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

August 2022

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DOE Solid-State Lighting Program, "Germicidal Ultraviolet R&D Meeting," August 2022.

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Comments

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Table of Contents

1 Introduction

On August 11, 2022, twenty-three subject matter experts on different aspects of germicidal ultraviolet (GUV) disinfection gathered at the invitation of the Department of Energy (DOE) Solid-State Lighting (SSL) 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 SSL Program. The Program also collects inputs from stakeholders at the annual Solid-State Lighting Workshop, via a Request for Information (RFI), and through 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 to minimize travel for the participants. The meeting commenced with "soapbox" presentations in which participants were invited to give a short presentation describing what they believe to be the key technology challenges for GUV over the next three to five years. Presentations were 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 experts in GUV relevant science and technology disciplines drawn from academia, national laboratories, government agencies, and industry.

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

1.1 Key Conclusions

The meeting format encouraged each of the attendees to participate and present his/her perspective 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, some recurring themes arose during these discussions regarding research areas that could lead to significant breakthroughs in technology development and implementation. The recurring themes are as follows and are outlined in more detail in Section 2 below:

- GUV Efficacy
- Risk Research
- GUV Source Technology
- GUV Implementation
- Standards & Regulatory

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 Efficacy

Participants discussed the importance of GUV efficacy in terms of understanding the photobiological effectiveness for pathogen inactivation, while also considering the energy consumption involved. Ultraviolet C-band (UVC) irradiation shows a strong reduction in pathogens in a space and can be implemented with more effective air changes per hour (ACH) compared to mechanical ventilation systems, while simultaneously being less energy intensive. Quantifying pathogen inactivation is important to deploy the most effective GUV treatment strategies. Quantification requires understanding many parameters such as UV dose, spectral sensitivity, and the pathogen's surrounding environment. Expanding UV inactivation data across wavelengths for respiratory, food, and water pathogens is essential to further optimize GUV design effectiveness.

Research is needed to better elucidate the germicidal action spectra since the inactivation process of viruses and other pathogens are not fully known. UV disinfection mechanisms are different for viruses and bacteria. Genome (DNA/RNA) damage interferes with replication, whereas protein damage impacts the structure and function of the virus infection process. Furthermore, the UV wavelengths for protein damage are different than those for genome damage. There is an opportunity to investigate wavelength-specific molecular damage to DNA/RNA and proteins and the synergies between UV wavelengths. Further research on the mechanisms of DNA/RNA repair across the UV wavelength range is essential since wavelength impacts the effectiveness to limit the molecular repair processes. Studies have shown synergies when applying UVA irradiation prior to UVC irradiation on the same organisms (bacteria or virus) because the UVA damages the proteins that help attach or infect a cell, or by damaging the enzymes that repair the UVC damage. Clarifying these mechanisms can lead to development of wavelength tailored disinfection optimization to improve inactivation and potentially save energy by deploying a better designed dose for a particular pathogen.

There is an opportunity to optimize built-in GUV systems to provide a range of "just-in-time" and continuous UVC delivery for effectiveness against a range of pathogens and bioburden while maintaining safety. This will require continued measurements of pathogen inactivation in air and the development of a protocol for dose determination. Another research area is developing a simple way to quantify live pathogens versus inactivated (dead) pathogens in air samples since genomic approaches do not distinguish between live and dead pathogens. This could lead to real time measurements to quantify the reduction of live pathogens in a room.

2.2 Risk Research

Risk research is meant to convey the benefits and risks associated with GUV. This includes balancing safety, biological efficacy, and risk of disease transmission. In other words, comparative risk research is needed to determine how much protection is possible through GUV and how much risk-reduction is acceptable. With UVC exposure likely the most effective control measure for reduction of airborne infective virus concentration, the link between GUV characteristics, infection risk, and safety risk is an important area for research. Participants suggested research is needed to determine how to balance UV exposure risk versus infection risk. Safety has long been a concern associated with GUV, therefore regulatory bodies have provided safeguards to help prevent eye and skin injuries. Further GUV safety research to determine threshold limit values (TLVs) with the incorporation of occupant time-motion dose study data into exposure evaluation would be beneficial. Many participants felt the current guidance for TLVs by the American Conference of Governmental Industrial Hygienists (ACGIH) is too stringent since time and motion protects people from overexposure. The conservative TLV thresholds reduce the effectiveness of GUV air treatment. Moreover, these limits do not consider far-UVC wavelengths, which is safer for skin and eyes. Research to develop rational application of UV exposure considering time-motion and balancing it against effective GUV wavelength and dose would help create safety guidelines with better GUV effectiveness. Additionally, educating the public to on UV exposure risks can put into perspective the difference in safety between UVA, UVB and UVC exposure.

