Roundtable Discussions of the Solid-State Lighting R&D Task Priorities

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DISCLAIMER

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COMMENTS

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1. Introduction

The Multi-Year Program Plan (MYPP) for the Solid-State Lighting (SSL) Program forms a basis on which the Department of Energy (DOE) develops research and development (R&D) funding solicitations. This plan is updated annually. As part of the annual update process the DOE invited a number of SSL experts to Washington, DC on November 10th to the 12th of 2010 for a series of "roundtable" planning meetings to advise DOE on which R&D tasks are currently most needed to advance solid state lighting products.

The meetings were conducted over three days. The first two days were dedicated to discussion on Light Emitting Diodes (LEDs) with the final day dedicated to Organic Light Emitting Diodes (OLEDs). The roundtables began with a brief introduction and summary of the goals of the meetings. This was followed by presentations from each of the roundtable attendees which allowed them to highlight what they believed to be the most important areas for research (see Appendix A).

During the discussion that followed, participants referred to the complete list of 62 tasks in the 2010 MYPP to consider which should be prioritized to support key near-term research requirements.[1] In early 2010, a total of 20 of the 62 tasks were identified as priorities and became "Areas of Interest" for funding solicitations, but several received little or no interest from the R&D community. Therefore, for this reason and likely funding constraints in 2011, the participants were charged with limiting the priority list to no more than ten priority tasks altogether. Ultimately, the roundtable participants identified a total of 14 preliminary priority tasks. The final selection of priority tasks will be made following the R&D workshop.

After the prioritization discussion, participants discussed the current status and targets for various metrics assigned to the prioritized tasks. The final stage of the roundtable was to review the DOE SSL Program's efficacy targets and milestones for LEDs and OLEDs.

2. Annual Planning Process

The November roundtable was only one important step in the annual MYPP update process.[2] Following the roundtable, the DOE will host the 2011 Solid-State Lighting R&D Workshop in February. During this workshop, the task discussion will continue and feedback on the preliminary priority R&D tasks identified at the roundtables will be solicited. These recommendations will be considered in the final decision on task priorities for the 2011 MYPP. This priority task list will heavily influence the solicited R&D topics in the competitive FOAs for fiscal year 2012.

[1] The definitions of Core and Product Development are provided in Appendix G of SSL MYPP. 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] For a list of previous stakeholder meetings please refer to Chapter 5 of the SSL MYPP.

3. Prioritization Discussion

The full R&D task list was originally developed for a DOE program planning workshop in November of 2003 and has typically been slightly modified each year. The current task list, which includes 12 LED core tasks, 22 LED product development tasks, 9 OLED core tasks, and 19 OLED product development tasks, resulted from a complete review and revision of the task structure for the 2009 MYPP. In 2009 a new direction was initiated to provide additional emphasis on manufacturing R&D, resulting in an SSL Manufacturing Roadmap[3]. As was the case in 2010, SSL manufacturing issues, objectives, tasks and priorities will be explored in a separate workshop with an updated Manufacturing Roadmap in 2011.

Roundtable participants reviewed the set of R&D tasks and offered their suggestions for priorities for the coming year. This discussion is summarized below in Section 3 of this report. Ultimately the LED participants proposed three core technology priority tasks, all of which were priority tasks in 2010, and five product development priority tasks, two of which were priority tasks in 2010. The OLED participants proposed three core technology priority tasks, all of which were priority tasks in 2010, and three product development priority tasks, one of which was a priority task in 2010.

After the initial prioritization, participants discussed the specifics of each prioritized 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. Participants also provided the current status and the 2020 target. Targets are intended to be challenging but achievable.

[3] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2010_web.pdf

3.1. LED Core Research Priority Tasks

The following tables and bullet points summarize the conclusions and discussions for each of the selected preliminary priority tasks for 2011. To be consistent among the tasks, the definitions in the table below for various colors and color temperatures are used throughout.

LED emission wavelengths and color definitions for sections 3.1 and 3.2

Color		Wavelength/CCT range	CRI
Blue		440-460 nm	-
Green		520-540 nm	-
Amber		585-595 nm	-
Red		610-620 nm	-
White	Warm	2580-3710 K	≥80
	Neutral	3711-4745 K	≥70
	Cool	4746-7040 K	≥70

A1.2 Emitter Materials Research		
Description: (1) 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. **(2)** Identify and demonstrate means to reduce current droop and thermal sensitivity for all colors through both experimental and theoretical work. **(3)** Develop efficient red (610-620 nm) or amber (585-595 nm) 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)	**2010 Status(es)**	**2020 Target(s)**
IQE @ 35 A/cm^2	80% (Blue) 40% (Green) 75% (Red) 20% (Amber)	90% (Blue, Green, Red, Amber)
EQE @ 35 A/cm^2	64% (Blue) 30% (Green) 38% (Red) 10% (Amber)	81% (Blue, Green, Red, Amber)
Power Conversion Efficiency @ 35 A/cm^2	50-55% (Blue) 21% (Green) 35% (Red) 9% (Amber)	75% (Blue, Green, Red, Amber)
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	85% (Blue, Green) 50% (Red) 25% (Amber)[4]	95% (Blue, Green) 75% (Red, Amber)

Discussion Points:

- There is a need to look at accelerated testing methods and identify the degradation mechanisms, particularly droop, and the fundamental science behind them for LEDs. The development of both theoretical and experiment approaches for solving droop are a high priority.
- It was also indicated that once droop is resolved input power density will increase; therefore research into the improved thermal handling capabilities of LEDs is also extremely important.
- Further research efforts are needed surrounding the multiple reliability degradation processes that are occurring – especially for lumen maintenance and color.

[4] This status is representative of direct emitters. Amber phosphor-converted LEDs can currently achieve thermal stability of up to 83 percent.

- In addition, the importance of producing high quality white light and reducing glare was clearly emphasized.
- The discussion led to the addition of amber LEDs for each of the applicable metrics (IQE – 20%, EQE – 10%, and Power Conversion Efficiency – 9%), and the thermal stability for amber LEDs was suggested to be 40%. However, following the roundtables, it was subsequently adjusted to 25% based on current Luxeon products. It was also questioned as to whether green LEDs should be eliminated from the status and 2020 targets.
- The development of efficient red LEDs between the 610 and 620 nm linewidth was considered to be a high priority for this task, and was explicitly added to the descriptor.
- Furthermore, the description for the emitter research task was modified to express the imperative need for improvements to the current droop and thermal stability for blue LEDs.
- For droop, the metric was changed to be ‘relative EQE at 100 A/cm^2 vs. 35 A/cm^2. Also the 2010 status was updated to 77% and the 2020 target was change to 100%, with the goal of having no droop.

