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Lighting R&D Program:

LED Advanced Luminaires and Manufacturing R&D Meeting

October 2020

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DOE Lighting R&D Program, "LED Advanced Luminaires and Manufacturing R&D Meeting," October 2020.

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Comments

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Jake Steinbrecher	Dow Performance Silicones
John Trublowski	Eaton
Tom Veenstra	Innotec
Lincoln Xue	Oak Ridge National Laboratory
Jeremy Yon	GE Current, a Daintree company

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1 Introduction

On August 31, September 1 & 2, 2020, twenty-four subject matter experts on light emitting diode (LED) based lighting 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 for both advanced luminaire concepts and manufacturing development. 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 which may be incorporated into DOE's technical roadmaps.

This year, for the first time, the meeting was held virtually due to travel difficulties and concerns related to the ongoing COVID-19 pandemic. The meeting commenced with "soapbox" presentations where each participant was invited to give a short presentation describing what they believed to be the key technology challenges for SSL over the next three to five years. This was followed by a general discussion of the most critical technology challenges facing the industry today. Following these discussions, the participants were asked to contribute ideas regarding program content for the upcoming R&D Workshop to be held February 1-4, 2021.

The meeting format provided an opportunity for lighting experts across the research spectrum to exchange ideas and explore collaborative research concepts. Participants included invited experts in LED lighting-relevant science and technology disciplines drawn from academia, National Laboratories, and industry. They included DOE-Lighting R&D-funded researchers and non-DOE-funded researchers.

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 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 SSL technology; however, there were some recurring themes that arose during these discussions regarding research areas that could lead to significant breakthroughs in SSL performance. These themes are as follows and are outlined in more detail in Section 2:

- Lighting Application Efficiency
- Advanced Luminaires Architectures
- Germicidal UV Lighting
- Advanced Manufacturing
- Sustainability

2 Critical R&D Topic Areas

2.1 Lighting Application Efficiency

Lighting application efficiency (LAE) describes the amount of generated light that reaches the final recipient for the intended lighting application. A conceptual framework was proposed by the DOE Lighting R&D Program to better define the main criteria for LAE including the source efficiency, optical delivery efficiency, optimum emitted spectrum, and intensity effectiveness (i.e., right amount of light). [1] Developing more effective definitions and a more detailed framework for characterizing application efficiency and its various elements is required to better quantify application benefit and energy savings.

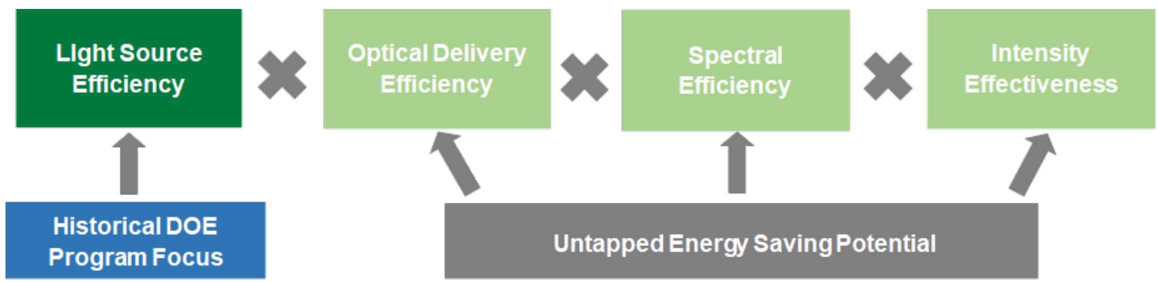

Figure 1. Proposed Lighting Application Efficiency (LAE) framework. Each of the four major efficiency elements are multiplied to provide the overall lighting application efficiency. [1]

Progress is required in several areas to complete the LAE concept and achieve "the right light when and where it is needed." Establishing the appropriate criteria and detail in the framework is necessary to ascertain and quantify all the critical factors of "ideal" lighting. Participants discussed how to better improve this LAE framework including adding the temporal aspect of light as a major building block. They also advised that more specific sub-level categories beyond the four main boxes in Figure 1 are needed to account for all the metrics of ideal lighting. In addition, participants expressed that existing lighting metrics do not provide a complete framework to develop the ideal lighting for both visual acuity and non-visual benefits. The development of an updated human visual sensitivity model and suitable metrics for visual effects such as perceived brightness would greatly aid the development of an accurate LAE framework. Developing metrics for non-visual impacts is an area that is heavily researched and a topic of another R&D Discussion Meeting on human physiological impacts of light.