Far-UVC radiation has shown much potential to be safe for direct human exposure while efficiently inactivating airborne viruses. There is minimum penetration of far-UVC radiation into the living skin (because of the stratum-corneum layer) and eyes (because of the tear-layer). Because these layers do not contain living cells, they absorb a significant fraction of the far-UVC fluence. Additionally, UV spectral absorption in ocular tissues undergoes successive filtration by the different layers in the eye, with the UVC totally absorbed in the cornea before it reaches the lens or retina. Several research areas need further exploration to improve safety understanding, including research to determine the relative photocarcinogenic risk of the various UVC and far-UVC wavelengths in human skin; quantifying inter-individual variations in stratum-corneum and tear-layer thicknesses; studying the tear-layer thickness by far-UVC to ascertain if guidance to limit dose rate is warranted; and establishing the action spectrum for erythema in the UVC to further assess acute exposure risks.

2.3 GUV Source Technology

Participants considered different GUV source technologies, though most of the discussion was centered around UV LED technology. UV LED technology has seen optical output increases 20-fold and the price/output decrease by a factor of 10 over the past decade. The higher efficiency and lower cost of UV LEDs, coupled with refined system design and manufacture to exploit the unique LED characteristics, have led to wide deployment of UV LEDs for water disinfection. UV LED efficiency continues to climb and is catching up to mercury-based UV lamps in terms of true efficiency (when considering the standby time, power supply and light use efficiency of mercury lamps). Additionally, UV LEDs do not contain mercury and will not be restricted by regulatory drivers such as the Minamata Convention recommendations limiting the use of mercury-based products. Designing with LEDs allows for systems to take advantages of their distinctive properties (e.g., small device, better control of optical distribution, etc.), thus creating value with improved holistic system designs.

UV LEDs have reached a practical cost and performance level for use in GUV air treatment systems. Many companies are already designing GUV products with UVC LEDs. The development history of visible LEDs had shown rapid performance increases over time and some participants believe that UV LED development will follow the same improvement trajectory as visible LEDs. The majority of participants suggested that more research is needed on GUV source technology and manufacturing, including targeted support for U.S. based UVC LED device research and the manufacturing of UV LED based GUV systems. Other related research includes advancing UVC LED modules by improving the beam shaping optical design for UV radiation, integrating UV sensors into modules, and improving manufacturing processes for more cost-effective UVC LED solutions.

2.4 GUV Implementation

GUV is an emerging field in the building industry. Implementation involves several aspects, including modeling and design practices, field studies to validate performance, and application case studies to help improve education and user confidence. For the building industry to properly design and implement GUV systems, industry-accepted design tools combined with computational modeling for air and surface disinfection applications must be developed. One focus area is extending GUV design processes to mirror lighting design processes by developing computational UV modeling that calculate pathogen inactivation and human exposure using radiometric modeling tools. Modeling should estimate the equivalent ACH of the GUV dose to create practical computation models for application planning and infection prevention investigations. These tools must be validated by comparing calculated values against measured values. Research into translating the biological efficacy of GUV into proxy measurements that can be used to develop the application design guidelines for effective GUV design. Demonstration projects in different settings can document the biological efficacy and energy implications of various of GUV strategies and technologies (e.g., upper room, direct illumination below exposure level, in-duct application). Results from the demonstration projects can feed back into design guides and best practice approaches. These can also improve customer confidence in GUV effectiveness and lead building managers to consider faster deployment of the technology.

A major challenge is understanding how much disinfection is needed in each treated space, a factor which can continually change. Better understanding infection risk in each use case can allow for the appropriate treatment according to the equivalent ventilation requirements. Once the requirements are understood, disinfection efficiency must be quantified – which is difficult in real-world settings. Research is needed to develop viable real-time pathogen detection methods along with well-aligned standards and testing strategies. Real-time detection and monitoring of the space to give an absolute measurement of the infection risk with feedback would be ideal, though research is required to develop real-time sensing. Implementing real-time sensing also has the potential to reduce the energy consumption of GUV systems since the treatment could be scaled to the level of the real-time risk. Designing systems to be dynamically tailored to the specifics of the treated space can improve the overall efficacy of the GUV solution.

Participants also highlighted the importance of developing effective GUV solutions that are also energy efficient. A review of upper room GUV studies has examined the effectiveness and energy implications of this technology compared to heating ventilation and air conditioning (HVAC) related technologies that increased the fraction of outdoor air, increased the air change rate, or implemented improved filtration. The analysis found, when comparing the effectiveness and energy use in terms of equivalent ACH and annual energy cost per equivalent ACH, that a potential large-scale energy efficiency and decarbonization opportunity exists with GUV relative to HVAC measures. Future research includes developing a standardized framework to assess energy and effectiveness of GUV and HVAC mitigation strategies, studies to assess energy and effectiveness of GUV and HVAC mitigation strategies across building types and climate zones, and quantification of electrification and decarbonization benefits of GUV relative to HVAC strategies.