A1.3 Down Converters		
Description: Explore new non-toxic, high-efficiency wavelength conversion materials for improved quantum yield and phosphor 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.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Quantum Yield (25°C) across the visible spectrum	80%	95%
Quantum Yield (150°C) across the visible spectrum	70%	85%
Thermal Stability across the visible spectrum - Relative Quantum Yield at 150°C vs. 25°C	85%	90%
Avg. Conversion Efficiency[5] (phosphor converted LED)	58%	72%
Spectral Full Width Half Max. (FWHM)	150 nm (Red)	<50 nm (Red)
Color Stability (phosphor converted LED)	Color Shift 0.012 u 'v' over life	Color Shift < 0.004 u 'v' over life
LER	~315 lm/W	[To be calculated]

Discussion Points:

- It was decided that it was necessary to highlight the importance of improved spectral efficiency, as well as color and temperature stability in the description for the down converters task.
- In addition, the initial and lifetime color shift for LED products is significant, therefore, we need to determine better target values and track color shift over the lifetime of LEDs.
- There was concern that phosphor research groups are not existent at the core level and that manufacturer engagement is necessary to consider integration, however, some universities are working on down converter research.

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[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.

- Work on narrow band reds is still a priority to improve color quality and spectral efficiency.
- This could include work on nanostructures for non scattering phosphors.
- One participant mentioned that non-cadmium, ROHS compliant down converters should be specified.
- The 2010 status for average conversion efficiency was also updated from 65% (cool) and 50% (warm) to 70% (cool) and 58% (warm). Following the roundtable, all "cool" statuses and targets were removed from this task, given its focus on creating warm white light.
- For the average conversion efficiency metric, there was significant discussion that the 2020 target for this metric will be easily met by remote phosphors and that scattering losses, as well as the Stokes loss limit need to be accurately accounted for by the average conversion efficiency metric. Stokes losses also greatly limit the potential gain for the average conversion efficiency metric which brought about the question as to whether it should be considered at all, particularly for cool LED lighting.
- The LER metric was added with a focus on warm LED lighting since only small gains are possible for cool LED lighting across all of the above included metrics.
- Lastly, it was suggested that the quantum yield, spectral full width half-maximum and color stability metrics could be removed.

A2.2 Novel Emitter Architectures		
Description: (1) Devise novel emitter geometries and mechanisms that show a clear pathway to efficiency improvement; **(2)** Demonstrate a pathway to increased chip-level functionality offering luminaire or system efficiency improvements over existing approaches; **(3)** 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, system on a chip)		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
EQE @ 35 A/cm^2	64% (Blue) 30% (Green) 38% (Red) 10% (Amber)	81% (Blue, Green, Red, Amber)
Color Stability over Time and Temperature		
LER	339 lm/W (hybrid)	425 lm/W

Discussion Points:

- There was significant discussion surrounding the need to develop ultra high efficiency LED solutions.
- There was a great emphasis on not limiting the researcher's creativity and novelty within this task, and ensuring that the description makes clear the focus is not on creating manufacturable materials and architectures, but rather creative designs for radically improving the efficiency and functionality of the LED chip.
- Furthermore, a metric is needed that emphasizes the priority of overall system efficiency (in order to include the idea of "system on a chip"); therefore, another metric beyond EQE is needed.
- The description for this task was modified to place an emphasis on the need for new and radical ideas for increasing the efficiency.
- Subsequent discussion following the roundtable, suggested that color stability over time and temperature should be considered as a metric.

3.2. LED Product Development Priority Tasks

B1.1 Substrate Development		
Description: Develop alternative high quality substrates that enable low cost high efficiency LED packages. Demonstrate state of the art LEDs on these substrates and establish a pathway to target performance and cost.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Price of LED Package @ target efficiency	$10-15/klm (cool) $20-25/klm (warm)	$1/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)
Droop - Relative EQE at $100A/cm^2$ vs. $35A/cm^2$	77%	100%
Thermal Stability – Relative Optical Flux at 100ºC vs. 25ºC	85% (Blue, Green)	95% (Blue, Green)
GaN Transparency (absorption coefficient)	2-10 cm^{-1}	<0.5 cm^{-1}

Discussion Points:

- One participant emphasized the need for research funding that focuses on native substrate opportunities. Since they offer potential benefits including, ultra low dislocations, reliability at high current densities, simplified chip architecture, high thermal conductivity, as well as reduced droop.
- There was consensus that the substrate price metric should not be excusive to GaN, and that the price targets for 2020 were not aggressive enough. Therefore, they were updated to less than $500 for a substrate greater than 200 nm.
- The 2010 status for the price of an LED package was also updated to reflect the current market values. It was indicated that the prices have lowered to approximately $10-15/klm for cool and $20-25/klm for warm. The package price target for 2020 was kept at $1/klm.
- This task should be open to any kind of substrate that enables low cost and high efficiency LEDs.
- It was also identified that it is extremely important that researchers demonstrate a pathway to reach the targeted performance and cost metrics.

- Furthermore, it was mentioned that green LEDs are a priority to improve, but are not a priority to fund further in the upcoming year (possibly remove from status and 2020 target values).
- It was decided to add GaN transparency as a metric with the 2010 status being 2 to 10 cm^{-1} and the 2020 target being $<0.5\ cm^{-1}$.

B3.6 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, or other approaches to address these issues.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Change in Chromaticity over time	7 to 8-step MacAdam Ellipse	1-step MacAdam Ellipse over lifetime
Price of LED Package	$10-15/klm (cool) $20-25/klm (warm)	$1/klm
Price of Luminaire or replacement lamp	$50-60/klm	$8/klm
System Efficiency		
System Price		

Discussion Points:

- Industry is conducting a significant amount of research into package architecture, therefore, government funded R&D needs to focus on high risk projects that have the potential for non-incremental improvements.
- This task also should focus on increasing the integrated functionality of the package and incorporate the idea of "system in a package."
- The reduction of material use was emphasized as an important goal for this task, as well as a focus on creating overall more sustainable and environmentally responsible package designs.
- It was decided to remove the flux thermal sensitivity and luminaire optical efficiency metrics since they are not critical for this task, and potentially add two metrics: System efficiency and system price.
- In addition, the previous metric 'Change in CCT over time' was altered to be 'Change in chromaticity over time.' The 2010 status and 2020 target values were unchanged.
- The description for the package architecture task was also changed to deemphasize the need for better thermal handling and integration.

