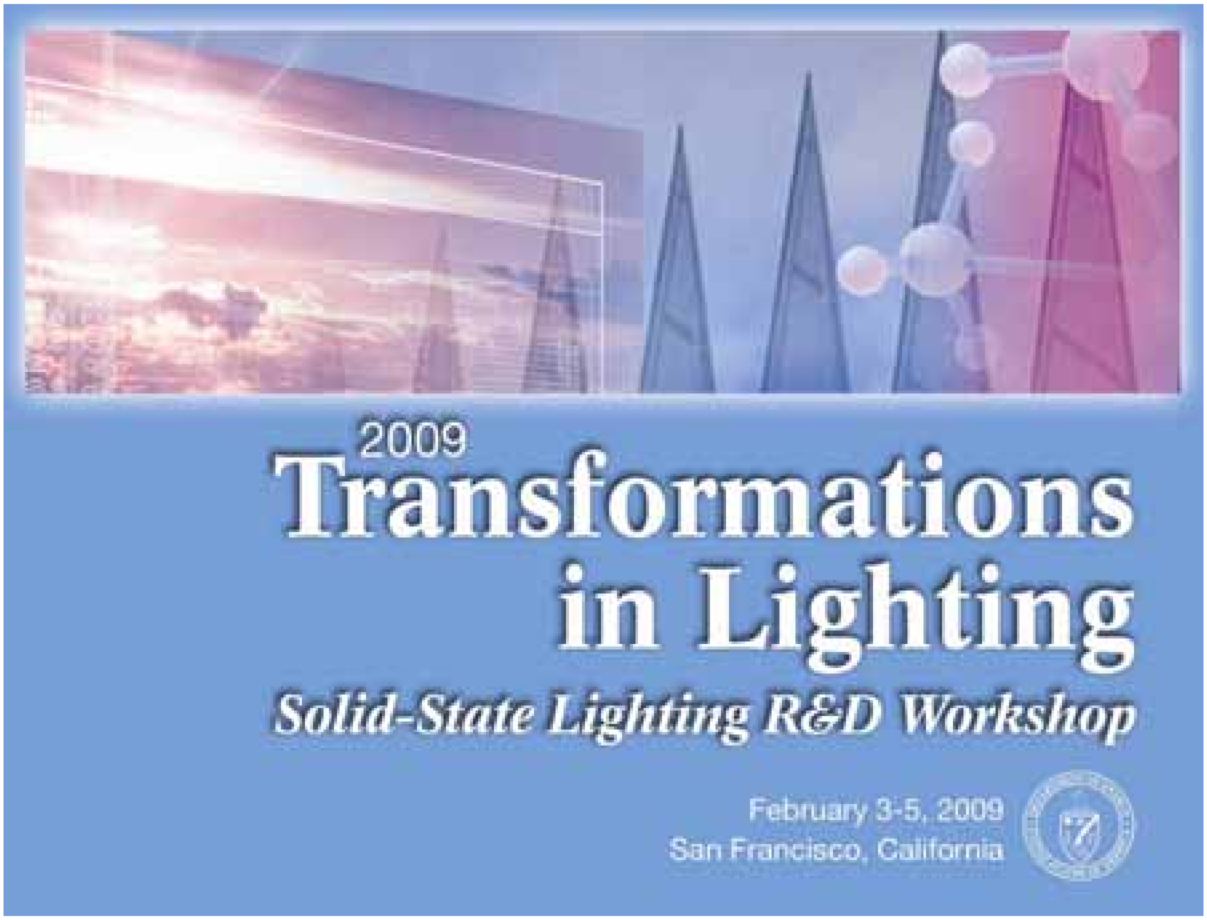

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

May 2009

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COMMENTS

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

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

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1. Introduction

On February 3–5, 2009, over 400 SSL technology leaders gathered in San Francisco, California, to participate in the sixth annual Solid-State Lighting (SSL) Program Planning Workshop hosted by the U.S. Department of Energy (DOE). Participants from the lighting industry, research organizations, universities, and national laboratories, along with representatives from efficiency programs, utilities, and the lighting design community, joined DOE to share perspectives on the rapid evolution of SSL technology. The workshop provided a forum for building partnerships and sharing strategies for continuing advances in high-efficiency, high-performance SSL technologies.

Chapter 2 of this report covers the launch of the 2009 “Transformations in Lighting” workshop, in which DOE SSL Program Manager James Brodrick highlighted the progress and pace of SSL advances: more products on the market that reflect the benefits of SSL and portend additional improvements and technological advances; the 2008 winners of the Lighting for Tomorrow competition; and the positive results from Phase III of the Oakland, California, GATEWAY street light demonstration. Chapter 2 also addresses overall product quality and provides insights on technology developments to ensure market acceptance, focusing on customer concerns and perceptions.

Chapter 3 summarizes results from SSL technology demonstrations ranging from outdoor bridge and street lighting in Minneapolis, San Francisco, and Oakland, to residential lighting in Connecticut. Chapter 4 discusses research findings of a study analyzing international SSL patents as well as a study on life cycle assessment of SSL applications.

Chapter 5 presents the first DOE ENERGY STAR® SSL products and plans for program expansion, the latest CALiPER test results, and an update on the L Prize™ competition for manufacturers of super-efficient, high-quality lamps. Also included is a description of SSL Quality Advocates—a new voluntary pledge program that uses a Lighting Facts™ label to document and assure consistent reporting of LED lighting product performance.

Chapter 6 focuses on the DOE SSL R&D portfolio, including a series of invited talks reporting 2008 project achievements and projects of interest for 2009, an update on the R&D SSL Multi-Year Project Plan, and the results from breakout sessions intended to update the MYPP and guide DOE planning for R&D solicitations.

Chapter 7 begins with the challenges architects and designers face when specifying today’s LED lighting products, and concludes with two lighting design competitions that recognize quality SSL products on the market—the new Next Generation Luminaires and Lighting for Tomorrow, for which the 2008 honorees present insights on their winning residential lighting products. Finally, in Chapter 8, DOE details upcoming program events and activities.

