that result mainly from the decay of terrestrial vegetation and aquatic detritus, constitutes the majority of the organic carbon in many lakes, rivers, and coastal waters. Humic substances make up an important part of CDOM. Photodegradation of CDOM results in loss of its UV and visible absorbance and fluorescence, a process referred to as "photobleaching," changes in the biological availability of its carbon- and nitrogen-containing constituents, and production of carbon dioxide, carbon monoxide, volatile hydrocarbons, and sulfur-containing gases (Fig. 1).

The photobleaching of CDOM has been observed by many investigators (Stewart and Wetzel 1981; Kouassi and Zika 1992; Williamson et al. 1996; Vodacek et al. 1997; Frimmel 1998; Miller 1998; Zepp et al. 1998; Moran et al. 2000; Blough and Del Vecchio 2002; Vahatalo et al. 2002; Osburn and Morris 2003; Zepp 2003; Vahatalo and Wetzel 2004). The process is illustrated by photoinduced changes in the absorption spectrum of the CDOM in ocean water over coral reefs in the Florida Keys (Fig. 2).The photobleaching process is mainly induced by the UV part of solar radiation (Whitehead et al. 2000; Del Vecchio and Blough 2002). When the water in a lake or the ocean becomes stratified, photobleaching can result in increased UV penetration and exposure in the upper water column. Recent observations have shown that the warm upper layers of the stratified ocean and lakes are generally much more UV transparent than deeper, cooler waters (Williamson et al. 1996; Vodacek et al. 1997; Nelson et al. 1998). These observations suggest that global warming may lead to increased UV penetration into aquatic ecosystems.

Photochemical production rates of dissolved inorganic carbon (DIC) [and concurrent photochemical oxygen demand from CDOM (Andrews et al. 2000)] generally are at least an order of magnitude greater than those of other known photoproducts (Graneli et al. 1996; Moran and Zepp 1997; Miller et al. 2002; Johannessen et al. 2003; Anesio and Graneli 2004). However, a recent study has shown that therates and quantum efficiencies for formation of biologically-labile photoproducts (compounds that are readily assimilated by bacteria) from CDOM are about the same as those observed for DIC photoproduction (Miller et al. 2002). (Fig. 3).

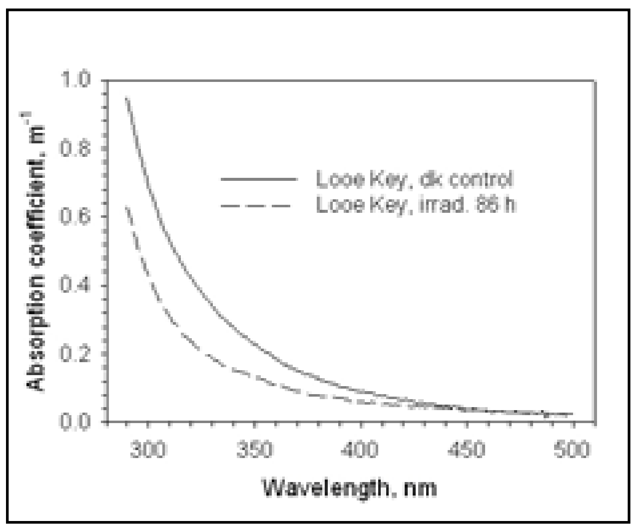

Figure 2. Photobleaching of CDOM in ocean water sample obtained from Looe Key Reef in Florida Keys on irradiation by simulated solar radiation.

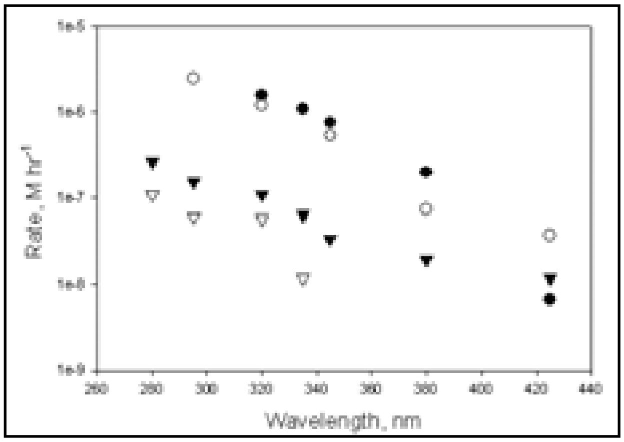

Figure 3. Comparison of the rates of photoproduction of biologically available photoproducts (circles) and carbon monoxide (triangles) in water samples from a saltmarsh and estuary on the coast of the Southeastern U.S.

The experiments shown in Fig. 3 were conducted by irradiating the samples using a xenon-arc lamp equipped with cut-off filters (cutoffs shown on X-axis) that blocked various parts of the UV spectrum. Rates of formation of BLPs were computed using cumulative bacterial oxygen consumption in inoculated samples during subsequent 2-week incubations (i.e., respiratory activity per absorbed photon) (Miller et al. 2002).

The effect of photoreactions on microbial interactions with DOM is dependent on the DOM source, however. The biological lability of refractory DOM (organic matter that is not readily assimilated by bacteria) is generally enhanced by exposure to sunlight (Wetzel et al. 1995; Moran and Zepp 1997; Osburn and Morris 2003; Vahatalo et al. 2003; Obernosterer and Benner 2004). However, the biological degradation of more reactive DOM may be little affected or, in some cases, can actually be decreased by exposure to UV (Benner and Biddanda 1998). The latter effect may be attributable in part to photoproduction of reactive oxygen species that inhibit biological activity or to UV-induced changes in DOM aggregates (Orellana and Verdugo 2003).

