Roundtable Discussions on Recommended R&D Tasks for Solid-State Lighting

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DISCLAIMER

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COMMENTS

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1. Introduction

The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Multi-Year Program Plan (MYPP) describes the current status of SSL technology, provides future projections for performance and price, and sets specific technology targets. It identifies the most critical SSL research and development (R&D) tasks to meet these projections and forms the basis by which the DOE SSL Program develops R&D funding solicitations. This plan is updated annually. As part of the annual update process, DOE invited a number of SSL experts to Washington, DC on the 8th and 9th of November 2012 for a set of roundtable meetings to discuss the current status of SSL technology, to advise DOE on future priorities, and to identify which R&D tasks are most likely to advance SSL performance and energy savings. In past years, further discussion at the DOE SSL R&D Workshop has helped narrow the list of R&D opportunities to a few priority tasks, most of which were subsequently the subject of a solicitation. In this year's deliberations, the emphasis has been on identifying a broader set of high-impact tasks recommended for attention by industry and academic research institutions, some of which may eventually be the subject of a DOE Funding Opportunity Announcement (FOA).

The roundtable meetings were conducted over two days. The first day was dedicated to the discussion of light-emitting diode (LED) based lighting, and the second day was dedicated to organic light-emitting diode (OLED) based lighting. Each roundtable began with a brief introduction and summary of the goals of the meetings. This was followed by short 'soapbox' presentations from each of the roundtable attendees, which allowed them to highlight what they believed to be the highest-impact areas for research (See Appendix A).

During the ensuing discussion, participants referred to the list of 63 core research and product development tasks from the 2012 MYPP to consider which should be emphasized in the near term to support the goals of the DOE SSL Program.[1] The participants highlighted a total of 16 tasks, ten LED tasks and six OLED tasks, and discussed the current status and targets of their associated metrics. The meetings concluded with a review of the overall Program milestones. Final conclusions on the most critical R&D tasks will be made after analyzing further stakeholder inputs from the R&D workshop.

In addition to the identification of important SSL R&D tasks, the roundtable attendees participated in a thorough discussion of the barriers and opportunities associated with the current state of SSL technology. Participants were also asked to assess the SSL Program milestones and comment on the organization and content of the MYPP report.

[1] The definitions of core research and product development and a complete list of R&D tasks are provided in Appendix C and D, respectively, of the 2012 SSL MYPP. This document is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf. In short, core is applied research advancing the communal understanding of a specific subject; and product development is research directed at a commercially viable SSL material, device or luminaire.

2. Annual Planning Process

The November roundtable meetings are the first step in the annual MYPP update process. DOE will host the 2013 Solid-State Lighting R&D Workshop on January 29th through the 31st in Long Beach, California. During this workshop, the discussion of R&D tasks and opportunities will continue, and feedback on the initial R&D tasks identified at the roundtables will be solicited. These inputs will aid in the development of the 2013 MYPP document. Any FOAs for fiscal year 2013 or 2014 will rely on the R&D opportunities identified in the MYPP to guide the focus of the solicitations.

3. Identification of Recommended Tasks

The original R&D task list was developed during a DOE program planning workshop in November 2003 and is regularly updated. The current task structure[2] includes 13 LED core tasks, 23 LED product development tasks, ten OLED core tasks, and 19 OLED product development tasks.

Roundtable participants reviewed the set of LED and OLED R&D tasks and identified high-impact areas of R&D for the industry to target in the short term. In their discussions, the LED roundtable participants identified four core technology research tasks and six product development tasks as the most critical R&D opportunities. Six of these tasks were identified as priorities in the 2012 MYPP, while one, A.8.1 Light Quality Research, is a newly-suggested core technology research task. The OLED roundtable participants recommended three core technology research tasks and three product development tasks for further R&D. Two of these tasks were identified as priorities in the 2012 MYPP. All 16 recommended R&D tasks are listed below in Table 3.1. These discussions of these recommended tasks are summarized in Sections 3.1 and 3.2 of this report for LED and OLED tasks, respectively.

Table 3.1 Recommended R&D Tasks

	Core Research	Product Development
LED	A.1.2 Emitter Materials Research A.1.3 Down Converters A.2.2 Novel Emitter Architectures A.8.1 Light Quality Research	B.1.1 Substrate Development B.3.6 Package Architecture B.6.3 System Reliability and Lifetime B.6.4 Novel LED Luminaire Systems B.7.3 Smart Controls B.7.4 Electronic Subsystems Research
OLED	C.1.2 Stable White Devices C.3.1 Fabrication Technology Research C.6.3 Light Extraction Approaches	D.2.1 Substrate Materials D.2.2 Low-Cost Electrodes D.6.3 Panel Light Extraction and Utilization

[2] The 2012 task structure can be found in Appendix D of the 2012 MYPP, available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf. In addition to these tasks, participants of this year's roundtable meetings suggested the introduction of an LED core technology research task on light quality research (A.8.1), shown above in Table 3.1.

After identification of R&D opportunities, roundtable participants reviewed the content of each identified R&D task. The first step was to verify that the description properly communicates the work to be performed. Participants then selected appropriate metrics that would best measure progress for the task, providing feedback on the current status and the 2020 target for each metric. Targets are intended to be challenging but achievable.

3.1. Recommended LED R&D Tasks

The following sections summarize the discussion points for each of the recommended LED R&D tasks. Substantive changes or additions to the task descriptions and metrics presented in the 2012 MYPP are denoted by red text. Likewise, deletions are represented by strikethrough red text. To be consistent among the tasks, the definitions for various colors and color temperatures in Table 3.2 below are used throughout Section 3.1. All LED device performance targets are referenced to a current density of 35 A/cm^2 and measurement temperature of 25°C (pulsed measurements).

Table 3.2 Emission Wavelengths and Color Definitions for Section 3.1

<table>
<tr><th colspan="2">Color</th><th>Wavelength or CCT Range</th><th>CRI</th></tr>
<tr><td colspan="2">Blue</td><td>440-460 nm</td><td>-</td></tr>
<tr><td colspan="2">Green</td><td>520-540 nm</td><td>-</td></tr>
<tr><td colspan="2">Amber</td><td>580-595 nm</td><td>-</td></tr>
<tr><td colspan="2">Red</td><td>610-620 nm</td><td>-</td></tr>
<tr><td rowspan="3">White</td><td>Warm</td><td>2580-3710 K
(ANSI 2700, 3000, 3500 K)</td><td>80-90</td></tr>
<tr><td>Neutral</td><td>3711-4745 K
(ANSI 4000, 4500 K)</td><td>70-80</td></tr>
<tr><td>Cool</td><td>4746-7040 K
(ANSI 5000, 5700, 6500 K)</td><td>70-80</td></tr>
</table>

3.1.1. LED Core Research Tasks

A.1.2 Emitter Materials Research		
Description: Identify fundamental physical mechanisms of efficiency droop for blue LEDs through experimentation using state-of-the-art epitaxial material and device structures in combination with theoretical analysis. Identify and demonstrate means to reduce current droop and thermal sensitivity for all colors through both experimental and theoretical work. Develop efficient red, green, or amber LEDs which allow for optimization of spectral efficiency with high color quality over a range of CCT and which also exhibit color and efficiency stability with respect to operating temperature.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
IQE @ 35 A/cm^2	80% (Blue) 38% (Green) 75% (Red) 13% (Amber)	90%
EQE @ 35 A/cm^2	~~64%~~ 75% (Blue) 30% (Green) 52% (Red) 10% (Amber)	81%
Power conversion efficiency[3] @ 35 A/cm^2	44% (Blue) 21% (Green) 33% (Red) 7% (Amber)	73%
Current droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	77%	100%
Thermal stability – Relative optical flux at 100°C vs. 25°C	~~95%~~ 90% (Blue) ~~95%~~ 85% (Green) 50% (Red) 25% (Amber)[4]	98% (Blue, Green) 75% (Red, Amber)

Roundtable Observations:

- Several roundtable participants noted that a comprehensive effort is needed to combat droop and thermal sensitivity to enable improved efficiency at higher drive currents. This would involve:

[3] Optical power out divided by electrical power in.
[4] This status is representative of direct emitters. Amber pc-LEDs can achieve thermal stability of up to 83%.

    - Maintaining internal and external quantum efficiency (IQE and EQE) at high current density and temperature;
    - Developing phosphor matrix materials with high thermal conductivity of >1 W/(m·K);
    - Improving solder materials to enable high operating temperature packages; and
    - Gaining a better understanding of reliability physics at high current density.
- Potential efficiency improvements of 20% could be realized by driving LEDs harder and solving related thermal challenges.
- It was suggested that the LED industry can benefit from gaining greater control over the emission spectrum.