Workshop presentations and materials referenced in this report can be found on the SSL Web site at www.ssl.energy.gov/past_conferences.html.

2. Strategies for "Transformations in Lighting"

2.1 Welcome

James Brodrick, U.S. Department of Energy

James Brodrick welcomed more than 400 participants to the sixth annual DOE Solid-State Lighting R&D Workshop by observing some key trends in 2008: lots of new products on the market, many good ones, with more products in appropriate applications that take full advantage of the inherent benefits of SSL. Brodrick went on to note product improvements and technology advances "that show us we have only scratched the surface of what is possible."

Brodrick congratulated the 2008 winners of the Lighting for Tomorrow competition, applauding the winners as industry leaders who are "getting it right," designing products that marry LED technology with appropriate optics, thermal management, and other design considerations that maximize the technology potential. He then highlighted another example of "getting it right" through product re-engineering and ongoing problem-solving. In a GATEWAY demonstration of street lighting in Oakland, CA, several Phase II luminaires were replaced with next-generation versions for Phase III, increasing energy savings by 25 percent relative to Phase II, and reducing costs by 34 percent from Phase II to Phase III.

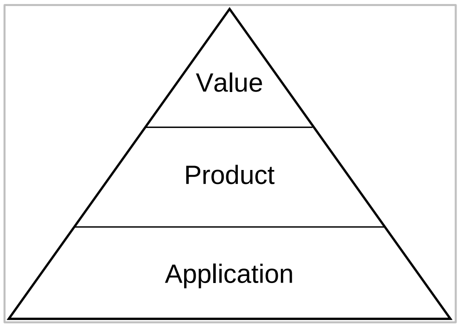
In Phase III of the Oakland demonstration, the installation of next-generation luminaires increased energy savings by 25% and reduced luminaire costs by 34%.

While many of the LED products coming to market are very good, some do not perform as claimed. "We know what needs to be done," said Brodrick, and he challenged his audience to solve the technology barriers to market acceptance by finding the optimum balance among efficacy, color, and cost. Brodrick also encouraged participants to provide input: "We're here…to discuss these thorny issues and gather a wide range of perspectives."

2.2 What Customers Want from LEDs

Jeff Quinlan, Acuity Brands Lighting

In his presentation on "What Customers Want from SSL," Jeff Quinlan of Acuity Brands Lighting offered insights on critical technology developments related to quality, lifetime, cost, and application that are needed to ensure successful SSL market introduction. Quinlan defined customers as manufacturers, specifiers, distributors, contractors, and owners/operators, and also cited the market influences of government, professional organizations, and trade associations.



He depicted the three primary areas of customer concern as a pyramid, starting with the base of "application," which involves appropriate consideration of placement, performance, and light level. The next layer of customer concern involves actual "product features" such as consistency, performance, and quality. The top level is "SSL value," encompassing specific application efficacy, total cost of ownership, environmental impact, and the difficult-to-define aspect of customer "emotion." Quinlan noted, "It's not just about dollars," pointing out that communication is the key element in successful adoption.

One of the important responsibilities of those in the SSL industry, Quinlan said, is "helping our customers understand how products are performing, so they can make informed decisions." To accomplish that, he continued, "We have to take a step back and look at customer perception, because one of the most difficult things we face is that our communication is complicated by perception." Customer perception can be influenced both by the quantity and quality of lighting, Quinlan observed, and lack of understanding on such intricacies as color rendering index (CRI), lamp burnout, thermal management, and energy balance are all important aspects that must be clearly translated to promote customer confidence. Emphasizing the value of DOE's CALiPER testing program, Quinlan stated, "It underlines an important problem that we as an industry have. We must work harder to make sure that what we say we can do, we can actually do."

Value—at the top of Quinlan's pyramid—is perceived by most customers as going beyond direct costs alone. Total cost of ownership (Figure 2-1) remains a key selling point in Quinlan's view, since LEDs can dramatically reduce energy and maintenance costs. Another strong consideration is SSL's reduced environmental impact. LEDs can be made using lead- and mercury-free technology, eliminating hazardous disposal requirements, and increased energy efficiency will reduce demand on fossil fuels.

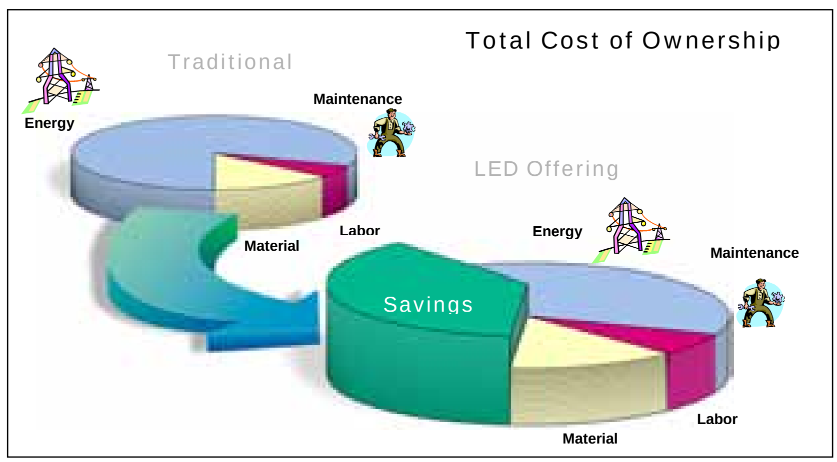


Figure 2-1: Total Cost of Ownership Between Traditional and LED Offerings

In all communications with customers, Quinlan emphasized the importance of "speaking a common language," citing ENERGY STAR® for SSL, the SSL Quality Advocates' Lighting Facts label, and industry standards including LM-79 and LM-80 as examples of positive steps toward helping customers better understand what they are buying. He concluded by reiterating the need to "…understand the application…develop quality products, and…drive value."