PHOTOREACTIONS AND INORGANIC NITROGEN PRODUCTION

UV radiation can affect nitrogen cycling through photoinhibition of nitrogen-related enzymatic activity. N cycling also is indirectly affected by enhanced decomposition of persistent dissolved organic nitrogen (DON) to biologically labile nitrogenous photoproducts (Bushaw et al. 1996; Bushaw-Newton and Moran 1999; Tarr et al. 2001; Bronk 2002; Koopmans and Bronk 2002; Mopper and Kieber 2002; Buffam and McGlathery 2003; Vahatalo and Zepp 2004). Biologically labile nitrogen compounds such as nitrate, ammonium and amino acids are rapidly recycled by the biota in aquatic systems, while N-containing substances whose structures are too complex or randomized to be readily assimilated accumulate in the water column. In aquatic environments with limited N fixation or low external inputs of labile N, the labile compounds drop almost to immeasurable levels in the photic zone where productivity occurs while the persistent dissolved organic nitrogen (DON) accumulates. Interactions of UV radiation and DON provide a pathway for the conversion of persistent DON to compounds that are more easily assimilated by aquatic microorganisms. A recent study has shown that the biologically-recalcitrant DON in the Baltic Sea can be decomposed to inorganic nitrogen, principally ammonium, by solar UV radiation (Vahatalo and Zepp 2004). This "photoammonification" process occurs most rapidly when UV radiation is absorbed by the DON (Fig. 4). The results of this study suggest that the rate of photoammonification equals the rate of atmospheric deposition of reactive inorganic nitrogen to northern Baltic Sea.

Two key inorganic species of nitrogen, nitrate and nitrite, photoreact when exposed to UV radiation to produce NO_x (nitric oxide plus nitrogen dioxide) plus reactive oxygen species, including hydroxyl radicals (Zafiriou and True 1979; Jankowski et al. 1999; Mopper and Kieber 2002; Zepp 2003). Free radicals produced by photoreactions of these species can have important effects on aquatic photochemistry (see Section 5 on reactive oxygen species in this paper). For example, the buildup of DMS in nitrate-rich Antarctic ocean waters is limited by its UV-induced photooxidation mediated by free radicals (Toole et al. 2004). Oceanic emissions of DMS produce particulates (i.e., sulfate aerosols) that directly and indirectly (via clouds) have a cooling effect on the marine atmosphere.

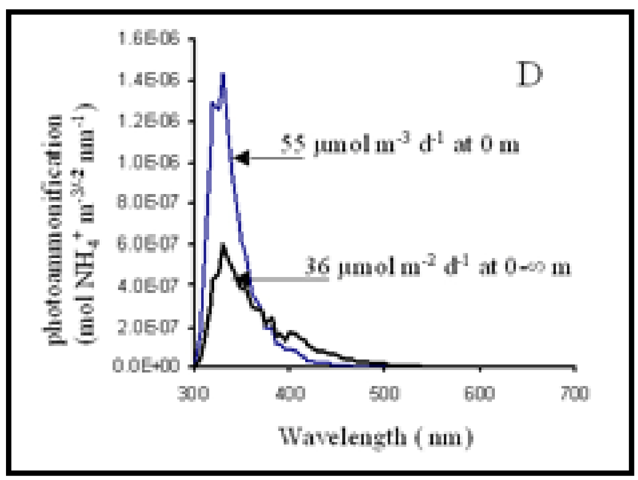

Figure 4. Computed wavelength dependence for the photochemical decomposition of biologically-recalcitrant dissolved organic nitrogen in the Baltic Sea to ammonium (Vahatalo and Zepp 2004).

PHOTOCHEMICAL METALS CYCLING

Photoreactions of metal oxides and organic complexes with metals (e.g. iron, copper, mercury) also are involved in environmental chemistry in aquatic environments, either via direct photoreactions of the complexes or reactions of the complexes with reactive oxygen species that are produced photochemically. Iron and copper are essential trace nutrients that can limit productivity in aquatic environments. In the upper ocean, lakes and in clouds these metals usually exist in forms that are not biologically available. UV-induced photoreductions of these metals produce reactive forms that are readily used by aquatic organisms (Sulzberger et al. 1990; Voelker and Sedlak 1995; Emmenegger et al. 2000; Zepp 2003).

The reactive forms of iron and copper also can affect aquatic carbon cycling by catalyzing oxidations of organic matter (Zafiriou and True 1979; Sulzberger et al. 1990; Gao and Zepp 1998; Emmenegger et al. 2000; Kieber et al. 2003; White et al. 2003). Iron can play a role in the photochemical production of •OH radicals in natural waters through reactions between Fe(II) and hydrogen peroxide (H_2O_2), two reactive compounds that are produced by UV-induced photoreactions of CDOM and its iron complexes. Such iron-mediated photoreactions, sometimes referred to as Photo-Fenton reactions, are involved in the photooxidation of CDOM in some freshwater ecosystems, e.g. the rivers that drain into the Atlantic Ocean and the Gulf of Mexico in the coastal U.S.A. The addition of strong Fe(III) chelating ligands to such river waters can significantly reduce CDOM photodegradation rates, presumably by reducing concentrations of photoreactive Fe-CDOM complexes that participate in photoredox reactions or that catalyze free radical oxidation of the CDOM. For example, the photoproduction of hydroxyl radicals in an iron-rich water sample from a U.S. estuary was strongly inhibited by the addition of desferal, a potent Fe chelating ligand (White et al. 2003).

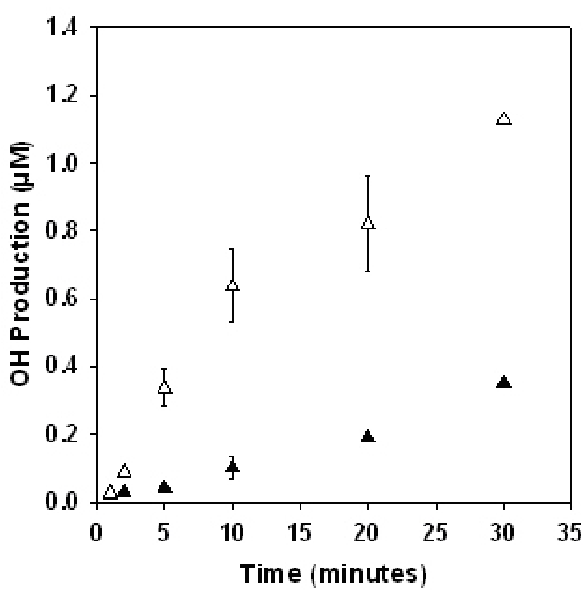

Figure 5. Photochemical production of hydroxyl radicals (•OH) in a water sample from an iron-rich (5 to 15 mM Fe) estuarine water sample (A) and estuarine water containing 0.100 mM desferal (A), a strong Fe chelating ligand. The samples were irradiated in an Atlas Suntest CPS tabletop solar simulator (White et al. 2003).