Beyond the developing an LAE framework and metrics, further research is needed to determine the ideal light patterns and properties for occupants in the space in terms of visual comfort, visual performance, and non-visual physiological impacts. Each lighting application will have different requirements and a process should be developed to weigh and balance the various competing factors in the application. A more detailed LAE framework will help elucidate all these factors that must be balanced. Improving modeling tools and leveraging machine learning to better quantify data relating to the lighting conditions can provide critical information to inform the right balance of lighting parameters for the specific application. Modeling tools that can handle the complexity of the many considerations of lighting (spectral, distribution, intensity, and temporal) are not readily available; these tools require further development.

Lastly, participants discussed technology development areas to support dynamic, tunable lighting systems that can deliver the "right light" for the occupants in the space. A fully dynamic light source requires individually addressable LED arrays, high spatial and spectral resolution, and new form factors to integrate the smaller pixels in the form of mini or micro-LEDs. R&D in mini and micro-LEDs is essential to explore the size-efficiency tradeoffs and create efficient devices; smaller downconverters are also required to provide the right spectral content for lighting. New optics designs should provide a variety of beam angles and distributions from these miniaturized LEDs at high optical efficiency and good visual comfort. In addition, scalable optics fabrication and assembly methods should be further studied and implemented. Electronics for driving a large array of adaptive pixels must be developed by considering integrated drivers and backplane integration. Lastly, sensors and controls algorithms must support system level design and interaction with the space to allow for the right dynamic functions over time.

2.2 Advanced Luminaires Architectures

Participants discussed research and development paths for different aspects of luminaires including new source architectures, drivers/sensors/controls, and luminaire reliability.

Dynamic Flexible Light Sources

Future luminaire concepts should provide dynamic localized brightness, spectral tuning, and optical distributions that create the ideal light when and where you need it. Creating a dynamic light source will require a high density of individually addressable LED arrays; mini/micro-LEDs can provide the required resolution for the spatial control and spectral tuning. Additionally, the compact form factor source can offer the lighting of any surface from any angle with any illuminance and spectrum, which is ideal for lighting application efficiency. This can lead to a paradigm shift that allows lighting to be designed by its features instead of its fixture type or form factor. Supporting technologies that need to be developed include improving the mini/micro-LED efficiencies, reducing the size of down-converters, scalable optics designs than can provide a variety of optical distributions, integrated drivers, control algorithms, and sensing technologies (as highlighted in Section 2.1).

Power Supplies, Sensors, and Controls

The participants identified several challenges for LED power supplies including improving efficiency performance over a broad operating range (and covering multi-channel operation), reducing form factor size, and improving reliability. Integration of wide bandgap semiconductor components into the power supply can lead to architectures that have the potential to address several of these challenges. More compact, higher efficiency power supplies can be realized by using the high frequency available with wide bandgap components; coupling these devices with high frequency planar magnetics can lead to additional size reduction benefits. Increased integration of drivers at the LED board level can help reduce overall luminaire size and provide more installation flexibility, though this requires compact driver schemes and less heat generation to incorporate in higher power lighting systems. Additionally, innovative circuit topologies, such as a multiplexing based circuit topology, can address the performance of multi-channel drivers with the potential of providing higher efficiency at dimmed operation, no flicker (no pulse width modulation), lower component count, and lower power supply volume.

To achieve an intelligent dynamic lighting system, high performance sensing technologies are required to better understand the use of the space and occupant information. Participants suggested continued implementation of the new sensor technology that continues to become available from developments in other industries. Research into new real time location systems and autonomous control systems employing machine learning for context aware lighting controls is also advised

Reliability

Participants discussed reliability of luminaire systems including LED components, phosphors, drivers, and sensors. Materials such as silicones play a large role in color shift mechanisms of LED packages, consequently improvements in thermal and photon flux stability of encapsulant materials would help improve reliability across luminaire platforms. While the understanding of the mechanisms of chromaticity shift have improved over the past 5 years, better models are needed to predict future chromaticity shifts accurately. The reliability of down-converters needs to be improved by developing more robust down-converter materials in certain spectral regions and enhanced particle coating technologies; these gains would benefit the long-term performance of LED components. Furthermore, the reliability of system controls must be explored to understand the long-term accuracy and performance of sensors in complex lighting systems (e.g. tunable/adaptive luminaires). R&D is needed to develop accurate overall lighting system reliability models that take into account the various subsystems and components effects.