3. SSL Technology Demonstrations

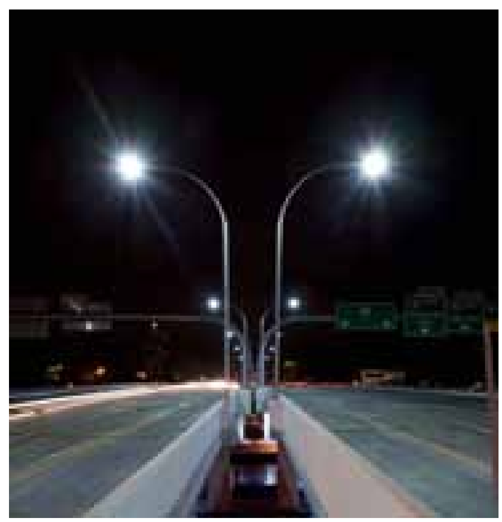
3.1 Navigating the SSL Technology Learning Curve

Bruce Kinzey, Pacific Northwest National Laboratory

Bruce Kinzey of Pacific Northwest National Laboratory (PNNL) introduced a panel of speakers to address the challenges of navigating the SSL learning curve. First, Kinzey reviewed several recent installations from the DOE GATEWAY demonstration program, which demonstrates SSL products in residential and commercial applications. Demonstration project teams conduct product tests and in-situ measurements, obtain user feedback on illumination quality, and conduct economic and performance evaluations. Results are documented and shared widely.

Kinzey emphasized the importance of carefully matching the right product to each application, and noted that “actual performance relies on a number of factors, including thermal management, thoughtful design, and quality components and construction.” He added that in general, the best performing products are designed from the ground up as LED products. He stated that “everyone is going through the same learning experience right now.” LED technology is vastly different from previous lighting technologies, and because of the complexity, answers to questions are often “it depends.” Performance-wise, the technology can already compete with incumbent technologies in many applications, but the learning curve and first costs remain hurdles to adoption of the technology.

Kinzey highlighted DOE’s unique long-term study of the I-35W Bridge installation in Minneapolis and noted the Minnesota Department of Transportation’s initial concerns about installing a new technology in such a high-visibility, high-risk installation. To address these concerns, DOE created an evaluation plan that included LM-79-08 photometric testing, LM-80-08 testing, site measurements and expert review, and an agreement that lighting would be monitored over three-year period using a mobile monitoring system developed by VTTI (Virginia Tech Transportation Institute). A final evaluation report will be issued in 2011, including documentation of all maintenance and other issues with the project.



I-35W Bridge in Minneapolis, Minnesota, with LED luminaires on main roadway

To learn more about GATEWAY results, or to participate in a DOE GATEWAY demonstration, information is posted at www.ssl.energy.gov/gatewaydemos.html.

3.2 Street Lights of San Francisco: Project Overview

Mary Matteson Bryan, Pacific Gas & Electric

Mary Matteson Bryan of Pacific Gas & Electric (PG&E) shared a utility perspective, discussing results from a current GATEWAY street light demonstration project in a nearby San Francisco neighborhood. The demonstration is part of PG&E's Emerging Technologies Program, which identifies and assesses emerging technologies to accelerate market penetration in pursuit of California's aggressive energy efficiency goals.

This field assessment is a collaboration with PG&E, DOE, and the City of San Francisco. Using the base case of 100W Cutoff High Pressure Sodium (HPS) street lights, PG&E evaluated four LED street lights installed on four adjacent city streets, with products from BetaLED, Cyclone, Leotek, and Relume.

Comparing LED (top) and HPS luminaires (bottom) in San Francisco neighborhood

The results are informative. All four streets showed promise of 50% energy savings or better, and lighting quality was generally good. Economic performance was evaluated, considering costs versus payback range, assuming PG&E electricity costs. Luminaire costs ranged from $300 to $700 per unit, and had a simple payback ranging from 4 to 15 years for new construction, and 7 to 20 years for a retrofit. The products with better lighting performance were more economically attractive.

There were a number of key lessons learned in the project, starting with all products are not created equal. Matteson Bryan encouraged the audience to "Install test luminaires. Seeing is believing." She stressed the importance of matching the performance to the task, and noted that while performance is improving and costs are coming down, variable product quality remains a challenge for incentive programs. Maintenance and operation cost savings are still difficult to quantify, with costs ranging from $12/year/fixture to more than $100/year/fixture. For example, longer life and fewer calls to the call center should reduce costs, but these factors are hard to quantify.

Other challenges for the development of incentive programs for outdoor lighting remain. Current practices do not fully address the different attributes of LED lighting sources, and variable product quality, high upfront costs, and the need to educate customers remain an issue. In addition, because street lighting is typically not metered by the utility, it is difficult to calculate payback. To address this, development of new rate schedules using wattage categories is under consideration.

PG&E has identified several areas for further research and development. The utility is following ENERGY STAR specifications where they exist, and looking at alternatives where no ENERGY STAR specification exists. For more on the San Francisco demonstration, see the full GATEWAY report at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/gateway_sf-streetlighting.pdf.

3.3 Refining Products for Marketability

Eric Haugaard, BetaLED

Eric Haugaard of BetaLED followed with insights on how a manufacturer can gain value from demonstrations, and reviewed lessons learned in an Oakland, California, GATEWAY demonstration project. The Oakland project was conducted in three phases. Phase I was an application mock-up in a parking lot, Phase II was a street level retrofit, and Phase III was a second street level retrofit. In Phases I and II, BetaLED's THE EDGE™ Architectural Area Light Luminaire was installed to replace 100W HPS lights. This achieved a 35% energy savings.

At this point, BetaLED went back to the drawing board, looking for further improvements. The result was a more optimized solution for Phase III, the Beta LEDway™ Street Light Luminaire, which achieved 52% energy savings (compared to the baseline HPS system) and reduced product costs by 34%. This new product was designed specifically for the street lighting market, incorporating the same desirable mechanical features and attributes available in the most popular cobrahead products. The lean design has new optics designed specifically for optimized street lighting performance, and three drive current choices—350 mA, 525 mA, and 700 mA.

