U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY & RENEWABLE ENERGY

Lighting R&D Program: Germicidal Ultraviolet (GUV) R&D Meeting

February 2021

(This page intentionally left blank)

Disclaimer

DOE Lighting R&D Program, "Germicidal Ultraviolet Lighting R&D Meeting," February 2021.

This report was prepared for:
Lighting R&D Program
Building Technologies Office
Energy Efficiency and Renewable Energy
U.S. Department of Energy

Authors:
Monica Hansen, LED Lighting Advisors
Gregory D. Thomson, PlanArchology LLC
Kyung Lee, Guidehouse, Inc.
Valerie Nubbe, Guidehouse, Inc.
Morgan Pattison, SSLS, Inc.

Comments

The Energy Department is interested in feedback or comments on the materials presented in this document. Please write to Brian Walker, Lighting Program Manager:

Brian J. Walker, Ph.D.
Lighting Program Manager
U.S. Department of Energy
1000 Independence Avenue SW
Washington, D.C. 20585-0121

Acknowledgements

The Department of Energy would like to acknowledge and thank all the participants for their valuable input and guidance provided during the R&D discussions. This report is the product of their efforts:

Lighting R&D Meeting Participants

Ian Ashdown	SunTracker Technologies
Holger Claus	Ushio America
Steve DenBaars	University of California Santa Barbara
Jim Gaines	Signify
Douglas Hamilton	Hubbell Lighting
Mark Hand	Acuity Brands
Paul Jensen	FAI
Bob Karlicek	Rensselaer Polytechnic Institute
Michael Kneissl	Technische Univeristät Berlin & Ferdinand-Braun-Institute
Denan Konjhodzic	Instrument Systems, Konica Minolta Group
Mike Krames	Arkesso
Oliver Lawal	Aquisense Technologies
Cameron Miller	National Institute of Standards and Technology
Ed Nardell	Harvard University
Dean Saputa	UV Resources
David Sliney	Independent Consulting Medical Physicist
Erik Swenson	Nichia
Richard Vincent	Mount Sinai Hospital New York
Jeremy Yon	GE Current, a Daintree company

Table of Contents

1 Introduction

On December 15, 2020, nineteen subject matter experts on different aspects of germicidal ultraviolet (GUV) irradiation gathered at the invitation of the Department of Energy (DOE) Lighting R&D Program to help identify critical research and development (R&D) topic areas in GUV from photobiology and application designs to luminaire products and UV sources. This small-group discussion meeting is one forum for experts to provide technical input to the DOE Lighting R&D Program. The DOE Lighting R&D Program also collects inputs from stakeholders at the annual Lighting R&D Workshop, via a Lighting R&D Request for Information (RFI), and other means. The guidance provided by stakeholders in these various forums helps identify critical R&D areas that may be incorporated into DOE's technical roadmaps.

This year the meeting was held virtually due to travel difficulties and concerns related to the ongoing COVID-19 pandemic. The meeting commenced with "soapbox" presentations in which each participant was invited to give a short presentation describing what they believed to be the key technology challenges for GUV over the next three to five years. This was followed by a general discussion of the most critical GUV technology challenges facing the industry today.

The meeting format provided an opportunity for experts across the research spectrum to exchange ideas and explore collaborative research concepts. Participants included invited experts in GUV relevant science and technology disciplines drawn from academia, government agencies, and industry.

This report summarizes the outcome of the discussions on critical technology challenges and identifies corresponding R&D tasks within the existing task structure. Outlines of the participants' soapbox presentations and related remarks are included in Appendix A: Participant Presentations of the report.

1.1 Key Conclusions

The meeting format encouraged each of the attendees to participate and present his/her perspectives on critical R&D challenges. The discussions that followed the soapbox presentations offered a variety of valuable insights into a range of research topics that could advance GUV technology; however, there were some recurring themes that arose during these discussions regarding research areas that could lead to significant breakthroughs in technology development and implementation. These themes are as follows and are outlined in more detail in Section 2:

- GUV Technology Development
- Understanding Photobiological Effectiveness
- GUV Deployment in Applications
- Standards Development and Guidelines

2 Critical R&D Topic Areas

The COVID-19 pandemic has greatly increased the spotlight on GUV irradiation for air and surface disinfection. Considering the potential jump in electricity load with increased implementation of GUV in buildings, this area represents a growing opportunity to embed energy saving designs.

2.1 GUV Technology Development

Participants discussed research and development paths for different aspects of GUV luminaire technology including ultraviolet C-band (UVC) sources, luminaire designs for effective delivery, and materials reliability with UVC exposure. Additionally, they noted further development work required to create reliable GUV modeling software and implement accurate characterization methods and tools.