Mercury cycling also is affected by UV exposure in aquatic ecosystems. For example, elemental mercury in brackish water is oxidized by UV to form mercuric species (Lalonde et al. 2004) that are precursors to toxic methyl mercury that can adversely affect human health through biomagnification in aquatic food webs.

REACTIVE OXYGEN SPECIES IN AQUATIC PHOTOREACTIONS

The aquatic photoreactions discussed in this paper are mediated in part by a variety of reactive transients that are excited states, oxidants or reductants. The reactive transients are produced on absorption of sunlight by organic and inorganic chromophores in aquatic environments (Blough and Zepp 1995; Blough 1997; Kieber et al. 2003). The most important organic chromophore for ROS photoproduction is CDOM. Photoreactions of inorganic substances such as nitrite, nitrate, trace metals (iron and copper), and/or hydrogen peroxide also produce reactive transients. There is abundant evidence that solar UV drives the photoproduction of these transients. Certain reactive transients that include oxygen atoms are referred to as reactive oxygen species (ROS). ROS include hydroxyl radicals, alkoxy and peroxy radicals, singlet molecular oxygen, superoxide ions, and hydrogen peroxide. These ROS also can be produced within living systems by the action of UV radiation (as well as other mechanisms) where they cause various types of damage. The discussion of ROS in this paper focuses on exogenous photoreactions that produce ROS. The wavelength dependence for hydrogen peroxide production in ocean waters from the tropics and Antarcti illustrates the generality of the role of UV in initiating photoproduction of this widely distributed ROS (Fig. 6).

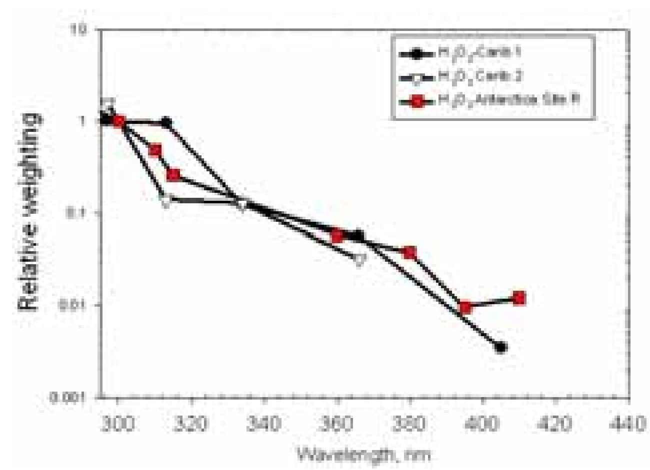

Figure 6. Action spectra (wavelength dependence) for photoproduction of hydrogen peroxide in water samples from the Caribbean Sea and from Antarctica (Kieber, Peake et al. 2003).

Secondary reactions between trace metals such as iron and copper and ROS can strongly influence the redox state and speciation of trace metals. Reactions between iron and hydrogen peroxide to enhance hydroxyl radical production have already been mentioned. More details about past research on metals, ROS and their interactions is available in several recent reviews (Kieber et al. 2003; Zepp 2003).

Reactive transients also play important roles in photoreactions of sulfur-containing compounds in marine environments (Erickson, Zepp et al. 2000; Mopper and Kieber 2002; Kieber et al. 2003). The sea is a major source of natural sulfur gases in the atmosphere . Of particular interest are DMS and carbonyl sulfide (COS). As noted earlier, oceanic emissions of DMS produce particulates (i.e., sulfate aerosols) may lead to a cooling effect on the marine atmosphere. Carbonyl sulfide is the most concentrated sulfur gas in the troposphere and it is believed to contribute to the formation of stratospheric aerosols. Both of these compounds are formed predominantly in aerobic marine environments, that is, the upper layers of the ocean, and their sources and sinks are affected by solar UV radiation. DMS does not absorb solar UV radiation and its major loss pathway involves indirect photoreactions in which photochemically-produced transients attack and oxidize the DMS (Mopper and Kieber 2002). Dimethylsulfoxide and carbonyl sulfide are two of the major products that are produced from indirect photoreactions of DMS in seawater. Although the nature of the transients involved in organosulfur photoreactions have not been defined, both CDOM and nitrate are involved in the photoreactions. COS photoproduction and DMS photooxidation may involve the intermediacy of dibromine radical ions and carbonate radicals, both of which can rapidly form via reactions of hydroxyl radicals with bromide or carbonate (Erickson et al. 2000; Mopper and Kieber 2002).

CONCLUSIONS

Aquatic photoreactions induced by solar UV radiation play an important role in carbon capture and storage, decomposition, and trace gas exchange. Photoreactions interact with microbial processes through effects on the biological availability of carbon and nitrogen substrates. One important aspect of UV interactions with carbon cycling involves the decomposition of UV-absorbing organic matter (photobleaching), principally chromophoric dissolved organic matter (CDOM). CDOM controls UV exposure in the sea and in many freshwater environments. Global warming may enhance the extent of CDOM photobleaching in the upper layers of lakes and the ocean by increasing periods of stratification. CDOM can be directly photodecomposed to dissolved inorganic carbon, carbon monoxide, and various carbonyl-containing compounds. UV-initiated photoreactions can potentially affect nitrogen and sulfur cycling in a variety of ways such as effects on the biological availability of dissolved organic nitrogen and on sources and sinks of dimethylsulfide and carbonyl sulfide. Metal cycling also interacts in many ways with UV radiation via direct photoreactions of dissolved metal complexes and metal oxides and indirect reactions that are mediated by photochemically-produced reactive oxygen species (ROS).

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A SPECULAR MODEL FOR UVGI AIR DISINFECTION SYSTEMS

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ABSTRACT

A model for predicting the ultraviolet (UV) irradiance field inside specularly reflective rectangular ultraviolet germicidal irradiation (UVGI) air disinfection systems is developed based on a view factor model of the UV lamps and a virtual image model of the specular reflections. The combined three-dimensional irradiance field, direct and reflective, is used to estimate the UV dose absorbed by airborne microorganisms in mixed air. Predicted inactivation rates are then compared with existing bioassay test data for the microorganisms *Serratia marcescens, Bacillus subtilis spores, Staphylococcus epidermis,* and *Mycobacterium parafortuitum*. A dimensionless analysis is performed using quantitative results of the computer model. Some conclusions are drawn regarding the design and optimization of UVGI air disinfection systems. Differences between this model and a diffusive model of reflectivity are discussed.