2.3 Germicidal UV Lighting

The COVID-19 pandemic has greatly renewed the interest in germicidal ultraviolet (GUV) lighting. Considering the potential jump in demand, this area represents a growing opportunity for energy savings. Participants spoke of the current challenges with GUV lighting and the benefit that solid-state UV-C sources could provide. The factors to weigh between UV light sources include size, lifetime, turn on time, emission wavelength, undesirable elements (e.g., mercury and ozone), energy consumption, and cost. Currently, UV-C LEDs are less efficient than low pressure mercury vapor and excimer sources but have potential to overcome current performance limitations and follow a performance improvement trajectory similar to visible LED devices. The past two decades of learning in GaN-based semiconductors for visible LEDs provides a firm materials foundation to leverage for future innovation. Beyond the light source, a better understanding of materials degradation issues under UV-C excitation is important to create a lighting system with long lifetime. Modeling software that can calculate the radiometric UV-C needs (such as absorption/reflection and fluence) can help aid efficient luminaire designs. One challenge will be to ascertain the energy load increase with the implementation of GUV fixtures and target improve lighting application efficiency in those fixtures.

2.4 Advanced Manufacturing

Advanced manufacturing approaches can help eliminate pain points in conventional product designs and can allow new approaches to managing supply chains over traditional manufacturing approaches. Participants discussed the benefits of additive manufacturing including fast, flexible, cost-effective prototyping and direct computer aided design (CAD) to fabrication without tooling or inventory. Additive manufacturing enables more product performance options through high configurability, unique designs, reduced parts counts (which lowers assembly complexity and cost), and easing of product lifecycle management (by allowing more changes as well as shorter cycles). There are multiple technical challenges to enable more production opportunities. These include developing faster additive manufacturing processes by increasing print speeds as well as creating systems with larger beds and multiple print heads to generate more parts per run, thereby reducing cost. It is essential to develop new printable materials with improved optical properties and UV resistance, polymer materials with higher thermal conductivities, and improved UV and infrared (IR) curing for electronic materials used to generate the circuit. Additionally, the developed materials must all be able to pass all safety ratings and standards. Another area requiring improvement is creating better "net shapes" so minimal post processing is required. Printing with better surface properties is critical, especially to prevent scattering centers in the optics or to prevent surface roughness on the heat sink from causing shorts in the printed electronic circuit.

Another area of advanced manufacturing involves high density LED assembly. The future use of high-density pixelated LED sources necessitates new methods to assemble large number of mini and micro-LEDs at speeds and cost levels that can be supported in the lighting industry. New approaches such as digital printers for self-assembly offer new promising paths to perform self-aligning mass transfer of chips (both LEDs and control electronics). The display industry is putting considerable resources into innovations for micro-LED mass transfer, which the lighting industry can leverage while also considering new approaches such as digital self-aligning chip printers.

2.5 Sustainability

Participants agreed that sustainability is an area that demands more attention by the lighting industry. More work is required to create eco-friendly designs with minimized component count, and use of low-embodied energy materials, recycled materials, or bioderived materials. Beyond the use of sustainable materials, it is important to eliminate unsafe chemicals from every component and for manufacturers to provide materials transparency through certification bodies (e.g., Living Building Challenge). Additionally, lighting products need to be designed for deconstruction to disassemble and recycle luminaire materials when the lighting is removed from the built environment. Currently, there is often no process through which luminaires that have reached the end of their useful lives are disposed in an environmentally responsible manner. Research is needed to jump start sustainable or natural supply chains (e.g., using materials like bamboo, flax seed or ocean plastics) and develop programs to recycle or reuse lighting at the end of construction (feed the circular economy). A goal would be to make every component of a lighting system recyclable, reusable and free of harmful chemicals. If a sustainable design rating was a competitive barrier, categories such as reduction in transport waste (mass x volume x distanced traveled), sustainable materials use (locally sourced, bioderived, or biodegradable), and efficient recycling (low labor disassembly) could be differentiators. Finally, participants encouraged DOE to consider adding sustainability requirements to funding opportunity announcements or to create R&D challenges to develop the highest lumen per watt per gram (at a specified quality threshold) lighting, or the best total lifecycle cost of lighting against a theoretically pure standard.

3 Suggestions for the DOE Lighting R&D Workshop

The 2021 Lighting R&D Workshop, which is to be held February 1-4, 2021, offers another opportunity to continue the discussion on critical R&D challenges. Another goal of this R&D meeting was therefore to gather input and suggestions for suitable topics and speakers, and ideas for panel discussions. Participants suggested the following topics:

1. Vision science
2. Modeling software development
3. Building design process and interaction with lighting designers
4. Germicidal UV lighting
5. Additive manufacturing
6. Sustainability and the circular economy

Appendix A: Participant Presentations

Kevin Houser, Oregon State University: Energy Reduction through Highly Structured Spectra