UVC Sources

When considering different UVC radiation source technologies, the factors to consider include size, lifetime, turn-on time, emission wavelength, undesirable elements (e.g., mercury and ozone), energy consumption, and cost. Currently, mercury lamps are the incumbent sources for GUV, while LEDs lag in terms of efficiency. Low pressure mercury vapor lamps (LPMV) have high efficiency (30-40%), low cost, a variety of sizes and shapes, and lots of field experience, but they also contain mercury (similar to all existing fluorescent light technologies). Quartz glass is used for these lamps to filter out the ozone generating peaks, thus leaving the 254 nm UVC emission line. Lifetimes of the lamps are typically around 9000-10,000 hours. KrCl excimer lamps provide a lower wavelength peak around 222 nm, which has potential benefits for reduced skin and eye hazard. These lamps also must also filter out the low wavelength peaks (which create ozone), thus dropping the source efficiency from ~ 6-8% unfiltered down to 2-3% once filtered. The lifetimes for these KrCl excimer lamps are in the range of 3000-5000 hours.

While UVC LEDs are less efficient than LPMV and excimer sources, they potentially have much headroom to improve efficiency, unlike the existing lamp technology which does not have the same room for significant performance improvements. Many participants suggested that AlGaN-based UVC LEDs should be the primary UV source technology for R&D investment. While efficiencies are low (~ 2-4% power conversion efficiency at 260 nm) due to difficult materials challenges, the past two decades of learning in GaN-based semiconductors for visible LEDs provides a solid materials foundation to leverage for future innovation. Specific areas for improvement include defect control in AlGaN heterostructure growth (point defects) and low dislocation density growth templates, UV transparent p-type epitaxial layers and p-contact materials, ohmic p-type contacts, enhanced light (photon) extraction, and UV transparent encapsulants (for packages). Lifetimes also have the potential to surpass conventional UV lamps. Today's devices available have a variety of lifetimes from 4000 hours up to 10,000 hours for 280 nm LEDs.

Materials Stability

UVC is damaging radiation for many common polymers; fabrics, paint, and other organic materials will also undergo UV damage under prolonged exposure. The higher energy UVC photons can also degrade materials used in luminaire construction (optics or polymer based diffuse reflectors). A better understanding of materials degradation issues under UVC excitation is important to enable GUV systems with long lifetime and to prevent damage to the objects in the space. Research is needed to develop new materials with better UVC resistance to mitigate the effects of GUV irradiation in buildings and to help create long-lifetime GUV luminaires. Participants indicated that creating library of common materials degradation properties under UVC irradiation will aid the GUV luminaire manufacturers, lighting designers, and implementers to better understand the implications of installing GUV products in buildings.

Modeling and Characterization

Modeling software that can calculate the radiometric UVC needs (such as absorption/reflection and fluence) will help aid the development of more efficient GUV luminaire designs. Modeling challenges include establishing accurate gonioradiometric intensity distributions for the UV luminaires and surface reflectance distributions (both diffuse and specular). Furthermore, the software may need to consider additional factors, such as airflow and room motion, which is different than traditional light modeling. Development work to improve GUV modeling software packages is necessary including implementing computational fluid dynamics models to address the airflow impacts, developing surface reflectance data in the UVC wavelengths (architectural materials catalog required), and developing virtual spherical irradiance meter to calculate the fluence rate.

Participants discussed how characterization tools for accurate UV measurements and sensors for airborne pathogen detection are required. Traceable calibration of all spectroradiometric systems with low measurement uncertainties over large spectral range from 200-1650 nm is difficult to attain. One challenge with UV measurements is accessing calibration samples required for the calibrating the radiant flux of integrating spheres in the UVC range. Another is optimizing the polytetrafluoroethylene (PTFE) reflective coating of integrating spheres for the low fluorescence of UVC sources. Further, UV detector performance has shown varying levels of accuracy due to poor cosine response behavior leading to inaccurate readings in the 2π measurement geometry. More research is required to deliver accurate detectors and sensors for the GUV application. There is an opportunity to develop innovative sensors for airborne pathogen detection, auditory detection of events (e.g., coughs), or for "biovigilant" systems that have the potential to use UVC as a counter measure for biological threats; this could be done by feature integration added alongside the LED chip or packages, essentially leading to a bio lab on-chip. Work is underway as the Illuminating Engineering Society (IES) and the International Ultraviolet Association (IUVA) signed a memorandum of understanding (MOU) in 2020 to assemble experts in the measurement of UVC emissions to develop American National Standards (ANSI Standards) for the measurement and characterization of UVC device performance.