INTRODUCTION

Ultraviolet radiation in the range of 225–365 nm is highly lethal to many microorganisms, especially viruses and bacteria. Air disinfection systems using UVGI have been in use for over seventy years but until recently, no detailed modeling tools were available to analyze the three-dimensional (3D) irradiance field and predict inactivation rates for airborne microbes. Previous methods for sizing UVGI systems have involved variations of the inverse square law or the line source inverse square law, but these models are unable to accurately predict the near field irradiance or the far field irradiance of UV lamps to the precision necessary for air disinfection applications. These methods may have proved effective for UVGI disinfection of water, but irradiation of water is highly dependent on near field absorbance (Severin et al. 1983). Since the absorbance of UV in air is negligible and the size of air disinfection systems typically involves distances of up to one meter or more, there is a need for higher precision than can be achieved with most previous methods.

The specular model presented here builds on the authors' previous research into UVGI lamp models based on view factors. The new model includes the same view factor lamp model but replaces the diffuse reflectivity model with a specular virtual image model. Although the previous diffuse reflectivity model provided good agreement with laboratory data, it included various assumptions. The present specular model includes no assumptions other than that the surface is purely specular, that is, that the reflective surfaces produce mirror-like virtual images of the lamp. In actuality, reflective surfaces are partly specular and partly diffuse, and therefore an ideal model would use both specular and diffuse components. The purpose of this research, however, is to address specular reflectivity only.

In addition to presenting the new specular model, this paper re-addresses laboratory data previously used to justify the diffuse model. It also summarizes the exponential decay curve for microbial exposure to UV irradiation and provides a summary of the dimensionless analysis of rectangular UVGI specular systems.

Thermal radiation view factors can provide considerably more realistic models of UV lamp irradiance fields than previous methods (Kowalski and Bahnfleth 2000). A view factor model of a lamp as a cylinder can provide more accuracy in the near field and far field than any form of the inverse square law and the use of such a model to predict lamp irradiance at any distance provides superior agreement with photosensor readings (Kowalski et al. 2000). A previous model of UVGI systems using a view factor for the lamp and a separate view factor for the reflective enclosure surfaces had good success predicting inactivation rates of airborne microbes based on laboratory tests (Kowalski 2001). However, view factors define only diffuse surfaces, which are adequate for lamps, but can only accurately depict diffusely reflective surfaces. This paper addresses specularly reflective surfaces and models them using a geometric method based on virtual lamp images. This method applies to rectangular UVGI air disinfection systems such as shown in Figure 1.

The placement of the lamp shown in Figure 1 is orthogonal to the x axis but this model can easily be applied to lamps oriented in any axis or at non-orthogonal angles. For simplicity's sake, however, this paper only addresses the condition in which flow is along the z axis, the lamp is orthogonal to the x axis, and the lamp has one end at $x = 0$.

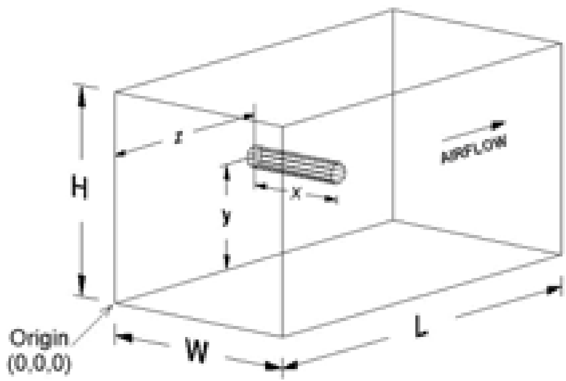


Figure 1: Layout of a rectangular UVGI system showing outside dimensions (W, H, & L) and the lamp coordinate reference system (x, y, and z).

THE VIEW FACTOR LAMP MODEL

The view factor model of the lamp has been previously developed (Kowalski et al 2000; Kowalski 2001) and is used to define the irradiance produced at any point inside the UVGI enclosure (see Figure 1) and is recapitulated here. The following view factor will define the fraction of radiative intensity leaving cylindrical area 2 that arrives at differential area 1 (Modest 1993):

[1] $$F = \frac{L}{\pi H}\left[\frac{1}{L}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{X-2H}{\sqrt{XY}}\tan^{-1}\left(P\sqrt{\frac{X}{Y}}\right) - \tan^{-1}P\right]$$

The parameters in the above equation are defined as follows:

[2] $$H = x/r$$

[3] $$L = \ell/r$$

[4] $$X = (1+H)^2 + L^2$$

[5] $$Y = (1-H^2) + L^2$$

[6] $$P = \sqrt{\frac{H-1}{H+1}}$$

In equations 1 through 6

ℓ = length of the lamp segment, cm
x = distance from the lamp, cm
r = radius of the lamp, cm

This equation applies to a differential element located at the edge of the cylindrical lamp segment. In order to compute the irradiance field at any point along the axis of the lamp and at any distance from the axis, the lamp must be modeled in two parts of lengths ℓ_1 and ℓ_2. The following relation will then describe the total irradiance field from the two segments:

[7] $$F_{tot}(x,\ell) = F_1(x,\ell_1) + F_2(x,\ell_2)$$

where ℓ_1 = length of lamp segment 1, cm
ℓ_2 = length of lamp segment 2, cm

The irradiance at any point from the lamp surface defined by a distance from the axis and a distance along the lamp length (from one end) is computed by multiplying equation 7 by the surface irradiance of the lamp. The surface irradiance is computed from the UV power output and the resulting equation is:

[8] $$E(x,\ell) = \frac{P_{uv}}{2\pi r\ell}\left[F_1(x,\ell_1) + F_2(x,\ell_2)\right]$$

where $E(x,\ell)$ = UV irradiance at any point from lamp surface, μW/cm^2
P_{uv} = UV radiant power output of the lamp, μW

The accuracy of equation 8 depends on the accuracy to which the UV lamp power output P_{uv} is known, and many of these have been tabulated or are available from lamp manufacturers (IESNA 2000). For details on computing the irradiance at points beyond the end of the lamp, refer to Kowalski and Bahnfleth (2000) or Kowalski (2003).