Drive current choices bring about a new question: when should low versus high current choices be used? Haugaard provided two examples that would benefit from different current choices. Example 1 might be in Hawaii: with its very high cost of energy, long daily operation, and a high average ambient temperature, the best choice for delivering a good ROI was likely to be the 350 mA option. Example 2 might be for a factory in a cool climate where energy costs are low, daily operation is short, and the average ambient temperature is low. In this case, the 700 mA choice is likely to yield the best ROI.

Haugaard recommended for a fair comparison that actual measured performance be used side by side. He added that "any good comparison must be done at the application level" using certified LM-79 photometric testing and IESNA LM-80 life data testing for the system from an independent testing lab. He also urged listeners to look at the appropriate maintenance factors/light loss factors for the competing systems, and do a cost/value analysis, including lighting performance, total power consumption, and maintenance.

	Oakland Phase II Beta 60 LED THE EDGE (type III) (350 mA)	Oakland Phase III Beta 30 LED LEDway (type II) (525 mA)	Alternate Phase III Beta 40 LED LEDway (type II) (350mA) (Predicted Performance)	Oakland existing 100 watt HPS
average	.53	.48	.46	.8
max	1.49	1.30	1.26	3.72
min	.09	.09	.09 +	.09
avg:min	5.7:1	5.2:1	5.2:1	8.7:1
max:min	16.0:1	14.0:1	14.0:1	40.0:1
Delivered Lumens	4468	3090	3200	~6698
Energy Consumption	77.7 w	58.3w	53 w	121 w
Luminaire Efficacy (LPW)	57.5	53	60.4	~55.4

Figure 3-1: Oakland Alternate Phase III vs. 100W

For more details on the Oakland demonstration, see www.ssl.energy.gov/gatewaydemos_results.html.

3.4 LEDs Head for the Homefront

Kevin Dowling, Philips Color Kinetics

Kevin Dowling of Philips Color Kinetics presented a unique residential lighting installation on North Dumpling Island, located off the coast of Connecticut. Owned by Dean Kamen, successful inventor, businessman, and educator, the island is the site of a Coast Guard lighthouse. The Coast Guard chose to install a solar array and “cut the cord” to the island lighthouse, which Kamen interpreted as a challenge: demonstrate how to make island living a self-sufficient, energy-saving example. Kamen looked to all renewable sources and a filament-free island.

To solve the power generation need, a wind turbine generates 10 KW, and two solar arrays are on hand: one for the Coast Guard, the other for the private residence. An efficient Stirling generator was also installed to supply energy. The Stirling engine can burn any fuel efficiently to generate power and provide co-generation capability. To store and manage the energy, deep cycle marine batteries and inverters were installed, along with a networked control system. Dowling noted that until solar direct conversion is a practical solution, AC to DC to AC loss remains a significant factor.

Kamen living room with LED cove, downlight, and PAR 38 lighting

To get to energy-independent island living, alternative consumption choices, from clean water to LED-based lighting, were also essential. For water purification, Kamen's own invention called Slingshot was installed. Slingshot uses vapor compression distillation to pull water out of anything remotely wet to provide 1,000 liters of fresh water daily. In the Kamen downstairs, where a shallow ceiling meant that canisters didn't work, the team used LED surface-mount downlights with a shallow junction box that meets code. The library was outfitted with Philips downlights and picture lights, while the living room used a combination of cove lighting, daylighting, and PAR 38 replacements. Discussing the challenges of this project, Dowling noted that "Edison sockets were never made to remove heat from the source," and trying to shoehorn LED technology into existing forms results in a tremendous tradeoff. While the fixtures selected worked well, he noted that not all lighting is well-suited to LEDs…yet. Someday, Kamen hopes the old xenon light in the Coast Guard lighthouse will also be filament-free.

Question and Answer Session

Following the presentations, a participant asked Kinzey why HPS fixtures were not being redesigned to achieve energy savings. Kinzey responded that there are incumbent technologies worth considering, but they often provide uncontrolled light and evenness is an issue. He encouraged the attendees to look at any solution available. Matteson Bryan added that PG&E is open to any technology that saves energy.

Another questioner asked about lighting possibilities that get beyond the old paradigms. Do we have to have street lights that look the way they do? Dowling responded that new form factors are being considered, and that an ANSI (American National Standards Institute) group is looking at this issue exactly. However, thermal management remains a big issue. Haugaard commented that BetaLED focuses on extracting as much light out of LEDs as possible and thermally managing it. For his firm, form follows function.

Another questioner asked whether the Minnesota bridge project managers had any concerns for users as they move through the lights as the color temperatures change on the bridge (from HPS to LED and back). Kinzey responded that the team had to meet strict RP8 (safety) requirements using modeling, because it wasn't possible to show existing/previous lighting, given that the bridge had collapsed. Most feedback indicated that the lighting on the bridge mimics daylight, and drivers like it.

Finally, an attendee asked the panel to comment on where the trades, design professions, accountants, and building owners fit into this picture. Dowling acknowledged that contractors tend to find the problems. He added that the industry is trying to make it easy to connect (devices) and pass codes, but once control systems become part of the picture, it leads into software and networking systems, which is more of an information technology management mode. This differs from the typical installation of traditional lighting projects. Matteson Bryan commented on the importance that education of contractors play in the matter.

3.5 Tour of LED Street Light Installations

On Tuesday evening, participants interested in seeing LED street lights in action were invited to take an informal tour to two nearby installations, featuring commercial and residential LED street lights assessed as part of DOE's GATEWAY Demonstrations. More than 70 participated, led by Mary Matteson Bryan, PG&E Emerging Technologies Senior Project Manager.

LEDs are able to overcome some of the limitations of traditional street lights, which are not "smart"—systematic outage detection and the ability to alter the power level have not been possible. In San Francisco, attendees first saw five BetaLED EDGE luminaires equipped with Echelon network controls installed at the PG&E Headquarters building on Beale Street. Each uses an array of 100 LEDs to produce light that is similar to what a regular streetlamp creates in terms of intensity and beam spread. John Sofranac, PG&E Manager of Street and Outdoor Lighting, demonstrated remote light operation (on/off and dimming) from his handheld PDA, explaining how municipalities could benefit from this kind of flexibility. He noted that the ability to monitor the entire system this way provides a basis for scheduling preventive and replacement maintenance, for reducing energy use, and for obtaining data on energy use to verifying the accuracy of electricity bills. Another big plus: if the city decides that it needs to turn off a streetlamp to save money or because the street is bright enough, there's no need to send a PG&E worker out at a cost of $120 an hour. And, when full power is being used, each street light draws only 127 watts, rather than the 290 watts consumed by traditional sodium lamps. A municipality faced with operating budget cuts can realize a tangible difference.