2.2 Understanding Photobiological Effectiveness

Participants discussed the need to better understand the photobiological effectiveness with GUV both for the safety (dose that is safe for skin and eyes), as well as dose levels that can inactivate the pathogens at various wavelengths. Studies to relate the pathogen deactivation level required for reduced transmission for specific pathogen types and viral loads are also needed. Further, studies to understand the action spectrum for various microbes and pathogens at varying UV wavelengths, including how much proteinaceous materials surround the microbes and how it affects the deactivation efficiency of UVC radiation, are also essential. Many participants agreed there is a need to develop a standardized library of inactivation constants (D90) at different wavelengths of UV-C radiation for a wide range of pathogens in all common states: surface, aqueous, aerosol, etc. Another area for development is the determination of dosing criteria to efficiently disinfect surfaces and/or air in the application. Questions that were discussed include how to define the parameters that go into the dosing criteria – e.g. room volume vs. irradiated volume or the quantitation of air mixing? How do the different room/space geometries affect efficacy and hence dosing criteria?

Additionally, the participants felt time-motion research is required for the rational application of UV exposure threshold limit values (TLVs). There were questions about the interpretation of the American Conference of Governmental Industrial Hygienists (ACGIH) published TLVs. Questions to answer through further research include: how much exposure is safe considering the duration and movement in of occupants in a particular space? Should TLV be considered as an 8-hour running average or daily dose? What eye height is appropriate? How to determine if/when to "adjust" for photosensitive individuals? If GUV is applied to a non-occupational setting such as schools, places of worship, homes, healthcare facilities, etc., how can the cumulative dose from other daily exposures be determined? Understanding the safe limitations and exposures in a variety of use-cases to create safe TLVs for different installations would be beneficial for GUV adoption.

2.3 GUV Deployment in Applications

Lighting application efficiency (LAE) describes the amount of generated light (or UV radiation) that reaches the final target for the intended application (i.e. microbes in air or on surfaces for GUV). Designing GUV products with LAE in mind is important to reduce energy consumption since GUV luminaires are typically louvered fixtures, which can be quite inefficient. Research into the application understanding of GUV deployed in a variety of spaces is needed to safely and effectively create energy efficient GUV delivery designs within the built environment. These application spaces can include new upper room implementation for safety and efficacy of disinfection, implementation in challenging occupied environments (e.g., big box stores) where the breathing zone is far from upper room, and in-duct disinfection of HVAC systems. Innovative use of ceiling designs and luminaire placement to help reduce the use of louvres and improve energy efficiency was discussed. Additionally, considering the building design to incorporate GUV can help improve energy consumption in buildings. For example, building integration strategies for air disinfection can balance GUV in HVAC equipment and in the upper room air disinfection. UVC disinfection upstream of the HVAC cooling coils can help with air disinfections and the UVC downstream of the coils help keep the coils clean and improves the energy efficiency of the HVAC system overall. The development of simple in-situ measurement systems for GUV luminaire setup, commissioning, and validation is also important in safe and effective use.

2.4 Standards Development and Guidelines

Forming standards and crafting implementation guidelines for GUV in buildings is a necessary area of development work. As described in the preceding sections, there is a need for standards in areas such as UVC dose guidelines (considering wavelength, time-motion, and pathogen types), product characterization methods, measurement procedures and instrumentation calibrations, and clear guidance for best practice implementation in buildings. Training and education on what is safe and effective germicidal radiation is essential as well. Many different bodies are working on developing these standards and guidelines for GUV. Participants felt that DOE leadership is critical for bringing some semblance of order to what they fear will be the "wild west" with products appearing in the market that are unsafe and/or ineffective. This can lead to major user acceptance issues if products do not perform as advertised. Regulating an uncontrolled GUV market can be done by reviving and adapting some of the mechanisms and programs the DOE SSL Program put in place to support a new and growing SSL industry more than a decade ago (including Lighting Facts, CALiPER, Gateway, technology roadmaps, and fact sheets). There is also the opportunity for DOE to foster and engage collaboration between multiple government agencies government to identify and target synergies in the different programs approaching this topic area.

Appendix A: Participant Presentations

Oliver Lawal, Aquisense Technologies: LED R&D Discussion Meeting - GUV

Oliver Lawal, President of Aquisense Technologies, started the discussion with an overview of the UV market and the primary applications of UV technologies based on the medium of the application (e.g., water, air, and surfaces), the type of configuration of the system (e.g., closed or open), and the lamp technology (e.g. LPMV, LED, xenon, and excimer). Lawal explained that, while most of the market conversation is currently in the air and surface applications, a vast majority of the existing market is in LPMV in closed systems for water disinfection. This large surge in market conversation is a result of the SARS-CoV2 pandemic and has resulted in a renewed interest in the technology. A substantial proportion of the market conversation recently has centered on far-UV (e.g., 222 nm wavelength from KrCl excimer lamps). Lawal also discussed LED-based UV disinfection commercialization efforts, pointing out that as LED devices increase in efficiency, are delivered at lower costs, have refined system designs and manufacturing processes, and regulatory drivers are brought to bear on the topic, there will be an increased deployment. He pointed out that this is already beginning with some lab devices starting to exceed conventional lamp efficiencies, costs coming down, design/manufacturing difficulties are being overcome, and regulatory drivers are coming online. Lawal opined that increased deployment is on the verge of happening at a larger scale to displace incumbent technologies. He concluded with a brief discussion of the knowledge gaps that exist for air and surface disinfection including: understanding what the best technology is for the job (what are the primary technology characteristics that match the task?), how that technology should be deployed (is the design of the product appropriate for the task?), how the product is used in the field (what are its operation methods?), and how the device effectiveness is quantified (what are the applicable validation standards?).