A.1.3 Down Converters		
Description: Explore new high-efficiency wavelength conversion materials for ~~improved quantum yield and down conversion efficiency for~~ the purposes of creating warm-white LEDs, with a particular emphasis on improving spectral efficiency with high color quality and improved thermal stability. Non-rare earth metal (REM) and non-toxic down converters are encouraged.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Quantum yield (25°C) across the visible spectrum	90%	95%
Thermal stability – Relative quantum yield at 150°C vs. 25°C	90%	95%
Average conversion efficiency[5] (pc-LED)	66%	69%
Spectral full width half maximum (FWHM)	~~150~~ 100 nm (Red)	<30 nm for all colors
Color shift over time (pc-LED)	~~Δ u'v'<0.012 over life~~ Δ u'v'<0.007 @ 6,000 hrs	Δ u'v'<0.002 over life
Spectral efficiency relative to a maximum LER ~345 lm/W	90%	100%
Flux density saturation – Relative QY at 1 W/mm^2 (optical flux) vs. peak QY		

Roundtable Observations:

- It was proposed that metrics for lumen maintenance (L_{70}) and quantum yield (QY) over time be added to this task.
- Further development of narrowband down converters across the visible spectrum could lead to greater improvements in spectral control.
- Several participants emphasized the development of robust narrowband red phosphors to improve efficacy at higher CRIs.
    - The development of new, non-quantum dot (QD) materials may also be necessary to achieve stable, narrow-line phosphors in colors other than red. This would require core research and an understanding of phosphor reliability (specifically, the relationships between defects, processing, and performance).

[5] Refers to the efficiency with which phosphors create white light using an LED pump. The phosphor efficiency includes quantum efficiency and the Stokes loss of the phosphor.

    - QDs are one possible method for achieving red-line emission; however, more core research is needed to overcome the potential issues with stability, costs, and scaling up.
- QD down-conversion materials were also discussed as a method of improving extraction efficiency by eliminating scattering in phosphor down-conversion systems.
    - Prior funding has reduced scattering in phosphor down-conversion systems, but has not eliminated it.
    - Gains of 10% or higher (at high conversion) could be possible from the elimination of scattering alone.
    - However, using nano-phosphors to decrease scattering raises issues of reliability and thermal quenching, which will require further R&D.

A.2.2 Novel Emitter Architectures		
Description: Devise novel emitter geometries and mechanisms that show a clear pathway to efficiency improvement; demonstrate a pathway to ~~increased~~ added chip-level functionality offering luminaire or system efficiency improvements over existing approaches; explore novel architectures for improved efficiency, color stability, and emission directionality including combined LED/converter structures. (Possible examples: nano-rod LEDs, lasers, micro-cavity LEDs, photonic crystals, luminaire-on-a-chip.)		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
EQE[6] @ 35 A/cm^2	~~64%~~ 75% (Blue) 30% (Green) 52% (Red) 10% (Amber)	81%

Roundtable Observations:

- The incorporation of micro-electromechanical technology at the package level might lead to novel microsystem luminaires with active light steering
- Chromaticity tunability might be achieved on a single chip via the application of electric fields to QDs.
- Nanowires could be used to achieve good electroluminescent efficiency in the green-yellow-red spectral region and could enable integrated functionality with 3D architectures.

[6] Metrics reference task A.1.2.

A.8.1 Light Quality Research		
Description: Develop improved metrics for brightness perception, color discrimination, and color preference. Employ human factors visual response or vision science studies to evaluate the impact of various spectral power distributions on the above, including line-based vs. broadband sources, violet- vs. blue-based pc-white LEDs, etc.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Additional or improved color metric	Current color metrics (CRI, CQS[7], CCT, CMF[8]) inadequately describe the color of light	Development of new metrics that accurately specify color preference and color fidelity and describe improvements in energy savings, health, and productivity

Roundtable Observations:

- This new task was proposed to address the need for a greater understanding of color science and its impact on LED product adoption. Expanding the knowledge base on this topic could help the LED industry better understand human perception of color and improve light quality.
- Some participants argued that light quality is critical to SSL adoption and that lack of research in this area may have hampered market penetration because retail operators care principally about revenue creation and customer experience. Others argued that the relative importance of light quality is very application-specific.
- Studies could be carried out to better understand how human perception of white light deviates from the white light described by the black body locus, and how this influences human color and quality preferences. There is general dissatisfaction with existing light quality metrics and photometric tools. Metrics (for brightness perception, color discrimination, and color preference, among others) could be created and mentioned in the 'barriers to adoption' section of the MYPP. The development of such metrics would require human factor studies, which raised the following concerns:
    - Human factor studies are expensive, time consuming, and very application-focused;
    - Due to high cost, this may be an appropriate role for DOE; and
    - Incumbent lighting manufacturers are unlikely to support research in this area if their products perform less favorably under new light quality metrics.

[7] Color Quality Scale
[8] Color Matching Function

3.1.2. LED Product Development Tasks

B.1.1 Substrate Development		
Description: Develop alternative substrate solutions that are compatible with the demonstration of low-cost, high-efficacy LED packages. Suitable substrate solutions might include native GaN, GaN-on-Si, GaN templates, etc. Demonstrate state-of-the-art LEDs on these substrates and establish a pathway to target performance and cost.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Price of LED package @ state-of-the-art efficacy[9]	~~$10/klm~~ $5-6/klm (cool) ~~$15/klm~~ 10/klm (warm)	$0.70/klm
Though the following metrics are examples for a GaN substrate, this task is not meant to be exclusive to GaN substrates		
GaN substrate price	>$2,000 (~~25-~~50 mm)	<$500 (>200 mm)
Current droop – Relative EQE at $100 A/cm^2$ vs. $35 A/cm^2$	77%	100%
Thermal stability – Relative optical flux at 100ºC vs. 25ºC	~~85% (Blue, Green)~~ 90% (Blue) 85% (Green)	~~95%~~ 98% (Blue, Green) 75% (Red, Amber)
GaN transparency (absorption coefficient)	$2\text{-}10\ cm^{-1}$	$<0.5\ cm^{-1}$

Roundtable Observations:

- It was agreed that the 2020 price targets should not be made more aggressive. The existing targets are reasonable, but to achieve them will require a large-scale manufacturing effort.
- Some participants advocated the use of GaN substrates, stating that they simplify overall operation of device development and performance; however, it is hard to develop native substrates due to cost, scalability, and growth challenges.
  - The 2020 target for GaN substrate price of <$500 (>200 mm) will require a huge effort to reach and is a huge opportunity for future investment. Reducing substrate cost is one of the most important areas of material cost reduction.
  - Significant advances are needed to achieve cost-effective GaN wafers with diameters of 4 inches and above.
- Particular emphasis was placed on the need to address defect and thread dislocation issues on GaN substrates in order to reduce droop. Bulk GaN and nano-patterning were discussed as areas of potential research for reducing droop through defect reduction.

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[9] Efficacy projections and targets can be found in Table 5.5 of the 2012 MYPP, available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf

B.3.6 Package Architecture		
Description: Develop novel LED package and module architectures that can be readily integrated into luminaires. Architectures should address some of the following issues: thermal management, cost, color, optical distribution, electrical integration, sensing, reliability, and ease of integration into the luminaire or replacement lamp while maintaining state-of-the-art ~~package~~ efficiency. The novel packages could employ novel phosphor conversion approaches, RGB+ architectures, system-in-package, hybrid color, chip-on-heat-sink, or other approaches to address these issues.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Color shift over time	~~Δ u'v'<0.003 @ 6,000 hrs~~ Δ u'v'<0.007 @ 6,000 hrs	Δ u'v'<0.002 over life
Price of LED package @ state-of-the-art efficacy[9]	~~$10/klm~~ $5-6/klm (cool) ~~$15/klm~~ 10/klm (warm)	$0.70/klm
Luminaire efficiency	~~68 lm/W~~ 88 lm/W (warm)	184 lm/W
Luminaire price		

Roundtable Observations:

- Several soapbox presentations mentioned system-level integration as an opportunity area for performance improvement (lm/W) and price reduction (lm/$). Participants expressed the need for collaboration regarding the optimum integration level (e.g., system/luminaire or chip) and which essential functions and/or additional features should be integrated. The scope of this task includes integration at the LED package and module level.
    - For example, control systems could be addressed on a lower level, enabling integrated sensors and drivers that could stabilize color point over lifetime.
    - System integration could enable color-mixed light engines that achieve higher system efficiency, similar to the hybrid LED packages currently on the market. Long term, fully color-mixed RGBA light engines could be developed.
    - Complete integration of all systems within a single package (i.e., integrated LEDs, driver, sensors, and controls) may be possible.
- Smart partitioning, or modularity, also garnered support due to the belief that complex architectures were a hindrance to product adoption and introduced reliability issues. Among the benefits of smart partitioning are: faster development cycles, lower development costs, higher performance, better system interoperability and flexibility, standardization, simpler value chain, lower bill of materials cost, and higher production volumes.