Workshop attendees watch John Sofranac of PG&E remotely control street lights at a commercial installation in San Francisco

The second part of the tour was located on three avenues in the residential Sunset District. Each avenue has a total of five street lights from the beginning to end of the block. The group first saw BetaLED luminaires on 41st Avenue, followed by Leotek luminaires on 42nd Avenue, and Relume luminaires on 44th Avenue. Participants noted firsthand the visible variations from street to street, in terms of light output, color, cutoff, and other factors. For more details, see the complete GATEWAY report at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/gateway_sf-streetlighting.pdf.

4. DOE SSL Studies: Technology Development and Commercialization and Life Cycle Assessment

4.1 SSL Technology Development and Commercialization in the Global Context

Kenneth L. Simons and Susan Walsh Sanderson, Rensselaer Polytechnic Institute

Kenneth L. Simons and Susan Walsh Sanderson of the National Science Foundation Smart Lighting Engineering Research Center and Rensselaer Polytechnic Institute presented their findings in a recently completed study analyzing SSL-related patents filed and acquired internationally. In this first-of-its-kind comparison of inter-country, inter-firm trends linked to a broader ongoing study, Simons and Sanderson looked at world patents, product creation in companies, national policies, and technology spread and economic impacts, working with a research team that included 17 research assistants fluent in Japanese, Chinese, Korean, and key European languages.

The team researched all patents from worldwide patent data collected by the European Patent Office with titles that included the terms LED(s), OLED(s), light-emitting diodes, or foreign-language equivalents, and included filings in all years, in approximately 70 nations. Excluding many materials patents, 34,451 applications were surveyed, of which 10,352 were granted patents, 5,033 were granted utility models, and 543 were other grants, such as design patents, provisional patents, and inventor's certificates.

Their DOE study focused on SSL patents in general illumination in two categories:

1. Narrow SSL: Focus on lighting-specific uses
2. Broad SSL: Lighting with fundamental technologies and LED designs with applications, excluding displays, printers, and scanners

These categories were in turn defined by international patent classifications with title keywords—for example, lighting included F21, H05B31-43, "lamp," and "luminaire." The table below illustrates some of the major findings of the study.

Parent Company	Narrow SSL Patents	Broad SSL Patents	All LED Patents
Siemens	110.3	176.0	230.5
Philips	102.0	170.6	228.8
GE	66.6	112.9	139.6
Matsushita	51.1	109.1	141.9
Samsung	44.3	269.7	425.9
He Shan Li De / Neo-Neon	41.0	47.0	49.0
Kodak	40.4	85.4	243.5
Stanley Electric	28.1	49.5	78.5
LG Electronics	26.0	122.7	136.7
911 Emergency Prod.	22.7	30.1	41.5
Dialight	22.6	28.9	34.4
Toshiba	21.4	53.2	75.4
Augux	17.0	17.0	17.0
Arima Optoelectronic	15.0	37.8	41.8

Figure 4-1: Firms Leading in Global SSL Patent Applications

The main conclusions of the study demonstrate that SSL R&D is spreading further in Asia, highlighting the growing role of China in manufacturing and R&D, especially in narrowly defined aspects of SSL. These applications came mainly from individual applicants, for short-term utility models with few full patents. Their findings also reflected international inter-dependence, with traditional lighting firms transitioning into SSL through joint ventures and acquisitions. Finally, while large firms are playing a more dominant role in the emerging international SSL industry, for small firms the major opportunities at this time are seen in materials, devices, and fixtures.

4.2 Life Cycle Assessment of Solid-State Lighting Applications

H. Scott Matthews and Deanna H. Matthews, Carnegie Mellon University

H. Scott Matthews and Deanna H. Matthews, members of the Green Design Institute at Carnegie Mellon University (CMU), described early progress on the DOE-funded life cycle assessment of solid-state lighting applications. The overarching goal of the study is to determine whether LEDs save energy, when considering materials and manufacturing efforts, the use of the devices, and their ultimate disposal. The CMU team first described the short-term project goals, to compare energy use of current SSL technology to existing mature technologies over their respective life cycle. In the long term, the study seeks to examine "materials of interest" over the SSL life cycle.

The team is working to refine the scope, and to model the life cycle energy of a "generic" SSL product, because specific types and potential applications of SSL products vary widely. One of the most familiar manufacturing processes is for automobiles, so the team is using a comparison to a "generic" U.S. family sedan. The study will compare five "buckets": raw materials extraction, materials and parts production, product manufacturing, use, and end of life. Just as an automaker hesitates to label a product "generic," and the results represent no single vehicle, the reference brings value when examining the process. As with autos, the team anticipates that the SSL use phase will consume the most energy. The theory is that SSL will have lower overall impact than other lighting technologies. But does the available data support this goal?

The project is initially focused on materials and parts manufacturing, and the product manufacturing stages. The boundaries are broad, and thus far are focused on LED chip manufacturing, bulk materials, and high-purity process gases.

To begin, the team had to make some assumptions. They chose to use a current generation replacement bulb in a downlight application, based on a CALIPER benchmark test. This assumes a luminaire with an array of 20 HB LEDs, luminaire efficacy of 60 lm/W, and a luminaire lifetime of 25,000 hours.

For the materials manufacturing stage, only LED materials are being considered, including trimethylgallium, ammonia, sapphire wafers, silicon, yttrium, and contact metals. Initial estimates indicate that high-purity levels of these materials require significant energy input.