David Sliney, Independent Consulting Medical Physicist: UV-C for Air Disinfection – Research Needs

David Sliney, an Independent Consulting Medical Physicist, discussed several research topics for air disinfection. Sliney stated the need for additional research examining the impact of wavelength on pathogens. Developing action spectra across a broad set of wavelengths, chip chemistry, and pathogens can lead to improved understanding of the efficacy of different wavelengths and lamp technologies. These studies should further seek to clarify the impact of the proteinaceous material that surrounds the microbes on the effectiveness of the UV radiation dose. He then discussed how to assess exposures to UV irradiation in upper-room ultraviolet germicidal irradiation (UVGI) applications and emphasized the use of time-weighted averaging (TWA) to properly account for scattered UVC rays. A room section graphic illustrated that vertical stratification in a space, and occupation within that stratification (height level) created different exposure times and amounts, so the TWA would better assess risk by understanding the total dosing over the entire time spent in the space. Sliney finished by addressing the importance of training of the professions who will engage in the design and implementation of GUV systems to ensure safe design, installation, operation, and service.

Bob Karlicek, Rensselaer Polytechnic Institute: UVGI – Recent Work, Future Directions

Bob Karlicek, Professor and Director of the Center for Lighting Enabled Systems & Applications (LESA) at Rensselaer Polytechnic Institute, discussed the recent work and future directions for UVGI. He began by discussing an R&D disinfectant system for N95 masks undertaken at the beginning of the COVID-19 pandemic. Early information derived from the work was determining the effectiveness of doses required to reach the SARS-CoV2 DNA through the protein layer. Karlicek noted that it may require higher dosage levels to achieve desired disinfection outcomes in aerosols, as compared to surfaces, as well as accounting for relative humidity. These all factor into the determination of correct dose to achieve the necessary logarithmic reduction in pathogens (log-kill). He continued with an examination of the application of UV radiation in the built environment. It can damage and discolor objects in the space (including building materials), as well as generating particulate matter. Further research on UVC and materials interactions must be conducted to ensure the lifecycle of common materials is not adversely impacted. Karlicek finished by discussing UV sources and explained that UVC LEDs still underperform mercury vapor lamps with respect to power, cost, and reliability. UVC device reliability and materials problems are much harder problems and there are smaller investment drivers since the UVGI market is much smaller than the visible light LED market.

Ed Nardell, Harvard University: UV Air Disinfection – R&D Priorities

Ed Nardell, Professor at the Harvard Medical School and T. H. Chan School of Public Health, discussed a few priority R&D topics, which included: time-motion research for rational application of UV exposure TLVs, new source and system design for UVGI, and better understand of the GUV efficacy on air disinfection in the space. Nardell drew attention to climate change creating an increased risk of airborne infections as one side effects of the increased use of air conditioning (AC), which results in a decreased use of outdoor air for cooling and CO_2 removal in spaces. He suggested using a combined approach of upper room disinfection and a split system AC unit with UV for cooling and air mixing. Nardell then shifted focus system design approaches to improve the efficiency of room air disinfection with UVGI. One novel application that has promise is an "eggcrate UV" like UV system, which is a whole ceiling upper-room UVGI approach to disinfecting air in occupied spaces. This system has suspended bare UV lamps inside empty ceiling tiles with a fan to provide disinfection in occupied spaces that is the equivalent of 2-3 times the number of air changes that a mechanical air change system would provide. The efficiency comes from reducing the losses in the louvered luminaire GUV products. Finally, Nardell addressed questions surrounding TLVs in upper upper-room UVGI by pointing to a study that showed room occupants receive a small fraction of the predicted dose by peak eye level from properly designed systems. A better understanding of on-site measures of UV efficacy in the space is important to estimate the adequate air mixing for upper room UVGI.