B6.3 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. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Mean Time to Failure (either catastrophic, lumen maintenance >70%, color shift, loss of controls)	Device Lumen Depreciation data	Tool to predict Luminaire lifetime within 10% accuracy

Discussion Points:

- System reliability was identified as a high priority task due to the apparent need for accelerated testing methods related to reliability, color shift, and lifetime.
- Furthermore, it was emphasized that it is important to keep this metric from being too constricted since it was unclear as to where the focus has been in the past, therefore, the task should not limit where the research will go.
- There was concern that the tasks for each subsystem should be broken-out to entice the right people to submit proposals, or that this task should be managed differently by having the DOE put out a call for white paper submissions in order to increase the specificity of research proposals.
- The description was modified to highlight the need to analyze the LED components individually (i.e. package, driver, optical components, etc.), as well as their interaction with one another.
- There was great consensus on the need for improved driver lifetime and reliability. It was indicated that the greatest challenge to increasing driver lifetime is the thermal management of the aluminum electrolytic capacitor case temperature, particularly for LED replacement lamps.
- Furthermore the reliability task description was revised to emphasize the need for both experimental testing and software modeling methods for increasing system reliability.

B6.4 Novel 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 (low weight, compact size, directionality, digital controllable, color tunability, durability).		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
System Energy Consumption		
Controls		
Environmental Impact		

Discussion Points:

- Due to great agreement on the need to develop novel luminiares with new form factors that most effectively utilize the benefits of LED lighting technology, a new task was created entitled Novel Luminaire Systems.
- This task needs to focus on the non-bulb socket luminaire paradigm which is essential for near-term product development.
- Potential characteristics of these novel luminaire designs were said to include, low weight, compact size, building interfaces, daylighting, digital control, color tunability, health benefits, dimmability, durability, etc.
- Emphasis was made on creating sustainable luminaires that consume far less material, particularly in the heat sink structure.
- There was concern that the tasks should not constrain R&D efforts to current lighting infrastructure systems. Selected projects should include finding a way to better distribute light and making having less light and less fixture efficiency more acceptable.
- Given this is a newly defined product development task, it was suggested that metrics be developed that emphasize the need for reduced system energy consumption and environmental impact, as well as the need for integration with smart system controls.

B7.3 Smart System Controls		
Description: Develop novel integrated lighting controls (network ready or stand alone) that take advantage the benefits of LEDs that save energy over the life of the luminaire system and accelerate market adoption of SSL luminaires and the control system. May include integrated luminaire system approaches to conventional controls such as sensing occupancy or daylight, communications, or methods to maximize dimmer efficiency. Proposed systems must be specific to SSL and should represent a simplification in the application of controls to lighting to enable more effective deployment of controls technology.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Complexity		
Cost		
Adaptive Control		
Energy Savings		

Discussion Points:

- In was determined that in order to achieve significant reduction in energy use it is necessary to develop smart system controls for LED luminaires that are specifically designed to function with SSL technology.
- Research in this arena should focus on high risk options that have the potential to dramatically improve sensing equipment since the current technology is between 15 and 20 year old. The proposals for this task should not include the application of conventional control systems for incumbent lighting technologies.
- This task could include digital light communications since this capability is specific to LED lighting technologies, and would enable light to carry control information from one luminaire to the next.
- However, there was concern that control theory, sensor design, and human factor modeling will be researched without additional government encouragement.
- Currently smart system control adoption is limited due to the complexity which results in limited energy savings, therefore, this task needs to focus on projects that offer the potential for simple designs.
- Presently, these lighting systems are not adaptable to changes in building space, and maintenance does not keep-up with these changes which greatly reduces the potential cost savings. Therefore, we need to consider the possibilities for adaptive controls that would enable the lighting system to adapt to a change of room characteristics.
- The task description was revised to make clear the importance that the smart system controls developed must be novel and utilize the specific attributes of LED luminaire systems. Metrics that incorporate complexity, cost and adaptive control targets were also added to the smart system controls task.

3.3. OLED Core Research Tasks

C1.2 Novel OLED Materials and Structures		
Description: Explore novel materials and structures (between the electrodes) that can be used to transport charge and emit white light more effectively; increasing EQE, reducing voltage, and improving device lifetime. Potential for radically reduced cost is desirable, for example through increased material robustness or through materials and architectures that enable simpler device fabrication. Investigation of internal OLED structures that offer greater control of the color or directionality of the light would be particularly timely.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
EQE without external extraction enhancement	~20%	25-30%
Lifetime (L70)	10,000 hrs at 3000 lm/m^2	>50,000 hrs at 10,000 lm/m^2
Voltage @ $2mA/cm^2$	~3.8V	<3V
CRI	84	>90
Cost		Factor of 10 reduction in cost
Complexity/Robustness		

Discussion Points:

- The importance of this task was strongly enforced by several of the soapbox presentations. It was agreed that work on materials and structures is a high priority for 2011, and that enabling low cost robust processing, simplified materials and device architectures, as well as greater thermal robustness needs to be stressed.
  - There was significant discussion on the need for reducing the number of layers per device and to increasing the amount of processing that is ambient as methods for simplifying OLED design
- The development of more stable blue emitters has received much attention in recent years. Some believed further work to this end should be given high priority, while others stressed that the major goal must be to produce a long-lived efficient white source and that the interaction between different components is as important as the development of better blue emitters.
- It was also suggested that light distribution control should be improved to produce more effective illumination and reduce glare. To reduce demands on the luminaire structure,

methods of controlling light emission need to be embedded into the basic structure of the OLED.

- The description should be worded so as not to discourage incremental progress for materials and structures. Taking existing materials and modifying them to improve performance may be more productive than starting with new materials.
- Some suggested that this task should include research into a saturated red emitter with narrow linewidth to improve efficacy without degrading CRI and color quality.
- The importance of color quality was discussed thoroughly resulting in the addition of a CRI metric. The addition of other color quality metrics, such as Duv and CCT, was also discussed, but has not yet been implemented.