Kevin Houser, a Professor at Oregon State University, discussed the control of lighting by modifying the spectrum, spatial pattern, light level, and temporal pattern. He mentioned how the human spectral sensitivity is dependent on light level (Hunt effect). The Hunt effect is active at interior light levels and impacts how colors are perceived.; however, this does not show up in our colorimetric tools or color calculations which are based on normalized spectral data that does not factor in light level. Houser challenged how industry currently quantifies energy savings potential (using lumens per watt) since using the "lumen" is not the way to quantify the human benefits of lighting. He asserted we need to consider other metrics like brightness per watt, perceptions of color quality per watt, and visual performance per watt. He suggested two technology pathways forward: a dynamic multi-channel LED platform with embedded intelligence that overcomes the Hunt effect, or a static LED spectra with engineered notches designed to overcome the Hunt effect. The benefit of these approaches includes the potential for deeper dimming without deleterious effects on brightness perceptions or perceptions of color quality.

Wendy Luedtke, ETC: Lumen vs Reality, The LAE Opportunity

Wendy Luedtke, a Product Technology Specialist at ETC, considered the challenge of developing a new LAE framework, but cautioned DOE to avoid the use of flawed legacy metrics (lumen, luminous efficacy of radiation, color rendering index). She stated that an updated human visual sensitivity model, including a metric for perceived brightness, is a prerequisite for an accurate LAE model. Luedtke also advised that gaps in the spectrum do matter and while narrow bands can enhance the lumens per watt, they do not render well. She asserted the merits of long wavelength red light and its importance in good color rendering, especially with skin tones, challenging the common assertion that the long wavelength red is "wasted" light.

Wouter Soer, Lumileds: Dynamic Light Sources Based on Mini/Micro-LEDs

Wouter Soer, Director of Illumination Product Development at Lumileds, discussed the benefits and requirements of dynamic light source technology for general illumination to "provide the right light where and when it is needed". The "right light" requires adaptive spectrum and intensity, high resolution spatial and angular control to put the light "where it is needed," and the dynamic control of all light source parameters to provide this right light "when it is needed." A dynamic light source often contains individually addressable LED arrays with projection optics. The required resolution and form factor steer the need for smaller mini and/or micro-LEDs. Soer pointed out that the use of a full-function dynamic light source can lead to a paradigm shift in lighting. It can light any surface from any angle with any illuminance and spectrum, which is ideal for lighting application efficiency. It can also lead to potential cost reductions in building construction/renovation, installation and commissioning. He finished by highlighting the R&D required in mini and micro LEDs (efficiency-size tradeoffs, smaller downconverters), optics (design, scalable fabrication and assembly), electronics (integrated drivers, backplane integration), and system design (control algorithms, sensing technologies).

Wendy Davis, University of Sydney: Application Efficacy: Using Light More Efficiently

Wendy Davis, an Associate Professor at University of Sydney, discussed how lighting design practices were built around the limitations the conventional technology, but now with SSL, those limits are removed. She identified a continuum of approaches for energy savings from incremental changes with modest energy savings (e.g., occupancy-based controls, auto-dimming) to radical changes with potentially large savings (e.g., absorption-minimizing lighting, gaze-dependent lighting). Absorption-minimizing lighting is a new energy savings approach to tune the spectra to reduce the amount of light that gets absorbed by the surfaces in the room. Another potential approach is gaze dependent lighting where the lighting is adjusted to the gaze direction since the central vision region requires the high-resolution lighting relative to the peripheral vision. Davis urged the development of strategies for using the generated light more efficiently.

Bob Karlicek, Rensselaer Polytechnic Institute: Improving the Performance of Lighting Control Systems

Bob Karlicek, Professor and Director of the Center for Lighting Enabled Systems & Applications (LESA) at Rensselaer Polytechnic Institute, examined the use of occupant centric controls as a key to energy savings. New sensor technology for occupant centricity is becoming more readily available and can help control tunable luminaires. He also discussed spatially and spectrally tunable luminaires that can generate a wide range of optical distributions and colors and recommended to align design platforms with emerging LED display concepts. R&D needs for these spatially and spectrally tunable luminaires include developing cost-effective high-density chip arrays, new packaging technologies, low cost thermal management, and improved optical design. Karlicek finished by suggesting a taxonomy for autonomous lighting control defining different levels of controls from occupant instructed controls systems to fully adaptive, context aware lighting controls.

Meg Smith, Signify: Applications of LAE

Meg Smith, Product Marketeer at Signify, spoke about applying the LAE concept in an office installation using spectrally tuned luminaires as part of a DOE funded project. The project quantified the energy savings of the installation while improving glare, color quality, and lighting uniformity. She described a second example in applying this LAE concept to a logistics center installation to demonstrate feasibility of utilizing workstation specific lighting only in these workstation areas. The project resulted in 20% energy savings, as wells as reduced construction cost, reconfiguration, and maintenance. The lighting in the installation was also enhanced to target melanopic efficiency (non-visual photoreceptors) for the occupants. This installation achieved the recommended melanopic daylight equivalency ratio at 12% lower energy level than the reference installation. These two case studies showed the benefit of a lighting application specific lighting design and the benefits to energy savings and performance. The biggest challenge Smith noted was how to measure the value provided and describe it to the customers and occupants.