B.6.3 System Reliability and Lifetime		
Description: Collection and analysis of system reliability data for SSL luminaires and components to determine failure mechanisms and improve luminaire reliability and lifetime (including color stability). Develop and validate accelerated test methods taking into consideration component interactions. Develop an openly-available and widely-usable software tool to model SSL reliability and lifetime verified by experimental data and a reliability database for components, materials and subsystems. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Mean time to failure (either catastrophic, L_{70}, color shift, loss of controls)	~~Device~~ LED package lumen depreciation data	Tool to predict luminaire lifetime within 10% accuracy

Roundtable Observations:

- A recurring theme at the roundtable was the need for system reliability models and metrics and more efficient ways to determine lifetime.
- Many participants supported the development of luminaire reliability models and metrics.
    - Reliability challenges arise from design-induced variability and manufacturing variability. These two sources must be better controlled (e.g., via design margins standardization) in order to improve system reliability.
    - Component stress testing is standard practice for the industry, but this approach neglects non-catastrophic system/luminaire failure mechanisms such as environmental effects (e.g., moisture integration and thermal management) on lumen depreciation and color shift.
    - A better understanding of the physics of luminaire failure is also needed. The industry's current knowledge of reliability is limited to lumen depreciation at the LED package level, which is estimated by IES LM-80-2008 (LM-80) and IES TM-21-2011 (TM-21).
    - New reliability test methods should be broadly applicable to product families, while providing clear extrapolation limits, in order to reduce testing burden on manufacturers.
- Adoption of more efficient lifetime test methodologies is another concern for the industry. Reliable lifetime tests do not exist. Long lumen-depreciation tests are burdensome to manufacturers and are inconsistent with product development cycles.
    - LM-80 and TM-21 lumen depreciation testing only pertains to LED packages. Estimation methods for lumen depreciation and light color and quality levels at the luminaire level are still needed.

B.6.4 Novel LED Luminaire Systems		
Description: Develop ~~truly~~ novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs to save energy and represent a pathway toward greater market adoption. An important element of this task could be the integration of energy-saving controls/sensors to enable utilization of the unique LED properties, as described in B.7.3 Smart Controls. ~~Luminaire designs should be consistent with the use of materials and production methods that minimize any negative environmental impact. Key attributes will include low weight, compact size, directionality, and/or durability.~~		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
System energy consumption		
Controls		

Roundtable Observations:

- It was suggested that greater emphasis be placed on the development of novel form factors in order to add functionality and capitalize on the ability of LEDs to add value beyond efficient lighting. Constraints on novelty (e.g., prescriptive attributes like low weight and compact size, as well as the use of current materials and production methods) were removed from the description.
    - One participant emphasized the possibility of dynamic spectral control in order to provide the desired light chromaticity on demand (e.g., mimicking the sun's illumination characteristics from any location or time of day).
- Efficacy and energy savings should not be degraded at the expense of novelty.

B.7.3 Smart Controls		
Description: Develop integrated lighting controls into the luminaire that save energy over the life of the luminaire. May include methods to ~~maximize dimmer~~ optimize luminaire dimming performance and efficiency as well as spectral tuning. May include sensing occupancy or daylight, or include communications to minimize energy use.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**

Roundtable Observations:

- Several participants supported the integration of intelligent controls into LED products as a means to save energy. Some believed that intelligent systems will drive adoption via reduced operating costs.
    - However, one participant noted that existing dimming controls sacrifice efficacy, power factor, and THD at reduced illumination levels and stressed that improved dimming performance may offer a means to save energy.
- Further incremental improvements in performance and price will be market-driven. Therefore, DOE should direct funding towards innovations that promise significant step improvements, such as innovative sensing and control technologies or innovative balance-of-system technologies.

B.7.4 Electronic ~~Component~~ Subsystems Research		
Description: Develop compact, long-life LED driver electronics and power converters that efficiently convert line power to acceptable input power of the LED source(s) while maintaining an acceptable power factor; encourage standardization in the long term.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**

Roundtable Observations:

- Many participants noted the need for standardized test methods for drivers and other electronics.
- Drivers and their effect on overall system efficiency are a growing concern. Drivers are becoming one of the greatest percentage losses within the system, and improvements represent low-hanging fruit for overall efficiency gains.
  - Currently, efficiency is around 85% for Class 2 drivers. Research is needed in order to reduce driver losses and achieve efficiencies of 90% or greater for all drivers.
  - Research is also required on advanced driver designs that better suit the characteristics of LEDs, such as maintaining efficiency while dimming smoothly over a wide range.
- Research for better thermal management technologies is needed to develop more robust drivers and luminaires with smaller footprints without sacrificing reliability.

3.2. Recommended OLED R&D Tasks

The following sections summarize the discussion points for each of the recommended OLED R&D tasks. Substantive changes or additions to the task descriptions and metrics presented in the 2012 MYPP are denoted by red text. Likewise, deletions are represented by strikethrough red text.

3.2.1. OLED Core Research Tasks

C.1.2 Stable White Devices		
Description: Develop novel materials and structures that can help create a highly-efficient, stable white device. The device should have good color, long lifetime, and high efficiency, even at high brightness. Color shift over time should be minimal. The approach may include the development of highly-efficient blue emitter materials and hosts or may comprise a device architecture leading to longer lifetime. Any proposed solutions should keep cost, complexity, and feasibility of scale-up in mind. Materials/structures should be demonstrated in OLED devices which are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate a significant improvement in stability, while maintaining or improving other metrics.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Lumen maintenance (L_{70}) from 10,000 lm/m^2	10,000 hrs	>50,000 hrs
Voltage rise		<15%
Color shift over time	Δ u'v'<0.004	Δ u'v'<0.002
EQE without external extraction enhancement	~22%	25-30%
Voltage @ 2 mA/cm^2	~3.4V	<3V
CRI	84	>90

Roundtable Observations:

- One of the greatest challenges in creating efficient, stable white OLED devices is the operating stability of blue phosphorescent emitters. The development of stable blue emitters could yield significant improvements in the luminous efficacy of phosphorescent white OLEDs.
- However, several arguments were made that lifetime and light intensity issues surrounding high-efficacy blue emitters will be solved by the display industry and that extraction efficiency is a more important focus for the lighting industry. It was generally agreed that this

is an important research task, but progress in this research area would be minimally impacted by DOE funding.

- There has been progress in blue emitter operating stability, but more academic research is needed. Specific areas or objectives include:
  - Gaining a fundamental understanding of intrinsic degradation processes that lead to poor stability in blue emitters;
  - Better understanding of the relationship between temperature and luminescent life and how this affects overall stability; and
  - The relationship between device architecture, material selection, bond breaking, and overall stability/efficiency.
    - Bond breaking is a significant issue with blue emitter non-radiative deactivation and directly affects thermal stability and luminescent efficiency.
- An appropriate role for DOE might be to facilitate cooperation between academia and industry to address the issues regarding stable blue phosphorescent materials that concern both parties.
- For OLEDs to compete in the color-sensitive lighting market, color quality should be an R&D focus with additional metrics beyond CRI.
  - Currently, OLED CRIs vary between 70 and 90.
  - However, higher CRIs can only be reached by compromising efficacy. A CRI of 85 is achievable, but a CRI >90 target will result in lower efficacy.

C.3.1 Fabrication Technology Research		
Description: Develop new practical techniques for materials deposition, device fabrication, or encapsulation of OLED panels with performance consistent with the Manufacturing Roadmap. ~~Should show potential for scalability and low cost.~~ Methods should use technologies showing the potential for scalability and reduced cost (for example, by enabling significant advances in yield, quality control, substrate size, process time, and materials usage).		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Relative material and ~~processing cost~~ total cost of ownership (TCO) reduction potential	1 relative cost	1/10 cost
Material utilization	5-50%	>70%
Thickness uniformity	5% variation over small areas	<5% variation over 200 cm^2
Yield of good panels		>90%

Roundtable Observations:

- This task was supported as an R&D opportunity because OLED cost reduction is paramount to increasing market competitiveness. Materials and equipment costs represent a large share of total panel cost.
- Techniques that significantly change the cost structure need to be developed. Manufacturing methods unique to OLEDs should be targeted, such as:
  - Roll-to-roll (R2R) coating;
  - Development of electroluminescent polymers; and
  - Deposition equipment that increases material utilization of the evaporated emitter materials.
- Focusing efforts on materials and processes that allow for long-term encapsulation is important for OLEDs to achieve reliable lifetimes for lighting applications.
  - Encapsulation techniques should retain the flexibility and transparency of OLEDs that appeal to customers.
  - Participants noted that thus far cost-effective thin-film encapsulation has been very resistant to a solution.
  - Any encapsulation solution should be scalable and low cost, even at low volumes.
  - The development of mass production-level, low-cost encapsulation processes is an area of research that the display industry is driving.
  - The industry uses borosilicate glass to encapsulate, which is too costly. Glass encapsulation techniques are used for smaller panel sizes (e.g., frit sealing of borosilicate glass, demonstrated in 40 cm^2 tiles). However, scaling to larger panel sizes could cause potential weight and cost issues.

- There was discussion over whether a single-layer encapsulation can yield performance comparable to that of multi-layer barrier structures and the tradeoff between performance and cost in the simpler device architecture.
- Further development of high-speed vacuum deposition was promoted as this fabrication process creates the highest-performing OLEDs, especially when tandem stacked.
- A potential role for DOE could be supporting companies that cannot afford to investigate paradigm-changing activities, like ultra-high speed vapor deposition.
- Currently, no commercial products use solely solution processing. Solution processing of flexible substrates would be a game-changing technology development. However, solution-processed OLEDs still face reliability, efficacy, and lifetime concerns.
- Any processing method solution should be high-throughput and low-cost without degrading the material.

