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

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Prepared by:
Bardsley Consulting,
Navigant Consulting, Inc.,
Radcliffe Advisors, Inc.,
SB Consulting,
and
Solid State Lighting Services, Inc.

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DISCLAIMER

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<u>DOE Roundtable Participants</u>

LED Participants

Mehmet Arik	GE Global Research Center
George Brandes	Cree, Inc.
Mike Coltrin	Sandia National Laboratory
Steve DenBaars	University of California, Santa Barbara
Kevin Dowling	Philips Color Kinetics
Alexei Erchak	Luminus Devices, Inc.
Eric Haaugard	Ruud Lighting, Inc./BetaLED
Mark Hand	Acuity Brands Lighting, Inc.
Gerard Harbers	Xicato, Inc.
Bernd Keller	Cree, Inc.
Steve Lester	Bridgelux, Inc.
Cameron Miller	National Institute of Standards and Technology
Mathew Sommers	GE Lumination
Daniel Steigerwald	Philips Lumileds
Jeff Tsao	Sandia National Laboratory
Christian Wetzel	Renssalaer Polytechnic Institute

OLED Participants

Norman Bardsley	Bardsley Consulting
Curtis Fincher	DuPont Displays
Troy Hammond	Plextronics, Inc.
Ruiqing Ma	Universal Display Company
Peter Ngai	Acuity Brands Lighting, Inc.
Asanga Padmapuruma	Pacific Northwest National Laboratory
Joe Shiang	GE Global Research Center
Gary Silverman	Arkema, Inc.
Franky So	University of Florida
Steven Van Slyke	Eastman Kodak Company
Yuan-Sheng Tyan	Eastman Kodak Company

COMMENTS

The Department of Energy is interested in feedback or comments on the materials presented in this document. Please write to James Brodrick, Lighting R&D Manager:

James R. Brodrick, Ph.D.
Lighting R&D Manager
EE-2J
U.S. Department of Energy
1000 Independence Avenue SW
Washington D.C. 20585-0121

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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 27 experts in SSL to Washington, DC on November 3rd to the 5th of 2009 for the SSL roundtables. The purpose of these roundtables was to advise DOE on which R&D tasks are currently most needed in order to advance solid state lighting products.

These 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 “soapbox” presentations, which allowed participants the forum to present topics for consideration they felt to be important. For additional information on these presentations see Appendix A.

The task prioritization conversation followed. During this conversation, participants provided for each R&D task general comments either in support for prioritization for DOE funding in 2010 or reasons they felt it to be untimely. A total of 12 LED core tasks, 22 LED product development tasks, 9 OLED core tasks, and 19 OLED product development tasks were covered[1]. From this master list an abridged list of suggested priority tasks was formed.

After the prioritization discussion, participants discussed the current status and targets for various metrics assigned to each prioritized task. The final stage of the roundtable was to review 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 2010 Solid-State Lighting R&D Workshop in February. During this workshop, the task discussion will continue and feedback on the task prioritization list developed at the roundtables will be sought. These recommendations will inform the final choices of priority tasks which will guide the DOE and the National Energy Technology Laboratory (NETL) in developing R&D competitive solicitations..

3. Prioritization Discussion

The 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

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

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. SSL manufacturing issues, objectives, tasks and priorities will be explored in a separate workshop and an updated Roadmap in 2010.

Participants reviewed each task offering their suggestions as to why or why not a task should be prioritized for the coming year. This discussion is summarized below in Sections 0 of this report. The LED participants proposed five core technology tasks for 2010 prioritization, three of which were high priority tasks in 2009, and five product development tasks, two of which were priority tasks in 2009. The OLED participants proposed four core technology tasks, three of which were high priority tasks in 2009, and five product development tasks, one of which was a high priority task in 2009. In addition, several tasks are listed as “close calls”. These tasks received a healthy amount of support for prioritization; however roundtable participants felt they were slightly less in need of immediate funding than the prioritized tasks.

Participants’ decision to prioritize a task was guided by two required criteria. The first being that for prioritization the task should substantially improve the efficiency, cost or lifetime of LEDs or OLEDs. If that criterion was fulfilled, then participants considered whether DOE funding was necessary for the task or if it would accelerate progress towards DOE goals beyond what market forces alone might accomplish.

After the initial prioritization, participants discussed the specifics of the tasks for which there was consensus they should be recommended for priority. The initial step was to verify that the description properly communicates the work needed to be performed. Participants then selected appropriate metrics that would best measure progress for the tasks. Participants also provided the current, or 2009, status and the 2015 target. Targets were selected that participants believed would be challenging but accomplishable.

3.1. LED Core Research Tasks

A1.2 Emitter Materials Research		High Priority
Description: Development of efficient green LEDs and a broader range of red (610-650 nm) LEDs to allow optimization of spectral efficiency for high color quality over a range of CCT. This task additionally includes efforts aimed at reducing current droop and minimizing thermal sensitivity for all colors including blue LEDs.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
IQE	Green: 40% (540 nm) Red: Unknown @ 35A/cm^2 Blue: 90% @ 35A/cm^2	90% IQE @ 150A/cm^2
EQE	Green: 26% (520nm) @ 35A/cm^2 Red: Unknown Blue: Unknown	75% EQE @ 150A/cm^2
Droop - Relative wall plug efficiency 35A/cm^2 vs. 150A/cm^2		Improve relative efficiency by a factor of 2

Prior to discussing whether A1.2 Emitter Materials Research should be a priority task some participants suggested dividing this task into two tasks, one focusing on droop and the other on thermal sensitivity.

Though there was not significant opposition to prioritization of this task, some participants believed that this task does not require core research and that prioritizing the corresponding product development task, B1.2 Semiconductor Materials, would suffice.

In support of prioritization, participants agreed that this research area has been a consistent priority for the DOE year in and year out. The group believed that there is still a substantial amount of core work to be performed in this task. As indicated by the several soap box presentations on this topic, eliminating or reducing current and thermal droop could allow a single chip to run at higher current densities, thus significantly reducing cost.

In reviewing the description, participants stressed that the task should be focused on performance at high current densities. In addition, there was consensus the description should be changed to highlight performance of over a broad range of red. Some stated that droop and temperature sensitivity in blue LEDs need to be emphasized as much as green and red IQE. Finally, some participants felt that research into alternative substrates should be permissible under this task, while others doubted that new alternative substrates were needed. For the metrics, participants proposed that given the difficulty and uncertainty in calculating IQE, EQE should be used as the metric. This idea did not have universal support since the principal thrust of this task is to improve the IQE no extraction efficiency. In addition, because the task description highlights reducing droop, droop was included as a metric. The 2009 statuses and 2015 targets are show above. In establishing the targets, participants emphasized the need for improved performance at high current densities by specifying IQE and EQE targets at 150 A/cm2. The target for the droop metric was kept consistent with the target established in task B1.1 Substrate Development.

A1.3 Down Converters		High Priority
Description: High-efficiency wavelength conversion materials for improved quantum yield, optical efficiency, and color stability over temperature and time. Explore novel approaches to conversion.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Quantum Yield	80% warm @ 100ºC 95% cool @ 25ºC	90% across visible spectrum @ 100ºC 95% across visible spectrum @ 25ºC
Color Stability	Color Shift of 0.012 u' v' over life	Color Shift < .004 u' v' over life
Temperature Stability	15% drop in yield from 25ºC to 100ºC	5% drop in yield from 25ºC to 100ºC
Spectral Full Width at Half Maximum	150nm width @ 610-620 nm	Achieve a narrow red peak response (<50nm width @ 610-620 nm peak)

Some commented that core research under this task is likely to be in such topics as new materials, quantum dots, and possibly new phosphor systems which could overlap with task A2.2 Novel Emitter Materials and Architectures.

In support of prioritization, several people pointed out that there is a need for phosphor research in the U.S. to expand the intellectual property portfolio which is dominated by non-domestic suppliers. This research has implications for a wide range of characteristics including color consistency, color reliability, efficacy, thermal efficacy degradation, and system reliability, all of which are drivers of customer adoption. While the conventional phosphors are performing very well, it was suggested that additional phosphor options could substantially improve spectral efficiency and color quality.

The description was changed to state that color stability over both temperature and time should be improved. Temperature stability and spectral full width were proposed as added metrics for this task, for consistency with task B1.3 Phosphors. For the 2009 statuses, though the values of quantum yield, scattering losses, and color stability did not change, the group added greater specificity to metric by adding actual temperatures at the quantum yield values. Stressing the high importance of color uniformity for market acceptance, the group modified the 2015 color shift target from 0.007 to 0.004 u'v' over the lifetime of the LED.

A2.2 Novel Emitter Materials and Architectures		High Priority
Description: Devise alternative emitter geometries and emission mechanisms in manufacturable configurations that show genuine improvement over existing approaches. (Possible examples: monolithic integrated RGB, 360 degree emitters, microcavities, lasers, photonic crystals)		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
EQE @ 35A/cm^2	Color-mixing LED: Green: 26% (520nm) Red: 38% red (610 nm) Blue: 64% Phosphor LED: 64%, Phosphor Conversion Efficiency=65%	EQE=81% (including all three colors in color-mixing LED)

Some participants believe that high light extraction is already achieved without using photonic crystals and thus additional research would be valueless. The extraction efficiency is believed to be 70-80%.

Conversely, certain members were particularly excited about the potential of using photonic crystals for light extraction and directionality. Others were equally excited by lasers and microcavities as new technologies and claimed they need further research. Exploratory research into these technologies has shown promising results. Participants also believed that research into novel emitter materials and architectures was a task from which the greatest breakthroughs to increase could come.