Sarah Safranek, Pacific Northwest National Laboratory: Improving Lighting Simulations for Application Efficiency

Sarah Safranek, Senior Associate Lighting Research Engineer at Pacific Northwest National Laboratory (PNNL), presented on simulation tools available for lighting design and the capabilities and deficiencies they have when considering a LAE framework. There are the traditional light modeling tools such as AGi32 and Radiance, as well as spectral modeling tools Lark and Alfa. These tools are based on different building blocks such as ray tracing, radiosity, or radiance lighting engines; the number of spectral channels vary from 1 to 81; some packages can integrate daylighting with the electric lighting. Safranek described a study by PNNL simulating the non-visual effects of light where they investigated the ability to meet existing recommendations for circadian metrics while ascertaining the energy implications. They found these targets are difficult to achieve and designing to recommendations requires greater illuminance levels, increasing energy use. She noted that dynamic lighting systems require software tools for increasingly complex simulations that include tunable and dynamic luminaires and variable daylight with time of day and time of year. Developing improved simulation tools will allow for data driven decisions. Safranek closed by reminding stakeholders that "it's still the early days!" The science, software, and recommendations are still progressing, and there is a need to establish a strong foundation for future design tools.

Tom Veenstra, Innotec: Total Lighting Efficiency: Think Outside of the Chip

Tom Veenstra, the Director of Product Development at Innotec, introduced his view on the LAE concept by asking how we can make the most use of every lumen. He contrasted what drove the lighting industry in the past – maximizing lumens per watt – to what should drive the lighting industry in the future – how many *effective* lumens are generated per watt of electrical power consumed. The efficient delivery and distribution of light for the specific application is important to drive the total lighting efficiency higher. For delivery, the ratio of how much light reaches the target compared to how much light was generated by the source is the critical metric, also termed the coefficient of utilization. To measure the distribution efficieny, it is critical to define the "ideal" light pattern on target and then normalize the acutal distribution to the ideal pattern. Future R&D

should be undertaken to learn and identify ideal light patterns for various spaces and functions. Veenstra further suggested the implementation of a common database to share ideal patterns. Increasing the industry language and communication around total solution performance will help drive continuous improvement. Finally, new manufacturing technologies that enable new ways to integrate lighting should continue to be used and developed.

Ron Gibbons, Virginia Tech: Balancing the Positive and Negative Impacts of Solid State Lighting

Ron Gibbons, Associate Professor and Director of the Virginia Tech Transportation Institute, discussed balancing the various factors of roadway lighting. There is a variety of dimensions to consider including roadway user safety, crash reduction, energy consumption, impact on user health, public perception and acceptance, impact on light pollution, and impact on surrounding flora and fauna. Gibbons explained how roadway lighting impacts much more than just a single group – it is not just drivers that are impacted, but people living close to the roadway (light trespass), skyglow, and flora and fauna. Each lighting valuation criteria can be weighted to provide guidance on how to approach the light source and light level selection in various applications. He discussed how the criteria needs to be weighted differently for the various roadway lighting applications, such as residential areas, urban arterials, interstates, and coastal areas. Guidance is needed on how best to balance the tradeoffs in various applications. Further R&D is needed to provide more understanding of the actinic curves and the overall dosage impacts. More work on the implications of balancing the various factors and a greater understanding of the interlinks between all these issues is essential.

Lynn Davis, RTI International: Considerations for SSL System Reliability

Lynn Davis, a Fellow in Engineering Research at RTI International, introduced several factors that impact SSL reliability. He discussed how the LED package and materials can affect lumen and color maintenance in the lighting system. Materials such as silicones play a large role in color shift mechanisms of LED packages, so improvements in thermal and photon flux stability of encapsulant materials would help reliability. Certain package form factors such as chip on board (COB) LEDs are less understood in terms of chromaticity shift behavior relative to the other package platforms. While the understanding of the mechanisms of chromaticity shift have increased, better models are needed to predict future chromaticity shifts based on LM-80 data. Davis also highlighted the development needs for narrow band down-converters. New phosphor materials and coating technologies that meet the performance of YAG:Ce phosphors at acceptable price points, along with the development of non-Cd based quantum dots for lighting applications, would be beneficial. Lastly, Davis touched on the reliability of system controls; more work is required to explore the long-term accuracy and performance of sensors in complex lighting systems (e.g., tunable/adaptive luminaires).