For the product manufacturing phase, the study will focus on LED chip production, including LED wafer processing. The approach is to estimate an energy value for each step, then add together corresponding values. Although more information on sapphire production is needed, preliminary estimates indicate that GaN is the biggest energy user in this phase.

Chemical vapor deposition (CVD), the chemical process used to produce high-purity, high-performance solid materials, represents another important energy consumer in this phase. Average preliminary CVD estimates using three methods are reasonably close, so the team estimates that energy used in the CVD step is likely "at most" 1 kWh for the final product.

The estimates for full LED chip manufacturing using metal organic chemical vapor deposition MOCVD, which includes CVD, metal deposition, photolithography, etching, and cleaning steps, is about 75–85 kWh/wafer, or ~1.5 kWh/SSL product. When including mounting, testing, packaging, phosphor coating, and encapsulation, the current "best guess" is double this figure. The team acknowledges that more information is needed especially on phosphor coatings.

Based on data from logic chip manufacturers, energy use from other facilities and equipment is not negligible, probably 200–700 kWh/wafer, or 8 kWh/SSL product, but this is difficult to scale. Preliminary estimates given each of these figures (materials + production) is between 900–2000 kWh, or about 15–50 kWh/SSL. Compared to compact fluorescent lamp (CFL) production, which is estimated at 4 kWh for a 15 W CFL, this is much higher. The cost of manufacturing incandescent lamps is extremely low.

Next, the goal is to compare apples to apples in the use phase. For this, the team is looking at LEDs using CALiPER data to compare current technologies in "functional equivalence." The current assumption of a functional unit is a 25,000 hour lifetime for an LED lamp in downlight setting. This is being compared to best-in-class reflector CFLs and incandescents, correcting for output, efficacy, and lifetime. Matthews stated, "For the same lumen-hours of light, bulb life is less important than efficacy. Efficacy is most important." Quite simply, the use phase dominates, much as it does for the auto manufacturing example.

Next steps for the study include expanding the boundaries and acquiring data for luminaire production and SSL end-of life, two other phases in the life cycle. The team will also consider other SSL products beyond an Edison replacement, and begin a materials inventory. Attendees were invited to participate in the study by sharing data on various aspects of the process, so the team can refine this analysis further.

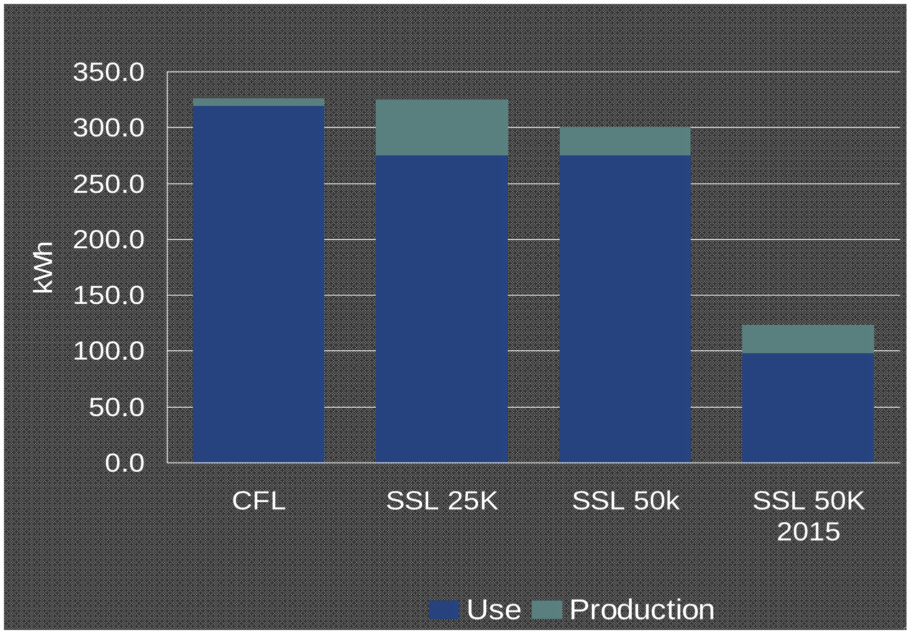


Figure 4-2: Life Cycle Energy Comparison of Lighting Technologies

Question and Answer Session

During the session, one attendee asked about the mean time to failure. Matthews responded that we need to learn how to talk about LED life in an entirely new way—unlike an incandescent, which most assuredly fails at 1,000 hours (+/- 100 hours), LEDs are decidedly different, and it is important to communicate useful life accurately to the end user.

Another participant pointed out that looking only at chip production is just one piece of the puzzle, and Matthews acknowledged that including other materials such as aluminum will also be a factor.

One manufacturer offered assistance in filling the gaps of information, and the team invited others to provide assistance as well, asking for other LCA studies, bill of materials (especially hazardous ones), and assistance with questions such as "is the GaN growth the biggest thing or not?" CMU would like to identify chemical manufacturer contacts as well, and invited input on products for future consideration, in terms of a full fixture system.

5. Defining Quality SSL Products

5.1 DOE ENERGY STAR® SSL Products on the Market

Richard Karney, U.S. Department of Energy

Richard Karney, DOE's ENERGY STAR® Program Manager, announced the first DOE ENERGY STAR SSL products as well as program plans for future expansion as LED technology continues to advance and improve. ENERGY STAR is a voluntary energy-efficiency labeling program providing a single set of performance criteria to help consumers identify products that save energy, relative to standard technology. As the national symbol for energy efficiency, Karney explained, the label serves as a marketing platform for retailers, manufacturers, and utilities to promote energy-efficient products by establishing industry-wide specifications for SSL products and ensuring the quality of all products bearing its mark.

ENERGY STAR for SSL reflects DOE's involvement in commercialization of SSL over many years, Karney stated, and establishes performance requirements early to avoid repeating negative consumer experiences that occurred with the introduction of CFLs. The DOE ENERGY STAR criteria for SSL focus on luminaire efficacy as the key metric, based on IESNA LM-79 and LM-80 test procedures. By offering ENERGY STAR-qualified products, appliance manufacturers have found that consumer loyalty to their brands has increased, and Karney anticipates that this will be true for the luminaire market as well.