Paul Jensen, FAI: UVC LED R&D Priorities

Paul Jensen, a Director at FAI presented on key R&D priority areas. He highlighted the need for a commissioning process to be included in all applications of GUV (e.g., in-room, in-duct, and air cleaners), accounting for scheduling, testing, adjusting, verifying, and training as part of the process, with an emphasis on testing and adjusting the systems when they are in place. The goals of this process should be to ensure that a facility, and the system equipment and devices in it, are fully functional and operating as described in the device specifications. He finished by describing a negative case study for where a good commissioning process was not implemented – in Jackson Memorial Hospital (Miami, FL), an improperly commissioned GUV system led to workers developing skin problems. Jensen also discussed the challenges of applying TLVs to occupational and non-occupational settings and asked questions that need to be studies, including how to measure the cumulative dose occupants receive elsewhere. Should TLVs be considered as an 8-hour running average or as a daily dose? How can settings be adjusted for photosensitive individuals? How is the appropriate eye height for measurement determined? He continued by discussing needed R&D for determining dosing criteria to efficiently disinfect surfaces and/or air. Determining what the "best" wavelengths are to use for different pathogens and how varying geometries affect efficacy, and therefore dosing criteria, are important research areas. Additionally, a better understanding is necessary to help define the parameters that go into the dosing criteria – e.g., room volume vs. irradiated volume, or the quantitation of air mixing. Finally, Jensen finished by discussing areas that need to be addressed for practical implementation of GUV, such as the fact that manufacturers, vendors, and specifiers must understand luminaire systems and layout guidelines to achieve proper dosing and disinfection. And installers and operators need to understand safe installation and accurate measurement of critical parameters as well as routine maintenance requirements and techniques to keep systems operating as intended and to avoid injury during installation and maintenance. Moreover, there is a need for qualified installers, commissioning agents, and maintenance personnel in these areas.

Dean Saputa, UV Resources: UV-C Coil-Surface Cleaning

Dean Saputa, the Vice President of Sales at UV Resources, explored the use of UVC irradiation to clean the coil surfaces in HVAC systems. UVC can be implemented upstream of the coils for airstream disinfection and also downstream of the coils to reduce particle build up that limits flow rates and to increase energy efficiency of the HVAC unit. The UVC fluence inside the coil structure (all HVAC air passes through the coil) allows for 24/7 cleaning during heating and cooling cycles and can increase HVAC equipment longevity. Compared to mechanical and chemical cleaning methods, UVC cleaning did not have the deleterious side effect of pushing dirt inward into the system (thereby increasing the static pressure at the coil). He pointed to the results of a study (ASHRAE RP-1738) that measured changes in coil performance after receiving UVGI treatment, finding there was a 21% decrease in mean coil airside pressure drop, and a 14% increase in mean overall heat transfer coefficient. Finally, Saputa suggested R&D to understand how much UVC fluence is needed to keep the coil surfaces clean for a healthy building and what are the required air changes per hour (ACH).

Ian Ashdown, SunTracker Technologies Ltd.: Virtual Dosimetry: Predicting UV-C Fluence

Ian Ashdown, Senior Scientist at SunTracker Technologies, addressed challenges with predicting UVC fluence in modeling software. These include the difficulty in predicting surface irradiance and determining disinfection efficacy of surfaces; determining fluence in upper room disinfection applications, simulating complex architectural spaces (e.g., airport, movie theaters, and other geometrically complicated and physically connected) where irradiance distribution from 222 nm excimer lamps is complicated; and establishing accurate gonioradiometric intensity distributions and surface reflectance distributions (both diffuse and specular). Ashdown then addressed the potential solutions to these challenges including adapting architectural lighting design software for GUV applications, with a focus on radiative transfer and photon mapping; development of surface reflectance data for common architectural materials; modeling airflow and the movement of aerosolized particles in terms of aerosol spread and disinfection optimization (adding computational fluid dynamics to light modeling software); and developing virtual spherical irradiance meter to calculate the fluence rate.

Richard Vincent, Mount Sinai Hospital New York: Upper Room GUV Air Disinfection

Richard Vincent, the Administrative Manager at the Icahn School of Medicine at Mount Sinai, suggested three areas that require further R&D including UVC sources, layouts for GUV in challenging spaces like upper room disinfection of big box stores, and smart controls/artificial intelligence (AI) for biovigilant systems. He discussed the challenges facing UVC LEDs to improve efficiency, extend wavelength range, increase lifetimes, develop better thermal management, and improve cost. Materials science research is required for improving the performance of UVC LED chips and packages. He also suggested research to better understand the efficacy of the different types of UVC source technology and what is each source’s best application area for GUV. With respect to the application side of UVC, Vincent discussed the difficulty in appropriately disinfecting tall (e.g., big box stores or warehouses) or other atypical spatial configurations. He pointed out that air mixing and GUV disinfection go hand-in-hand, as they are both methods for ensuring that UV-disinfected air is being mixed with the ambient air at the occupant level. These challenging spaces raise questions about how to ensure dosing from upper room installations in these spaces where air movement is problematic. Finally, Vincent raised the subject of smart controls/AI for biovigilant systems that have the potential to use UVC as a counter measure for biological threats; this could be done by intense feature integration added to the LED chip or packages, essentially leading to a bio lab on-chip.