C3.1 Fabrication Technology Research		
Description: Develop novel techniques (significantly differing from existing approaches) for practical materials deposition, device fabrication, or encapsulation to ultimately enable lower cost manufacturing of state of the art performance OLED panels. Show potential for scalability, high yield and shelf life of greater than 10 years.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Relative material and processing cost reduction potential	1 relative cost	1/10 cost
Material Utilization	5-50%	>70%
Speed or Processing Time	4 min TACT	20-30s TACT
Uniformity	5% variation over small areas	<5% variation over at least 200 cm^2

Discussion Points:

- This task could focus on encapsulation methods that will enable lower fabrication costs.
- Some suggested that the DOE should prioritize the development of mass manufacturing equipment for thin film encapsulation while others stated that research efforts that define pathways for lowering cost at all levels are essential.
- Yield of devices was also discussed. Suggested metrics for 2020 include a 10 year shelf life for panels and 95% device yield (no black spots) at 1,000 hours under 85°C/85%RH damp heat conditions.

C6.3 Light Extraction Approaches		
Description: Devise new optical structures and device designs for improving OLED light extraction while retaining the thin profile of OLED panels. The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, or external to the device. The approach should be scalable to large sizes and provide potential for low cost manufacturing.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Extraction Efficiency	45% (in laboratories)	75%

Discussion Points:

- Light extraction was considered to be a high priority for both the core and product development of OLEDs. There was discussion on whether it would be necessary for both Core and Product Development. Some participants believed that light extraction at the core level is necessary, and has greater potential for reducing costs. It was also believed that placing it as both a core and product development priority allows a variety of stakeholders (both industry and academia) to participate in the work.
- It was continually stressed that improving efficiency and thin film outcoupling are essential to increasing light extraction as seen from OLED efficiency MYPP figures.
- The extraction efficiency 2010 status was increased to 45%, which has been demonstrated in R&D labs, but not yet achieved in production.

3.4. OLED Product Development Tasks

D4.2 Luminaire integration		
Description: Develop an OLED luminaire with thermal, mechanical, optical, and properties sufficient to achieve a cost effective energy efficient product with long lifetime and marketability. A general illumination application and luminaire design should be identified which are advantageous for the OLED technology. The luminaire performance metrics should be suitable for the identified application and the potential for energy savings should be quantified. This task includes maximizing light utilization for the application, thermal management to limit OLED source temperature, and electrical connections with the driver and among OLED panels.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Luminaire Efficacy		127 lm/W
Cost		
Lifetime (L70)		>50,000 hours
Shelf Life		10 years
Light Output		>600 lumens

Discussion Points:

- Developing fully integrated luminaire products was identified as a high priority task for 2011 with the major concerns being improved luminaire operating lifetime and shelf life.
- To solve some of the large area OLED panel problems the driver, interconnects, and larger system need to be considered.
- It was indicated that this task should solicit partnering proposals between luminaire, panel, and driver manufacturers.
- Maybe some work should be done to identify the market and luminaire types that OLEDs should be geared towards.
- Furthermore, marketability, luminaire efficiency and energy savings potential were stressed as being highly important for this task and it was indicated that these should be included in the metrics. Specifically, it was indicated that proposals should aim for developing luminaires with 10 year shelf life, less than 5% darkspots, greater than 600 lumens, an efficacy of 50 lm/W or greater than a 25,000 hour operating life.
- Including luminaire efficiency as a metric was heavily supported by one of the soapbox presentations which emphasized that application energy efficiency is not receiving enough research attention, and that OLEDs need to show a more aggressive development roadmap in order to keep pace with the progress of LEDs. The group was unable to determine a 2020 luminaire efficacy target (the above task uses the 2010 MYPP

projection). However, they did suggest that an appropriate 2014 target would be 100 lm/W.

D6.1 Large Area OLED		
Description: Demonstrate a high efficiency OLED panel, with an area of at least 200cm^2, with high light uniformity and long operating lifetime, employing low cost designs, processes, and materials and with the potential for high-volume manufacturing.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Lumen Output	40 lm	> 200 lm
Efficacy	45 lm/W	>150 lm/W
Color uniformity		1.5 to 2-step MacAdam ellipse
Brightness uniformity throughout the lifetime	10% over a small sample	10% over at least 200 cm^2
Cost of panel		<$2 ($100/m^2)

Discussion Points:

- The need to move from pixel to panel production was clearly emphasized throughout the roundtable event, and it is important that this task consider current distribution and thermal stability.
- The color uniformity, brightness uniformity and panel cost metric status and targets were modified. The color uniformity target was changed from Energy Star requirements to a 1.5 to 2-step MacAdam ellipse. For brightness uniformity the 2010 status was decided to be 10% over the panel and the new 2020 target was adjusted to be 10% over a 200 cm^2 area. Lastly, 2020 targeted panel cost was lowered to less than $2.

D6.3 Light extraction		
Description: Demonstrate manufacturable approaches to improve light extraction efficiency and, possibly, directionality for OLED panels. The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, or external to the device. The approach should be demonstrated over large areas and provide potential for low costs.		
Metric(s)	**2010 Status(es)**	**2020 Target(s)**
Extraction Efficiency	45%	75%
Incremental Cost		<$10/$m^2$

Discussion Points:

- The light extraction status for 2010 was increased from 40% to 45%, while no changes were made to the cost metric.
- In order to progress OLED technology for general illumination efforts need to be made on getting more light out of a single panel by enhancing outcoupling and improving extraction efficiency.

4. Projections and Milestones Discussion

The final group activity at the roundtable meeting was to review the LED and OLED projections and milestones as reported in the 2010 MYPP (Chapter 4). Note that the target year for overall performance metrics has been moved out to 2020. There are many significant possible improvements still to be made, but several are very challenging, and therefore difficult to predict as to timing. The 2020 targets represent an approximation, given what we know today, as to the capability of the technology. The tables and charts below include the updates that were suggested at the roundtables. The listed performance targets assume adequate funding for both the SSL Program and industry for the duration of the Program.