The view factor in equation 1 considers the receiving surface to be oriented facing the cylindrical lamp axis no matter where the surface is located in space. It is assumed that airborne microbes are spherical and will, therefore, always present a circular profile to the UV lamp. The virtual images of the UV lamps, since they are also modeled by equation 1, carry the same implication. This view factor approach may not be a perfect definition of the reality of microbial exposure, since it ignores the possibility of refraction at the surface of the microbe, but it is a reasonable first approximation in lieu of future data to the contrary.

THE VIRTUAL IMAGE MODEL

The model developed in this study uses a single view factor to define the lamp irradiance field, and then uses multiple virtual images of the lamp to compute the reflected irradiance field. The virtual images are treated as separate lamps with lower UV power. The cylindrical view factor is applied to the lamps images at their virtual distance and their UV power output is reduced by the reflectivity of each surface the image passes through. For example, a lamp that is 10 cm from a 90% specular reflective surface has a virtual image 10 cm on the other side of the reflective surface, and the effective UV power of that virtual image is 90% of the real lamp UV power. Figure 2 illustrates the virtual image of a lamp in a single specular reflective surface.

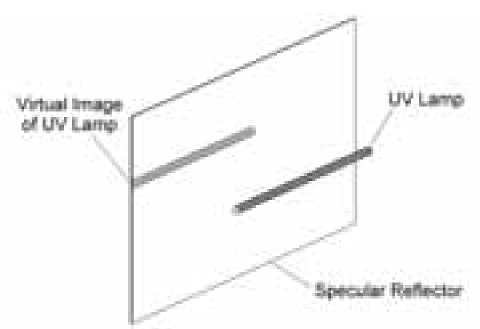


Figure 2. A specular reflector (mirror) will show a virtual image of the real lamp an equivalent distance behind the reflector surface.

Figure 3 shows a photograph of a rectangular UVGI system with one-way mirrors in which at least six virtual images of a single UV lamp can be seen reflected in the rectangular surfaces.

Figure 3. UVGI System made from one-way mirrors. At least six virtual images can be seen in this photograph. Photograph provided courtesy of Lumalier.

Figure 4 illustrates the model in terms of the real lamp in the center and the virtual images of the first two reflections. In the model used here, sixty virtual lamps are used covering the first five reflections. Contributions for reflections beyond the first five tend to be negligible, even for very high reflectivity, due primarily to the distances involved. It is possible, however, that the contribution can be significant for small systems with high reflectivity. The number of reflections has been limited in this model due to the amount of computation time required.

In mathematical terms, the reflected images provide contributions to the irradiance at a point as per the following:

[9] $$E_{avg} = \frac{P_{UV}}{2\pi r \ell} F_0 + \frac{\rho P_{UV}}{2\pi r \ell} F_1 + \frac{\rho^2 P_{UV}}{2\pi r \ell} F_2 + \ldots$$

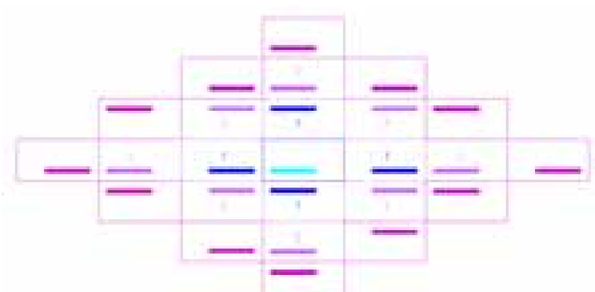


Figure 4. Schematic of the virtual image array showing the real lamp, the four first reflection images (1), the eight second reflection images (2), and a ring of third reflection images.

where F_0 = direct irradiance contribution from UV lamp
F_1 = irradiance contribution from all first reflections
F_2 = irradiance contribution from all second reflections

Equation 9 can be simplified as:

[10] $$E_{avg} = \frac{P_{UV}}{2\pi r \ell}\left[F_0 + \rho F_1 + \rho^2 F_2 + \ldots\right]$$

Figure 5 shows some example results for the average irradiance fields caused by each of the first five virtual lamp images.

UVGI INACTIVATION RATES

The inactivation rates due to UVGI exposure are based on the classic single stage logarithmic decay equation:

[11] $$\ln S = -kE_{avg}t$$

where S = Survival fraction of population
k = UVGI rate constant, cm²/μJ
E_{avg} = average UVGI irradiance, μW/cm²
t = exposure time

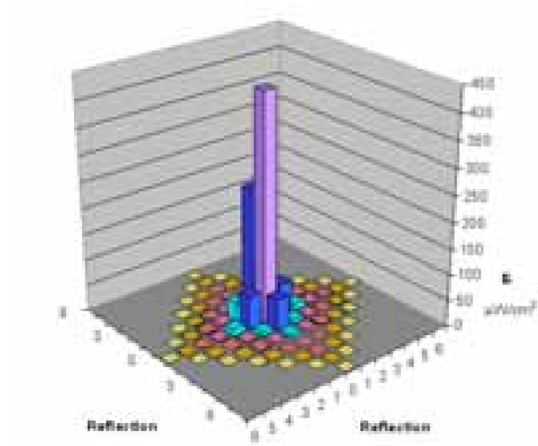


Figure 5. Irradiance contributions from virtual reflected lamp images. The tall bar in the center represents the direct lamp irradiance contribution.

The average irradiance in equation 11 is defined by the exposure to which the microbe is subject. In plate-based experiments, the irradiance is the radiative flux on the surface of the plate. In airborne experiments the irradiance is the spherical irradiance. It should be noted here that the term irradiance is used in accordance with current usage but that, in fact, the more technically correct term is 'fluence rate', since it refers to the irradiance passing through the entire surface of the airborne microbe modeled as an infinitesimal sphere. Insufficient data is available to determine how significant the differences are between rate constants predicted by airborne vs. plate-based tests, but the data that does exist suggests they are within a single order of magnitude (Kowalski et al 2000).

The inactivation rate, IR, is simply the complement of the survival rate, or:

[12] $$\mathrm{IR} = 1 - e^{-kE_{avg}t}$$

The UVGI dose is defined as the average irradiance multiplied by the exposure time. When the dose is low for resistant microbes like spores, there tends to be a two stage decay curve. That is, a resistant fraction of the microbial population behaves as if it were a second species and the population reduction occurs at a slower rate (i.e., a lower rate constant).