When reviewing the description, participants stressed that this task should include novel approaches, such as the use of lasers, which go well beyond conventional LED package designs. They suggested adding microcavities, lasers, and photonic crystals to the list of research areas provided as examples. Also, the 2009 EQE status of the green emitter for a color-mixing led was updated from 16% at 540 nm in 2008 to 26% at 520 nm. The 2015 target remained unchanged.

A6.3 System Reliability Methods		High Priority
Description: Develop models, methodology, and experimentation to determine the system lifetime of the integrated SSL luminaire and all of the components based on statistical assessment of component reliabilities and lifetimes. Includes investigation of accelerated testing.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Model Accuracy vs. Experiment	LM-80	99% at 6 kHrs, 90% at 50 kHrs

Participants discussed three general issues related to this task:

- Some stated that A6.3 (System Reliability Methods), A5.1 (Optical Component Materials) and A7.5 (Electronics Reliability Research) could be combined into one broader task.
- There is a need to find or develop a standard to characterize LED lifetime that people are familiar with and adopt it.
- A participant suggested that the scope of this task could include the development of a standard methodology for characterization of reliability for the industry to use as a reference. DOE does not directly support standards under the R&D solicitation process, but could fund technical work in support of standards development.

Some participants stated their concern that the models and methodologies developed through this task may quickly obsolete if the package architectures they represent are modified. In addition some on the team questioned what the benefits are of funding research in system reliability. They believed that the research may happen whether or not the DOE is involved.

In support of prioritization, participants stated that lumen maintenance per LM-80, is misused and not an adequate measure of reliability because it does not account for many additional potential failure mechanisms. The lack of an adequate industry standard to assess reliability increases the importance of research in this area to develop a better understanding of failure modes and new methods to assess failure. Participants stated that while the concern that the models may become obsolete is valid, there are ways to avoid or adapt for this issue. One possibility is that the research could aim to develop a global model for predicting reliability, which is general enough to work for any LED luminaire system. The team also stressed that work under this task need not actually solve the issues of systems reliability; only investigate methods to predict systems reliability. Finally, participants mentioned that this task should result in increased warrantee confidence, decreased product development time, and increased customer confidence in lifetime predictions.

Participants did not suggest any changes to the description, metric, or status.

A7.5 Electronics Reliability Research		High Priority
Description: Develop designs that improve and methods to predict the lifetime of electronics components in the SSL luminaire.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Potential Installed Lifetime or Accuracy of Predictive Model vs. Long Term Actual Results	Unknown	Comparable to the installed LED life

After discussing and deciding to prioritize task A6.3 System Reliability Methods, the group discussed this task. As it seemed like a subset of the previously discussed subtask, there was significant support that this task should be combined with task A6.3. Notwithstanding the possibility of combining the tasks, there was significant support to prioritize this task for similar reasons to the ones stated above. Participants stated that a combination of performance uncertainty, the lack of long term empirical data, and insufficient reporting standards has made reliability a major barrier to implementation of LED luminaires, thus necessitating prioritization of this task.

The group did not suggest any changes to the description. However, for the metrics, participants suggested that "lifetime" should be specified as "installed lifetime". The group was unable to provide a 2009 status and stated that the 2015 target should be comparable to the installed LED lifetime in a particular application.

A1.1 Alternative Substrates
Description: Explore alternative practical substrate materials and growth for high quality epitaxy so that device quality can be improved.

Participants argued against prioritization, by stating that there is not a current need for entirely new substrate materials. In addition, it was mentioned that substrate research should not be done without demonstrating some sort of performance or cost improvement so the task is not appropriate for core. If researchers are focusing on performance improvements, the work can be done under task A1.2 Emitter Materials Research. If cost improvement is the goal, the work is more appropriate for task B1.1 Substrate Development. Participants also stated that since the substrate research is generally well below the maturity level of other core work, demonstrating the benefits to funding such a task may be low. In support of this task, one participant mentioned that if the task was to focus on new growth techniques, an area needing more research is new crystal growth techniques.

A3.4 Device Packaging Thermal Control Research	Close Call
Description: Simulation of solutions to thermal management issues at the package or array level. Innovative thermal management solutions.	

In opposition to prioritization, participants stated that manufacturers are currently experiencing diminishing returns in their chip performance by improving thermal management. Manufacturers at the roundtable also believed that very good thermal materials existing in the market today, but they are very expensive. Thus research is needed to solve the costs, which is more of a product development task. In support of prioritization, one participant insisted that thermal management is arguably the most important part of the LED technology and therefore should be prioritized.

A4.4 Manufacturing Simulation
Description: Develop manufacturing simulation approaches that will help to improve yield and quality of LED products.

This task will be covered in the SSL Program's manufacturing work and was not discussed further at the roundtable.

A5.1 Optical Component Materials
Description: Develop optical component materials that last at least as long as the LED source (50k hours) under lighting conditions which would include: elevated ambient and operating temperatures, UV and blue light exposure, and wet or moist environments.

In opposition to prioritization, the group mentioned that the SSL industry is sufficiently working on this task independent of DOE investment. In addition, the optical material industry is quite mature and data on their products are available. The consensus was that given the maturity of the technology, this topic was not readily addressable through Core research. Some participants question what the overall system benefit would be to improving optical materials.

A7.4 Driver Electronics
Description: Develop advanced solid state electronic materials and components that enable higher efficiency and longer lifetime for control and driving of LED light sources.

In opposition to prioritization, participants questioned whether there was core research that could be done on driver electronics. This concern was supported by the fact that since the priority for this task must be to reduce costs, the team believed that research would be driven by market forces. Finally, members stated that the status of driver efficiency is currently very high, only 7% less than the 2015 target.

In support of prioritization, participants stated that dimming drivers are hard to come by in the market and could use research. In addition there has been original concept of developing components using new wide band gap materials which can solve some of the issues with existing drivers.

3.2. LED Product Development Tasks

B1.1 Substrate Development		High Priority
Description: Develop alternative low cost, high quality substrates amenable to high efficiency manufacturing at low costs and demonstrated improvement in LED performance (e.g. reduced droop, better thermal performance, Green EQE)		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Cost of LED Device ($/klm);	$10-20/klm (cool white, SiC or sapphire) +$7 for bulk GaN substrate (excluding fab, yield, etc) ($35A/cm^2$)	$2/klm ($35A/cm^2$)
Substrate Cost ($)	Bulk GaN: 2" nonpolar/C-plane @ >$2,000 for a 2" wafer	$1,000 for a 4" wafer (GaN)
Droop - Relative wall plug efficiency $35A/cm^2$ vs. $150A/cm^2$	Green (520nm) 30% EQE Blue 69% EQE (20A/cm2)	Droop – improve relative efficiency by a factor of 2 Green EQE > 81% @ (540 nm, 35A/cm2)

Participants discussed general issues prior to discussing whether B1.1 Substrate Development should be a priority task:

- This task was discussed at the manufacturing workshop and was referred to this group as an area that should be prioritized in product development. The manufacturing workshop believed this task was not ready to be funded in the manufacturing initiative as there was still work to be done to prove it was a viable investment.
- Some believed that this task belonged under Core Technology rather than Product Development. However, others supported its classification as product development because alternative substrates are commercially available, and because demonstration of improved performance in an actual LED is critical to determining viability.

In opposition to prioritization, participants stated that manufacturers will be hard pressed to adopt any resultant solutions (alternative substrates) of this task because of the re-optimization of their manufacturing process that would be required. Participants pointed out that the manufacturing and infrastructure impacts of this research will require a very large program, one that would require substantial resources.

In support of prioritization, participants stated that there is the need to scale up to 4" (and even potentially 6") from 2" substrates, even with conventional choices, in order to bring the costs down, remarking that the semiconductor materials industry perceives 6" to be relatively small. This task would enable that product development for LEDs. Another advantage of this task was that new substrates could enable whole new levels of performance. The roundtable also stated that in several areas there are diminishing returns in efficiency with the substrates currently begin used in LEDs. Also, historically only the government has been willing to fund this task, other will not do so. Thus, if this task is not supported here, then it will not be supported anywhere. In addition, participants stated that a basic cost benefit analysis shows that this task would have a greater impact than task B5.2 Color Maintenance, which the group decided to prioritize.

The participants revised the description to emphasize that in addition to cost the alternative substrates should demonstrate improved performance, specifying droop, thermal performance and green EQE of particular areas of interest. For metrics, participants strongly supported $/klm because it combines both the cost and performance aspects of this task. Then also added substrate cost as a separate metric. The group updated the 2009 status and created targets for this task focusing on increased substrate size and improved performance to ultimately result in an over commercially viable $/klm.

B1.2 Semiconductor Material		High Priority
Description: Improve wall plug efficiency at optimal wavelengths for producing white light across the visible spectrum (red: 610nm; green: 540nm). Improve droop and thermal sensitivity.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Wall plug efficiency	Blue: 50-55% (450 nm, 35A/cm^2) Green: 21% (green 520nm) Red: 35% (615 nm, 35A/cm^2)	75% @ 35A/cm^2 for all three colors (460nm, 540nm, 620nm)
Droop - Relative wall plug efficiency 35A/cm^2 vs. 150A/cm^2		Improve relative efficiency by a factor of 2

Participants discussed two general issues related to this task:

- The roundtable decided that this task envisions a packaged LED (prototype close to commercialization) as a deliverable. It should demonstrate a better green or red LED or a droop free blue LED, for example.
- This task was recommended for prioritization at the manufacturing workshop.

While some participants believed that chip manufacturers are already doing this work on their own, others believed that this task would greatly benefit from DOE support. This task would support projects which generally pursue higher risk approaches than the LED companies would fund internally.

In support of prioritization, participants stated that there is a need for more research geared towards lumens per watt (performance). In addition this task follows the SSL program strategy of buying down risk that industry is not willing to take. This work would then be helpful to smaller companies. Another support was that this task was originally suggested through the manufacturing roadmap. Finally, participants believed as of yet there is still no good solution for the reduced droop and thermal sensitivity in red and green regions of the spectrum and thus research is needed.