4.1. LED Projections and Milestones

Table 4.1 LED Efficiencies – 1: Phosphor-converted LED packages (warm-white)

Metric	2010	2020 Target
Electrical Efficiency	90%	95%
Internal non-radiative (IQE, blue)	80%	90%
Extracted light	80%	90%
EQE Current droop (35 A/cm^2 vs. peak)	92%	100%
Phosphor conversion efficiency	58%	72%
Scattering and absorption/ color mixing	80%	90%
Spectral Efficiency	77-80%	95%

Discussion Points:

- It was determined that the 2010 status for EQE current droop @ $35A/cm^2$ has increased from 85% in 2009 to approximately 92%, and the 2020 target value was made more aggressive and increased to 100%.
- It was noted that it would be much easier to provide updates for these metrics if the assumptions for each were included in the table.
- The spectral efficiency for phosphor converting LED packages was also increased to between 77-80% for 2010.
- It was stated that the phosphor conversion efficiency should be defined as on chip and was modified to be reflective of warm white.

Table 4.2: LED Efficiency Components – 2: Phosphor-Converted LED Luminaire (warm white)

Metric	2010	2020 Target
Additional EQE current droop (100 A/cm^2 vs. 35 A/cm^2)	77%	100%
Flux thermal stability to op. temp.	80%	90%
Phosphor conversion thermal stability	85%	90%
Driver efficiency (Power supply and controls)	85%	88-90%
Fixture and optical efficiency	84-90%	90%

Discussion Points:

- The additional current droop metric status for 2010 was increased to 77%, and it was noted that EQE efficiency droop does not account for the V_f change.
- It was agreed that a power level and current drive need to be added to the driver efficiency metric – a 40W driver is currently at 85% and has a target of 88-90%.
- For fixture and optical losses the range for 2010 was determined to be around 84-85%, however, some products have reached 90%. It was also indicated that this metric is extremely application dependent and simple diffuser designs will more easily get to the upper range.

Table 4.3: LED Efficiencies – 3: Color-mixed LED package

Metric	2010	2020 Target
Electrical Efficiency	90%	95%
Internal non-radiative (IQE, blue)	80%	90%
Internal non-radiative (IQE, green)	40%	90%
Internal non-radiative (IQE, red)	75%	90%
Internal non-radiative (IQE, amber)	20%	90%
Extracted light	80%	90%
EQE Current droop (35 A/cm^2 vs. peak)	92%	100%
Scattering and absorption/ color mixing	80%	90%
Spectral Efficiency	<75%	95%

Discussion Points:

- In was determined that we should begin looking at four color lines – RGBA which includes amber LEDs along with the red, green and blue, LEDs for color-mixed packages.
  - Currently amber LEDs are at an EQE of 10% and an IQE of 20% with an IQE target of 90%.
- It was indicated that the spectral efficiency will need to be recalculated if amber LEDs are to be included.

Table 4.4: LED Efficiency Components – 4: Color-mixed LED Luminaire

Metric	2010	2020 Target
Additional EQE current droop (100 A/cm^2 v. 35 A/cm^2)	77%	100%
Thermal Stability – Relative Optical Flux at 100 C vs 25 C	85% (Blue, Green) 50% (Red) 25% (Amber)	95% (Blue, Green) 75% (Red, Amber)
Driver efficiency (Power supply and controls)	80-82%	85%
Fixture and optical losses	84-90%	90%

Discussion Points:

- The inclusion of amber LEDs for color-mixed LED packages will cause the thermal stability for the luminaire to decrease.
- In addition, the driver efficiency status for 2010 has increased to between 80% and 82%. It was also determined that the previous driver target of 92% was too aggressive, and it was lowered to 85%.

Table 4.5: LED Milestones

Milestone	Year	Target
Milestone 1	FY08	LED Package: 80 lm/W, < $25/klm, 50,000 hrs
Milestone 2	FY10	LED Package: > 140 lm/W cool white device, >90 lm/W warm white; <$13/klm cool white
Milestone 3	FY12	Luminaire: 100 lm/W; ~1000 lumens; 3500 K; 80 CRI; 50,000 hrs
Milestone 4	FY15	LED package: <$2/klm (cool white)
Milestone 5	FY17	Luminaire: >3500 lumens (neutral white); <$100; >140 lm/W
Milestone 6	FY20	<$85 Smart Luminaire Troffer

Assumption: packaged devices measured at 35 A/cm2.

Discussion Points:

- It was noted that for Milestone 3, given the reference wattage of 75 W, the luminaire lumens of 1700 lm for neutral white is too high. Therefore, the 2012 target was modified to having a commercial grade down light for less than $100 at 100 lm/W (3500 K, 80 CRI) and a target of 1000 lumens with a lifetime of 50,000 hours.
- For Milestone 4 it was indicated that an LED package currently costs between $15 and $20/klm and that a target of $2/klm by 2015 for cool white implies a 200 lm/W package for $0.40. However, some are predicting that this target cost will be hit a year earlier. Milestone 4 also needs to specify that the target cost is for cool white LED packages.
- It was decided that Milestone 5 should be between 3,500 and 4,100 K with a CRI of 80, not 70-80. It was also determined that the target year should be changed to 2017.
- Milestone 6 was created for the target year 2020; however a clear target was not defined. It was determine that the target should consider that lumen maintenance, lifetime, and

smart system controls with all be important luminaire attributes. It was indicated that a price target could be set to between $70 and $100 for a luminaire troffer replacement that included some "intelligence."

- It was generally discussed that separate metrics should be provided and tracked at higher current density and temperature values since 35 A/cm2 and 25°C is not realistic for real world conditions. This information would be much more useful for tracking future progress.
    - Real world conditions are better represented by a 85°C case temperature and 350-700 mA drive current, as used in LM-80 testing.
- In addition, providing a separate graph for warm white LEDs would be useful.

4.2. OLED Projections and Milestones

Table 4.6: OLED Efficiencies – 1: OLED Panel

Metric	2010	2020 Target
Electrical Efficiency	55-60%	80%
Internal Quantum Efficiency	85%	95%
Light Extraction Efficiency	45%	75%
Spectral Efficiency	86%	95%

Discussion Points:

- It was determined that the 2010 status for electrical efficiency has increased from 2009 to between 55% and 60%, however the 2020 target value was considered to be accurate since Stokes losses prevent the target from increasing.
- The status for the light extraction metric has also increased for 2010 to about 45%.

Table 4.7: OLED Efficiencies – 2: OLED Luminaire

Metric	2010	2020 Target
OLED Panel	20%	54%
Power supply, driver, LED controls	80%	90%
Fixture and optical losses	70%	90%

Discussion Points:

- UDC indicated that they have reached an OLED panel efficiency of 20% for 2010.