2.5 Standards & Regulatory

Progress is being made in GUV standards development, with several UV standards published and several more GUV-related standards under development. The National Institute of Standards and Technology (NIST), the Illuminating Engineering Society (IES) and International Ultraviolet Association (IUVA) worked together to develop optical measurement standards focused on the accuracy and consistency of UV source measurements, measurement of UVC systems, and the calibration of UV detectors and radiometers. Additionally, NIST works on accreditation for laboratories to measure UV devices and perform measurement assurance programs for these laboratories to ensure they are capable of conducting these measurements accurately. GUV standards under development by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) are developing standards for a test method of test for evaluating in-room devices and systems for microorganism removal or inactivation in a chamber, and to establish a test method for evaluating the efficacy of UV disinfection systems for microbial inactivation on multiple surface locations in a test room.

Participants discussed the need for public and private sector research to support standards development. Focus areas for the standards include developing methods of validation testing that are translatable to the end-use application, methods of describing GUV efficacy, as well as consideration of existing recommendations for human exposure limits. Additionally, participants agreed that the incorporation of occupant time-motion dose study data into exposure evaluation and guidelines is important. Developing this application information and publishing case studies can better inform the field and help in developing standards and regulations.

The regulatory environment is critical to build safe, effective systems while increasing consumer confidence. One of the challenges faced by GUV system manufacturers is the changing regulatory framework for this growing application space. There can often be confusion since regulations and regulatory bodies can change by setting, disinfection type (e.g., air, surface, or water) and the application space.

The DOE SSL Program is focused on improving education by implementing the CALiPER GUV Product Testing Program, which conducts radiometric testing of commercially available products and publishes objective reviews of the testing results. CALiPER test reports validate product performance claims and are an effective tool in addressing inaccurate or inflated performance claims, calling attention to low performing products and educating stakeholders on how products should be tested and evaluated. Furthermore, the DOE SSL Program will carry out GUV field evaluations and demonstrations to develop application case studies that better understand the biological efficacy and energy consumption associated with GUV technology.

Appendix A: Participant Presentations

Ed Nardell, Harvard University: "Mis-regulation" – A Barrier to Effective GUV Implementation

Ed Nardell, Professor at the Harvard Medical School and T. H. Chan School of Public Health, began by highlighting two conflicting perspectives on GUV – that of regulatory and that of public health. The regulatory perspective views ultraviolet radiation from GUV fixtures as intrinsically unsafe and that harm must be prevented regardless of the impact of regulation on biological efficacy. Nardell suggested that all known UV injuries have been accidental, not from use as intended. Therefore, guidelines requiring no more than 0.1 $\mu W/cm^2$ irradiance for 8-hr stare time at a height of 7 feet do not assure safety (since injuries have not been from use settings) but does impair GUV effectiveness. From the public health perspective, GUV using UVC wavelengths has proven to be *intrinsically safe* due to limited tissue penetration and almost 100 years of safe application. Nardell noted that time and motion protect people from overexposure, but that is not reflected in today's regulations. Additionally, the shape of our heads and our eye lid geometry helps protect occupants from upper room exposure. He cited several studies showing the actual measured exposure of people in the field studies is about 1/3 of the threshold limit value (TLV). Field trials in hospital settings have shown upper room GUV to be 80% effective in preventing serious airborne infection. Nardell identified several R&D priorities, the first of which is comparative risk research to determine how much protection is possible through GUV and how much risk-reduction is acceptable. He proposed considering an 80% reduction of illness instead of the 2 to 3 log reductions for surface disinfection. Nardell noted that for many health interventions, such as masks and many vaccines, a 50% risk reduction is an acceptable target. Research is needed on how best to balance UV exposure risk versus infection risk.

Richard Vincent, Mount Sinai Hospital New York: Emergence of Hybrid UVC Systems and Controls: Modeling, Demonstrations and Standards—Biosecurity

Richard Vincent, Administrative Manager at Icahn School of Medicine at Mount Sinai, discussed several key research areas, including GUV modeling tools, demonstration projects, and standards for biosecurity. Ongoing research is mapping out the potential of various wavelengths for inactivation of various disease-causing microbes. Modular approaches for introducing UVC radiation into occupied spaces and in-duct systems are beginning to emerge both for excimer modules and UV LED sources. Vincent asked if there are ways to optimize built-in GUV systems that will provide a range of "just-in-time" and continuous UVC delivery for effectiveness against a range of pathogens and bioburden while maintaining human safety. GUV modeling tools should be further developed to implement various UV wavelengths into GUV fixtures. These modeling tools can be improved with feedback from field studies. Vincent also highlighted the need for planned demonstration projects in different settings to document the effectiveness and energy implications of different types of GUV strategies and technologies (e.g. upper room, direct illumination below exposure level, in-duct application). Developing this application information and publishing case studies can better inform the field and help in developing standards and regulations. Finally, Vincent pointed to the need for public and private sector research to support standards development. Progress is being made in GUV standards, such as some ASHRAE standards that are under development. These standards aim to establish a test method for evaluating in-room devices and systems for microorganism removal or inactivation in a chamber, and to establish a test method for evaluating the efficacy of UV disinfection systems for microbial inactivation on multiple surface locations in a test room.