Participants felt that the previous description which focused on IQE was inappropriate as a product development task and was difficult to calculate. Therefore, they changed both the description and metric to refer to wall plug efficiency. In addition, because the task description highlights improving droop, droop was also added as a metric. Accordingly, the status and the targets were updated to be consistent with wall plug efficiency and task B1.1 Substrate Development statuses and targets for droop.

B1.3 Phosphors		High Priority
Description: Optimize phosphors for high efficacy LED white light applications, including color uniformity, color maintenance, thermal sensitivity and stability.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Quantum Yield	80% longer wavelengths, 95% shorter wavelengths	90% across visible spectrum
Color Stability	Color Shift of 0.012 u' v' over life	Color Shift <.004 u' v' over life
Temperature Stability	15% drop in yield from 25ºC to 100ºC	5% drop in yield from 25ºC to 100ºC
Spectral Full Width at Half Maximum	150nm width @ 610-620 nm	Achieve a narrow red peak response (<50nm width @ 610-620 nm peak)

Participants discussed three general issues prior to discussing whether B1.3 Phosphors should be a priority task:

- A source of data on existing phosphors would be useful in developing statuses; however, information on many phosphors is held confidentially by many companies
- This task should be more focused on the development and application of somewhat mature phosphor technologies into LED lighting products.

In support of prioritization, participants stated that better phosphors (with better stability) are needed, preferably from the U.S. In addition, development in this area could result in other colors, commercialization of quantum dots, or solutions to thermal issues. Roundtable participants also stated that the private sector has been hesitant to invest in this area because of uncertainty and because it's difficult to determine a return on investment. In general the roundtable believed that this task is a good, high risk project based on fundamentals.

There was significant discussion of adding lumens per watt, CCT, and CRI as metrics for this task. However, because these metrics represent how the phosphor is ultimately used in LED (a higher level performance attribute) and not metrics of phosphor level performance, they were included. The group revised the color shift target to be less than 0.004 u'v' shift in line with what they believed was necessary for market acceptance of LEDs in indoor applications. In addition, they commented on the importance of achieving a narrow red emission at the specified wavelengths above. Temperature stability statuses and targets were included for this task as well.

B5.2 Color Maintenance		High Priority
Description: Ensure luminaire maintains the initial color point and color quality over the life of the luminaire. Product: Luminaire/ replacement lamp		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Change in color over 6,000 hrs		2-step MacAdam Ellipse over lifetime

Participants discussed three general issues prior to discussing whether B5.2 Color Maintenance should be a priority task:

- Color maintenance is largely a phosphor issue for a phosphor-converted LED and is only weakly dependent on the exciting wavelengths.
- There was a concern that we don't truly understand the types of projects this task would fund.

- The task could be re-phrased to include work to make luminaires less susceptible to color variations of LEDs, as suggested in the manufacturing workshop.

In support of prioritization, participants believed that color maintenance is a communal concern and the highest risk to LED market adoption. This is largely because color maintenance is hard to characterize and lighting designers and consumers have a general lack of faith in color stability. In addition, participants stated that as lumen output and efficacy becomes more satisfactory to consumers, color maintenance will become of greater importance. Participants also believed that low cost improvements in the areas of color quality, maintenance, and consistency could open up LEDs to new applications.

In modifying the description, the participants stressed that the product that will result from this task should be a LED luminaire or replacement lamp. In addition, the group developed the task target of a 2 step MacAdam ellipse in change in color over the lifetime of the luminaire.

B6.3 Optimizing System Reliability		High Priority
Description: Includes system reliability analysis to determine and analyze (collect industry wide data) failure mechanisms and improve. Develop an openly available and widely usable software tool verified by experimental data.		
Metric(s)	**2009 Status(s)**	**2015 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

In opposition to prioritization, participants stated that there is an uncertainty as to how this work could be performed. However, in support of prioritization participants agreed that this work is necessary to increase market adoption. It was proposed that an industry consortium be formed to address this issue as it benefits the entire industry and that the funding opportunity be structured to encourage this type of response.

The group decided that the description needed revision to focus on getting industry wide data to create a software tool that is not proprietary and can benefit the whole industry. For metrics, the group suggested including additional causes of failure such as color shift and loss of controls. Currently the only data relevant to this task of which the group was aware is device lumen depreciation data. For the target, the group felt that the predictive tool should be within 10% accuracy of empirical results and that it should characterize the whole luminaire, rather than solely the device.

B2.3 Electrical design of packaged LED
Description: Reduce the operating voltage of LED chips or arrays by increasing lateral conductivity or architectural improvements or package design, etc.

Several in the group felt electrical issues such as this are not currently a problem so this is not a top issue at this time.

B3.1 LED Package Optics
Description: Beam shaping or color mixing at the LED package or array level.

In general, there was not a lot of support for this task. It was noted that though Lumileds used to do this type of work, it doesn't seem like the market is demanding it. In addition, this work could potentially be completed under task B3.6 Package Architecture or task A2.2 Novel Emitter Materials and Architectures.

B3.2 Encapsulation materials
Description: Develop a thermal/photo resistant encapsulate that exhibits long life and has a high refractive index.

In opposition to prioritization, some participants believed that extraction efficiency is high enough such that there is not much to gain from improving encapsulation. While some voiced concerns that environmental impurities eventually migrate through the encapsulation, the consensus was that the actual effects are still relatively uncertain and not a high priority.

B3.4 LED Package Thermal Control
Description: Demonstrate an LED or LED array that maximizes heat transfer to the package so as to improve chip lifetime and reliability.

In opposition to prioritization, participants agreed this is the most developed part of the technology and getting diminishing returns for large chips. In addition, participant comments that any necessary improvements in this area would likely occur independent of DOE funding. In addition, participants believed it does not work to call out improvement in a single aspect of the product which may come at the expense of other performance attributes of the product. Some participants did comment that this task could be combined with B3.6 which should be strongly considered for prioritization.

B3.5 Reducing Environmental Sensitivity
Description: Develop and extensively characterize a packaged LED with significant improvements in lifetime associated with the design methods or materials.

Participants discussed three general issues prior to discussing whether B3.5 Environmental Sensitivity should be a priority task:

- The focus of this task needs to be on extending lifetime and exploring environmental effect on LEDs.
- There was a question of what the product would look like that is to be developed from this task.
- Participants believed the description needed to be adjusted to more properly reflect the work that is required.

In opposition to prioritization, participants believed that academia is already working on this task. In support of prioritization, it was noted that we do not know the long term effects of pollutants on an LED and this research could be fruitful.

B3.6 Package Architecture	Close Call
Description: Demonstrate a packaged chip or multi-chip product employing practical, low-cost, designs, materials, or methods for improving light out-coupling and removing heat from the chip to produce a product with high total lumen output efficiently.	

Some participants had difficulty visualizing projects conducted under this task. In addition, people believed competitive forces seem to already handle this situation and that manufacturers are working on this task. Participants also stated that this technology is already available; it just needs to be re-applied. Therefore, though this task was believed to be important, some participants did not consider it to be urgent.

In support of prioritization, some participants believed that this task represents an opportunity for DOE to support higher risk package approaches that might not get internal company support. One participant estimated that 60% of LED costs are in the packaging, thereby indicating that this task represents an area with high potential of decreasing costs. In addition, success under this task could raise the performance across the board for all luminaires using LEDs. Finally, participants noted that work under this task could result in a wider variety of package architectures more appropriate for specific lighting applications.

B4.1 Yield and Manufacturability
Description: Devise methods to improve epitaxial growth uniformity of wavelength and other parameters so as to reduce binning yield losses. Solutions may include in-situ monitoring and should be scalable to high volume manufacture.

The Roundtable team agreed that this task would be best addressed through the manufacturing program.

B4.2 Epitaxial Growth
Description: Develop and demonstrate growth reactors and monitoring tools or other methods capable of growing state of the art LED materials at low-cost and high reproducibility and uniformity with improved materials use efficiency.

The Roundtable team agreed that this task would be best addressed through the manufacturing program.

B4.3 Manufacturing Tools
Description: Develop improved tools and methods for die separation, chip shaping, and wafer bonding, and testing equipment for manufacturability at lower cost.

The Roundtable team agreed that this task would be best addressed through the manufacturing program.

B5.1 Light Utilization		
Description: Maximize the ratio of useful light exiting the luminaire to total light from the LED source. This includes all optical losses in the luminaire; including luminaire housing as well as optical losses from diffusing, beam shaping, and color mixing optics. Minimize artifacts such as multishadowing or color rings.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Useful Light Output from Luminaire/Total Light Generated by LED Source	80%	95%

Participants noted that there are already products with light utilization rates of 92%, very close to the task target. In addition, participants believed that market forces would be able to drive work on this task.

B5.3 Diffusion and Beam Shaping
Description: Develop optical components that diffuse and/or shape the light output from the LED source(s) into a desirable beam pattern and develop optical components that mix the colored outputs from the LED sources evenly across the beam pattern.

Participants noted that there are already diffusion materials available at 92% efficiency. In support of prioritization, participants stated that we need to be able to fine tune the diffusion without sacrificing efficiency.

B6.1 Luminaire Mechanical Design
Description: Integrate all aspects of LED based luminaire design: thermal, mechanical, optical, and electrical. Design must be cost effective, energy efficient and reliable.

Participants believed that market forces are already great enough for luminaire manufactures to handle this work. Other mechanisms such as prizes and competitions and existing rating systems were deemed to adequately take care of this task.

B6.2 Luminaire Thermal Management Techniques Close Call
Description: Design low-cost integrated thermal management techniques to protect the LED source, maintain the luminaire efficiency and color quality.