Table 4.8: OLED Milestones

Milestone	Year	Target
Milestone 1	FY08	> 25 lm/W, < $100/klm, 5,000 hrs (pixel)
Milestone 2	FY10	> 60 lm/W panel
Milestone 3	FY12	< $45/klm panel
Milestone 4	FY15	>110 lm/W panel @ 10,000 lm/m^2
Milestone 5	FY18	50,000 hour lifetime; 10,000 lm/m^2 panel

Assumptions: CRI > 85, CCT < 2580-3710 K for an OLED panel >200 cm2. All milestones assume continuing progress in the other overarching parameters - lifetime and cost.

Discussion Points:

- It was extensively emphasized by the luminaire manufacturers that 100 lm/W for Milestone 4 is too late, and that this target needs to be met much sooner in order to remain competitive with LEDs.
    - CREE LR24 HE has reach 100 lm/W in 2010.
- The luminaire manufacturers (i.e. Acuity) stressed they would like to see 150 lm/W by 2015, however, R&D researchers stressed that the target should be no higher than 110 lm/W.

Appendix A Participant Presentations

Participants were given the opportunity to prepare short "soapbox" presentations outlining what R&D tasks they believed are particularly important and should be included in the SSL program, or on new areas of study that offer a potential for innovation and energy savings. The presentations were limited to 10 minutes and were followed by an open floor for questions. Summaries of these presentations are given below in the order that they were presented.

LED Presentations, November 10, 2010

I. Mark Hand, Acuity Brands Lighting, Inc.

- Only photopic vision is considered in current metrics, however, he suggests scotopic cool LEDs are more efficacious and states that more research should be done so that industry can move in the same direction as the market.
- Regardless, it is necessary to improve the quality of LED white light; definitive gains are essential.
- Driver life needs to be standardized for better communication and comparison, and the entire system needs to last as long as the LED.
    - Reliability is getting better and good work is being done in this area
- Additional research should also be directed towards glare. Glare affects the users' perception of brightness, and can be perceived differently based on physiologic and environmental factors. The lumen specification should incorporate perception based on the type of source.
- In addition, we need to focus on getting more and more lighting out of a particular light source

II. Fred Maxik, Lighting Science Group

- Focused on how the material consumption of LED lighting is far greater that the traditional technologies it is competing with.
- Emphasized that research efforts should be funded to create LED lighting sources and luminaires that consume one fourth the amount of material that is currently required.
    - Heat sinks are extremely material intensive and conductive polymers for this application could be an answer.
- We need to focus on creating sustainable structures and form factors of tomorrow, and should center attention on developing different and innovative ways to put LED products together.

III. Paul Pickard, Cree, Inc.

- The LED industry needs to focus on "using less stuff," and step away from tradition means of creating and integrating light.
- Paul emphasized that the market is going above and beyond CRI and efficacy projections, and that LEDs have in almost all cases reached the capabilities of the incumbent lighting technologies.
- However, in order to significantly increase the adoption of LEDs for general illumination it is now necessary to focus on decreasing time to payback.

- In addition, core technology funding needs to concentrate on projects that will enable leapfrog advancements in efficacy, and to do this we need to gain a better understanding of efficacy chokes.
    - Particularly research into understanding the fundamental science of droop will allow for rapid advancements in efficacy.
- Furthermore, Paul commented that the government needs to target more risky projects that private industry will not fund.
    - Paul defined a risky project that has only a 30% chance of success.

IV. Dennis Bradley, GE Lumination

- Dennis stressed that currently LED color reproducibility is not adequate, and that improvements to thermal capabilities and droop are necessary.
- Furthermore, standardization of packaging (a supply chain issue) is necessary to reducing cost.
    - The move to standardization greatly aided the consumer electronics industry.
    - Comment: However, if enacted to quickly this could constrain and limit innovation of LED products.
- He also emphasized the importance of increased driver efficiency and the need for better lifetime predicting.

V. Jim Anderson, Philips Color Kinetics

- Highlighted the high level system prospects for LED lighting products and the compatibility for dimability and controllability, sensors and intelligence software.
- He described how lighting systems in buildings use commissioning (a form of smart system controls) where zones within each building are defined based on the type of space and then sensors are installed according. The problem is that currently these systems are not adaptable to changes in building space, and maintenance does not keep-up with these changes which greatly reduces the potential cost savings. Therefore, improving the sensing intelligence and controllability of LEDs will greatly aid light commissioning in building spaces.
- LEDs have the potential for more effective integration of lighting control systems and we need to determine what types of sensors should be imbedded into the LED luminaire structure.

VI. Nathan Gardner, Philips Lumileds

- Emphasized that droop is extremely important, however when the problem is resolved, LEDs will be driven at higher current densities resulting in higher operating temperatures, which will generate problems with thermal control and thermal materials, particularly solders. Currently, low cost high temperature solders are unavailable, and therefore material development for solders is necessary.
- Research will also be required into improved thermal handling capabilities of LEDs.
- He also pointed out the need to determine the potential negative impacts of 450 nm blue light from LEDs on animals and humans. The released reports and studies on these potentially negative health impacts could have significant consequences for the LED market because they provide doubt for the consumer

along with forcing industry to spend time/money and focus away market adoption activities.

- Comments: There is somewhat unwarranted elevated concern in regards to the effects of blue light from LEDs on human health, however, we need to be aware of the possibility for increased media attention which is very difficult to mediate.

VII. Mark Pugh, Xicato

- Field studies have indicated that the initial and lifetime color shift for LED products is significant, therefore, we need to determine better target values and track color shift over the lifetime of LEDs.
- He emphasized that the key sources of color shift are the light source, secondary optics and large acceptable CCT range.

VIII. Wendy Davis, National Institute of Standards and Technology

- Wendy indicated that current LED products have a tradeoff relationship between color quality and luminous efficacy.
- In order to help direct a greater focus on improved color, two changes have been proposed for the ANSI C78.377 SSL specifications for chromaticity:
    - The current boundary lines have jumps and dips which are not consistent with the flexible CCT, therefore it is proposed that the boundary lines be smoothed.
    - It is also proposed that the center points be lowered down to the blackbody locus to put a greater emphasis on better color and less efficacy.
- In addition, she also highlighted the problems with the CRI metric since products that have good color rendering are not meeting CRI standards. This is because CRI does not represent red vibrance which is something unique to LED lighting sources. Therefore, she indicated that NIST is looking at CQS as an additional metric for color quality.
    - Comments: However, there are still multiple concerns with CQS since it penalizes less for over saturation.