Marc Dyble, OSRAM Opto Semiconductors: Lighting Beyond Light – What Should We Expect from HCL in the Future?

Marc Dyble, Senior Product Marketing Manager at OSRAM Opto Semiconductors, presented the importance of the spatial distribution of the light in illumination scenarios. He highlighted a study that indicated the existing conventional illumination setups may have potential to improve melanopic active illumination. The incorporation of vertical illuminance on the walls and surroundings, rather than only focusing on the horizontal illuminance on the tables, can provide more melanopic targeted lighting to the user. Dyble also discussed new luminaire concepts based on small cluster of LEDs with multiple colors and white tones which may offer dynamic conditions for light with varying timing, uniformity, location and spectral composition. Developing a high density and addressable multi-LED cluster that can address an even more natural degree of dynamic lighting with vertical illumination would be beneficial.

Jake Steinbrecher, Dow Performance Silicones: Optimizing LED Luminaire Efficiency: The Use of Advanced Materials & Methods

Jake Steinbrecher, an Applications Engineer at Dow Performance Silicones, examined the role of silicones in luminaire performance and manufacturability. Silicone materials are integrated in several different places in a luminaire, from adhesives and sealants to thermal interface materials to electronics coatings and optics. Silicone adhesives and sealants can reduce the assembly complexity by reducing the use of fasteners and gaskets, while providing ingress protection. Integration of silicone in thermal interface materials that can also perform the function of a fastener or gasket makes the silicone material dual functioning and reduces component counts. Silicone coatings of electronic assemblies can reduce the sealing requirements in the overall luminaire. Moldable optical materials can be designed in new optics shapes to improve light output in the fixture and improve durability over time. It can also be multifunctional as an optic and a gasket. Steinbrecher proposed taking advantage of new manufacturing techniques available with silicones including differing materials options and cure systems that can enable new design opportunities. Advanced materials are more expensive, but they can add more features or improve manufacturability to increase the overall value proposition.

Ranjit Jayabalan, OSRAM Digital Lighting Systems: Lighting Components & Solutions Advancements

Ranjit Jayabalan, a Senior Engineer at OSRAM Digital Lighting Systems, touched on several luminaire research needs to improve performance. He discussed the challenges with drivers – which have especially high efficiencies of 90% or more at high input power levels, but drop in efficiency as the power levels drops. The efficiency needs to increase across the entire operating range for luminaires. Additionally, improved integration of drivers on board needs to be leveraged for more LED luminaire product categories. Currently, it is implemented with downlights, but improved integration is more of a challenge for higher power products like troffers. Better thermal dissipation on board is required, as well as assembly approaches to meet UL safety requirements. Jayabalan also discussed system reliability and the need to improve system lifetimes to 10 years to realize lower maintenance costs and reduce waste. R&D should be focused on developing improved system reliability models. Lastly, he argued the need for a simplified lighting ecosystem. Today's lighting ecosystem involves a lot of components, is expensive, and has maintenance challenges. Product designs should be simplified to allow for easy commissioning, maintenance, and replacement.

Lincoln Xue, Oak Ridge National Laboratory: Emerging Power Electronics Concepts and Technologies for LED Drivers

Lincoln Xue, an R&D Staff Member at Oak Ridge National Laboratory, discussed the challenges for LED drivers including multi-channel tunability, small form factors, and improved performance (efficiency and flicker) over a broad operating range and high reliability (long lifetimes). These result in design tradeoffs, unless one can leverage new technology approaches. Wide bandgap semiconductors power devices can lead to driver architectures that address these problems by leveraging the higher frequency and innovative circuit topologies. Other industries are driving the implementation of wide bandgap devices such as SiC devices for electric vehicles and GaN devices for phone chargers; this market pull is improving the availability and cost of wide bandgap devices overall. Smaller more compact drivers can be designed using the high frequency available with wide bandgap components and coupling that with high frequency planar magnetics. Planar magnetics will reduce labor costs (eliminate hand winding) and allow for a surface mount assembly process. Lastly, Xue suggested using a multiplexing based circuit topology to address the performance of multi-channel drivers. This has the potential of providing higher efficiency at dimmed operation, no flicker (no pulse width modulation) and lower component count and lower driver volume.