Jeremy Yon, GE Current, a Daintree company: U.S. DOE LED R&D – GUV

Jeremy Yon, Industry Relations Leader at GE Current, discussed efficacy and safety of whole room irradiation below exposure limits by using direct GUV irradiation in occupied spaces as an approach to pathogen inactivation. This approach is complementary technology to other GUV and disinfection approaches. Yon also highlighted SSL system component performance challenges in GUV applications. First, LED UV sources need to expand their wavelength ranges, efficiency, radiation output maintenance, and broad availability. Furthermore, materials in luminaires such as reflective materials, paints and aluminum coatings, and lenses or diffusers must be developed to improve their UV optical performance, durability/longevity (UV resistant), and cost. He then discussed GUV application efficiency and effectiveness and its impact on energy use since the energy required is a combination of the effectiveness in creating the UV radiation and its pathogen inactivation effectiveness. For best effectiveness, the UV wavelengths should be specifically tailored to the pathogens; the development of a standardized library of inactivation constants by medium (surface, air, water) and by biomaterial (aerosol size and pathogen composition) would be a huge value to addressing the effectiveness of the GUV irradiation recipe. Improved tailoring can lead to optimized energy performance by enhanced pathogen inactivation through pulsing, dosage variation, or time impacts of the GUV irradiation. Another aspect of application effectiveness is proper installation and operation of GUV luminaires, which requires the development of simple in-situ measurement systems for setup, commissioning, validation, etc. Yon finished by discussing the opportunity of developing of innovative sensors (airborne pathogen detection, auditory detection of events – coughs, etc.) while also incorporating existing environmental sensors (temperature, humidity, contaminants) and conventional presence detection (passive infrared) into GUV luminaires.

Douglas Hamilton, Hubbell Lighting: GUV Is Here To Stay!!!

Douglas Hamilton, the Vice President of Advanced Development of Hubbell Lighting, began by examining different UVC source types, including traditional UVC low pressure mercury vapor (254 nm), UVC LEDs (275-280 nm), and far UVC excimer lamps (222 nm). When comparing these sources, Hamilton pointed specifically to a metric of combined efficiency that addresses both source efficiency and germicidal efficiency (destruction of DNA/RNA). The combined efficiency is highest for LMPV lamps showing why it is difficult to move away from these mercury containing sources. He emphasized the need for R&D to improve the performance of UVC LED source (efficiency, lifetime, shorter wavelengths) so as to minimize the environmental impact of GUV systems while still achieving high efficiency. Hamilton identified other R&D efforts to aid the development of GUV including further understanding of UVC material degradation issues and adapting software modeling to radiometric UVC needs (absorption/reflection, fluence, etc.). Additionally, he asserted the need for standards bodies to revisit the current TLV limits on UVC so direct luminaire integration can be considered. Hamilton concluded by stating the need for standardized reporting of GUV luminaire efficacy (similar to the DOE Lighting Facts program developed for general illumination) to create market confidence in product efficiency, costs, and lifespan and prevent the marketplace from getting out of control with false claims.

Mark Hand, Acuity Brands: UV Lighting SSL R&D

Mark Hand, the Vice President of Engineering at Acuity Brands, began with the assessment that UV LEDs will require all of the elements that are expected of LEDs in the visible light spectrum – long life, low cost, high efficiency. An investment in R&D is required to improve the performance of UV LEDs to meet these expectations. Hand acknowledged that much of the LED manufacturing takes place outside the U.S., but pointed out that this is an opportunity to support domestic UVC researchers and help foster more innovation in the U.S. He continued by emphasizing the need to establish accepted performance standards and safety regulations to ensure that the UV marketplace is not totally unregulated and irreparably damaged by bad actors. Hand urged DOE to take a leadership position and help prevent unregulated market conditions as they did with the programs such as Lighting Facts and CALiPER used in the early days of SSL. He reminded the impact that CALiPER test reports had to warn consumers away from bad market actors.

Holger Claus, Ushio America Inc.: GUV Opportunities and challenges

Holger Claus, the Vice President of Technology of Ushio America, discussed the different the applications of GUV, particularly the primary applications such as use in water treatment, HVAC coil disinfection and cleaning, and upper room air disinfection. Like other industry experts, he felt there would be more of an emphasis in increasing surface disinfection in the future. Claus stated that current UVC sources, such as LPMV lamps or UVC LEDs are primarily coming from outside the U.S. Shorter UVC wavelength sources (below 230 nm) are getting a lot of interest now since they have the same germicidal effects and dose requirements as 254 nm UVC lamps, and they have the safety benefit in that the lower wavelengths cannot penetrate layers of skin and eye, thereby creating the potential opportunity of safe application in occupied spaces. Next, Claus addressed current GUV challenges and R&D needs including photobiological research, developing application specific pathogen reduction data sets, developing standards for testing protocols and calibrations. He ended by discussing remaining UVC technological questions, including the limited potential that significant improvements can be achieved with current deep UVC excimer sources – they must be filtered causing a reduction in efficiency, have short lifetimes, and are expensive. Research into investigating other sources like UVC LEDs or frequency doubled blue lasers is required to achieve higher source efficiencies in the deep UVC range.