Several members noted that there is already an entire industry that addresses thermal management techniques for other applications such as laptop computers. Therefore it would perhaps be a better to address this issue through improved LED material design, making the lED less susceptible to thermal degradation, and improved LED package design. Getting heat out of an enclosed luminaire was recognized as a significant issue but it seems that it could be difficult to work on this issue without taking into account the total integration of the luminaire unless the product was an active cooling system. Therefore any solutions found through research into this task could be made obsolete as components in the LED system change. Finally the roundtable recognized that there are already many products coming to the market that make use of passive cooling or heat sinking, and there are even some thermal management technology start-ups that are gaining traction.

In support of prioritization, participants noted that we are starting to get higher wattages in enclosed cans and need an effective method to remove the heat therefore need to research this task. It was also noted that though there are industries already researching cooling, these thermal control technologies are not designed for the high lifetime, harsh environments experienced by, or low required cost of LEDs. Participants also believed that the lighting industry has been historically slow to develop thermal management solutions. And finally even if other tasks improve efficiency gains, LEDs perform better when they are cooler.

B7.1 Active Electronics for Color Maintenance
Description: Develop LED driver electronics that maintain a color set point over the life of the luminaire by compensating for changes in LED output over time and temperature, and degradation of luminaire components.

In opposition to prioritization, participants believed the best method to fixing color maintenance problems is at the component level, not through active electronics. In part, they felt that it is not cost effective to solve color maintenance problems through the electronics. Furthermore the electronics developed through this task would only be applicable to a small range of products. Some participants believed that task B5.2 Color Maintenance is more important and should be prioritized instead. In support of prioritization, participants believed that controls could shift the financial burden away from chip manufacturers.

B7.2 Color Tuning Controls
Description: Develop efficient electronic controls that allow a user to set the color point of the luminaire.

In opposition to prioritization, participants believed that the functionality would only be applicable for a very small range of products and in general would not aid inincreasing the efficiencies of OLED luminaires. Participants remarked that this would be a nice feature of SSL but not necessarily something that advances the DOE SSL Program's mission.

B7.3 Smart Controls
Description: Develop integrated lighting controls that save energy over the life of the luminaire. May include methods to maximize dimmer efficiency. May include sensing occupancy or daylight, or include communications to minimize energy use, for example.

In opposition to prioritization, some participants believe that the market would take care of this task, and that many control issues are not exclusive to LED technology. One participant believed the future is modulation and communication so this task is not productive.

In support of prioritization, participants noted that dimmability needs to be developed as current methods (pulse width modulation, etc.) can drop the driver efficiency from 90% to 60%. Another supporting comment was that there is a need for building and system controls, as there are very few commercial products currently available.

B7.4 Electronics Component Research	Close Call
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.	

In opposition to prioritization, participants noted that there are drivers available at 2015 targets today. In addition, there is plenty of market motivation to accomplish this task. Participants also stated that the power requirement is dropping, thus we need to maintain driver efficiency.

In support of prioritization, participants believe that replacement lamps need smaller components (i.e. drivers), and that the available drivers are not at the needed cost/size. And though there are drivers that currently meet the efficiency target, there are none at this level for small scale. Participants also believed that big chip has few players, a large driver R&D burden, and needs public investment. Roundtable members also stated that we should develop thermal technologies that enable high efficiency technologies. Finally the luminaire manufacturers agreed that they needed drivers at desired sizes.

3.3.OLED Core Research Tasks

C1.2 Novel OLED Materials and Structures		High Priority
Description: Materials to enable white light: increase IQE, reduce voltage and improve device lifetime. Explores novel materials that can be used to emit light (especially blue) highly efficiently with the ultimate goal of generating highly efficient white light. Potential for radically reduced cost is a plus.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Voltage @ 1mA/cm^2		Close to band gap Voltage
L70	L50=20kHrs	L70=50 kHrs
EQE without extraction enhancement		EQE 20-30%

Participants noted that this task addresses work on both OLED materials and device structures. The group agreed that materials and device architectures and performance cannot be decoupled. They also noted that this task would include most research at the device level rather than light extraction. Given the breadth of this task, there was consensus that it should be prioritized. Improvements through novel materials could influence the efficiency of the device and thus the light output. Others commented that research under this task should include non emitting materials as well. Further support came from participants who felt that research into causes of device degradation is necessary. These same participants stated that a lifetime analysis should be included in this task. Some participants also commented that this task should emphasize improving efficacy and lifetime at higher luminous emittance. Present status is given for luminous emittance of 6000 lm/m^2 but consideration should be given to specifically requiring higher values of 10000 lm/m^2 for the future targets. This might best be addressed by an overall statement to this effect that would apply to all tasks.

In reviewing the task description, the roundtable participants proposed slight wording changes that increased the scope of the task. In terms of the metrics, participants felt that CCT and CRI were unnecessary as this task was focused on efficiency and lifetime. While the voltage at EQE 2015 targets remained the same, the participant proposed that the L70 target should be increased to 50 kHrs. This lifetime issue was brought up during the soap box presentations as a necessity for OLED luminaires to be competitive with other conventional lighting technologies such as fluorescent. Participants stated that, instead of performing the full lifetime test, one could measure degradation over a shorter period of time, in order to demonstrate progress toward the ultimate target.

C2.2 Electrode Research		High Priority
Description: Develop a novel transparent electrode system for uniform current distribution across a (>200 cm^2) panel. Solutions must have potential for substantial cost reduction with long life while maintaining high OLED performance. Work could include more complex architectures such as grids or patterned structures, p-type and n-type degenerate electrodes, two-material electrodes, electrodes that reduce I*R loss, flexible electrodes, or other low-voltage electrodes.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Cost reduction potential	Current solution in ITO on Glass on small devices: $20/m^2	$4/m^2
Absorption over the visible spectrum	<1% absorption	Maintain
Effective area resistivity (including any grid structure	ITO/Glass: 18 ohms/sq	1 ohm/sq

In support of prioritization, participants stated that a cost effective electrode is important in bringing down cost, which is a major barrier for OLEDs. In addition, participants agreed that in order to do this the industry should find alternative to ITO. In addition, one participant believed that poor ITO layer quality is a major cause of yield losses, which is the major roadblock to advancing OLEDs.

Participants believed that the description needed to further specify the types of projects that could be conducted under this task. In addition, due to the importance of improving performance at a panel level, a minimum panel size of 200 cm^2 was added to the description. It was stressed that the novel transparent electrodes should be broadly interpreted and could include, for example, 1) an ITO replacement deposited on a polymer with an ITO on glass level performance, 2) an improved charge injection layer, or 3) a replacement for ITO on glass, but 80% lower costs, or 4) more complex hybrid structures that improve the equivalent resistivity of the electrode. A solicitation in this area should consider work that is already adequately funded and direct attention to genuinely new approaches.

C3.1 Fabrication Technology Research		High Priority
Description: Develop new practical techniques for materials deposition, device fabrication, or encapsulation. Should show potential for scalability and low cost.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Relative material and processing cost reduction potential	1 relative cost	1/10 cost
Material Use	<5% Material Utilization	>50% Material Utilization
Uniformity	Uniformity of <5% thickness variation over device area	<10% Variation over 6" square

There was consensus at the roundtable that this task should be prioritized. Projects under this task could potentially decrease OLED manufacturing costs and increase yield, both of which are unacceptable with existing manufacturing techniques. It was emphasized that this task should be focused on coming up with new, breakthrough approaches to manufacturing. In addition, participants commented that this task should not be limited to organic materials, but also include manufacturing other components of the OLED, such as light extraction structures. While there was overall support at the roundtable for this task, some participants stated their concern that metrics would be difficult to establish for this task, potentially making it difficult to evaluate proposals.

Participants stated that the old description could be abbreviated to exclude the "development of a model for the fabrication of OLED devices." In addition, the task description was modified to include research in areas of OLED fabrication beyond organic materials deposition. To more properly measure progress in this task, participants included relative material and processing costs as a metric. Though these costs were not currently quantitatively known, the roundtable agreed that the appropriate target needs to be cutting the current costs by 90%. The statuses and targets were updated accordingly.

C6.3 Light Extraction Approaches		High Priority
Description: Devise new optical and device designs for improving OLED light extraction. The work should be scalable to a panel, and provide a potential of lowering costs.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Extraction Efficiency (relative improvement compared to optimized structure with no enhancement)	2.3x	3.5x

In support of prioritization, participants commented that light extraction is critical to improving OLED efficacy. They supported this task as it is meant to describe device level light extraction techniques such as the insertion of optical interlayers into the device stack. One participant also suggested that addressing directionality of the extracted light could be included in this task as well. One participant also noted that this task is very similar to task C1.1 Novel Device Architectures.

In reviewing the task description, the roundtable participants agreed that this task, as a core project, should simply focus on light extraction from the basic OLED structure, and that a "pixel-sized" demonstration could be adequate. However, the designs developed do need to be scalable to a panel. Participants also added that the designs need to offer the potential of lowering costs. Changes were made to the description in accordance with these comments. For the metric, status, and targets, the participants felt that the values established for the parallel product development task, D6.3 Panel Outcoupling, were appropriate. See the discussion under that task for further details.

C1.1 Novel Device Architecture
Description: Device architectures to increase EQE, reduce voltage, and improve device lifetime that are compatible with the goal of stable white light. Explores novel structures like those that use multi-function components, cavities or other outcoupling strategies to optimize light extraction. Could include studying material interfaces.

Participants acknowledged that research into novel device architectures, especially light extraction techniques is important. However, because architectures are often reliant on the materials, the priority for core research should be in materials. In addition, most participants believed that most of the work under this task would fall under task C1.2 Novel Materials or C6.3 Light Extraction Approaches, which participants supported for prioritization.

C1.3 Material and Device Architecture Modeling
Description: Developing software simulation tools to model the performance of OLED devices using detailed material characteristics.