To date, the two SSL applications with qualified products are recessed downlights and under-cabinet kitchen lighting. The first SSL product to achieve the ENERGY STAR label was Kichler's Design Pro™ undercabinet kitchen lighting system, and according to Karney, the product demonstrates the complexity of SSL qualification decisions. "This unique system is qualified only as a group of components," Karney observed. "By themselves, individual pieces of the system are not qualified. This was allowed because, on the market, Kichler has assured us that consumers will not be able to purchase just one component, but a mix of the offerings to compose a system that meets ENERGY STAR criteria. A combination of any three components and a power supply has been tested to provide over 400 lumens of light at a luminaire efficacy of nearly 37 lm/W."

Downlights receiving the ENERGY STAR label so far are the Cooper Halo downlight and the Kichler Rail Light, but Karney added that more products are "in the queue." Many manufacturers are still in testing and clarifications are still being provided on specific testing requirements, while some early kinks with the online product submittal tool have also been resolved. (Note: As of April 2009, 26 residential and 23 commercial products have qualified for the ENERGY STAR label. See www.energystar.gov/led for a complete listing of qualified products.)

Karney then provided an update on the DOE ENERGY STAR program plans. In January 2009, a draft of criteria for replacement lamps was issued for public comment. In February 2009, the expansion of Category A came into effect. New SSL applications for residential lighting include surface- and pendant-mounted downlights, ceiling-mounted lights with diffusers, cove lighting, surface-mounted lights with directional heads, and outdoor pole/arm-mounted decorative lighting. For non-residential SSL lighting, new applications include surface- and pendant-mounted downlights, wall-wash lighting, and bollards.

Karney concluded with an overview of partner tools and resources. A new partner resource guide provides talking points for use by manufacturers, retailers, and utilities, with graphs and tables that can be customized to meet users' needs. The guide provides simple messaging for explaining the technology to consumers and compares LEDs to other light sources in clear, accessible terms. Additional details on DOE's ENERGY STAR program for SSL are available at www.ssl.energy.gov/energy_star.html.

5.2 Identifying Quality Through Product Testing

Mia Paget, Pacific Northwest National Laboratory

Mia Paget of Pacific Northwest National Laboratory (PNNL) brought workshop participants up to date on the latest CALiPER test results and analysis, detailing which products are performing well and how this round of products stacks up. Paget first discussed how the CALiPER program identifies quality through product testing and provides unbiased performance information on SSL products for the general illumination market. Results guide DOE planning for R&D, GATEWAY Demonstrations, and ENERGY STAR initiatives, and inform the development of industry standards and test procedures.

The test results also serve to discourage low-quality products, helping reduce the risk of buyer dissatisfaction from products that do not perform as claimed. "Thinking back to two years ago when we announced the CALiPER program," Paget stated, "We knew almost nothing about the performance of these products. We did not really have testing standards. Today, we've tested more than 200 products and have all sorts of reports and information. We have come a long way."

Seven rounds of testing to date have revealed an upward trend in efficacy of tested products (Figure 5-1) Paget reported. While the range from best to worst luminaire efficacy remains wide, and some products still fail to deliver on promises, she continued, “We are finding that the best products are now really, really good. There is no doubt that we are seeing definite progress.”

Paget next offered the audience a “sneak peak” at Round 7 products tested, including outdoor fixtures (street lights and bollards), downlights, and directional and omni-directional replacement lamps. There were also some direct side-by-side comparisons, she noted, in which testing is done on “exactly the same product in multiple versions—an LED version and a CFL version or an LED version and a halogen version. Those are very telling.” In both bollard and downlight side-by-side comparisons, she reported, SSLs are demonstrating higher efficacy and competing successfully with CFLs and other lighting formats.

In conclusion, Paget cautioned attendees to watch for color variations, and to always compare performance at the luminaire level using absolute photometry, noting that product literature is often erroneous or misleading. She reminded her audience that CALiPER Summary Reports and detailed test results are available on the DOE SSL Web site at www.ssl.energy.gov/caliper.html.

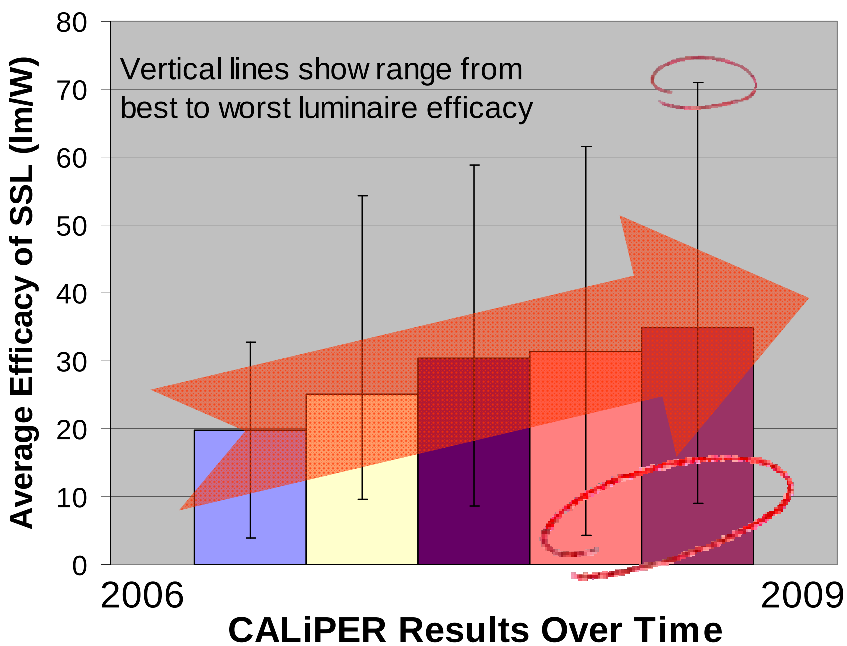
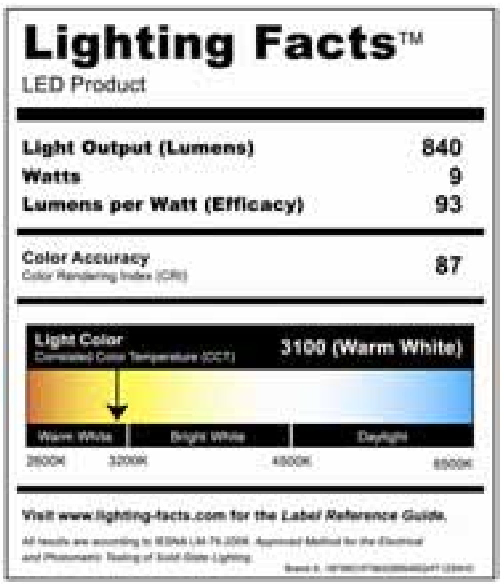