IX. Bob Karlicek, Smart Lighting ERC, RPI

- Bob emphasized the importance of designing SSL lighting for the benefit of humanity that delivers the full potential of engineered light for improved human health, productivity and safety.
- In order to increase the benefits of LED lighting, it is necessary to focus attention on the system portion of lighting and moving to digital lighting and smart lighting environments that incorporate sensors and adaptive lighting control systems.
- He emphasized that currently sensing technology is not designed for LEDs and is currently bulky, expensive and does not offer a high level of performance. Therefore, he highlighted the need to look at optoelectronic integration by incorporating the electronic sensing into the emitter (i.e. moving the system into the chip).

X. Bill Weiss, Power Integrations

- Bill presented the need for improved driver lifetime rather than reliability, and indicated the limiting factor of driver lifetime is that the thermal designs for the capacitors.
  - Aluminum electrolytic capacitors are solely used for LED drivers since other options, such as electrolytic free systems are too high cost, bulky and require more solder joints which infringes upon driver reliability.
- Therefore, the greatest challenge to driver lifetime is the thermal management of the aluminum electrolytic capacitor case temperature, particularly for LED replacement lamps.
- In addition, he emphasized that the end of life for aluminum electrolytic capacitors is not characterized by a catastrophic failure, but rather by changes in capacitance and dissipation factor, as well as increased leakage current which in turn increase the LED ripple current.
- Furthermore, improved driver design and better capacitor section by manufacturers will also greatly enable the extending the lifetime of LED drivers.

XI. Bernd Clauberg, Philips Advance

- Bernd indicated that adding controllability to LEDs that allows light levels to be reduced offers the potential for significant energy savings and reduced maintenance and system costs. This controllability can be obtained by adding controllability features to the driver that allow light level adjustments to exactly match the levels needed under all conditions.
- Controllability can be added to the driver through the use of sensing or by using a digital addressable remote controlled network LED drivers.
- In addition, he highlighted the importance of increasing the reliability of LED drivers and developing more accurate ways of testing for it. Unlike lifetime, reliability is difficult to predict and customers are demanding product documentation on reliability.

XII. Jeff Tsao, Sandia National Laboratories

- Jeff argued that the private investment target traditional lighting, therefore, government research funding needs to focus on ultra high efficiencies at the source and system levels.
- Lasers have the potential to offer these ultra high efficient lighting needs. Lasers for general illumination offer narrow linewidths which can be used to achieve very high luminous efficacy over a broad range of color temperatures. In addition, lasers produce simulated emission enabling high power at low carrier densities which could potentially eliminate droop, and achieve superior directionality.
- Jeff emphasized that narrow linewidths of RYGB lasers do not limit their potential for general lighting applications and that they do offer good color rendering and light quality
- Lastly, he indicated the needed to bring luminaire functionality into the LED chip electronics. This increased functionality presents a great opportunity for much higher efficiency and productivity of light use.

XIII. David Hum, Bridgelux

- David stressed that rapid technology improvements in the SSL market have led to the inability to test for product reliability before it has been released.

- Current reliability tests are measured in real time and are long in relation to innovation cycles in component design, therefore, in order to keep pace with innovation, there is a critical need for accelerated reliability testing and better predictive modeling methods.

XIV. Monica Hansen, Cree, Inc.

- Monica indicated that there is a significant lack of understanding surrounding the fundamental science of droop in nitride LEDs. Although advances in materials and heretrostructure design will continue to result in incremental improvements, research funding needs to be allocated to projects that offer potential to bypass droop entirely.
- Furthermore, she emphasized core technology research needs to focus on finding a proven method to eliminate droop, and then product development research and the industry needs to advance technology forward.

XV. Mike Krames, Soraa

- Mike presented that there is need for increased research funding into the development of cheap large area substrates. He indicated that there are numerous issues with silicon and sapphire foreign substrates and that they both require complex backend removal and processing.
- He then recommended that research funding focus on native substrate opportunities since they offer potential benefits including, ultra low dislocations, reliability at high current densities, simplified chip architecture, high thermal conductivity, as well as reduced droop.
    - In particular he emphasized that bulk GaN offers significant potential as a low cost and low material demand substrate.
- Comments: It is first necessary to demonstrate that GaN offers significant performance (and cost) benefits before committing significant funding for bulk growth.

XVI. Claude Weisbuch, University of California, Santa Barbara

- Claude indicated the need for improved measurement and simulations for the testing of SSL technologies.
- Particularly he pointed out the poor extraction efficiency with conventional photonic crystal (Phc) LEDs and that using embedded Phc LEDs great increases the extraction efficiency due to its short extraction length.
- He emphasized temperature-dependent PL is not an accurate method to measure IQE and instead proposes using a simple LED geometry.
- He indicated that better phosphor conversion is achieved by employing methods to achieve improved LED-phosphor coupling, such as the use of waveguides.
- Lastly, he specified that extraction development for SSL products needs to be expanded to the phosphor.

OLED Presentations, November 12, 2010

I. **Michael Lu, Acuity Brands Lighting, Inc.**

- Michael emphasized that application energy efficiency is not receiving enough research attention and that OLEDs need to show a more aggressive development roadmap in order to keep pace with the progress of LEDs
- In terms of efficiency, he indicated that OLEDs are expected to achieve parity or better after 2013 based on Mike Hack's UDC projections, however this will be too late
- In order to increase the rate of OLED development, research into proper lumen distribution is key since this may enable a reduction in the total luminous output needs by 25% or more
- Michael also indicated that OLEDs for general illumination need to focus on improving their indoor lighting applications

II. **Shelley Wang, WAC Lighting**

- Shelley indicated that the OLED community needs to focus on what the customers want which is quality white light
- She specified that there are a variety of opportunities for OLEDs to outperform LEDs
- Efficient glare control in OLEDs can be obtained by reducing the number of layers in controlling the light
- Full spectrum color can be achieved through OLED layering
- OLEDs offer dimming capabilities similar to that of incandescent lamps, however we need to ensure that at reduced light level the color remains warm
- In addition, she emphasized that OLEDs have opportunities as an upscale light source, however in order to achieve this clear distinction from LEDs is necessary. Furthermore, OLEDs should not be designed to replace conventional lighting, and should instead focus on creating new form factors.