Robert Lee, Signify: Standardized Data Protocol for Lighting Control

Robert Lee, the Senior Director of Product Strategy & Marketing for Connected LED Electronics at Signify, asserted that standardized data protocol for lighting control is essential. With the number of products and vendors of networked lighting controls available today, there is a strong need for standardized intra-luminaire data protocol. A "common language" for connected lighting starts at the LED driver. Digital drivers helped unleash the full potential of a connected lighting system by providing actionable data with a bi-directional intra-luminaire data communication. Lee opined that the future of connected lighting is rooted in machine learning, augmented reality and all digital lighting infrastructure. He noted the research opportunities for LED drivers, which include improving cost-effectiveness, adding more options for indoor/outdoor applications, building compatibility with new sensor types, and increasing data analytics.

Mark Hand, Acuity Brands: UV Lighting, A Fad or the Future?

Mark Hand, the Vice President of Engineering at Acuity Brands, presented on the topic of UV lighting. He discussed how the COVID-19 pandemic has renewed the interest in germicidal UV lighting and the benefits of UV lighting for disinfection, as well as the burdens like safety. In addition, Hand compared the attributes of UV LED sources against conventional UV light sources; factors to consider include size, lifetime, energy consumption, turn on time, emission wavelength, undesirable elements (e.g., mercury and ozone), and cost. The primary applications for GUV lighting include healthcare, education, retail, and commercial office installations. Finally, he identified elements for development to better implement GUV safely and efficiently. UV SSL requires the properties already realized in visible light LEDs today – high efficiency, long lifetimes, and low cost. Hand recommended DOE to consider research in effectivity and safety of UV-C lighting and encourage the development of UV-C LEDs. He pondered if a Caliper Program for UV products can help bring order to the rapid influx of GUV products.

Doug Hamilton, Hubbell: SSL Opportunities

Doug Hamilton, the Vice President of Advanced Development at Hubbell, spoke about the various source solutions for germicidal UV-C lighting and compared their performance metrics for the application. He stated that usage of low pressure mercury vapor and excimers sources are taking a step backward in efficiency and environmental mindfulness. He recommended the following research efforts: the development of high efficiency UV-C solid-state sources, establishing a better understanding the UV-C material degradation issues for the luminaires, and development of software modeling to calculate radiometric UV-C needs (absorption/reflection, fluence, etc.). Hamilton also touched on R&D needs in visible lighting applications. Improved power conversion efficiency should be explored by integration of wide bandgap components into drivers, development of direct AC driving schemes, or a focus on DC building architectures. He advocated for adding more sensing capacity to luminaires and lighting systems and encouraged investigation into the concept of “sensor fusion” ecosystems.

Jeremy Yon, GE Current, a Daintree company: Luminaire-LED Supporting Needs

Jeremy Yon, the Industry Relations Leader at GE Current, a Daintree company, discussed two areas of development for LED luminaires. The first area Yon covered was investing in R&D to improve the efficiency of UV-C LEDs. With improved efficiency, solid-state emitters will be able to displace discharge emitters in more applications, particularly GUV. With GUV use expected to dramatically expand considering the COVID-19 pandemic, this area represents a large and growing opportunity for energy savings. The second area involves the technology to improve emitter and down-converter efficiency for use in horticultural lighting applications. Improvement of the efficiency of green emitters would help with plant productivity from horticultural lighting fixtures since green light can improves biomass accumulation and improve phytochemical profile and coloration. Additionally, Yon suggested R&D to evaluate the potential benefit of broader blue and red sources in horticultural lighting systems. Broader-spectrum (50-100 nm width) blue and red LEDs could provide different light transmittance to the leaf and penetration of plant canopy, thereby exciting chlorophyll at different leaf depths, reducing the risk of over excitation, and increasing plant productivity.

Eugene Chow, PARC: Microassembly Manufacturing for LED and Electronics

Eugene Chow, a Principal Scientist and Area Manager of the Microsystems Group at PARC, discussed challenges with manufacturing high chip count lighting systems such as displays and thin light sheets. He introduced a new platform for integrating chips via a high throughput, low cost digital printer assembly. The digital nature of the micro-assembly printer allows heterogeneous sorting of chips (LEDs, photocells, silicon chips), custom patterns, and rapid prototyping. More work is needed to increase the throughput and cost of this approach. Chow then finished by illustrating new lighting opportunities enabled by the thin, flexible form factor that micro-LED assembly allows. Customizable shapes and formats can be printed, aesthetic and functional can be intertwined, and emissive and reflective pixels can be mixed in this thin sheet format.