David Sliney, Independent Consulting Medical Physicist: Research Needs: Ultraviolet Exposure Limits at Shorter Wavelengths – UV-C

David Sliney, an Independent Consulting Medical Physicist, examined the ultraviolet exposure limits at shorter UV wavelengths. He started by describing how far-UVC radiation is absorbed superficially by the skin (penetration depth is smaller at shorter UV wavelengths). UV spectral absorption in ocular tissues undergoes successive filtration by the different layers in the eye, with the UVC totally absorbed in the cornea before it reaches the lens or retina. The American Conference of Governmental Industrial Hygienists (ACGIH) revised the exposure limits under UVC radiation last year, but Sliney indicated that the reduction factors of the exposure limits were insufficient based on skin and eye safety with far-UVC irradiation. He concluded by identifying four research needs to answer questions related to UVC safety. First, research should determine the relative photocarcinogenic risk of wavelengths between 200 and 254 nm in human skin. Human experiments with molecular markers for DNA damage at different depths in the epidermis can be one approach to this research. Determining if there are significant differences in the thickness of stratum corneum and epidermis in different skin types is also important. A second research need is to determine the risk to the cornea and conjunctiva. This can be investigated by studying the direct effects on the surface epithelial cells of the conjunctiva and cornea and reassessing the action spectrum for photokeratitis and photoconjunctivitis. Also, studying the evaporative loss of tear-film molecules by far-UVC can help determine if the guidance to limit dose rate is warranted. A third research priority is determining the action spectrum for erythema in the UVC to further assess acute exposure risks. A final research need is to extend the International Commission on Illumination (CIE) International Standard Action Spectrum for UV photocarcinogenesis below 250 nm.

David Brenner, Columbia University: Far-UVC Light

David Brenner, Professor of Radiation Biophysics at Columbia University, focused on far-UVC radiation for germicidal applications. Far-UVC irradiation is a new technology with the demonstrated potential to safely reduce airborne disease transmission in occupied public spaces. The ideal UVC wavelength would inactivate airborne viruses but could be directly used in occupied spaces. Because far-UVC (222 nm) has minimal penetration into living skin or eyes, it has the potential to be safe for direct human exposure while efficiently inactivating airborne viruses. Brenner stated that there are two basic questions that need to be addressed: "Is it safe?" and "Does it work?" There is minimum penetration into the living skin (because of the stratum-corneum layer) and eye (because of the tear-layer) since these layers do not contain living cells and absorb a significant fraction of the far-UVC fluence. There are many published safety studies for the skin and some for the eye to validate safety for far-UVC wavelengths of 235 nm and below. Brenner pointed out a need for further research to quantify inter-individual variations in stratum-corneum and tear-layer thicknesses. Far-UVC does work based on studies in field settings showing a strong reduction in pathogens in a room. He described one specific study evaluating the pathogens in a room when UV lamps were off and comparing it to pathogen levels after the UV lamps were turned on. This study showed greater than 90% reduction of pathogen levels in the air and maintained this low level even with pathogens still being introduced into the room. This level of pathogen reduction was equivalent to 180 ACH. Another research priority area is developing a simple way to quantify live pathogens versus inactivated (dead) pathogens in air samples. Genomic approaches do not distinguish between live and dead pathogens, so there is a need for a simple way to measure reduction of live pathogens in a room.

Ernest Blatchley III, Purdue University: Action Spectra of SARS-CoV-2 in Various Media

Ernest Blatchley III, Professor in Environmental Engineering at Purdue University, began by pointing out that the UV dose is the master variable – it governs the extent of any photochemical reaction and the performance of all UV disinfection systems. In practical applications, a dose distribution will be delivered by the fixture. Factors that affect the system performance include the flow field, fluence rate field, system geometry, lamp power, and optical characteristics. Using well-established methods, such as ray tracing (fluence rate field) and computational fluid dynamics modeling, allows for improved design and implementation. Blatchley examined the action spectra of SARS-CoV-2 in various media using a tunable laser on a rotating platform. This method represents the "gold standard" for quantification of intrinsic kinetics (i.e., dose-response of microbes). The research showed inactivation responses of SARS-CoV-2 that were similar for all media at wavelengths greater than 290 nm. For UVC wavelengths tested (between 222 nm and 280 nm), inactivation was more rapid in an aqueous suspension than in other media. Further research on the quantification of intrinsic kinetics of airborne and surface-associated pathogens is needed. Blatchley finished by considering the incorporation of risk – a design approach based on the risk is a rational approach (as is done in water disinfection). The likelihood of infection is strongly influenced by dose (number of virus particles) with UVC exposure likely the most effective control measure for reduction of airborne, infective virus concentration. The link between UV system characteristics and risk reduction is another area from future research. Finally, more work is needed in the development of validation protocols.