Jim Gaines, Signify: Research in GUV

Jim Gaines, the Standards and Regulations Professional at Signify, started by examining the fundamental research problems and where DOE involvement would be best targeted. In his opinion, the research important to manufacturers includes: the use of short wavelengths in occupied spaces and its effectiveness in this application; measurement details at different wavelengths as well as in different applications (and the resulting and germicidal effectiveness in logs for each wavelength and pathogen). Gaines stated that Signify did not see a role for DOE research in mercury and excimer lamps, and instead the focus should be turned to UV LEDs. Research is needed to address the low efficiency at the deep UVC wavelengths due to the materials and light (photon) extraction challenges occurring at the chip and package level. He finished by suggesting that DOE should investigate how to modify lighting systems and building design to incorporate GUV, from the building energy perspective, by including GUV in HVAC and other building sub-systems as well.

Mike Krames, Arkesso: Ultra-Violet Germicidal Irradiation (UVGI): LEDs vs. Hg Lamps

Mike Krames, President of Arkesso, examined the UVGI electricity consumption of implementing upper room UVGI in a facility compared to the electricity consumption of LED lighting in the same facility and projected that UVGI will consume ~2.5x more electricity today than the lighting. Part of the efficiency challenge with existing GUV luminaires is they are heavily louvered to keep the UVGI array from the occupants, thereby greatly reducing the overall efficiency of the fixture compared to a bare bulb in a closed system. Krames went on to discuss the importance of UV transparent epitaxial stacks to the success of UVC LEDs reaching efficiencies to gain market competitiveness. He compared the distinct challenges that UV LEDs face compared to blue LEDs including lack of UV transparent epitaxial stacks, the lack of highly reflective UV p-contact, higher dislocation densities and lower light (photon) extraction. Krames finished by looking UVC LEDs efficiency projections, where he explained that a 10x increase in power conversion efficiency is believed to be possible in the coming decade. This rise in efficiency will enables dramatic reduction in both initial and operating costs for UVGI systems over LPMV lamps. He indicated that UVC LED R&D is a good opportunity for DOE to invest in U.S. researchers since investment from the private sector has been very weak.

Erik Swenson, Nichia: Nichia's GUV LED Focus

Erik Swenson, General Manager of Nichia America, began by examining the four primary markets for GUV: surface disinfection, HVAC, water disinfection, and biological application (targeting specific pathogens). He noted that the current market conditions have a wild-west characteristic (i.e. unregulated products with false performance or safety claims), which needs oversight. Swenson addressed LED-based GUV sources and their range of wavelengths and applications. One approach is to use single white LEDs pumped at 405nm to provide bacterial deactivation simultaneously to general illumination within one luminaire. While this technology approach to disinfection is simple in design, has high efficiency sources, a long lifetime, and is safe for occupancy, it can take a long time for pathogen deactivation. He then highlighted UVC LED sources and described how the different wavelengths impact the sterilization efficiency for different pathogens. Swenson explained the trade-offs between selecting different UVC wavelength LEDs, pointing out that while shorter wavelengths of UV radiation have a higher relative sterilization efficiency, they also have lower radiant flux output, lower lifetimes, and lower efficiency. For these reasons Nichia is focused on 280 nm, as it more efficient for disinfection due to higher radiant flux output (even at lower sterilization efficiency), which, in combination with overall longer life and efficacy, can result in greater overall sterilization impact. To conclude, Swenson described steps that need to be taken to improve GUV implementation: ensure designs implement safety redundancy; rigorous testing to ensure safety measures are functional; ensure corners are not cut (i.e. quality, false claims) to take advantage of a short-term market opportunity; consider all the parameters that impact the GUV system performance when designing products (irradiation, time, geometry, targeted organisms); and to be aware of and engaged with developing standards and requirements.