C.6.3 Light Extraction Approaches		
Description: Devise new optical and device designs for improving OLED light extraction while retaining the thin profile and state-of-the-art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, or external to the device. Applicants should consider how their approach affects the energy loss due to waveguided and plasmon modes and should include modeling or quantitative analysis that supports the proposed method. The approach should provide potential for low cost and should be demonstrated in a device of at least 1 cm^2 in size to demonstrate applicability and scalability to large-area (panel size) devices.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Extraction efficiency	40% (laboratory, small area)	70%
Angular dependence of color		2 step MacAdam ellipse

Roundtable Observations:

- Light extraction remains one of the largest obstacles to realizing OLED performance targets, and improvement in this area would be the most cost-effective performance enhancement available to OLEDs.
- Only 20-40% of light is extracted (with a standard ITO on glass) due to internal reflection and index mismatching.
- Extraction enhancement structures have increased the efficiency of white OLED panels by up to 1.7x. Attendees suggested a 2x improvement in light extraction from OLED panels should be a near-term target, while a 3x improvement should be a long-term goal.
    - To achieve the suggested 3x improvement target, a combination of internal and external light extraction techniques and attention to surface plasmon losses are needed.
- The use of high-index glass is another possible solution to light extraction losses.
    - However, high-index glass is currently too costly to make this option viable for large-production applications (although it could be applicable for niche applications). Achieving substantial reductions in the production cost of high-index glass would require a very large investment that could not be justified solely by the anticipated demand for OLED lighting.
- If light extraction efficiency can be improved, reduced current density would increase lifetime.

3.2.2. OLED Product Development Tasks

D.2.1 Substrate Materials

The existing task, as presented in the 2012 MYPP, does not accurately represent the discussion at the roundtable as reported below. Some roundtable participants felt that the most productive approach would be to offer a new integrated substrate task. While this change is not reflected in the current document, it is marked for discussion at the upcoming R&D Workshop and may be subject to modification in the 2013 MYPP report.

Roundtable Observations:

- Advancements in lower-cost materials were a recurring theme, and substrates were noted as a particular area of focus. Several participants stressed the need for improved lower-cost substrate materials.
- The use of soda-lime float glass as an inexpensive alternative to standard borosilicate display-grade glass was discussed as an attractive option, which would allow for a rapid reduction in cost without major changes in OLED processing or substrate characteristics.
  - While OLEDs have been demonstrated on residential float glass, further developments are needed before float glass can be incorporated into panel manufacturing lines. In particular, the defect levels on float glass substrates must be reduced to retain the performance and yield achievable with borosilicate glass.
  - The DOE substrate cost targets are difficult to meet given current float glass defect levels, and participants suggested that this issue should be discussed in the MYPP as a barrier to adoption.
- It is critical that the substrate is compatible with light extraction layers and electrode materials employed.
- Due to compatibility concerns, the idea of expanding the substrate materials task to an integrated substrate task (including substrate, low-cost electrode, and light extraction layers) was discussed, but a conclusion was not reached.
  - Some participants advocated the use of polymeric substrates to reduce weight and thickness and increase flexibility, though the group did not conclude that research into flexible substrates was a critical research task,
    - The use of flexible substrates could allow for luminaire designs that capitalize on the unique form factor of OLEDs.
    - If the emissive material is also a polymer, fewer index-mismatching interfaces would be present, thereby improving light extraction efficiency and potentially raising EQE to 50-70%.
    - One participant noted that semi-transparent single-sheet polymer substrates can be produced on 1 cm^2 squares and has the potential for roll-to-roll coating for larger areas.
- High-index glass is another substrate option. While high-index glass could meet performance targets (and improve light extraction), the volume required cannot be met in a cost-effective manner.

D.2.2 Low-Cost Electrodes		
Description: Demonstrate a high-efficiency OLED panel employing a cost-effective, transparent electrode technology on low-cost glass that is ~~low-cost,~~ low-voltage and stable, with the potential for large-scale manufacturing. The electrode surface should be smooth enough to prevent shorting. Design could include a conducting grid or segmented structures.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Cost reduction potential	$20/m^2$	$5/m^2$
Absorption over the visible spectrum	<1% absorption	Maintain
Current uniformity		<5% variation over a 200 cm^2 panel
Voltage @ 2 mA/cm^2	~3.8V	<3V
Peak-to-peak roughness	20 nm	10 nm

Roundtable Observations:

- Developing low-cost, transparent electrodes was discussed in several soapbox presentations and identified as an important R&D task. One of the key issues mentioned was panel luminance uniformity issues caused by high sheet resistivity.
- The light-emitting area of panels has been limited because sheet resistance increases as panel size increases unless a conductive grid or other current-spreading technique is employed.
    - Specifically, typical ITO resistances are >5 Ω/square, but sheet resistance must be reduced to 1 Ω/square in order to improve power efficiency and luminous uniformity of large-area OLED panels.
    - Printing metal grids was proposed as a solution. However, printing materials and processes still need development. Specific areas for development include:
        - New metal ink materials and printing processes are needed to achieve low sheet resistance (1 Ω/square) and high optical transparency (at least >80%). Low grid thickness helps avoid planarization issues and decreases the cost of materials and processes.
        - R&D is needed to solve potential silver migration issues.
        - A new annealing process is needed to improve conductivity.
- It was pointed out that the low-cost electrode must be compatible with any internal extraction technology to be employed.

D.6.3 Panel Light Extraction and Utilization		
Description: Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels while providing some control over the angular beam distribution of the intensity of the emitted light in order to maximize the useful light for specific applications. The approach should retain the thin profile and state-of-the-art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and/or external to the device. The approach should be demonstrated over large areas (>25cm^2) and must be amenable to low-cost manufacture.		
Metric(s)	**2012 Status(es)**	**2020 Target(s)**
Extraction efficiency	40%	70%
Incremental cost		<$10/m^2
Angular dependence of color		2 step MacAdam ellipse

Roundtable Observations:

- Modifications to this task emphasize the importance of effectively utilizing the light that is extracted from the device (e.g., by shaping and directing the light output for certain applications), which could increase application efficiency.
- Effective light utilization improves the effective luminance, and therefore the effective efficiency, of the light source. This would reduce operating costs and immediately boost OLED cost-competitiveness with incumbent technologies.
- Any efficient light extraction solution must be low-cost at the outset, even at low production volumes.
- Total light extraction efficiency of OLED lighting panels can be further enhanced by 2.7x by applying an internal extraction scattering layer between transparent electrodes and glass substrate to create light passage through entire stack.

4. Milestones Discussion

The final activity at the roundtable meetings was to review the LED and OLED program milestones as reported in Chapter 5 of the 2012 MYPP. Milestones for LEDs and OLEDs extend to 2020 and 2018, respectively. The following tables summarize the updates suggested at the roundtables. The performance targets assume adequate funding for the SSL Program.

4.1. LED Milestones

Milestone	Year	Target
Milestone 1	FY10	LED Package: >140 lm/W (cool white); >90 lm/W (warm white); <$13/klm (cool white)
Milestone 2	FY12	Luminaire: 100 lm/W; ~1,000 lm; 3500 K; 80 CRI; 50,000 hrs
Milestone 3	FY15	LED Package: ~$2/klm (cool white); ~$2.2/klm (warm white)
Milestone 4	FY17	Luminaire: >3500 lm (neutral white); <$100; >150 lm/W
Milestone 5	FY20	Luminaire: 200 lm/W

Assumption: packaged devices measured at 35 A/cm^2.

Roundtable Observations:

- Luminaire efficacy in Milestone 2 was surpassed in 2012 by a product reaching 110 lm/W.
- The group suggested that the cost differential ($/klm) between cool-white and warm-white LED packages in Milestone 3 should be larger than $0.2/klm.
- With respect to milestone targets in general, the group advised that lifetime metric targets should not be set as there is currently no method of establishing LED lifetime ratings.

4.2. OLED Milestones

Milestone	Year	Target
Milestone 1	FY08	Pixel: >25 lm/W, <$100/klm; 5,000 hrs
Milestone 2	FY10	Panel: >60 lm/W
Milestone 3	FY12	Laboratory panel: 200 lm/panel; >70-80 lm/W; L_{70} >10,000-20,000 hrs
Milestone 4	FY15	Panel: <$25/klm (cost); >100 lm/W @ 10,000 lm/m^2
Milestone 5	FY18	Panel: 50,000 hour lifetime; >10,000 lm/m^2

Assumptions: CRI > 85, CCT < 2580-3710 K for an OLED panel >200 cm^2. All milestones apply to commercially-available products unless otherwise noted and assume continuing progress in the other overarching parameters (lifetime and cost).