Marco de Visser, Luximprint: Additive Fabrication Technology for Custom Optics in Lighting

Marco de Visser, Co-founder and Director of Marketing & Sales at Luximprint, considered the value of additive manufacturing for optics. Additive manufacturing can help eliminate pain points in conventional product designs. The benefits an additive approach brings to the industry include fast, flexible and cost-effective prototyping; direct CAD to fabrication without tooling or inventory; enhanced flexibility to incorporate design variations or iterations; and the ability to do low volume production designs more economically. Additionally, an additive approach can help with the design process of optics for lighting by developing mockups for design performance validation and customer demonstrations. The technical challenges with additive manufacturing for optics includes maintaining sufficient surface quality, developing new plugins for optical modeling to enable the design software, and the development of new optical materials with spectral enhancements (coatings), more resistance to yellowing, aging, and high temperatures, and the ability to use multi-materials (e.g., optics with embedded nanoparticles). Key R&D areas include materials research into printable optical materials and software development for implementing designs to manufacturing.

Michael Bremser, Tempo: Additive Manufacturing for LED Lighting

Michael Bremser, President of Tempo, considered why additive manufacturing is beneficial for lighting products. Additive manufacturing enables more product performance options through high configurability, leads to unique designs, reduces parts counts (lower assembly complexity and cost), and eases product lifecycle management (more changes, shorter cycles). It requires a lifecycle cost perspective to balance the new costs associated with additive manufacturing (e.g., machine expenses, materials costs, post-processing equipment) with the cost savings that can be realized by eliminating tooling, inventory managements, product phase in/phase out issues, and end of life scrap inventory. A big benefit of additive manufacturing for lighting products is reducing the pain point with optics design and tooling. Providing more optics options quickly allows for adjustments to achieve specific engineered output to meet performance targets and energy codes. The additive manufacturing R&D challenges include improving material stability under UV and thermal exposure to meet UL compliance, allowing for co-additive processes to engineer properties (optical and thermal), and eliminating post printing processes.

John Trublowski, Eaton: Additively Manufactured Luminaire: R&D Challenges and Technology Gaps

John Trublowski, Senior Specialist for Engineering at Eaton, examined the key technology challenges to moving to an additive manufacturing approach for SSL luminaires. First is the cost associated with the current equipment and processes. Faster additive manufacturing processes are needed to address cost; this can be achieved by increasing print speeds and creating systems with larger beds and multiple print heads to generate more parts per run. The other big improvement must be creating better "net shapes," so minimal post processing is required. Printing with better surface properties is critical, especially to prevent scattering centers in the optics or to prevent surface roughness on the heat sink from causing shorts in the printed electronic circuit. Additionally, low cost, mass volume polishing methods for optical polymers or metals can be a mitigating approach. Trublowski also discussed the need for improved materials for additive manufacturing, printable materials with improved optical properties and UV resistance for the optics, polymer materials with higher thermal conductivities, and improved UV and infrared curing for electronic materials to generate the circuit.

Aaron Smith, Finelite: Lighting for Sustainability

Aaron Smith, Vice President of Technology and R&D at Finelite, spoke of lighting sustainability and the role of corporate social responsibility in creating eco-designs with minimized component count, and recycled materials selections. He encouraged the lighting industry to drive towards the circular economy. Smith encouraged manufacturers to design differently by using more sustainable materials (e.g., ocean plastics or a bamboo), and to deconstruct differently by creating intentional designs to disassemble and recycle luminaire parts and materials. He mentioned how Finelite is focused on eliminating unsafe chemicals from every component and providing materials transparency with a “Declare” label under the Living Building Challenge. Finally, Smith recommended the research needed to jump start sustainable supply chains: research programs to recycle or reuse lighting at the end of construction (feed the circular economy), develop natural supply chains like bamboo or flax seed for use in new lighting technologies, make lenses and other components out of ocean plastics, explore repurposing trash for large scale 3D printing, and make every component of a lighting system recyclable, reusable, and free of harmful chemicals. He also challenged the DOE Lighting R&D Program to consider adding sustainability requirements to all funding opportunity announcements.

Brad Koerner, Cima Network: Sustainability Drives Adoption

Brad Koerner, Vice President of Product Development and Marketing at Cima, asserted that the lighting industry should do better on the topic of sustainability. He asked, “What is holding us back?” It is not essential to wait for every component, luminaire, or supporting process to be sustainable to start on the path to sustainability. Moving forward is important. Koerner encouraged using a sustainable design rating as a competitive barrier. Three categories are reduction in transport waste (mass x volume x distanced traveled), sustainable materials and components (locally sourced, bioderived, biodegradable), and efficient recycling (low labor disassembly). He proposed an R&D challenge and encouraged DOE to consider two possible competitions. The first was a “Featherweight performance” challenge to develop the highest lumen per watt per gram (at a specified quality threshold), which would drive innovation in reducing materials consumption, fixture size and complexity. The second challenge proposed was the “Total Lifecycle Cost” challenge of a complete luminaire, which is measured against a theoretically pure standard. Koerner felt these challenges could spark creative innovation and problem solving in the sustainability domain.

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