Karl Linden, University of Colorado Boulder: Wavelength-specific UV Inactivation Mechanisms and Standards for Comparing Systems and Efficacy

Karl Linden, Professor of Environmental Engineering at University of Colorado Boulder, explored wavelength-specific UV inactivation mechanisms and standards for comparing systems and efficacy. UV disinfection mechanisms are different for viruses versus bacteria. Genome (DNA/RNA) damage interferes with replication, whereas protein damage impacts the structure and function of the virus infection process. The UV wavelengths for protein damage are different than those for genome damage. 222 nm radiation is more effective for virus inactivation than 254 nm, whereas the trend is reversed for bacteria (254 nm is more effective for inactivation). More research is needed on the mechanisms of UV action and potential for repair across the UV wavelength range. Linden discussed wavelength tailored disinfection optimization and considered whether multiple wavelengths would improve inactivation and save energy. He highlighted several studies exploring the UV sensitivity and inactivation of common pathogens at different UV doses and wavelengths between 200-300 nm (using various UVC source technologies). Developing more UV inactivation data across wavelengths for respiratory, food, and water pathogens is essential to further optimize GUV design effectiveness. Linden closed by discussing the need for development and validation of new methods and standards for UV inactivation studies on different surfaces (and in air). The transmittance of different types of suspending media of the pathogen impacts the UV absorbance and should be reported for inactivation studies on surfaces.

Sara Beck, University of British Columbia: GUV R&D Discussion

Sara Beck, an Assistant Professor in the Department of Civil Engineering at the University of British Columbia, presented on three key R&D priority areas for GUV. Beck began by discussing the studies exploring spectral sensitivity (action spectra) of different pathogens using a tunable laser. There is a need to continue measuring inactivation of pathogens in air and developing a protocol for dose determination. She suggested developing action spectra for organisms responsible for healthcare-associated infections such as MRSA, B. subtilis, Clostridioides difficile (C. diff), or tuberculosis (TB). The second research area Beck discussed was related to wavelength-specific molecular damage to DNA/RNA and proteins. There is an opportunity to investigate synergies between UV wavelengths. Studies have not shown synergy when applying both UVB and UVC irradiation to the same organisms (bacteria or virus), however, there have been synergies when applying UVA irradiation prior to UVC irradiation on organisms. This is because the UVA damages the proteins that help the pathogen attach or infect a cell, or by damaging the enzymes that repair UVC damage. Research into DNA/RNA repair is needed since damage at 280 nm can be more effective than 254 nm to limit repair processes. Also, R&D to develop cultivation-independent methods for verifying UV inactivation and show damage more quickly would be beneficial. The third priority area Beck discussed was further development in UV in low-resource contexts. For example, GUV can be used to prevent contamination and infection of health practitioners during donning and doffing of personal protective equipment (PPE) in under-resourced health care environments. Understanding the efficacy of GUV disinfection of PPE for different pathogens and at different wavelengths can help improve reuse of PPE in regions where supplies are lacking. Additionally, integration of UV LEDs at the point of collection in water storage tanks can help reduce contamination.

Katherine Ratliff, Environmental Protection Agency: U.S. EPA Office of Research and Development's Air Treatment Technology Efficacy Research

Katherine Ratliff, a Physical Scientist at the U.S. Environmental Protection Agency (EPA) Office of Research and Development, discussed air treatment technology efficacy research. The goal of this work was to evaluate the efficacy of air treatment at real-world scale using a standardized testing approach and inform development of testing methodologies for these technologies. The study used a 3000 ft^3 test chamber with a mock HVAC system to create a room sized environment. Aerosolized non-pathogenic virus (MS2) was used, and air sampling was performed for viable virus and particle size/concentration measurements. This test setup was used to evaluate in-duct purification technologies, a 3-stage air filtration and purification system, and portable filtration technologies. Comparing high efficiency particulate air (HEPA) filtration to far-UV upper room sources found similar rates of inactivation and particle removal for far-UV and HEPA units under test conditions. During this testing, a 2 $\log_{10}$ reduction in control tests (with no technology active) was seen due to natural decay and wall loss. There is a need for further control tests and replicate testing to characterize air treatment technology efficacy. Additionally, many other factors must be considered in extrapolating lab results to applied settings (e.g., soil load, particle size, temperature, humidity, etc.). Ratliff finished by suggesting further research to evaluate impacts of test methodology (e.g., air flow, aerosolization fluid, chamber size) to efficacy for different technologies.