III. **Vsevolod Rostovtsev, DuPont Central Research and Development**

- Vsevolod indicated that there are a variety of major challenges for OLED SSL manufacturing. Some of which include the need for drastically lower cost for every component and manufacturing process step both in core and product development, as well as decreased power consumption and increased lifetime.
- In order to mitigate these challenges he suggested a variety of focused research efforts, including:
  - Simplify OLED architecture by introducing 1 micron thick layers, and reducing the number of layers per device to reduce process variables. This will aid in making OLEDs more cost effective
  - Focusing on the use of sustainable materials and moving away from rare electrode and emitter materials
  - Reducing the encapsulation cost
  - Increasing OLED efficiencies through enhanced outcoupling
  - The improvement of plastics substrates to enable simpler fabrication

- Improving the thermal management of OLEDs since luminance loss accelerates as operating temperatures increase

- Vsevolod commented after his presentation that increasing the simplification of OLED architecture by reducing layer thickness to 1 micron, and increasing process robustness are the most important tasks.

IV. Michael Hack, UDC

- Michael stressed that there are many critical elements to improving OLEDs for general illumination, and that the industry needs to think about the integration of all the OLED components
- He particularly emphasized three technical areas that are of high importance, these include the development of cost effective thin film out coupling, intensity shaping/removing glare, and the moving towards designs that allow for high yield with color reproducibility and no failures
- He presented that the industry also needs to move away from pixels and to panel production, and if a practical OLED limit is 180 lm/W for a pixel, panels need to exhibit 90% of the pixel and luminaires should be 85% of the panel
- When asked when panel products will be available on the market he responded that OLED panels will be for available for purchase starting in 2012

V. John Hamer, OLEDWorks LLC

- John emphasized that the general illumination OLED market need to learn from the failures of the OLED display industry by ensuring there are quantifiable benefits to adopting OLEDs compared to the incumbent technologies
- Furthermore, OLED production needs to be firmly established in the U.S. or else a large opportunity with have been missed
- Three key areas of focus were identified by John as able to inhibit the sustainable growth of the OLED industry: Lower cost of production in order to increase efficiency, the creation of niche OLED products that offer profit at medium to low volumes, and collaboration among suppliers, manufacturers and universities.
- John indicated that in order to obtain a profit at low product volumes there is a need for joint projects between luminaire makers and panel makers that focus on 6k-8k lm/m2 operations that exploit the beauty and simplicity of direct OLED light
- If order to achieve a profit at low product volumes, low cost is essential. This will involve increasing throughput and material usage efficiency, lowing the cost of equipment and light extraction, as well as increasing yields
- When asked which area is the highest priority for advancing OLEDs in 2011 Mike responded that light extraction is most critical

VI. Joe Shiang, GE Global Research Center

- Joe indicated that the efficiency and lifetime for OLEDs are progressing, and that the major barrier is cost, and therefore, it is necessary to develop a pathway to reducing the costs associated with manufacturing OLEDs
- For core research he highlighted that production speeds need to get faster. In order to achieve this designs need to be simpler and more robust by reducing the number of layers, increasing the amount of processing that is ambient, and using longer lifetime materials
- For product development fully integratable luminaire products that have longer lifetimes (both shelf and operating life) are essential. It is also imperative that process robustness be incorporated to luminaire systems so that designs can tolerate variability in manufacturing
- It was also indicated that right now OLEDs are comparable to a compact fluorescent in terms of lifetime and efficacy, however, they are 100 times the cost

VII. Mathew Mathai, Plextronics

- Matthew argued that a OLED luminaire must provide a minimum of 600 lumens to be considered a light source, therefore, in order to progress OLED technology for general illumination we need to increase the light output by improving efficiency and outcoupling
- He indicated that efforts need to be made on getting more light out of a single panel
- Specifically he noted that there are needs for significant improvement to thermal management, light outcoupling, light extraction, color uniformity, reduction of non uniform degradation and current leakage

VIII. Robert Jan Visser, Applied Materials

- Robert argued that real manufacturing systems of OLED lighting panels are not available; therefore there is a clear need to invest in manufacturing technology. Specifically, the DOE should prioritize the development of mass manufacturing equipment for thin film encapsulation, as well as focus on large scale OLED panel manufacturing
- In addition, he indicated there in a need to reduce the number of multilayer coatings and increasing product lifetimes

IX. Franky So, University of Florida

- Franky specified that reducing cost, and increasing lifetime and light extraction are key areas for prioritization
- We need to work on extracting more light from the substrate and thin film, and that extraction of the thin film guided mode has the potential to provide more light
- He recommends the exploration of top emitting devices which can use metal foil instead of plastic substrates for roll to roll processing. This can provide better

thermal management because of higher thermal conductivity and reduces concern over encapsulation. However, more light is trapped in the substrate for top emitting devices, therefore, optical buffer layers need to be considered with offer the potential for double the light output

X. Asanga Padmaperuma, Pacific Northwest National Laboratory

- Asanga clearly expressed the importance of light extraction, thermal management, and the need for white architectures with long lived stable white, control color quality and stable blue for OLED core research. As well as the need for developing low cost flexible metal foil, or plastic substrates which will help in reducing the cost of web processing
- Particularly for thermal management, he indicated that there is a need to study the effect of temperature on color and efficacy and how to measure, model and then mitigate these impacts

XI. Jian Li, Arizona State University

- Jian suggested that device operational stability, quality of white light, simplified device structures and color aging were key issues for OLED lighting. He argued that materials can be made better using existing device structures and focusing on less demanding architectures
- Furthermore, he indicated that Excimer-based WOLEDs show promise and that the Pt based emitters can be used to create stable blue emitters. Jian then recommended further development of single emitters for monochromatic OLEDs which would greatly simplify manufacturing

XII. Ching Tang, University of Rochester

- Ching emphasized that instability is an important limitation for OLEDs, and that there are variety of issues associated with the stability of the emitting layers. Therefore, we need to determine how each layer interface leads to instability and degradation
- In addition, he argued for great corporation between universities, manufacturers and suppliers since there is a reluctance to share data the is inhibiting research effects in academia

XIII. Arnold Tamayo, Colorado School of Mines

- Arnold indicated that materials that have different properties need to be combined to develop a material that is a phosphorescent, stable and processable solution. Particularly, he emphasized combining materials that have already undergone significant study, and processing non conjugated polymers to make emissive wide band gap solutions. He also commented that processing of phosphorescent and fluorescent solutions needs to be researched because they offer potential for less complex and cheaper designs with only a single or double layer.