Roundtable Observations:

- One researcher reported that the targets of Milestone 3 have been achieved on a 6 x 6 inch laboratory panel at 3000 cd/m^2 and 75 lm/W.
- The Milestone 4 cost target ($/klm) is a reasonable goal to set for manufacturing cost.
- Participants suggested the addition of an aggressive cost target to Milestone 5.
    - One such suggestion was ≤$10/klm.
    - However, there is no basis on which to set these future cost targets because OLED luminaires are not currently in high-volume production.
- Others proposed adding a target efficacy improvement of 2.5x to Milestone 5.
- Participants agreed that the Milestone 5 target lifetime is achievable.
- There was discussion as to which metric should be stressed the most from 2015 to 2018 in order to separate OLEDs from the competition: cost or efficacy?

Appendix A Participant Presentations

Participants were given the opportunity to prepare short "soapbox" presentations outlining what R&D activities they believed are particularly important to achieve the ultimate aims of the SSL Program. The presentations were limited to 10 minutes and were followed by an open floor for questions. Summaries of these presentations are given below.

LED Presentations, November 8, 2012

1. Jeff Tsao, Sandia National Laboratories

- R&D should focus on smartness and ultra-efficiency. Directing light is one way to achieve smart lighting.
    - Potential benefits include higher efficiency and productivity of light use.
    - Eventually, inexpensive microsystem luminaires that have the same functionality as a luminaire but are steerable at the chip level may be possible.
- Currently working on chromaticity tunability on a single chip via the use of quantum dots and electric fields.
    - The down-conversion characteristics of each quantum dot layer are adjusted by applying an electric field.
    - It would be possible to tune the absorption and emission spectra and shift colors and chromaticity along and off the Planckian locus. This would allow the red/blue and green/blue power ratios to be adjusted for the desired color temperature.
- There are several options for achieving good efficiency in LEDs:
    - Back off to very low current densities. Maximum efficiency occurs here, but it is not a cost-effective solution in terms of lm/$. In order for the chips to be economical at low lumen output, the cost must be below $1/cm^2, which is a factor of ten lower than what many people consider reasonable.
        - An alternative approach is to move to higher current densities (similar to lasing). In this case, the approach could be practical with area costs as high as $600-700/cm^2 due to a significant increase in lumen output.
    - GaN nanowire structures may offer improved LED efficiency in the blue spectral region and have demonstrated emission into the red, suggesting the prospect of extending operation into the green-yellow-red spectral region. Such structures also allow for the possibility of integrated functionality with 3D architectures.

2. Michael Krames, Soraa

- Gallium nitride (GaN) substrates:
    - GaN substrates simplify overall device development and performance (just as other III-V compounds have done). However, it is hard to develop native substrates from an investment and technological point of view (due to challenges associated with cost, scalability, and growth).
    - GaN substrates currently being produced are far from perfect (e.g., warpage issues); nevertheless, these substrates successfully propelled the Blu-ray industry. The 2020 target for GaN substrate price (task B.1.1) of <$500 (>200 mm) will require a huge

effort to reach and is a huge opportunity for future investment. Reducing substrate cost is very important for lighting and power electronics.

- Light quality:
    - Light quality is a critical factor for SSL adoption, and neglect in this area has hampered market penetration.
        - There has been too much focus on reducing cost and improving efficacy, while light quality has been neglected. This explains low levels of penetration.
        - Cost is not as important as quality and appearance to retail operators, who care principally about customer experience.
    - Light quality is not adequately understood. Improved light quality metrics should be developed, and DOE should discuss light quality as a barrier to adoption in the MYPP.
        - Existing color quality metrics and photometric tools are inadequate. Light quality metrics for brightness perception, color discrimination, and color preference are needed.

3. Christian Wetzel, Rensselaer Polytechnic Institute

- Droop reduction:
    - Droop reduction is still an important concern in order to achieve higher efficiency and lumen output. Defects and threading dislocations in GaN materials need to be reduced.
    - M-plane structures yield good quantum wells, but C-plane structures do not.
    - Nano-patterning of substrates has been effective in reducing defects. There is opportunity in further exploration. It may take a long time, but discontinuing such work would be a significant opportunity lost.
    - Should discontinue funding R&D based on the use of sapphire substrates and promote the study of silicon or other substrates instead.
- Direct spectrum LEDs are an area of significant opportunity:
    - Integrating LED and phosphors enables full-spectrum emission out of a single LED, thereby replicating the solar spectrum.
    - Green, yellow, and red direct emitters can be made with rare earth-free, phosphor-free, and index-matched materials.
        - Heavy efficiency losses are associated with the color-mixing, making it an area for improvement that has not been supported thus far.
        - Other areas of opportunity are semipolar and bulk GaN-based individual RGBA, as well as micro-structured multicolored RGBA.
    - Direct spectrum LEDs are not currently supported by funding, but have received considerable funding in the past.
- Integrated AC LED system:
    - An AC LED system is composed of integrated LED, driver, sensor, and controls. This is the full integration of all systems and should be the ultimate goal.
    - When integrating LEDs and electronics, electronic components built with the same high-quality material as the LEDs might inherit positive reliability attributes, thus minimizing the incidence of component (e.g., transistor or capacitor) failure and premature device failure.
    - With sensor integration, you also want to select materials with similar reliability.

4. **Craig Breen, QD Vision**

- DOE has done a good job of recognizing the importance of tunable narrowband down-conversion materials. Further improvements in spectral control can be made.
  - Spectral control in the red region will have the biggest impact on the spectrum, but spectral control across the whole spectrum is also important.
  - A set of emitters across the visible spectrum could address current and future needs (e.g., the "green gap" and high-CRI cool-white/daylight).
  - In the context of a hybrid system, using a green phosphor to convert the blue spectrum yields an improvement in efficiency.
- Light extraction with down-conversion materials can be improved:
  - One way to reach the MYPP package extraction efficiency goal of 80-90% is through non-scattering down-conversion materials.
    - Gains in the range of 10% or more (at high conversion) are possible from eliminating scattering alone.
    - Prior funding has helped reduce scattering in ceramic phosphor down-conversion systems, but scattering is still present and increases with phosphor loading. Therefore, we will be unable to achieve 80% extraction efficiency with high loading.
    - Nano-phosphors can achieve non-scattering down-conversion composites. However, there are issues of thermal quenching and stability at this level.
  - Funding opportunities to explore alternative quantum dot solutions could yield some improvements in light extraction.
    - There are no fundamental limits to the temperature performance of QD down-conversion materials. They are able to achieve high efficiency and demonstrate high reliability in the required temperature ranges. Non-scattering QD down conversion materials with excellent temperature performance could enable MYPP pc-LED goals.
    - Funding opportunities in the area of light extraction and LED package architecture that make use of this material set should be considered.
    - The U.S. industry will be strengthened by eliminating a dependence on rare earth metals for down-conversion materials. QD materials will serve as a hedge against bottlenecks in the supply chain.

5. **Anant Setlur, GE Global Research**

- Typical LED phosphors result in reduced efficacies at CRIs above 90. However, narrower emission results in higher efficacy at equal CRI.
  - This effect is stronger for red spectral regions than green or blue. Thus, narrowband red emission is a viable pathway to increasing efficiency at high CRIs.
    - Two possible routes for red-line emission are QDs and Mn^{4+} in fluorides. Both have potential issues with stability, costs, and scaling up.
    - QD and Mn^{4+} red line emission down-converters are best demonstrated in remote phosphors.
  - For colors other than red, only QDs meet spectral and absorption requirements.
    - If another option is desired, it will require core research because these materials do not yet exist.

        - Line-emitting LED phosphors will require core or basic science programs research.
        - Transition elements were explored to circumvent REM scarcity issues, but they either have slow decay times, low absorption, or are too broad and do not meet spectral requirements. Some materials with sharp transitions emit phonons instead of light.
        - The stability of some of these materials in LED applications is unknown.
- It is important to note that after any new material development there is a need to assess and understand phosphor reliability.
    - We have some understanding of photo-oxidative processes and hydrolysis, but less understanding for the relationship between defects, processing, and performance.

6. Dennis Bradley, GE Lighting

- Improvement in narrow red and green down converters is an area of opportunity.
    - It would be a big accomplishment to develop LEDs that are both robust (in terms of flux, temperature, and RH) and RoHS- and REACH-compliant.
- Benefits of developing a robust red dies include:
    - Match blue die current droop;
    - Match blue die thermal droop; and
    - Allow for higher efficacy and higher CRI.
- It is time for standardization in the LED industry.
    - Claims that standards stifle innovation are unfounded, and there are plenty of counterexamples in the lighting industry.
    - Standardization makes it easier for manufacturers to source components and eliminates dependence on a single supplier.
    - Standardization still allows flexibility for tradeoffs between performance and cost.

7. Monica Hansen, LED Lighting Advisors, representing Cree, Inc.

- For SSL systems to be valuable, each subsystem must deliver value.
    - A whole-system, holistic design approach should be taken instead of looking at components in isolation.
    - Metrics and goals should consider the whole system at a given cost, (e.g., system lm/$ or lm/W/$).
        - Component or subsystem metrics are inadequate because tradeoffs may exist (e.g., you can reduce component count or component cost, but doing so may increase cost elsewhere in the system).
- State-of-the-art technology is rapidly evolving. We are currently close to 80% power efficiency at 350 mA.[10]
    - Focus should be on substantial step changes in performance rather than incremental improvements.
    - Future goals should be ambitious leaps beyond today's products.
        - New funding solicitations should promise a big leap in innovation (factor of 2 improvements are inadequate) that impact products on a 3-5 year timescale.