The application of equation 12 carries the assumption of uniform air mixing. In the case of unmixed air the inactivation rate must be computed for each and every point in a three-dimensional (3D) matrix defining the enclosure volume. This latter approach will invariably produce inactivation rates that are lower than the mixed air case due to inefficiencies that are associated with local extremes in the irradiance fields. Evidence suggests that complete mixing is more likely to be the case in any real world UVGI system (Severin et al. 1983). A practical approach, and the one used here, is to use both the unmixed air condition and the mixed air condition to define a range of inactivation rates.

BIOASSAY TEST RESULTS

Table 1 summarizes the results of some 32 tests on four different microbes. Three separate laboratories performed these tests. The bioassay inactivation rate in the final column is compared against the predicted inactivation rates of the program. The predicted inactivation rates are shown in terms of the range between the unmixed air condition and the mixed air condition. In the unmixed air condition the streamlines are considered parallel. In the mixed air condition the entire microbial population is assumed to be exposed to the same average irradiance inside the enclosure. The overall average range of predicted inactivation rates for all microbes is 57 – 78% and the average measured inactivation rate is 76%.

Figure 6 displays the results of Table 1. Two data sets that produced bioassay inactivation rates of approximately zero percent for *B. subtilis* spores were not included in Figure 5 or Table 1. The B. *subtilis* test results show two bioassays each from two different laboratories. Results from the separate labs gave different results and it was not possible to rectify them. The second two *B. subtilis* data points are based on a two stage decay model.

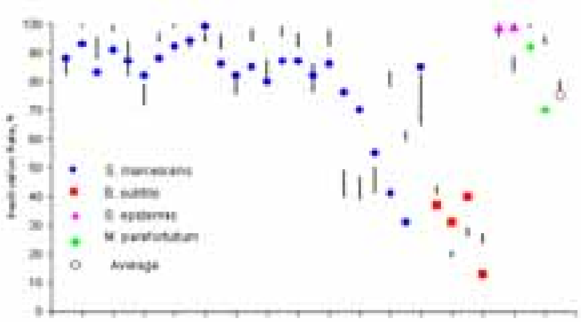


Figure 6. Range of Predictions vs. Bioassay Test Results.

Two additional bioassay test results for *S. marcescens* were excluded due to gross deviations that were anomalous and which were believed due to incorrectly stated reflection coefficients that could not be verified. Two additional data sets for *S. marcescens* that appeared to be anomalous were included, since it was not clear that any laboratory error had been made. The latter are the twentieth and twenty-first data sets in Table 1 and Figure 6.

Table 2 summarizes the rate constants used in the previous test result comparisons (UVDI 2000, 2002). The rate constant for *S. marcescens* was computed based on the test results themselves and is similar to that produced by other studies (Collins 1971, Peccia et al. 2001). The rate constant for *B. subtilis* spores is based on the average of the five indicated studies. The rate constant for *M. parafortuitum* is based on a normal indoor relative humidity range of 70-80%.

Table 2. Rate Constants for Test Bacteria

Microorganism	UVGI Rate Constant cm^2/μJ	Source
S. marcescens	0.002909	UVDI 2000
B. subtilis spores	0.000324	Sharp 1939
B. subtilis spores (multi-hit model)	0.0001529	Nagy 1964; Chang et al. 1985; Nakamura 1987; Sommer et al. 1989, 1995 (average)
S. epidermis	0.0008372	Harris et al. 1993
M. parafortuitum	0.00135	Peccia, et al. 2001

DIMENSIONLESS PARAMETER COMPARISONS

The performance of rectangular UVGI air disinfection systems can be defined with a set of variables describing enclosure geometry, lamp characteristics, airflow conditions, and characteristics of the microbe. Table 3 lists the critical variables and units that define the inactivation rate of rectangular UVGI systems. The flow rate Q effectively defines the air velocity and the exposure time, in combination with the dimensions, and therefore these factors are redundant.

Some variables that may be important to the disinfection process are not yet well understood or sufficiently quantified to be useful, such as the effects of photoreactivation rate, temperature, and relative humidity on microbial rateconstants. The temperature and air velocity may also impact the performance of individual manufacturers' lamps. The latter effects cannot be generalized but the UV power for the lamp will usually include the effect of these parameters when they are known from manufacturer's information or when lamp operating conditions are defined by a design velocity and temperature range.

Table 1: Summary of Bioassay Results vs. Program Predictions

						% Inactivation Rate	
Test Microbe	HxWxL (cm)	Airflow m^3/min	ρ %	UV Power (W)	Average *E* (μW/cm^2)	Mixed-Unmixed	Bioassay
S. marcescens	46x46x188	34	7	11.78	1063	83 - 88	88
	46x46x188	34	7	34.77	3136	99 - 99.8	93
	30x64x91	85	7	35.76	2219	88 - 96	83
	46x46x183	34	7	28.35	2556	98 - 99	91
	46x46x183	34	7	17.34	1456	83 - 94	87
	46x46x183	34	7	8.94	792	72 - 79	82
	46x46x183	51	7	29.16	2629	94 - 97	88
	46x46x183	34	7	36.51	3316	99 - 99.9	92
	46x46x183	57	7	29.37	2648	92 - 96	94
	46x46x183	57	7	64.08	2909	94 - 97	99
	30x64x91	57	57	17.56	6091	91 - 96	86
	30x64x91	57	57	9.05	3160	76 - 82	82
	30x64x91	57	57	21.82	7534	94 - 98	85
	30x64x91	57	57	11.07	3848	81 - 88	80
	25x64x91	40	57	19.01	7480	96 - 99	87
	30x64x91	57	57	18.13	6436	92 - 97	87
	30x64x91	57	57	8.35	3600	77 - 86	82
	30x64x91	57	57	16.75	7187	92 - 98	86
	30x64x91	57	57	4.18	1237	40 - 49	76
	30x64x91	57	57	3.83	1161	39 - 47	70
	30x64x91	57	57	5.7	1287	41 - 50	55
	30x64x91	57	57	10.6	3320	79 - 84	41
	30x64x91	57	57	5.8	1817	59 - 63	31
	30x64x91	57	57	21.52	3216	65 - 83	85
B. subtilis spores	30x64x91	57	57	24	9405	41 - 44	37
	30x64x91	57	57	24	3883	19 - 21	31
	30x64x91	28.3	22	36	1473	26 - 29	40
	30x64x91	28.3	22	18	2695	24 - 27	12.8
S. epidermis	30x64x91	28.3	22	36	1473	96 - 98	99
	30x64x91	28.3	22	18	826	84 - 89	99
M. parafortuitum	30x64x91	28.3	22	58.32	2886	99 - 99.8	92
	30x64x91	28.3	22	29.16	1497	93 - 96	70