Steve Martin, Safe Antivirus Technologies Inc. (SATI): Inactivating Viruses

Steve Martin, Founder at SATI, described his work using UV-LEDs to inactivate viruses. The benefits of UV for disinfection are underscored by the simple mechanism of action - nucleotide bases of DNA and RNA absorb UV, thereby disrupting the structure of nucleotide sequences and introducing 'road- blocks' in genome replication. Safe deployment is crucial. The use of automated sensors and controls can help ensure people are not exposed to UV radiation during a cleaning cycle. The risk of chemical exposure is drastically reduced with GUV since no bleach, ammonia or other potentially hazardous materials are required. Martin discussed a study using high power UV LED arrays, which were demonstrated to inactivate two distinct virus models – human coronavirus 229E and human immunodeficiency virus (HIV). Importantly, the same dose of UV that inactivated human viruses also elicited complete inactivation of UV-resistant bacterial spores (Bacillus pumilus), a gold standard for demonstrating UV-mediated disinfection. This work demonstrates that seconds of UV LED exposure can inactivate viruses and bacteria, highlighting the potential utility and practicality for broad sanitization of public spaces. The UV LEDs used in the study comprised high-density chip-on-board (COB) devices supplied as two sets – one with nine 275 nm LEDs in a 3×3 COB array and the other with twenty 380 nm LEDs in a 4×5 COB array. The LEDs were approximately 5 cm from the irradiated sample, with each array delivering between 0.4 and 0.6 mW/cm^2 of UV irradiation. The maximum irradiation time was 30 s, resulting in a total delivered dose for the combined arrays of 8 mJ/cm^2 to 20 mJ/cm^2 to the irradiated samples.

Oliver Lawal, AquiSense: LED R&D Discussion Meeting – GUV

Oliver Lawal, Chief Executive Officer at AquiSense, began with a UV applications overview. He noted that about 80% of the UV market size is for water disinfection, while air and surface disinfection are growing applications. Lawal then reviewed the UV LED technology and cost evolution that has seen optical output increase 20-fold and price drop by a factor of 10 over the past decade. This higher efficiency and lower cost of UV LEDs, coupled with refined system design and manufacture to exploit the unique LED characteristics (e.g., high power density, small footprint, instant-on, etc.), has led to wide deployment of UV LEDs for water disinfection. Further UV LED deployment can be achieved with regulatory drivers such as standards developments and enforcing the Minamata Convention guidance (a limit on manufacture of mercury-based products). Lawal concluded by highlighting a few key areas for future development. First is improving regulatory pace and education. Issues include higher regulatory barriers to entry for new UV-LED technologies/products, the fact that many regulators do not understand new UV LED technology, and the impact of misleading UV product claims. A second key area is increasing user education (industrial, municipal, and consumer) to dispel misconceptions around alternatives to mercury-lamp technology and the need for non-chemical disinfection methods. Third, more research is needed on technology and manufacturing, including targeted support for US-based UVC LED chip device research and manufacturing. Development of pilot studies to show real-world innovative application uses of UVC LED-based products will help build best practices and establish consumer confidence.

Jeannine Fisher Wang, Acuity Brands: Requirements to Design, Validate, and Build Customer Confidence in GUV

Jeannine Fisher Wang, the Director of Technology Solutions at Acuity Brands, discussed the key requirements to design, validate, and build customer confidence in GUV. Today, the GUV landscape has many different product types, application methods, and guidelines. The resulting standards and regulations are not always in-sync, which slows market confidence. Another focus area is advancing GUV design processes to mirror lighting design processes by developing computational UV modeling that calculate pathogen inactivation and human exposure using radiometric modeling tools. These tools must be validated by comparing calculated values against measured values and perhaps developing a proxy measurement. She also highlighted the importance of customer education, which must be improved by making GUV easy to understand and compare. The scientific work and understanding of UV for inactivation of pathogens runs deep, but GUV is an emerging field in the building industry. The building industry needs this expert level knowledge boiled down to simple design guidelines that can deliver results. Using industry-accepted design tools while adding computational modeling for air and surface applications is important. Features such as simple look-up tables that everyone uses for standard references, like surface reflectance, pathogen dose requirements derived from standard laboratory conditions (or industry-wide agreed upon set of standard references), impact of airflow to mitigate need for CFD analysis for air applications, and design targets by application and pathogen, would be valuable. Finally, Fisher Wang closed by expressing the need to quantify economic value of investing in GUV to the customer. Determining the economic benefits by end-use application supported with published case studies can serve as a model for similar customers and businesses while providing third party credibility and confidence for the customer.