In general there was limited support to prioritize this task. Some participants stated that this task is not necessary since many believe the IQE is already near 100%. However, a participant also commented that having good software simulation tools could enable more rapid development of materials and device structures.

C1.4 Material Degradation
Description: Understand and evaluate the degradation of materials during device operation.

Participants felt that that this task is not needed until there are novel materials that show promise. In addition, participants noted that material degradation is also addressed under task C.1.2 Novel Materials. Some participants commented that companies have an understanding of degradation effects that they choose to keep proprietary.

In support of prioritization, participants stated that work for this task could be an opportunity to increase the understanding of degradation mechanisms, as opposed to simply characterizing overall lifetime, particularly at high current densities, to achieve reliability desirable for cost effective OLED lighting products.

C1.5 Thermal Characterization of Materials and Devices
Description: Involves modeling and/or optimizing the thermal characteristics of OLED materials and device architectures with the goal of developing less thermally sensitive and hydrolytically more stable materials and devices.

Many participants believe that OLED technology should not need additional thermal management components because of the large area of emission. The possibility of avoiding external structures contributes to OLED attractiveness and is one of its strongest advantages over LEDs.

In support of prioritization, a participant stated that looking at the impact on the materials and devices at higher lumen output is important. He commented that higher lumen outputs and brightness are expected in the future and thermal issues will likely emerge as materials are driven harder (4,000 cd/m2, 12,000 lm). Another participant supported this task claiming that the fact accelerated lifetime testing reduces life is an indication that driving devices at higher currents increases OLED thermal degradation. In response, another participant pointed out that the degradations from this process is not necessarily due to thermal effects. Participants in support of prioritizing this task stated that manufacturers do not want to be surprised by thermal issues when ultimately designing their products. The conclusion was that it is premature to prioritize this task now, but a new look may be needed as luminaire design evolves.

C4.3 Optimizing System Reliability
Description: Research techniques to optimize and verify overall luminaire reliability. Develop system reliability measurement methods and accelerated lifetime testing methods to determine the reliability and lifetime of an OLED device, panel, or luminaire through statistical assessment of luminaire component reliabilities and lifetimes.

Though participants agreed that improving the reliability of OLEDs is important there was hesitation to prioritize this task for reasons similar to the above task on thermal management. Firstly, many participants believed that this task was premature given the lack of OLED luminaires available to conduct a worthwhile study. In addition, some participants question the value of this task as a core research task, arguing that it may result in DOE funding purely academic exercises that are difficult to ultimately apply to products. In addition, the lack of industry standardization in characterizing reliability would be a major hurdle to achieving success under this task.

3.4. OLED Product Development Tasks

D2.2 Low-Cost Electrodes		High Priority
Description: Demonstrate a high -efficiency OLED employing a transparent electrode technology that is low-cost, low-voltage, and stable, with the potential for large-scale manufacturing. Design could include a conducting grid.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Effective Ohms/Square (including any grid structure)	<10 Ohms/sq	<0.1 Ohms/sq ($200cm^2$)
Effective absorption over the visible spectrum;	<1% absorption	Maintain
$/m^2 (material + processing)	~ $20/m^2	<$5/m^2

In discussing this task, several participants this task and D2.1 Substrate Materials are very similar and only one of the two should be prioritized. Some also questioned the difference between this task and the parallel prioritized core research task, task C2.2 Electrode Research.

In general, many participants agreed that ITO was not a viable TCO and new TCOs need to be explored thus supporting D2.1. Some participants were hesitant to de-prioritize D2.2 for the core technology task because they feel that this task's focus on large scale manufacturing is important. There was a consensus that this task could greatly decrease the cost of OLEDs. In addition to cost improvements, participants observed that conduction losses need to be much reduced to get from pixel to panel.

Participants agreed that the description properly framed the work needed to be done under this task. Participants also agreed that absorption was a better metric than transparency, and estimated the status of absorption for TCO sheets at less than 1%. For the resistivity and cost metrics (for which they added the cost of processing) the participants provided two sets of targets, one for a TCO replacement and one for a conducting grid. These resistivity and cost targets are shown in the table above.

D6.1 Large Area OLED		High Priority
Description: Investigate obstacles unique to the fabrication of OLED panels. Demonstrate a high efficiency OLED panel, with area of at least 200cm^2, with good thermal performance, employing low cost designs, processes, and materials and with the potential for large scale manufacturing.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Lumen Output	100Lm	> 200Lm
Efficacy	45lpw	>150 lpw
Color uniformity	3000K – 1 quadrangle CRI -84	Energy Star Color
Cost of panel		<$10

Though there was consensus that this task should be prioritized, some participants questioned what was considered to be "large area" for this task. In addition, some participants pointed out that task D2.2 Low Cost Electrodes might be subsumed by this task, suggesting that both may not need to be prioritized. In support of prioritization, participants noted that as small devices with reasonable performance have already been developed, the devices now need to be integrated into an architecture that is useful for lighting. They also commented there is considerable degradation in performance as an OLED device is fabricated into a panel and it is critical to address this issue in order produce high efficacy luminaires. In addition, while discussing the prioritization of task D1.1 Practical Implementation of Materials and Device Architectures, participants noted that many of the issues highlighted in that task (such as robustness, lifetime, efficiency, and color quality) need to be addressed at the panel level, and therefore would fall under this task.

In reviewing the description of the task, participants believed that the most important requirement of this task was to demonstrate a high efficiency OLED panel with good thermal performance and low cost. Participants proposed eliminating the language specifying that the panel demonstrate reduced conductive (I*R) losses, defect density, or shorting density and increase color and luminance uniformity of light. Instead they suggested adding efficacy as a metric to encompass all of these performance improvements. In addition, the participants proposed adding OEM price as a metric to address the "low-cost" aspect of this task. In addition, one person described a current prototype result with 100 lumen output, 45 lpw, and a CRI of 84; these parameters are noted as the "status" for the task. Targets were provided which would make this envisioned product competitive with current technologies.

D6.2 Panel Packaging		High Priority
Description: Scale up practical, low-cost packaging designs that result in improved resistance to the environment (particularly water and oxygen impermeability) and thermal management. Encapsulation considerations should involve compatible materials, appropriate processes, etc. Edge effects should also be considered. Demonstrate a high-efficiency OLED panel that employs such a packaging design and exhibits improved lifetime.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Panel Operating Lifetime		50khrs operating life (L70)
Panel Shelf Life	>6 year shelf life (display)	20 yr shelf life
$/m^2	$50-75/m^2 barrier cost flexible	<$5/m^2

Participants questioned if this task is subsumed by D6.1 Large Area OLED which is already prioritized. In support of prioritization, participants stated that the panel needs to demonstrate better environmental resistance than the OLED devices, enabling reasonable lifetimes, and thus allowing OLED luminaires to compete with conventional lighting technologies. In order to achieve this, reducing edge leakage and producing a low cost barrier coating is essential.

The roundtable participants did not propose any changes to the description. However, for the metrics, the roundtable participants chose to eliminate water and oxygen permeability as metrics and use panel shelf life and operating lifetime instead. In addition, given the focus of the task on low cost packaging designs, they proposed adding a metric of $/m2. They estimated that the current panel shelf life status (based on OLED products for display applications) is approximately 6 years. The participants could not estimate an operating lifetime status. For the 2015 targets, consistent with the soapbox presentations that emphasize the nexcessity of improved lifetime of OLEDs, the participants suggested 50khr operating lifetime. This lifetime, when converted to a shelf life, assuming average operating hours for general service lighting applications, would require a 20yr shelf life. Some participants felt that by 2015, buildings would undergo lighting retrofits more often. Thus 20 year shelf lifetimes may not be necessary. For the packaging costs, the participants suggested a 2009 status and 2015 target as indicated above in order to meet the MYPP OLED cost targets.

D6.3 Panel Outcoupling		High Priority
Description: Demonstrate manufacturable approaches to fabricate OLED panels with improved light extraction efficiency.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Extraction efficiency (relative improvement compared to optimized planar structure)	2.3x	3.5x

In support of prioritization, participants stated that developing panel architectures external to the OLED device which optimize extraction efficiency will be critical to creating a cost effective light source. Many participants believed that working in this task is a path to higher brightness and that attention should be given to maximizing light output and beam intensity shaping.

While some participants believed that directionality of the light output should be considered as part of the description, the group ultimately did not propose any changes to the task description. Participants believed the best metric to measure work in this task was extraction efficiency, or EQE/IQE. In addition, the group proposed a metric that compared efficiency of the panel with and without the light extraction architectures. The group provided current statuses of metrics based on the best available light extraction approaches..

D6.4 Panel Reliability		High Priority
Description: Analyze and understand failure mechanisms of OLED panels and demonstrate a packaged OLED panel with significant improvements in lifetime.		
Metric(s)	**2009 Status(s)**	**2015 Target(s)**
Median L70 lifetime at >6,000lm/m^2		>50kHrs

In support of prioritization, participants stated that OLEDs lifetimes are currently very low and nowhere near what they need to be in order to compete with other technologies. As mentioned in the soap boxes, some participants argued that we may need to reach lifetimes near 50Khr by 2016 in order to penetrate conventional lighting markets. It was also emphasized that attaining these lifetimes at 6000 lm/m^2, or perhaps higher, is essential to compete with other light technologies. There was also support for this task because it was focused on the panel rather than small device level. Participants discussed shorting as one of the primary causes of failures in OLED panels. It was agreed that prioritizing this task would allow for necessary development to understand these failure mechanisms, find solutions, and ultimately improve reliability and OLED panel lifetime.