[10] Current density not disclosed

8. Wouter Soer, Philips Lumileds

- From a system-level perspective, the areas with a lot of opportunity for lm/$ improvements are performance, cost, and integration.
  - o We can improve LED performance in terms of lm/mm^2 with improvements in WPE (lm/W), conversion efficiency (lm/W_{opt}), and power density (W/mm^2).
  - o Can improve LED cost ($/mm2) by reducing the cost of the wafer/substrate or by improving manufacturing efficiency/volume.
  - o We can make substantial improvements in the overall system level performance using integration to combine higher efficiency system designs (lm/W) with smart partitioning to reduce system costs (lm/$).
- Efforts to improve LED lm/W performance should focus on warm-white LEDs. We need to work on the efficacy gap between warm-white and cool-white, which is now around 30%, and develop narrow red/QD phosphors.
- One way to improve lm/mm^2 performance is to drive LEDs at high currents. To successfully improve LED performance as high current density, we will need a comprehensive effort to:
  - o Improve droop and reduce thermal sensitivity;
  - o Maintain IQE/EQE at high current density and temperature ;
  - o Develop better phosphor matrix materials for high thermal conductivity;
  - o Develop better solder materials to enable high-temperature operation; and
  - o Develop better understanding of reliability physics at high current density.
- System integration is a big opportunity for improving system efficacy.
  - o Mixed-color light engines, like pc off-white + direct red hybrid systems could enable higher system efficiency and should be a short term focus. In the long term, we should look into fully color-mixed RGBA light engines.
- Currently, control systems are addressed at a higher system level. Addressing them at lower levels could enable better technology down the line, such as integrated sensors and drivers that stabilize color point over lifetime. We do not want to miss opportunities from lack of system-level integration.
- Integration could also help lower system cost.
  - o Right now there are a lot of peak designs with short economic lifetimes because essential functions and additional features are often addressed at system/luminaire level, but perhaps should be addressed at a lower level.
  - o We should be working toward a state of "smart partitioning". Being modular in our approach and addressing issues at the right level to reduce complexity.
    - ▪ The benefits of smart partitioning are a simpler value chain, lower bill of materials cost, and higher volumes, which will ultimately result in lower system costs.

9. Cameron Miller, National Institutes of Standards and Technology

- The MYPP should support manufacturers in the short term to complement the existing long-term vision.
  - o This entails a shift in focus from basic chip R&D to reliability and manufacturing.
  - o The industry needs models for analyzing system reliability; it currently only uses component stress testing.
  - o The industry needs to focus on determining the failure mechanisms of LED devices and developing solutions in order to produce high-quality products.

- Advanced manufacturing and new methodologies should be a focus over the next couple years.

10. Jose Sierra, Lighting Science Group Corporation

- Quality and reliability are not the same. Reliability is a measure of quality over time. Reliability is a challenge today, especially with respect to variability and robustness.
    - There is variability in quality as received from the supplier, specifically in characterization of the product as compared to LM-80 data. There are many differences in the products.
    - Robustness of design versus manufacturing induced variability:
        - Design robustness: There are inherent design weaknesses. We currently design for the most important parameters (and use these parameters to measure and compare products), but neglect other parameters. These other parameters will vary, resulting in variability in the product.
        - Manufacturing variability: Manufacturing induces weakness and variability in the product, and variability can cause early failure. Thus product designs should be robust and impervious to manufacturing variability.
        - The industry needs to achieve component quality and reliability for both driver electronics and the luminaire.
    - Products should be designed to be impervious to abuse. Weaker designs will cause earlier deterioration or failure. Important design parameters (e.g., lumen maintenance) should be robust enough to withstand stresses down the line.
- The SSL market is quickly changing, and product development cycles are shorter. The industry needs quicker ways to design for reliability and achieve reliability growth in order to keep pace with agile and dynamic market competition.
    - We need electronics components that are reliable as marketed and standardized design margins.
    - Adopting accelerated life testing methods that give more flexibility would also benefit the industry.
        - ENERGY STAR test programs need shorter testing time, which is now eight months. The industry's product development cycles are short enough that the product may already be obsolete by the time testing is done.

11. Eric Haugaard, Cree, Inc.

- The LED industry needs performance and reliability models that provide accurate results for a range of luminaires in order to meet customer expectations. Warranties are not sufficient. Specifically we need:
    - Improved accelerated life test that reduces test time;
    - Standardized test methods for drivers and other electronics; and
    - A method that covers a broad range of environmental effects. The environment affects lumen maintenance and recommended maintenance schedules.
- TM-21 focuses on a specific component of the light source; there is no test for color and light quality at the luminaire level and no test for color point stability. The industry needs:
    - Correlation methods for luminaire-level maintenance values and color quality maintenance;

    - A system for creating base case predictions for broad use in product groups, and extrapolation limit definitions; and
    - Accurate testing methods that do not burden the manufacturing community. Testing burden has become a big topic of discussion recently.
- Thermal management technologies for more robust drivers and luminaires with smaller footprints that do not sacrifice reliability need to be developed.
    - These advancements should be topology-related, allowing more versatility.
    - The footprints ought to be smaller and better, and products need to be designed from the ground up.
- The industry needs novel luminaire designs that improve efficiency and material utilization. This entails:
    - Using cheaper materials and less material mass, especially in terms of thermal management materials, such as heat sinks; and
    - Designing for manufacturability and assembly with simpler assemblies, less automation expenses and higher repeatability.
- Moisture integration is a significant failure mechanism for outdoor luminaires. Low-cost packaging technologies that improve environmental resistance (such as moisture resistance) and thermal management should be developed.
    - Thermal resistances within the system should be reduced in order to simplify thermal management.
    - There is a need for more useful primary optics materials, such as silicone, but less tacky and less permeable to water.
- We need a luminaire reliability model using a systems-level approach to understand lumen reliability. LM-80/TM-21 data on LEDs is not sufficient. Testing is needed to better characterize the system.

12. Jim Anderson, Philips Color Kinetics

- The industry needs a convergence of SSL, sensors, controls, and networking. We need dimmable light technology and integration of controls and sensors so not just energy efficient lighting but intelligence in systems. But there are questions to be answered, such as:
    - How much functionality should be combined?
    - Should we package more together on the chip?
    - How much of this needs to be networked, and how can we enable that?
- There are several factors influencing SSL control which include:
    - Application needs;
    - Inherent controllability of LEDs; and
    - Low cost to add control and intelligence.
- System architecture: moving from integrated designs to modularization (partitioning) could lead to mass adoption. The goal of modularization is to promote the development, modification, and refinement of individual pieces independently. More specifically, modularity could allow for:
    - Specialization (optimization of pieces) and higher typical performance;
    - Faster development cycles and lower development costs;
    - Better system interoperability, flexibility, and connectivity; and
    - Standardization.

- Modularity can be approached from a hardware, software (embedded and user interface), sensors, controls, or communication perspective.
- To take advantage of modularity, the LED system boundaries and the associated interface rules need to be established. This raises other questions which should be considered, like:
    - Should the industry, government, or standards drive modularization?
    - How do we drive modularity to accelerate LED adoption without sacrificing potential gains?
    - How will the design rules for interfaces be developed?

13. Mark Hand, Acuity Brands, Inc.

- Studies indicate that yellow light allows us to see better and further on roadways than conventional white light. More human factor studies are necessary to gather sufficient data that would allow for the creation of new standards that will allow us to implement systems using yellow light and achieve improved visibility and greater energy savings.
    - Areas of focus for future human factor studies might include:
        - Light preferences at high speed;
        - Light preferences in conflict zones;
        - Light preferences in adverse weather; and
        - How physiology affects preferences.
        - How white is too white? Are there disadvantages associated with higher CCT?
- The white line versus black body locus is another area that needs better definition.
    - Recent human factors studies by RPI show that the perceived white point at different color temperatures diverges significantly from the black body locus. This is a perception issue and merits more discussion and research.
    - It is already known that customers prefer light sources that are below the black body locus, especially in retail applications.
    - Manufacturers could use this knowledge to optimize efficiency and customer acceptance.
- Drivers are becoming one of the greatest percentage losses in overall system efficiency.
    - Current efficiency is around 85% for Class 2 drivers.
    - Research is needed to attain efficiencies above 90% for all drivers.
    - Dimming adversely affects power factor, efficiency, and THD. Why are we still pushing dimming as a way to save energy?
        - Is it possible to have dimming with good PF and THD? Are there better topologies than 0-10 V, or 0-100 V for commercial applications? R&D is needed to resolve this issue.
- The industry needs a standard test method for lifetime. But first we need specifications and research that allows a standard to be created. Other testing related needs include:
    - Fewer testing requirements and/or shorter testing time;
    - A standard to allow for scaling of LM-79: and
    - Improvements in LM-80.