Jim Gaines, Signify: GUV Discussion

Jim Gaines, a Standards and Regulations Professional at Signify, discussed two major challenges for GUV implementation. One major obstacle is the perceived safety risk. While GUV is not new for the medical and scientific communities, it is newer for the public. If this gap of understanding is not bridged, then even effective GUV technical solutions may not be used. Further confirmation by leading medical experts and case studies to the safety of UVC technology can lead to greater acceptance by the public. Providing people the ability to monitor their own dose exposure with a sensor (e.g., a dosimeter worn or a mounted sensor in the treated space) and comparing to the typical UV dose experienced in the sun, could help build confidence. The second major challenge is understanding how much disinfection is needed in each treated space, which then can allow for dynamic factors tailored to the specifics of the treated space. The infection risk must be understood in each use case so the appropriate treatment can be provided according to the equivalent ventilation requirements. Once the requirements are understood, then disinfection efficiency must be quantified, which is difficult to do in real-life settings. One approach is to develop proxy measures to evaluate the risk and necessary treatment to address that risk. Artificial intelligence can be applied to these proxies to estimate the real time infection rate and needed disinfection level. Research to develop viable real-time pathogen detection methods along with well-aligned standards and testing strategies is needed. Real-time detection and monitoring of the space to give an absolute measurement of the infection risk with a feedback loop would be ideal, however, R&D is required to develop this real-time sensing. Implementing real-time sensing also has the potential to reduce the energy consumption of GUV systems since the treatment could be scaled to the level of the real-time risk. If these two major obstacles can be addressed, then the benefits of GUV can be leveraged. Gaines closed by noting that GUV is a proven disinfection technology for a wide range of pathogens that has been applied already for decades and is more energy efficient than ventilation and filtering approaches for air treatment.

Holger Claus, Ushio America: GUV for Air and Surface Disinfection

Holger Claus, Vice President at Ushio America, opined that GUV use is the best option to prepare for the "next pandemic." Infections can be airborne or surface related, but GUV can treat both applications. Additionally, all pathogens are susceptible to GUV and there is no indication that pathogens can become GUV resistant (in contrast to chemicals or antibiotics). GUV is environmentally friendly and can be energy efficient. Far-UVC can be used in occupied spaces and provide disinfection closest to the pathogen "source" (humans). There should also be strong consideration for GUV use in agriculture, domesticated animals, and other food supply industries. Claus then moved to discuss the benefits of GUV for air treatment. The Center for Disease Control (CDC) and ASHRAE recommend 4 to 10 (or more) ACHs to dilute pathogens in room air and reduce the risk of infections. This ACH recommendation assumes fresh air (outside or heavily filtered), but in typical settings the air is not fresh, resulting in effective ACH of less than 1. Increasing ACH with conventional methods is very energy intensive, and the HVAC equipment is not running constantly to achieve consistent

ACH. Achieving the target ACH with traditional HVAC methods will negate many previous achievements in improved HVAC energy efficiency. On the other hand, achieving equivalent ACHs greater than 20 is easier to achieve with far-UVC or upper air GUV. Claus finished by highlighting key research areas needed to enable GUV air disinfection in more applications. These include further research into modeling of equivalent ACH and verification of pathogen reduction in testing laboratories (especially of far-UVC); research on airborne pathogen reduction; UVC susceptibility studies for pathogens at various wavelengths; the development of practical computation models for application planning; and infection prevention investigations (in hospitals or other settings).

Yuya Harada, Nichia America: Full Ecosystem UV LED Disinfection Devices Can Be Realized Today

Yuya Harada, a Technical Support Manager at Nichia America, highlighted the ecosystem of today's UV LED disinfection devices that are used for air treatment, surface disinfection, and for auxiliary disinfection using visible light (UVA). While a single preventative device is not all-inclusive, multiple preventions can comprehensively reduce the risk of viruses and bacteria. Air circulation (via upper room GUV disinfection) can safely disinfect the air in a large space without direct human irradiation but is not suitable for disinfecting viruses or bacteria attached to the surfaces in the room. A surface disinfection device can disinfect the surface in a short time, but the treatment area is limited. Finally, UVA can be added to white general lighting fixtures to help prevent an increase in pathogens. Harada then shifted to the efficiency of UV LEDs, which he said will exceed mercury lamps soon. UV LEDs are already catching up in terms of true efficiency (when considering the standby time, power supply and light use efficiency of mercury lamps). Designing with LEDs is highly flexible, so new system designs can take advantages of the unique properties of LEDs (e.g., small device, better control of optical distribution, etc.). Harada compared three UV source technologies in a GUV system for surface disinfection to illustrate this point. He closed by stating that there is no need to wait for discrete LED efficiency and price to become affordable – the value of UV LEDs can be realized today in a holistic design. UV LEDs have reached a practical level for implementation and many companies are already designing with them. As the history of visible LEDs have shown, the performance increases rapidly. History will repeat itself as UV LEDs will dramatically evolve in the near future.