Roundtable participants did not propose any changes in the description. For the metric, participants observed that while there is no standard way to measure a panel's reliability, L70 B50 would be an appropriate metric. Participants agreed that a lifetime target for this test should be greater than 50khrs as brought up during the soap box presentations. This lifetime appears to be necessary to compete with commodity grade fluorescent lighting.

D4.1 Light Utilization Close Call
Description: Maximize the ratio of useful light exiting the luminaire to total light from the OLED sources. This includes all optical losses in the luminaire; including optical losses from beam distribution and color mixing optics.

Some participants questioned whether this task is necessary because OLEDs are flat panel devices. Perhaps more importantly, participants believed that the issue of light utilization is currently not limiting market penetration and therefore is not an urgent priority.

In answer to the first point, it was mentioned that lighting distribution impacts the visual comfort of the consumer and market acceptance. Participants also stated that beam distribution control is important in order to achieve distributions that are appropriate for most lighting tasks. Controlling the distribution can be done through controlled texturing of the panel, lens-ing, or other optical techniques.

D1.1 Practical Implementation of Materials and Device Architectures
Description: Develop materials and device architectures that can concurrently improve robustness, lifetime, efficiency, and color quality with the goal of stable white light over its lifetime. The device should be pixel-sized, demonstrate scalability, and have a lumen output of at least 50 lumens.

There were concerns that this task was targeted at the pixel, or device, level rather than the panel. Participants believed a more urgent effort needs to be put into improving the panel, and perhaps this issue would be best handled by task D6.1 Large Area OLEDs. The participants commented that once panels are created which can match the performance of the devices then this task should be considered for reprioritization.

D2.1 Substrate Materials
Description: Demonstrate a substrate material that is low cost, shows reduced water and oxygen permeability, and enables robust device operation. Other considerations may include processing and operational stability, weight, cost, optical and barrier properties, and flexibility.

Participants believed that perhaps window glass is sufficient. They also stated that reducing the weight of the substrate is not incredibly important for the installation of the OLED.

Other participants were of the opinion that what is really required is not necessarily glass or plastic, which are available at commodity prices, but these substrates with layers on them to make them suitable for OLEDs and also compatible with the electrode layer. The roundtable felt that this task has the potential to reduce manufacturing costs. Participants concluded that the solution needed in this task is the ability to produce a low cost barrier coating, and currently the industry is very far from this solution.

D3.1 Panel Manufacturing Technology
Description: Develop and demonstrate methods to produce an OLED panel with performance consistent with the roadmap using integrated manufacturing technologies that can scale to large areas while enabling significant advances in yield, quality control, substrate size, process time, and materials usage using less expensive tools and materials than in the OLED display industry and can scale to large areas.

It was noted this work is more appropriate for the manufacturing initiative and should be included in the manufacturing roadmap. In addition the roundtable members noted that viable panel architectures incorporating the goals all of the other product development priority tasks need to be developed before manufacturing of the panels can be considered.

In support of this task, one participant commented that even though this work will be done through the manufacturing initiative, there is preparatory research needed before the work can commence on the manufacturing level.

D3.2 Quality Control
Description: Develop characterization methods to help define material quality for different materials and explore the relationship between material quality and device performance. Develop improved methods for monitoring the deposition of materials in creating an OLED panel.

Again, the group agreed that this task should be directed to the manufacturing portion of the SSL Program. Still, it was also agreed that better quality control during the manufacturing process leads to better product and is important in order for OLEDs to ultimately achieve market acceptance.

D5.1 Electronics for Color Maintenance
Description: Develop OLED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in OLED output over time and temperature, and degradation of luminaire components.

Participants agree that color maintenance is important, but they were uncertain of whether electronics controls were the optimal solution. In addition, participants felt that given the state of the OLED technology and products, prioritizing this task would be premature.

D6.5 Panel Mechanical Design
Description: Integrate all aspects of OLED based luminaire design: thermal, mechanical, optical, and electrical. The design must be cost effective, energy efficient and reliable.

Participants believed that most of this task has already been covered by D6.2 Panel Packaging and D4.1 Light Utilization. A second concern was that because this task is supposed to support a final product luminaire which has yet to be developed, funding this task as a priority may be premature.

4. Projections and Milestones Discussion

The final group activity at the roundtable was to discuss the LED and OLED projections and milestones. Existing projections and milestones were established in consultation with the LED and OLED Technical Committee calls which took place in the fall of 2008. Participants offered suggestions as to what changes in the last year should be made to either the statuses or the targets.

The tables and charts below include the updates that were suggested at the roundtables. The present versions of these figures can be found in Chapter 4 of the 2009-2014 MYPP. The updates to the tables, as proposed at the roundtable, have been highlighted red. 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

The efficacy projections in figure 4.8 of the 2009 MYPP show the package efficacy improvement goals for cool white "lab" results, as reported in press releases and public announcements, and for warm white and cool white commercial products. Several issues were identified with the present forecasts:

1. Participants believed that the warm white asymptote should be raised above the current values of 162 lumens per watt. Studies suggest that warm white efficacies comparable to those of cool white are achievable, although considerable work is required for this improvement. Innovations would be needed in phosphors, LED color availabilty, and development of color-mixed sources, as well as in the basic emitting materials.

2. Participants also noted that for proper comparisons of published data from chips of different sizes and drive currents, the assumptions should reference a current density, rather than current. There was agreement that the assumptions will need to be refined and the past data will need to be filtered through the new criteria to ensure the chart uses reliable historical data. These changes will be done in the course of preparing the efficacy chart for the 2010 MYPP.

3. CCT/CRI combinations that might be appropriate for this filtering are as follows:
   a) Cool-white efficacy projections assume CRI=76 → 90, CCT = 4746-7040°K,
   b) Warm-white efficacy projections assume CRI=76 → 90, CCT =2580-3710°K
   c) All projections for packages with a 35 A/cm2 current density.

For the phosphor-converting device performance status and targets (**Error! Reference source not found.**) participants noted that EQE is a more easily measured metric than IQE. The suggestion was that only EQE be identified as a metric. Participants also proposed that the criteria for this chart should be a neutral white CCT of 4100K, with a CRI of 85.

Table 4-1: Phosphor Converting Device Performance

Metric		2008	2009	2015 Target
Electrical Efficiency		90%		95%
IQE	EQE	80%	64%	81%
Extraction Efficiency		80%		
Phosphor Conversion		65%		73%
Scattering		80%		90%
LED Device Conversion Efficiency		30%		51%

Note:
1. Efficacy targets are for an LED package with a CCT ~ 3500-4100°K, and CRI of 85.
2. All projections are for packages with a 35 A/cm^2 current density, and reasonable package life.

Unfortunately, there are few actual products available with these values, so this choice may need further consideration.

Turning to the luminaire targets, many thought it would be useful to select a stalking horse, a specific luminaire design, to compare and track LED luminaire performance projections (**Error! Reference source not found.**). The roundtable agreed that a neutral white downlight at or near 4100K would be appropriate. The prior projections compared cool white luminaires with a broad CCT range of 4100-6500K. Participants stressed that the values provided in the tables are examples and targets for practical performance. A specific design may achieve the same overall efficiency with a different choice of individual system element performances, and, of course, different applications may exhibit a completely different breakdown. The updated status for the downlight is provided in the 2009 column.

Table 4-2 Summary of LED Luminaire Performance Projections

Metric	2008*	2009	2015* Target
Device Efficacy (lm/W)	108	95	188
Thermal Efficiency	85%	95%	95%
Efficiency of Driver	85%	85%	92%
Efficiency of Fixture (Optical Efficiency)	80%	80%	92%
Luminaire efficiency	58%		80%
Luminaire Efficacy (lm/W)	62	55	151

Notes:
1. Efficacy projections for neutral white downlight with a CCT ~ 4100°K,
2. Device numbers are for packages with a 35 A/cm^2 current density, and reasonable package life.
3. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the package efficacy values.

There remains an issue with this tabulation, in that it represents the best performance of each metric, but not necessarily all at the same time in a single product.   Further work may be needed for the MYPP to provide a different tabulation representing various specific examples to more clearly represent present status and available "headroom" for improvement.

There was additional discussion on an appropriate luminaire application to serve as the basis for the milestones. Participants decided that the milestones should represent high quality, low power density products, with a higher minimum lumen output so that the product is comparable to premium CFL 8" can downlights. **Error! Reference source not found.** displays the recommended targets for the LED portion of the SSL Program as set by the roundtable.

There is no change to Milestone 1 (past) or Milestone 2 (FY10). However, for FY12, Milestone 3, participants agreed that the luminaire efficacy target should be reduced from 126 lm/W to 100 lm/W due the warmer CCT (4100K). In addition, participants agreed that the milestone should represent a luminaire with lumen output of 1800 lumens rather than 1000 lumens. For Milestone 4, the cost target is increased from $2/klm to $3/klm to reflect the higher output and loweriCCT. Finally, the participants added Milestone 5 to represent an SSL product comparable to a linear 4-foot fluorescent luminaire.

Table 4-1: LED Milestones

Milestone	Year	Target
Milestone 1	FY08	LED pkg : 80 lm/W, < $25/klm, 50,000 hrs
Milestone 2	FY10	Comm LED pkg: > 140 lm/W cool white device, >90 lm/W warm white device; <$10/klm;
Milestone 3	FY12	Luminaire: 100 lm/W ; ~1800 lumens ; CCT~4100K
Milestone 4	FY15	LED pkg: < $3/klm; CCT ~4100K
Milestone 5	FY20	Luminaire: 140 lm/W, <$5/klm; CCT ~ 4100K;>3500 lumens

Note: LED package results at 35 A/cm^2

It was noted that these targets are not exactly the same as those developed in the Manufacturing Roadmap, so some reconciliation of the two reports may be appropriate.