Table 3. Critical Parameters of Rectangular UVGI Systems

Parameter	Description	Units
W	Duct Width	cm
H	Duct Height	cm
L	Duct Length	cm
r	Lamp Radius	cm
ℓ	Lamp Arc Length = x, the lamp end coordinate	cm
P	Lamp UV Radiant Power	μW
Q	Air Flow Rate	m^3/min
x	Lamp end coordinate (= lamp arc length with base at $x = 0$)	cm
y	Lamp Y position or distance above bottom surface	cm
z	Lamp Z position or distance from duct entrance	cm
k	UVGI Rate Constant	cm^2/μJ
ρ	Surface reflection coefficient	---

Previous research has identified ten dimensionless parameters that define the performance of rectangular UVGI systems (Kowalski et al. 2003). Table 4 lists these parameters and their typical range.

Table 4. UVGI Dimensionless Parameters

Parameter	**Description**	**Typical Range**
W/H	Aspect Ratio	1–4
r/ℓ	Lamp aspect Ratio	---
kPL/Q	Specific UV Dose	~1–2
x/W	X Ratio	<0.25 or >0.75
y/H	Y Ratio	>2*r*
z/L	Z Ratio	0.5
H/L	Height Ratio	0.25–10
ρ	Surface reflection coefficient	0.50–0.99

These dimensionless parameters provide a convenient means of studying the performance of UVGI systems in a quantitative way. These dimensionless parameters have been found to have negligible interaction in most cases, and minor interaction in only a couple of cases (Kowalski et al. 2003). This fact allows the parameters to be compared on a one-to-one basis to observe their behavior.

Each parameter can be compared with each other by computing the performance of specular UVGI systems for 100 cases that represent the range of dimensionless parameters shown in Table 4. Several thousand computer runs were used to evaluate all possible combinations of the dimensionless parameters, and the most important or representative results are summarized here. The results are plotted in 10x10 contours and discussed following.

Figure 7 shows a comparison of the inactivation rates predicted for the dimensionless parameters of the duct aspect ratio (*W/H*) vs. the specific UV dose (*kPL/Q*). It can be observed that as the specific UV dose in increased the inactivation rate increases in an exponential fashion and approaches a 100% inactivation rate asymptotically. This is true regardless of which parameter it is compared against due to a lack of interaction. The duct aspect ratio is observed to have a slight dip when the duct is square, *W/H* = 1.0, or to produce higher inactivation rates when the duct aspect ratio is above approximately 2.0.

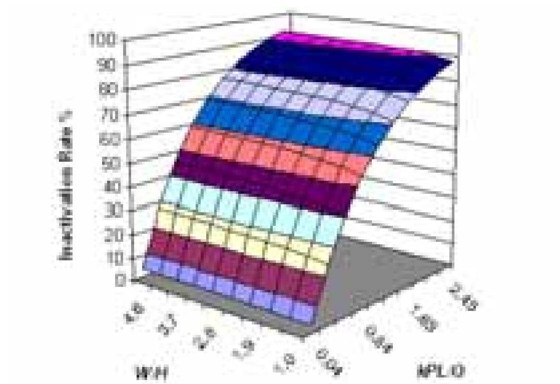


Figure 7. Duct Aspect Ratio vs. Specific UV Dose.

Figure 8 shows the X ratio (*x/W*) vs. the duct aspect ratio (*W/H*). It can be seen that the duct aspect ratio produces the highest inactivation rates when the width is twice the height or greater. This is, of course, for lamps that are parallel to the width. This is true regardless of what parameter the duct aspect ratio is plotted against since there is negligible interaction between these terms. The X ratio, which is the lamp length over the duct width, produces maximum inactivation rates at values near 1, or when the lamp spans the full length of the duct. It can be observed that the curve for the X ratio is slightly bi-modal and has a slight discontinuity near the value of 0.5 (when the lamp is centered). This is true regardless of the parameter the X ratio is plotted against and can be explained, at least theoretically, in terms of the fact that as the length of the lamp exceeds half the width, the contribution of the opposite reflective surface becomes more significant.

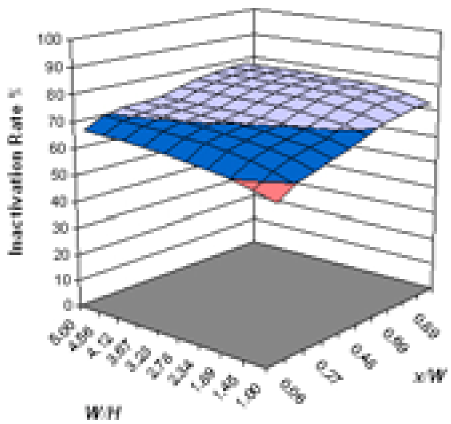


Figure 8: Duct Aspect ratio vs. X Ratio.

Figure 9 graphs the specific UV dose vs. the reflectivity. The reflectivity produces an approximately linear increase in inactivation rates only up to a point, since the inactivation rates cannot exceed 100%. The specific UV dose causes an approximately exponential increase in inactivation rates but again only until the inactivation rates approach 100%. It can be theorized that there must exist some optimum combination of UV power and reflectivity that maximizes inactivation rate and minimizes cost for any given UVGI system, but this result will depend on a full economic evaluation and economics are not addressed here.