Lynn Davis, RTI International: UV LED Reliability Studies and Systems Development

Lynn Davis, a Fellow at RTI International, examined the reliability behavior of a variety of UV LED product types. Davis discussed a UV LED benchmarking study with room temperature operating lifetime (RTOL) measurements performed on 14 different UV LED products spanning the UVA (365 nm), UVB (~310 nm), and UVC (~275 nm) wavelengths with up to 3,000 hours of lifetime data. The device population was divided among different tests including a high current test (at maximum rated LED drive current) and a low current test. UVB and UVC LED packages have a flat quartz lens, whereas UVA packages typically have a domed lens. Blue LEDs used for white solid-state lighting, as well as UVA LEDs, use InGaN active regions that allow for a threshold voltage near the band-gap of the semiconductor. UVB and UVC LEDs, on the other hand, use an AlGaN active region, which leads to higher threshold voltages and lower electrical efficiencies. UVB and UVC LEDs have a radiant efficiency of about 3 to 5%, with exception to a new style UVC LED with transparent p-type layers that result in an improved optical performance over the other UVB and UVC LEDs tested (~11% radiant efficiency). The reliability findings show failure types that were abrupt (i.e., no radiation) or parametric (i.e., radiant flux maintenance < 50%). The study found three key failure modes: 1) electrical shorts in semiconductor material (abrupt); 2) growth of parasitic diode in parallel with the main UV LED diode (parametric) that occurred mostly in UV-B and UV-C products; and 3) package-related issues (parametric) involving mostly silicone cracking and degradation that reduced emissions. This last failure mode occurred only in UV-A products, since they were the only ones using a silicone encapsulation. Davis concluded by mentioning considerations for GUV systems used for air cleaning and pathogen deactivation. Effective GUV technology must be complementary to building ventilation controls and other mitigation methods. Increasing ventilation rates and/or using GUV technology increases a building's energy use. Research is needed to understand the tradeoffs between building design, treatment effectiveness, and energy use. Sensors that detect changes in the concentration of biological particles in the air (i.e., bioaerosols) may be useful control sensors for optimizing energy use and occupant comfort, but require more research and development work.

Belal Abboushi, Pacific Northwest National Laboratory: PNNL GUV Research Update

Belal Abboushi, Senior Associate Lighting Research Engineer at Pacific Northwest National Laboratory (PNNL), provided an update of various GUV research activities ongoing at PNNL. The first project he discussed was a review of upper room GUV studies to examine the effectiveness and energy implications of this technology compared to HVAC related technologies (including those increasing the fraction of outdoor air, increasing the air change rate, or those implementing improved filtration). The analysis compared the effectiveness and energy use in terms of equivalent ACH and annual energy cost per equivalent ACH. PNNL found that a potential large-scale energy efficiency and decarbonization opportunity exists with GUV relative to HVAC measures. Future work includes developing a standardized framework to assess energy and effectiveness of GUV and HVAC mitigation strategies; a simulation study to assess energy and effectiveness of GUV and HVAC mitigation strategies across building types and climate zones; and quantification of electrification and decarbonization benefits of GUV relative to HVAC strategies. Abboushi shifted gears to describe another key PNNL activity, the CALiPER GUV Product Testing Program. The program conducts radiometric testing of commercially available products and publishes objective reviews of the testing results. CALiPER test reports validate product performance claims and are an effective tool in addressing inaccurate or inflated performance claims, calling attention to low performing products, and educating stakeholders on how products should be tested and evaluated. The first round of GUV product testing is underway with 13 different products; the summary report will be published later this year. A separate companion report will also be published to characterize the current state of product testing standards, methods, and test lab capabilities. Planning for three more rounds of CALiPER product testing is also underway. Abboushi closed by highlighting future plans for field evaluations and demonstrations. PNNL is working on design-to-application field evaluations/demonstrations where they are involved early in the design process through to installation to verify GUV performance. Additionally, PNNL is performing field surveys of existing GUV field installations to evaluate energy use, safety, material degradation, installation experience, occupant experience, O&M practices, and germicidal effectiveness.

Cameron Miller, National Institute of Standards and Technology: NIST Role in Germicidal Ultraviolet

Cameron Miller, the Optical Radiation Metrology Group Leader at NIST, considered the overall GUV economy and what infrastructure needs to be in place for this methodology to survive the commercial environment. He covered six steps and phases of development for GUV standards: 1) documentary standards to measure GUV device optical radiation distribution; 2) measurement and standards for minimum requirement to inactivate pathogen; 3) methods for assessment of environment factors in application; 4) documentary standards and guides on implementing the GUV devices in the application; 5) documentary standards or guides for the verification of correct implementation; 6) guides on required maintenance and validation of the implementation. Miller then gave examples of how NIST has implemented some of these steps. NIST began the process by bringing together the International Ultraviolet Association (IUVA) and the Illuminating Engineering Society (IES) to work collectively on five measurement documents for measuring different types of UV technologies (LPMV, LEDs, excimers), measurement of UVC systems, and the calibration of UV detectors and radiometers (Step 1). This allows for proper measurement of the UV devices. NIST then worked on a demonstration project to understand how much UVC dose is needed to achieve a log kill for SARS-CoV-2 (Step 2). NIST also carried out studies to understand the environmental factors – disinfection on surfaces, bio-films, or carrier materials – to put the safety guidelines into the application (Step 3). Finally, Miller described NIST's work on accreditation for laboratories to measure UV devices and perform measurement assurance programs for these laboratories to ensure they are capable of conducting these measurements accurately (Step 5).

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