4.2.OLED Projections and Milestones

Participants recommended that for a better record of progress towards practical OLED lighting, the MYPP should include an efficacy projection for OLED "panels". As the size of devices becomes greater than 2x2cm, issues such as IR loss and light extraction become more prominent, decreasing efficacy. However, it was noted that if the plot assumptions were to require that devices be greater than 2x2cm, most of the historical points would be eliminated. Accordingly, it was agreed that the historical "pixel" data will be retained, but going forward we should look for results on larger devices of perhaps 200 cm^2.

Participants also believed that the footnotes should indicate a tighter definition of color such that it be close enough to the black body curve so as to fall within the ANSI or EnergyStar bin color requirements The present notes only designate   a "CCT between 2700K and 4100K" which could allow large departures from "white". Another suggested footnote was that the data points should represent results at a minimum luminous emittance of 6000 lumens per m^2 rather than the present designation of brightness (cd/m^2). A final suggestion was that the MYPP recomment a standardized form of reporting for laboratory results.

The following data were offered by several participants to provide a basis for a future projection based on "panel" sized devices. The older data do not meet the desired larger size for future results, but are large enough to exhibit some of the limitations not present in the very small pixels:

- 45 lpw (2009) Kodak
- 30 lpw (2008) GE
- 15 lpw (2003) GE
- 7 lpw (2002) GE

A revised efficacy projection for the MYPP will be developed using the new data and suggested criteria. Participants updated the OLED performance projections in a few areas per **Error! Reference source not found.**. Present estimates are for a panel ~5cm^2; for the later targets the larger size, ~200 cm^2 would be preferred. Because no product is available, there are no available metrics for a commercial product.

Table 4-2: OLED Panel Efficacy and Price Projections

Metric	2009	2010	2012	2015
Efficacy- Lab (lm/W)	45			
Efficacy- Commercial (lm/W)	NA			135
OEM Device Price- ($/klm)	NA		45	10
OEM Device Price- ($/m^2)	NA			
Device Life- Commercial Product (1000 hours)	NA			50
Lumen Density		3,000		10,000

Note:

1. OLED projections are for a panel of at least 2x2cm^2.
2. Minimum requirements of qualifying points are luminance of >1,000lm/m^2 ,CRI >80, and CCT falling in ANSI bin color requirements, respectively.

Participants provided an example breakdown of panel element efficiencies per **Error! Reference source not found.**. Participants agreed that these projections are for a panel. A panel was selected as there are certain problems, such as IR loss and light extraction, which are not experienced by pixels. The EQE provided is an average of several sample points provided: GE provided ones of 20% for a panel, and Kodak provided one of 27% for a panel.

Table 4-3: OLED Panel Efficacy Projections

Metric	2009	2015 Target
Electrode Efficiency		95%
Electrical Efficiency		80%
IQE		
Extraction Efficiency		
Substrate Optical Transmission Efficiency		
EQE	25%	53%
Panel Conversion Efficiency	15-18%	40%

Note:
3. OLED projections are for a panel of at least $2x2cm^2$.
4. Minimum requirements of qualifying points are luminance of >1,000lm/m^2 ,CRI >80, and CCT falling in ANSI bin color requirements, respectively.

Agreed OLED milestones are shown in **Error! Reference source not found.**. For Milestone 2, participants felt that the efficacy milestone was not high enough and changed it from 45 lm/W to 60 lm/W and added that it should be for a panel. For Milestone 3, participants felt that an appropriate target would be <$45/klm. They arrived at that number by assuming a luminaire composed 40 200 cm^2 panels, at 2000cd/m^2, at $7/panel, and a total lumen output of 6000 lumens. Though there was significant discussion about increasing the FY15 milestone to an efficacy greater than 135 lm/W for a panel, it was ultimately recommended that the milestone should remain at 100 lm/W but for a panel of higher luminous emittance. .. However, Peter Ngai of Acuity Brands Lighting maintained that 140 lm/W might be necessary for OLEDs to become an option for commodity grade lighting applications. Milestone 5 was added to represent targets consistent with required OLED performance in commodity grade applications.

Table 4-4: 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	> 100 lm/W panel @ 10,000 lm/m^2
Milestone 5	FY18	50,000 hour lifetime; 10,000 lm/m^2 panel

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 3, 2009

George Brandes, CREE
George Brandes focused on the need to drive down cost as a primary concern as it pertains to DOE’s involvement in the progress of LED technology. Currently, the LED package typically accounts for 30-40% of LED luminaire costs across the price spectrum. This percentage has dropped significantly to the surprise of some of the participants. Brandes urged a greater focus on product development beyond the basic LED device.

Kevin Dowling, Philips
Kevin Dowling focused on four main concerns: reliability, sockets, cost and architecture. Most importantly, Dowling feels that LED reliability is not well understood in the industry. Dowling stated that the commonly used metric, lumen maintenance per LM-80, is misused and not an adequate measure of reliability because it does not account for many additional potential failure mechanisms. Dowling also mentioned an EPA / ENERGY STAR movement to mandate the use of GU-24 sockets. According to Dowling no currently existing standard base is thermally compatible with SSL. In addition, Dowling claims that the LED device itself is reaching the efficiency threshold and the focus should be shifted to the packaging of the LED. Dowling believes driving down costs is also a major concern. Dowling believes LED light quality is satisfactory and prohibitive costs are preventing adoption. This is partly a scale problem as it was suggested that a 2 fold increase in production would drive down prices by 30-40%. Lastly, Dowling discussed the need to focus on overall system architecture and energy management issues. As an example, Dowling mentioned Wal-Mart’s ability to increase its ROI from LEDs from 10% to 90% with the simple integration of controls.

After Dowling’s presentation, a discussion focused on lifetime metrics was held. The currently used 50,000 hr is necessary to justify the high initial cost of LED lighting. It was mentioned that certain applications require much shorter lifetimes. The entertainment industry, as an example, usually requires a lifetime of only 5,000 hrs. A better understanding of LED system reliability and better reliability metrics would allow for more realistic lifetime requirements.

Michael Coltrin, Sandia National Laboratory
Michael Coltrin spoke specifically about InGaN devices. Sandia researches the negative effects of C-Plane polarization and droop on IQE. They attribute much of this efficiency loss to hot electrons bypassing the quantum wells and hole recombination in the p-GaN layer and Auger processes, whereby

an electron rather than a photon is emitted upon recombination. Sandia is exploring methods to go beyond the 2-dimensional methods currently used for growth. This has resulted in work on non-polar growth orientations. Sandia also explored using lasers and other narrow linewidth sources for lighting applications. To promote successful research Coltrin suggests using the recent developments of the DOE's Energy Frontier Research Centers as a funding/research model.

After the Sandia presentation, participants had a discussion about the use of narrow-linewidth phosphor-converted red LEDs to achieve warm-white light. Philips reported successfully developing amber LEDs for this purpose. Lumileds said they have achieved 200 lm/W using a red LED at 50nm, 2700K, 90 CRI and 3.4 Volts (forward voltage). Thermal dependence was questioned as a potential issue. A Sandia paper exploring this issue is available.

George Harbers, Xicato

Gerard Harbers expressed the need to get LED performance to surpass that of the current industry gold standard, Halogen performance. Among other things, Harbers mentioned the necessity for improvement in categories such as color, size and dimmability. Harbers made a number of suggestions as to how to achieve these performance goals, including making standards/requirements more stringent, developing more-efficient, dimmable drivers and standardizing mechanical/electrical interfaces across the industry.

Regarding the use of the LM80 test method to characterize LED luminaires, many participants began to discuss the possible implications of doing so. Luminaire manufacturers claimed such a requirement would force them to test every luminaire design for 6,000 hours to measure color shift, which would be impossible to do in the industry's current 9 month product launch cycle. In addition, LM80 color shift measurements do not account for remote phosphors. Others brought up the modification of existing or use of new color metrics. Harbers suggested including R-9 should be included as a metric, but other participants mentioned the shift to newly developing CQS metrics. According to some, a decision on CQS metrics is due by June of 2010. Also mentioned was the lack of standards in self-qualifying for color uniformity. Harbers stated that a LED halogen competitor needs to have an R9>75 and CRI~90, 95. In additional he stated that we need to achieve less than 2 MacAdam ellipse variation in color for indoor and architectural applications.

Eric Haugaard, BetaLED

Eric Haugaard focused on reliability issues. BetaLED specializes in competing with metal halide technology for outdoor (street-lighting, landscape, etc.) applications. According to Haugaard, performance uncertainty, the lack of application experience and insufficient reporting standards has made reliability a major barrier to implementation. Essentially, reliability uncertainty creates a knowledge gap that makes LEDs, which have a high first cost, harder to sell.

Eric offered specific advice to buyers regarding how to fairly compare LED luminaires. The five tips are to 1) compare performance at the application level; 2) request certified photometric data; 3) validate lumen depreciation; 4) apply the appropriate light loss factors; and 5) evaluate lifetime luminaire value. Haugaard also included his task prioritization suggestions in the presentation (A.5.1, A.6.3, A.7.4, A.7.5, B.1.3, B.3.5, B.4.1, B.6.2 and B.6.3).

In a discussion following the presentation, someone added that there was no standardized reliability metric at the luminaire level. Haugaard added that, as a result, luminaire performance data had to be extrapolated from chip manufacturer LM80 data which doesn't account for bi-modal use (idle mode). Haugaard also noted the incompatibility of the LM80 data with the product introduction cycle. In parking lot applications BetaLEDs are used for 100,000 hrs 24/7, but data is only available out to 15,000 hrs.

Seven DenBaars, University of California, Santa Barbara's Solid State Lighting & Energy Center
Fundamental Limits to Efficacy of SSL Materials and Devices
Steven DenBaars stressed the importance of funding fundamental research to explore and eliminate issues such as efficiency losses from current density and thermal droop. Specifically, DenBaars attributes these limitations to substrate defects and, as a result, is working to understand the fundamentals of Auger in LEDs, ultimately to develop defect free bulk GaN. SSLEC work is also exploring whether semi-polar growth can solve the green gap.