Michael Kneissl, TU Berlin & Ferdinand-Braun-Institute: The prospects of AlGaN-based deep UV LED technologies

Michael Kneissl, a Professor at Technische Universität Berlin & Ferdinand-Braun-Institute, covered the prospects of AlGaN-based deep UV LED technologies. First, Kneissl discussed the state-of-the-art of external quantum efficiency (EQE) status of LEDs across the UV wavelengths. The majority of research in the field has been focused on the 260-280 nm wavelength range, since this is where devices are more efficient in the UVC band. There is a steep efficiency drop off as the wavelengths approach the deep UV wavelength range (< 240 nm). Kneissl discussed the advantage of deep UV wavelengths since the photons cannot penetrate past the epidermis layer of human skin, meaning that in-vivo disinfection can occur without causing damage to the skin. He went on to describe the current performance challenges of deep UV LEDs; in addition to the steep drop in EQE for as wavelengths decrease, there is a drop in radiative recombination efficiency, current injection efficiency, and light (photon) extraction efficiency. R&D approaches for improving the efficiencies of deep UV LEDs include reducing defect density for both threading dislocations (developing low-cost, low threading dislocation density templates) and point defects (epitaxial growth conditions of the AlGaN active region); advanced heterostructure designs for improved carrier injection; implementing UV-transparent layer structures to improve light (photon) extraction; and implementing tunnel-junctions UV-reflective contacts to improve device performance.

Steve DenBaars, University of California Santa Barbara: Essential Development Needs for GUV LEDs

Steve DenBaars, Mitsubishi Distinguished Professor of Materials and of Electrical and Computer Engineering at the University of California Santa Barbara, identified key research areas for UVC LEDs to address the low power conversion efficiency (PCE). R&D in epitaxy and chip designs is needed to improve light (photon) extraction efficiency, reduce epitaxial defects, and reduce device voltage, all of which contribute to an increase in PCE. DenBaars discussed how UCSB is addressing some of these challenges; one focus has been to fabricate LEDs in the flip chip configuration with surface roughing and improved p-type mirror contact reflectivity to increase light (photon) extraction out of the chip. He also described the implementation of tunnel junctions in the UVC LED to help reduce voltages and increase the PCE. DenBaars closed his talk by looking forward to projected performance improvements and moving from today's LEDs with a 4% PCE to 20% in the next few years. He predicted that in 5+ years it will be possible to get to 50% PCE. While optimistic, he noted the complex nature of the technology challenges ahead in improving UVC LEDs and advocated for DOE to establish a focused program on this topic.

Denan Konjhodzic, Instrument Systems, Konica Minolta Group: Calibration of UV Measuring Equipment

Denan Konjhodzic, Product Manager of Customer Solutions at Instrument Systems of the Konica Minolta Group, presented information about challenges of calibrating UV measurement equipment. Konjhodzic started by discussing how standards are required for the calibration of integrating spheres to the radiant flux in the UV range. The lack of absolute LED standards for calibration of UVC measurement systems has been a barrier up to now. His team developed a traceable calibration to the radiant flux using a goniophotometer and an irradiance calibrated detector to address this issue, and now they can provide LED calibration standards for radiant flux in the UVB and UVC range. He then talked about concepts for addressing measurement uncertainty. Three measurement uncertainty scenarios were described: calibrating to irradiance using Monte Carlo simulations; alignment, distance measurement, and scanning using standard guide to the expression of uncertainty in measurement (GUM) calculations; and device under test (DUT) operation with a special controller to improve device stability. Konjhodzic concluded with an outlook for GUV measurements and calibration R&D by highlighting the use of LED calibration standards as reliable audit sources for irradiance and radiant flux; optimizing PTFE coatings in integrating spheres for low fluorescence; and developing traceable calibration of all spectroradiometric systems with low measurement uncertainties over the UV to infrared spectral range (200-1650 nm).

Cameron Miller, National Institute of Standards and Technology: NIST UVC Activities

Cameron Miller, the Photometry Project Leader at NIST (Sensor Science Division), covered some of the UVC related activities underway at NIST. First, Miller highlighted the physical standards activities at NIST which are developing methods for measuring total flux, radiant intensity distribution, and electrical power, as well as extending and leveraging existing standards infrastructure and standards. He then described some of the UVC detector calibration and characterization activities to address the issue with UV detector performance showing a lot of variability. They found that the detector variation was due to poor cosine response behavior leading to inaccurate readings in the 2π measurement geometry. More research is required to deliver accurate detectors and sensors for the GUV application. Miller continued by describing the work underway in developing UVC measurement standards; the Illuminating Engineering Society (IES) and the International Ultraviolet Association (IUVA) signed a memorandum of understanding (MOU) in 2020 to assemble experts in the measurement of UVC emissions to develop American National Standards (ANSI Standards) for the measurement and characterization of UVC device performance. These methods under development include methods for electrical and UV measurement of different UV source types (including LPMV, excimer, and LED sources), the electrical and UV measurement of UVC disinfection products, and finally the calibration and characterization of UVC detectors. Finally, Miller expressed the need for the development of a D90 library for various pathogens in order to best describe pathogen sensitivity across pathogens and different wavelengths of UV-C radiation. He also emphasized that the best role DOE can have in the LED-based UVC development is to foster the relationships between different departments and organizations within government.

(This page intentionally left blank)

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

For more information, visit:
energy.gov/eere/ssl

DOE/EE-2344 ▪ February 2021