14. Brian Chemel, Digital Lumens

- Phases of LED development and adoption:
    - Stage 1: Fifteen years ago, LEDs were a niche, novelty product and offered pure aesthetics without any cost argument;

    - Stage 2: People started buying LEDs based on lifetime and lumen maintenance and realized the low total cost of ownership due to long life;
    - Stage 3: Customers became interested in shorter payback, and purchases were driven by product efficiency; and
    - Stage 4: Initial cost parity, in which purchase cost is comparable to incumbent technologies. We are currently in pursuit of this inflection point.
        - Will we hit the inflection point naturally, or will DOE have to catalyze it? What is DOE's role here?
- In the current lighting market, LEDs have a dramatic lifetime and TCO advantage but lag in initial cost compared to HID and linear fluorescent systems. However, LEDs are getting closer to HID in terms of initial costs. So where should we focus R&D dollars? Where will they have the most effect?
    - Cost per lumen has dropped significantly (by a factor of eight), and LEDs themselves represent just 25% of the total product cost. The goal should be to reduce the costs to the customer.
    - Operating expense (kWh) represent a significant portion of the total cost of lighting to the consumer. In a five-year view to a customer with a high-brightness (HB) fixture, 60% of the total cost of lighting was operating costs. High wattages (for HB fixtures) cost a lot to operate.
    - Therefore focus should be on improving efficacy because a decrease in fixture wattage will have a greater effect on total lighting cost for high-output systems than reducing component/initial cost.
        - Reducing costs of components other than the LEDs will have a bigger impact than LED cost reduction.
- Intelligent lighting systems could drive adoption by reducing operating costs.
    - The industry should use intelligent controls, sensors, and networking to reduce payback.
    - If smart devices are designed ground up, customers will see significant energy savings with a similar BOM.
- Device performance and price are good enough today. The industry is reaching a plateau where small, incremental price or performance improvements are not good enough.
    - DOE should not focus on performance and price improvements. The market will drive performance and efficiency fast enough that investments are not needed.
    - Instead, DOE should shift focus downstream and fund big step-function improvements such as innovative sensing and control technologies or innovative balance-of-system technologies.

15. Steve Paolini, NEXT Lighting Corp.

- It is widely-agreed that the best SSL products today exceed the performance of vacuum alternatives, except the price is too high.
- In the past, the focus has been on replacement lamps and luminaires. Going forward, we should stop funding pc-white and standard form factors and start taking advantage of what SSLs can do by focusing on what vacuum lighting cannot do, such as:
    - Controlling the spectrum;
    - Controlling the beam; and
    - Using new wavelengths (e.g., green).

- Energy savings is not a sufficiently compelling reason for customers to buy LED products. We need to accelerate adoption by offering unique functionality, such as:
    - Spectral control and time varying daylight.
        - LEDs are uniquely positioned to be able to replicate the solar spectrum, whereas other light sources cannot.
        - LEDs have the opportunity to tailor the light quality to mimic light from any place or time of day (e.g. sunset) by adding or removing wavelengths from the emission spectrum.
        - However, integrated, multi-channel AM/PWM drivers are expensive today because they are done discretely. Another challenge is low-cost spectrometers which are needed to "record" the light spectrum. We need more than an RGB sensor.
    - Collimated light.
        - Collapsed beam devices would be useful and get us closer to collimated light (like the sun) and allow us to steer the beam.
    - Tunable wavelength that is tuned by a three-terminal device to lock onto a specific color as well as efficient direct emission at all wavelengths.
- The industry needs to push the boundaries of what we can do with SSL. Examples of past watershed events include:
    - Nichia pc-white in 1993;
    - Cree BSY + R LED-based luminaire in 2007; and
    - Philips HUE lamp in 2012.
        - Provides something more than just energy efficiency.
        - First product to exploit the unique characteristics of LEDs.

OLED Presentations, November 9, 2012

1. David Maikowski, Guardian Industries

- To meet the OLED component material cost and performance goals, the targets should be:
    - <$52/m^2 by 2015 for integrated substrates;
    - <$20/m^2 by 2015 for encapsulation; and
    - <$10/m^2 by 2015 for organics.
- Enhancing light extraction is the main vehicle to improve efficacy and meet DOE performance targets.
    - Internal reflection and index mismatching are the main causes of poor light extraction. Only 20-30% of light is outcoupled when a standard indium tin oxide (ITO) anode plate on glass is used.
    - The addition of an outcoupling scattering layer stack between the electrode and the substrate has the potential to increase light output by creating a path for the light to get through. Small-scale modeling has shown a 2.7x increase in efficacy.
    - Improving light extraction to target values is not a surface issue; the solution will be from within the device stack.
- For substrates, the DOE cost target for glass is $5/m^2 by 2015.
    - Specifying float soda lime glass with thicknesses >1.0 mm with reasonable defect quality levels is the primary path to realizing price and performance targets.
        - High-index glass is an option to meet performance targets (good light extraction). However, the volume required cannot be met in a cost-effective manner.
    - There is a mismatch between the set cost target and the quality level and thickness of glass that OLED customers want.
    - Defect levels in float glass are unacceptably high for this industry.
    - There has to be a tie between glass thickness and defect level, and there must be convergence between defect level and cost.
- For OLED devices to achieve acceptable and reliable lifetimes for lighting applications, glass-based encapsulation materials should be used.
    - To achieve 20-30 year device reliability, we need materials that are <0% total mass loss (TML) and provide a hermetic seal.
    - To get a long-term hermetic seal with <0% TML on a glass substrate, a glass seal is required.
    - Efforts should be focused on developing materials and processes to allow for a glass-based edge for long-term encapsulation without degrading organic materials in the OLED device. The edge needs to be processed at ≤120°C because organics typically burn off at 125°C. Glass frit is the only substance that consistently shows 0% TML.

2. Michael Boroson, OLEDWorks LLC

- Reducing cost is the key to building sales volume for OLED lighting. Current efficacy and lifetimes statuses are not far behind DOE 2012 MYPP goals, but price is very far off.
- Current statuses of OLEDs panels are:
    - Price: $500-2,000/klm or $5,000-20,000/m^2;
        - DOE targets are $45/klm or $270/m^2;
    - Panel efficacy: 25-60 lm/W; and

        - This is an unacceptably wide range of panel efficacies. The lower end of the efficacy range is only suitable for niche, specialty applications where efficacy is not the paramount concern. The high end is acceptable for initial products but price is too high, and further performance improvements will be required.
    - Lifetime: 1-15,000 hours (L_{70} at 3,000 cd/m^2).
- The market will grow if products with good performance can be manufactured at a reasonable cost. Manufacturers need to lower the price at low volumes and be able to expand volume while maintaining costs.
    - Current equipment and processes will not meet cost targets. DOE can help by funding novel, low-cost processes and performance enhancements.
    - To meet manufacturing capacities, we need to lower the cost of panels and increase the performance over current levels using existing processes and materials.
    - Current manufacturers are in Asia and Europe. We would like to have at least one U.S. manufacturer. For the U.S. to have a real market presence, the U.S. needs to participate and collaborate in all areas of the industry (material supply, equipment, etc.).
- Improving light extraction approaches (task C.6.3) will yield the biggest performance improvement for the investment and is an area of opportunity for funding.
    - R&D should enable novel, low-cost light extraction (<$10/m^2).
    - Light losses due to surface plasmons have not received much attention to date.
- Breakthrough OLED luminaires (D.4.2) should also be considered for funding opportunities.
    - R&D should focus on enabling novel, low-cost, thin, transparent encapsulation to enable products based on thin and/or transparent and/or flexible OLEDs (<$10/m^2).
- Flexibility and transparency are highly-desirable properties. Very high-throughput vacuum deposition should be considered as a new priority task for funding.
    - The industry needs a way to vacuum deposit OLEDs. These are the highest performing OLEDs, especially when tandem stacked.
    - High-speed vacuum deposition of complex OLEDs must be low-cost and high-throughput without degrading the material.
- Any new materials or processes must be low-cost and scalable even at low volumes (as well as future high volumes) if OLEDs are to be competitive.

3. Michael Weaver, Universal Display Corporation

- OLED lighting R&D should concentrate on areas that the display industry is not already focusing on.
    - Lifetime will be solved by display industry so efforts should be focused on other areas that will bring the cost down.
    - To achieve efficacies of 90 lm/W, outcoupling efficiency needs to improve. These outcoupling solutions must be cost-effective and thin.
        - An increase in efficacy of 1.7x is achievable through outcoupling improvements, which would allow us to achieve the higher efficacy targets.
        - We are on track with the MYPP.
- Niche applications for OLED lighting should be sought initially because the consumer will have to be charged a premium. General illumination applications will follow.

    - OLED lighting qualities such as CRI quality, thinness, and form factor must be promoted. Directing customer focus on OLED color quality and form factors is an area of focus for the industry.