After the presentation, some questioned the benefits of funding this research and achieving its goals. According to DenBaars, eliminating performance droop due to Auger would allow a single chip to run at higher current densities and possibly match the performance of 10 of today's chips. The SSLEC can provide defect density and performance data of new substrates. Others mentioned the time to market increases related to relying on foreign (Japanese) substrate suppliers.

Jeff Tsao, Sandia National Laboratory
Jeff Tsao focused on garnering support for the use of lasers to improve LED technology. According to related work at Sandia, lasers provide existing proof that 70% plus efficiencies can be achieved for lighting. In addition, Tsao presented a cost comparison based on a $0.28/W target to make any new lighting technology cost competitive. According to Tsao, lasers are as close to this target as the current technologies on which LEDs are based. Tsao claims laser-enhanced LEDs have additional benefits, primarily based on their ability to achieve narrow line-widths. Narrower line-widths increase the theoretical LED efficacy ceiling achievable from 316 lm/W to 408 lm/W, according to Tsao.

Participants questioned the color comparison between traditional LEDs and laser enhanced LEDs. It was agreed that all research should be based on the future CQS metrics. Current commercial product uses for lasers were also discussed. According to Sandia, lasers are currently limited to modal applications, such as DVD players. Some suggested broad lasers may achieve better results specific to LED performance. Participants also added that, despite performance benefits, UL would be hesitant to allow "lasers" in homes.

Christian Wetzel, Renssalaer Polytechnic Institute
Christian Wetzel discussed challenges associated with increasing quantum efficiency of LEDs. In particular he cited efficiency droop at high current densities and lower efficiencies at green wavelengths as major challenges. He championed the need to support fundamental research aimed at eliminating defects/dislocations in existing epitaxial growth. This is a matter of reducing the defect density on GaN substrates and understanding the physical mechanisms that generate defects in the quantum well growth for longer wavelength emitting LEDs such as green and beyond. Possible approaches for

reducing defects in the active region are the use of In alloyed underlayers in the GaN template or the use of non-polar GaN crystal growth orientations.

Alexei Erchak, Luminus

Alexei Erchak stressed the need to alter the focus of the MYPP to both small chip and big chip architectures. The MYPP is standardized to 1mm chips. Luminus is the developer of the first photonic crystal LED and specializes in “big chip” LED architectures for use in products such as projectors and HID applications. Erchak suggests altering certain metrics on which the MYPP is based. For example, Erchak would like to see the MYPP base comparisons on drive current density (35 A/mm^2) instead of normalizing to a specific drive current (350 mA).

After the presentation, participants discussed issues specific to high-lumen-output LEDs. One participant mentioned glare issues that could result from the increase in the lumen output and decrease in the points of origin associated with using big chip LEDs vs. an LED array. A luminaire manufacturer also brought up the possible negative effects of having to scale optics. According to Luminus, their packages include a lens, which eliminates the optics burden on luminaire manufacturers. A participant also mentioned that metal halide lighting may be better suited (higher lm/cm2) for the applications for which big chip LEDs may be better than small chip LEDs. Others questioned whether the chip was the best component to focus on in order to optimize luminaire performance, especially with so many driver issues. Big chip LEDs require a higher drive current, but lower forward voltage.

Mehmet Arik, General Electric Global Research Center

Mehmet Arik stressed the need to shift the industry’s focus from optimizing at the chip level to optimizing at the system level. Specifically, Arik encourages emphasis being placed on system level thermal management (focusing especially on electronics), reliability and standardized test methods. GE suggests creating a JEDEC-like group to develop LED specific testing standards. He stated that it is not proven that the LED systems will work beyond 50,000 hours. In addition he suggested that steady state measurements be taken rather than pulse measurements since that would more clearly demonstrate actual reductions in efficiency. He stated that ultimately the thermal solution should comprise only 5-10% of the overall luminaire cost.

OLED Presentations, November 5, 2009

Ruiqing (Ray) Ma, Universal Display Corporation
Phosphorescent OLEDs: Enabling an Energy Efficiency Lighting Industry

Ma foresees five critical elements in which OLEDs need to improve in order to gain market acceptance. These are development of 1) energy savings products, 2) cost-effective products, 3) a supply chain, 4) standards, and 5) consumer education. Currently Ma believes that OLEDs fill niche roles. In order to expand upon this role, the DOE will need to assist the market in improving the critical elements.

UDC set a primary goal of increasing the efficacy OLEDs to levels that are higher than current lighting solutions. However, Ma acknowledges that achieving high efficacy over large areas is a significant challenge. A second technical challenge to this goal is the current status of substrates – costs are too high, resistance of anodes is too high, the costs of thin outcoupling is too high, and thermal management requirements need to be better understood. Another technical challenge requiring additional work is flexible or conformable products.

Ma also mentioned that UDC achieved 102 lm/W at the pixel level, achieved 68 lm/W for a 5cm x 5cm panel, and achieved 40-50 lm/W for a 15cm x 15cm panel. Ma explained that the efficiency loss from scaling up was likely a result of IR losses and outcoupling; however, he stated that more research was definitely need in that area.

Peter Ngai, Acuity Brands Lighting
Potential OLED Lighting Applications as Fluorescent Lighting Replacement in Commercial and Institutional Markets
Ngai perceives that the replacement Luminaire market in commercial and institutional buildings needs to unfurl according to the specification in Table 7. Ngai defines replacement as a redesign of a buildings lighting system, not retro-fitting old systems with OLEDs. To accomplish this path, the most important elements will be improving efficacy, lumen output, product lifetime, and lowering price. Ngai estimates that the market share for high-end products is about 15% of the market, and is 40% of the market for specification grade products. Following the soapbox presentation there was substantial discussion on the lifetime requirements of OLED luminaires. While Ngai estimates certain lifetimes for OLED luminaires to be competitive with other lighting technologies, he acknowledges that the lifetime targets are more challenging to achieve. He also, stated that OLED luminaires may not necessarily need to achieve lifetimes greater than 30 years. As lighting technology progresses forward more quickly, building owners will have greater incentive to retrofit their lighting more often.

Table 5 Acuity Brands OLED Luminaire Projections

Metric	**Specialty 2010-2013**	**Specification Grade 2013-2016**	**Commodity >2016**
Efficacy (lm/W)	80	110	140
Product Price Range	$400	$200	$100
Luminous Emittance (lm/m^2)	6000	6-12K	6-12K
Lifetime (1000 hours; L70)	20	35	50

Gary Silverman, Arkema, Inc.
Gary Silverman focused his soapbox presentation on substrate issues and potential benefits. Substrates have typically been flat panel display glass. For the purpose of this presentation, a “substrate” consists of a glass substrate, an undercoat, an anode, and potentially a metal oxide. Trying new prototype materials, improving TCO boundaries, and allowing for a longer lifetime at low voltage all could modify and improve substrates. Arkema has shown that the addition of an oxide topcoat to a transparent conductor can increase the power efficiency by 50-60% and perform many of the functions of existing hole injection layers. Gary believes there are three targeted solicitation needs for substrates: net anode structures, improved anode and processing costs, and solicitations that target both.

Franky So, University of Florida

So stated that the major roadblock to advancing OLEDs is the yield. Yield losses are typically due to three problems: 1) device shorts, 2) foreign matter, and 3) poor ITO layer quality. The ITO smoothness needs to be improved to reduce these problems. So has examined two potential methods to improving the yield. Improving yield may be accomplished through solution-processed HIL, or through solution-processed HIL and HTL. Ultimately, improving blue OLED is the key to achieving high efficiency white lights. The University of Florida has demonstrated that efficacies in excess of 100 lm/W can be obtained using a blue OLED with external phosphors for down-conversion.

Joe Shiang, General Electric

Joe Shiang from GE brought up the OLED industry's need to focus on developing a value proposition for OLEDs. GE believes OLEDs are on pace to be as efficacious as necessary, but the industry needs to make great strides in increasing OLED lifetimes and making OLED technology cost-effective. As of right now the OLED industry has no supply chain and lacks well-developed manufacturing processes.

Shiang also estimated that the efficacy limit (assuming no energy losses) corresponding to the spectra produced at GE is around 300 lm/W. This is about 25% below that obtainable with narrow RGB lines.

Yuan-Sheng Tyan, Eastman Kodak

Yuan-Sheng Tyan discussed the problems of IR loss. He pointed out that the resistivity of current transparent conductors is so high that if the current is transported at low voltages (~3V) IR losses will be unacceptable for panels of dimension greater than 1 cm. Kodak believes that the solution is to separate the panel into segments connected in series and to transport the current across the panel at much higher voltage. Others recommend the use of metal grids to supplement the transparent conductor. Tyan also stressed the importance of maintaining acceptable color in the quest for higher luminance. Tyan also referred to the difficulty of achieving long lifetimes at high brightness. He believes that a light level around 6000 lm/m2 might be a good compromise and would be competitive with traditional fluorescent troffers.

Norman, Bardsley, Bardsley Consulting:

Norman Bardsley suggested that the lifetime problem would be ameliorated if the efficiency were improved substantially. For example, in a device operating at 150 lm/W, output levels of 10,000 lm/m^2 could be reached with current densities of only 2-3 mA. Good lifetimes have already been achieved at this current density. Tyan confirmed that lifetimes depend more strongly on current density than light output.

Bardsley also suggested that the Lambertian distribution of light emitted by most OLEDs may not be optimal for luminaire designers, who often wish to focus the light in specific directions. He also pointed out that light extraction would be more effective if the light were emitted preferentially in the direction normal to the panel and asked whether this might be a suitable topic for future R&D, perhaps as one option in a solicitation on light extraction.