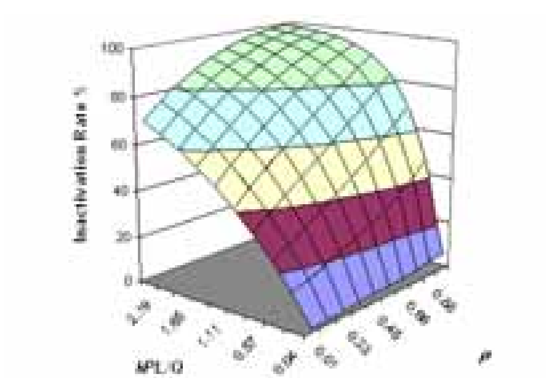


Figure 9: Reflectivity vs. Specific Dose.

Figure 10 shows the duct aspect ratio plotted against the Z ratio. The duct aspect ratio is optimum at values of approximately 2 or greater, as seen in previous charts. The Z ratio represents the depth within the duct that the lamp is located. It is clear that the optimum location of the lamp is a value of 0.5, or centered within the duct depth. This is, of course, rather intuitive and also represents common practice.

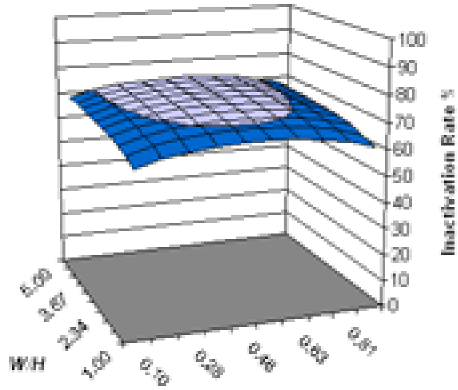
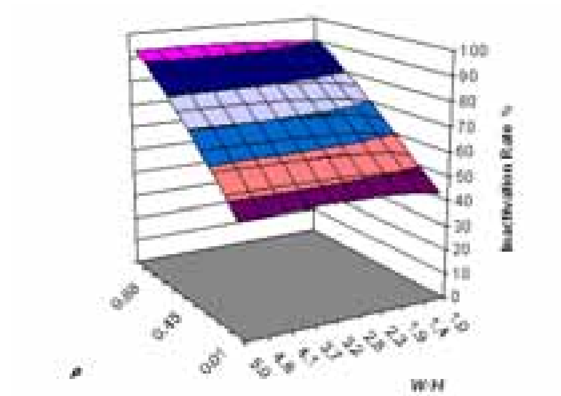


Figure 10: Duct Aspect Ratio vs. Z Ratio.

Figure 11 shows the reflectivity plotted against the duct aspect ratio. For both these parameters the chart shows the same characteristics seen previously. Reflectivity causes a nearly linear increase in inactivation rates while the optimum duct aspect ratio occurs at values somewhat above 2.

Figure 11: Reflectivity vs. Duct Aspect Ratio.



The lamp aspect ratio (r/l) has a negligible impact on inactivation rates and this is true in all cases and so no graphs are provided. No further contours need be shown since all the remaining combinations of parameters produce the same essential features shown in the previous graphs. That is, since there is negligible interaction, all the remaining contours are merely repetitions of the ones previously shown.

SPECULAR VS. DIFFUSE REFLECTIVITY

Although a previous model for diffusely reflective surfaces has been developed, the bases of these models are too different to allow valid direct comparison. The specular model tends to produce higher overall predictions of average irradiance fields but not in all cases. Both the diffuse and the specular models had predictive accuracies of approximately ±30% in over 90% of cases tested, although the differences in individual test results could vary widely between the models (approximately ±10%) and the diffuse model was slightly more accurate overall. The specular model yielded conclusions regarding lamp placement that vary considerably from the diffuse model. Further research is necessary to verify the irradiance field predictions of both these models before definitive conclusions can be drawn regarding the superiority of either type of surface reflectivity, but the simplicity of the specular model leaves less room for error than the more complex diffusive model. Research is also needed to combine these models to produce one that would incorporate partly diffuse, partly specular real-world reflective surfaces.

CONCLUSIONS

A specular model of UVGI systems has been summarized in which a view factor model of a UV lamp is used to create virtual images of the lamp and compute the irradiance field inside rectangular enclosures. Predictions of the model have been compared with 32 sets of test data and yield a predictive error of approximately ±30% in over 90% of test cases. Computer modeling results are presented in terms of dimensionless parameter comparisons. These comparisons suggest the following conditions may produce optimum inactivation rates for specular reflective systems:

- The duct aspect ratio should be greater than 2.
- The lamp should be centrally located along the depth of the duct.
- The lamp should be located at mid height in the duct.
- The lamp arc length should preferably span the duct width.

An interesting and possibly useful corollary of the dimensional analysis is the fact that the dimensionless parameters most critical in determining inactivation rates are the specific UV dose and the reflectivity. Combining these and rearranging a hypothetical function can be written to predict the UV power for any desired inactivation rate as follows:

[13] $$P = C\frac{Q}{\rho k L}$$

where C is some constant. If one assumes a constant reflectivity (i.e., 50%) and a standard rate constant (i.e., *Serratia*), it can be seen that the UV power is a linear function of the airflow per unit length of duct, for any given inactivation rate (i.e., 90%). This will only be true if the system is well designed in accordance with the above conditions and the inactivation rate is not extreme (i.e., in a shoulder or second stage region of the decay curve). Furthermore, this is merely an estimate of the UV power subject to the same error of the analysis (±30%) and is not a substitute for a detailed analysis of all factors.

No conclusions can be drawn regarding the benefits of specular versus diffusive reflective surfaces due to the fact that the models are merely approximations of the UV irradiance fields and, for reasons that are not yet clear, results do not corroborate well. The specular model predicts higher overall levels of irradiance than the diffusive model, but the diffusive model produces more accurate predictions of inactivation rates. Further research is needed to verify the irradiance field predictions of both the specular model and the previous diffusive model. Since the irradiance field predictions are, in fact, fluence rate predictions for spherical microbes, corroboration through testing may have to await perfection of the technology of spherical actinometry (Rahn et al. 1999).

Further conclusions regarding optimization of performance depend on the economics of UVGI systems and these matters remain to be addressed by future research. Additional research that remains to be performed includes further study of the effects of relative humidity and the photoreactivation effect. Other research needed for a complete description of UVGI system performance includes study of alternate geometries and lamp orientations, and the effect of reflective surfaces that are part diffusive and part specular. Ultimately, this research should lead to new guidelines for designing UVGI systems that have predictable performance in applications and that are energy efficient.

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