4. Hongmei Zhang, Plextronics, Inc.

- Increasing panel sizes causes electrode uniformity problems due to sheet resistance.
    - Typical ITO resistances are greater than 5 Ω/square.
- Metal grids are necessary in order to reduce sheet resistance to 1 Ω/square and improve power efficiency and luminous uniformity of large-area OLED panels.
    - The current process to obtain substrates with metal grids is standard vapor deposition, an expensive 7-step process.
    - Obtaining metal grids through a 3-step process with printed metal grids and a printed HIL process would reduce the cost of electrodes.
        - A printed HIL process would remove the insulator coating and photolithography steps.
        - Printing metal grids instead of the current method of metal deposition removes the need for the additional photolithography and etching stages.
- Currently, there are several issues with printing metal grids:
    - Printing processes:
        - Inkjet printing has good resolution and thickness control, but yields less than half-micron thickness and requires multiple paths for thicker film with current ink technology.
        - Screen printing is a higher-throughput, faster, and more mature process, but it has lower resolution, poorer thickness control, and poorer surface roughness.
    - Printing materials:
        - Commercially-available screen printable inks are nanoparticle-based with higher resistivity, which therefore requires wider and thicker grids to achieve the necessary conductivity and maintain optical transparency.
        - Evidence of silver (metal) migration is also an issue.
- New metal ink material and printing process development are required to achieve metal grids that are low cost for OLED panels. Important specifications to achieve this are:
    - Optical transparency >90% (or at least >80%),
    - Sheet resistance <1 Ω/square,
    - <1 um thickness and <150 um line width,
        - Thick grids pose issues with planarization, which adds to the cost of materials and the processes.
    - A new ink technology to improve upon current nanoparticle-based inks,
    - A new annealing process to improve conductivity,
    - An ink focused on metallic silver with resistivity lower than 2x bulk Ag, and
        - R&D is necessary to solve potential issues with silver migration.
    - A printing process that yields finer line widths and a new annealing process to improve conductivity.

5. Paul Magill, Rambus Inc.

- If OLEDS do not establish themselves soon, LEDs will become an embedded solution, at which point it will be extremely hard for OLEDs to compete and OLEDs may miss out.

    - To prevent being crowded out of the market, OLEDs need to leapfrog some of their technical problems (e.g., getting away from the Lambertian light distribution).
    - For example, the light output of the OLED device can be utilized more effectively by shaping and directing it.
        - Home and office lighting applications require minimum and maximum requirements for luminance, and OLEDs cannot currently meet those market requirements because their brightness is insufficient.
        - Making light distribution less Lambertian (but not a focused beam) would make OLEDs immediately more competitive. Illumination requirements can be reduced by directing light output, leading to lower required power while maintaining same level of illuminance. This improves cost competitiveness.

6. Sebastian Reineke, Massachusetts Institute of Technology

- Outcoupling is essential to making the leap forward for OLED.
- Rational decisions must be made to design products to fit our needs.
- There is no consensus on OLED materials. The breadth of materials available is a hurdle for the OLED lighting industry. (In contrast, LEDs only have a handful.)
    - There are 241 functional materials to choose from for OLED research.
    - These materials have not been characterized in order to determine if they are good for lifetime, efficiency, etc.
    - This causes the research to splinter and stall. There is no consensus on direction, which prevents us from building upon each other's knowledge and hinders faster progress.
    - The pool of available materials must be narrowed.
- Likewise, there is no consensus on device structure either.
    - There are 15 major concepts in development.
    - We are running constant basic research on the material and device structure level.
    - We need to decide on a device structure and move forward.

7. Lewis Rothberg, University of Rochester

- The OLED lighting industry needs paradigm-shifting advancements in technology.
    - OLED lighting needs stable blue phosphorescent materials and hosts.
        - We have communications failures. Academia and industry need to collaborate to address issues that concern both parties. Facilitation of this cooperation would be an appropriate role for DOE.
    - The root cause of chemical degradation is insufficiently understood.
        - We do not have enough information and need a long-term rational strategy.
    - The OLED industry needs to develop better transparent contacts.
        - Need to get rid of indium as a transparent contact sooner or later. This is also true in the display industry.
- Changing the cost structure of OLEDs is critical and will be manufacturing issue.
    - Manufacturing methods that are unique to organics should be used (e.g., roll-to-roll coating).
    - Development of electroluminescent polymers promise different physics that can change the game.

8. Peter Djurovich, University of Southern California

- Non-radiative decay processes in cyclometalated iridium complexes is not fully understood.
- Iridium is used because it is robust and has high (almost unity) photoluminescence (PL) efficiency.
    - Robustness and high efficiency are closely linked.
- There are a limited number of efficient blue emitter materials. Red materials are more abundant and more stable.
- Different combinations of blue-green emission colors yield varying PL efficiencies and quantum yields.
- Temperature dependence of lifetime is the most critical issue.
- Temperature dependence of luminescence is also a factor.
    - For example, a particular blue emissive material has good blue color at 77 K, but at room temperature it produces almost no light at all.
    - At low temperature, the material displays very long emission lifetime, but light output decreases as temperature increases.
    - The relationship between stability and temperature dependence is not understood.
        - A model using a Boltzmann kinetic scheme can be created to get the desired activation energies.
        - Ideally, activation energies at room temperature should be around 4,000 cm^{-1} or greater.
- A variety of materials were examined in the non-radiative processes models and only a subset has high activation energy. However:
    - As quantum yields decrease, so do activation energies, and
    - As the enthalpy change (ΔH) goes from negative to positive, the emission level goes from very low to very high.
- Bond breaking affects stability and is a significant issue with blue emitter non-radiative deactivation. This reduces luminescent efficiency. Good stability will translate to good efficiency.
    - This is a complicated issue that will be a challenge in the future.
    - It will be solved via incremental improvements rather than a breakthrough solution.
        - There will not be a breakthrough molecule that can no longer break a bond because the current materials all have similar bond strengths.

9. Jian Li, Arizona State University

- The issues of concern for OLED lighting that the industry should focus on are:
    - Light extraction,
    - Quality of light,
    - Complexity and cost-effectiveness of the device, and
    - Device operational and color stability.
- Should the industry focus on new materials or new device structures? Producing white light involves the use of three different materials (blue, green, and red) in single-layer, multi-layer, or more complex structures.
    - More layers translate to higher costs, and the goal is to decrease costs.
- Emitting blue light is the toughest problem to solve for the OLED lighting industry, and progress in this area would benefit both the OLED lighting and display industries. We need a

tunable device structure that can achieve the narrow band emission without sacrificing extraction efficiency.

  - Triple-doped emissive layers and multiple emissive layers are the most commonly used technologies. The OLED industry focuses on triple-doped emissive layer.
  - Academia could explore the use of single broadband emitters or monomers and excimers as alternative approaches to achieving efficient blue emission.
  - WOLEDS with a single emitter producing two types of emissions have shown:
    - Peak EQE of >20%,
    - Power efficiency >5%, and
    - Efficacy of >29 lm/W.
  - A broadband triplet emitter compound can have the following benefits:
    - Gaussian distribution of emission intensity over observed wavelength ranges;
    - Controlling the ratio of intensity with a broad emitter. Iridium complexes can also achieve broader emission spectrums, although the reason for this is predominately unknown.
  - With non-cavity blue color stacked OLEDs, the EQE does not improve because blue phosphor OLEDs have narrowband emission, but narrow emission is used to excite phosphors to generate white light.
    - What if a narrowband blue phosphorescent emitter is developed?
  - A blue microcavity OLED with down-conversion phosphors has the potential to achieve an efficacy as high as 99 lm/W.

10. Qibing Pei, University of California, Los Angeles

- One step towards achieving a price reduction by a factor of 100 is using a polymer substrate instead of glass. While glass has many nice features, it is also heavy and thick. The benefits of using a polymer substrate are:
  - Lightweight,
  - Thin,
  - Flexible (benefits manufacturers and customers), and
  - Higher light extraction efficiency.
- How do you make a single layer that can produce high efficiency?
  - Process a single layer, then form a PIN junction in situ.
    - This improves charge injection at high current density, sliding it above the band gap and thereby producing higher brightness at low voltage.
    - However, this process requires additional materials and effort.
  - Test results with an aluminum PIN junction device with one layer of spin-coated polymers showed an efficiency of 12 cd/A, which is comparable to that of the best polymer in a typical LED structure, as well as a lifetime of 27,000 hours.
- Academic research shows it is possible to achieve performance as good as multiple-layer structures with a single-layer system.
  - Substrate material is semi-transparent.
  - All materials included in a single sheet.
  - Resistance of the integrated substrate is on par with that of glass substrates.
  - The integrated substrate has a very smooth surface with surface roughness <5 nm.
  - If emissive material is also a polymer, index matching can be performed to increase light extraction in the polymer layer because the interface is not reflective.

        - A 4x increase in light extraction might then be possible with a single-layer polymer anode/substrate, rather than the 3x anticipated with traditional glass substrates.
    - Polymer LEDs on this substrate/composite electrode have been constructed.
        - A transparent flexible single layer sheet has been produced at sizes of $1ft^2$ and has the potential to be made in larger areas with R2R coating and processing.
- Availability of materials is a problem for academic research, so not everything can be tested.