Figure 5-1: CALiPER Testing – Measurable Progress

5.3 Join the DOE SSL Quality Advocates

Fred Welsh, Radcliffe Advisors

Next, Fred Welsh provided an update on the DOE SSL Quality Advocates, a new voluntary pledge program designed to assure that LED lighting product performance is represented consistently and accurately. SSL Quality Advocates pledge to use a Lighting Facts label, similar to a food nutrition label, to document the performance of products they manufacture, sell, distribute, or promote, based on the industry standard for testing photometric performance, IESNA LM-79-2008. The label provides a quick, simple summary of product performance data as measured by LM-79 testing, and reports product performance results in five areas: lumens, efficacy, watts, correlated color temperature (CCT) and color rendering index (CRI).



A joint effort of DOE and NGLIA (Next Generation Lighting Industry Alliance), the SSL Quality Advocates program does not set performance requirements, Welsh cautioned, but rather asks manufacturers simply to tell "where your product *is*." Consumers need to know not just "pass/fail" on a product, he continued, but also what the level of performance actually is, and what various measures indicate about product quality. Noting that luminaire efficacy is a concept that is not always well understood by customers, Welsh predicted that consistent reporting of key parameters will foster continuous quality improvement throughout the value chain.

In addition to the Lighting Facts label, other program elements already in place include a Luminaire Manufacturers' Guide—to help manufacturers better address luminaire efficacy questions—and the voluntary SSL Quality Pledge Program, where Quality Advocates can enroll and pledge to use/ask for the label. Finally, Welsh concluded, "We've established the Lighting Facts Web site (www.lightingfacts.com), which is the place where you will soon be able to get labels as well as locate listings of products and manufacturers supporting the program."

For more information on SSL Quality Advocates, see www.ssl.energy.gov/advocates.html.

5.4 L Prize™ Competition Update

James Brodrick, U.S. Department of Energy

"The race is on for the L Prize!" James Brodrick reminded attendees as he concluded the panel session with an update on the race to achieve super-efficient, high-quality lamps that will replace the common light bulb. Specifically, the L Prize competition challenges industry to develop replacement technologies for two of today's most widely used and inefficient products: 60W incandescent lamps and PAR 38 halogen lamps. It also calls for development of a 21st Century Lamp that delivers ultra-high efficiency and performance.

The first government-sponsored technology competition designed to spur lighting manufacturers to accelerate America's shift from inefficient, dated lighting products to innovative, high-performance products, the L Prize will drive innovation and market adoption for SSL products. Created under the Energy Independence and Security Act (EISA) of 2007, the competition will award significant cash prizes, plus opportunities for federal purchasing agreements, utility programs, and other incentives for winning products.

He encouraged manufacturers to participate in the L Prize race, adding that winning products will have opportunities for immediate recognition and volume sales through partnering utilities and energy efficiency organizations, which now represent the potential to reach more than 100 million customers from coast to coast.

Program partners are the key to success for the L Prize, Brodrick stated, noting their capacity to drive sales up and prices down. "We wanted to develop the specifications you see here (Figure 5-2), so this lamp will meld very easily with what utilities are looking for. Because after a company wins the L Prize and receives their award from the Secretary of Energy, the next day the utilities will pick up the ball and begin program activities."

Requirement	60-Watt Incandescent Replacement	PAR 38 Halogen Replacement
Efficacy	More than 90 lm/W	More than 123 lm/W
Light Output	More than 900 lumens	More than 1,350 lumens
Wattage	Less than 10 watts	Less than 11 watts
Lifetime	More than 25,000 hour life	
Color Rendering Index (CRI)	More than 90	
Correlated Color Temperature (CCT)	2700–3000 K	
Form Factor	Same lamp form factor as incumbent technology	
Beam Distribution	Beam characteristics	Equivalent to incumbent technology
Dimming	Products must be compatible with at least three widely available residential dimmers, and must be continuously dimmable to at least 20% of maximum light output	

Figure 5-2: L Prize Competition Specifications

Competition requirements are stiff but achievable and include exceptional efficacy, long life, and form factor identical to lamps being replaced. Additional details are specified for quality, performance, and mass manufacturing. To join the competition, manufacturers must provide 2,000 lamp samples and verify their continuous production run, produce a manufacturing capability plan with 250,000 unit capacity in the first year, and use U.S.-based LED chip production.

Brodrick concluded by asking, “Why should you compete?” His answer: “To be recognized as ‘the best of the best,’ to tap into the immediate market potential for sales, to gain an intense media spotlight for your company, to earn automatic ENERGY STAR qualification—and, oh yes, for that cash prize—going to the first winner in each category!” Additional information on the L Prize competition can be found at www.lightingprize.org.

6. DOE Solid-State Lighting Research and Development

6.1 DOE SSL R&D Program Update

James Brodrick, U.S. Department of Energy

James Brodrick began the next session with his annual update on the DOE SSL R&D portfolio, budget, investments, and areas of focus, and then gave recognition to project teams making significant contributions in 2008. Brodrick reported that, in FY2008, the SSL program received $24.3 million in congressional appropriations and invested a total contract value of $75.1 million (including cost-share) for DOE R&D projects. These investments included $30.4 million for 18 OLED projects and $44.7 million for 26 LED projects.

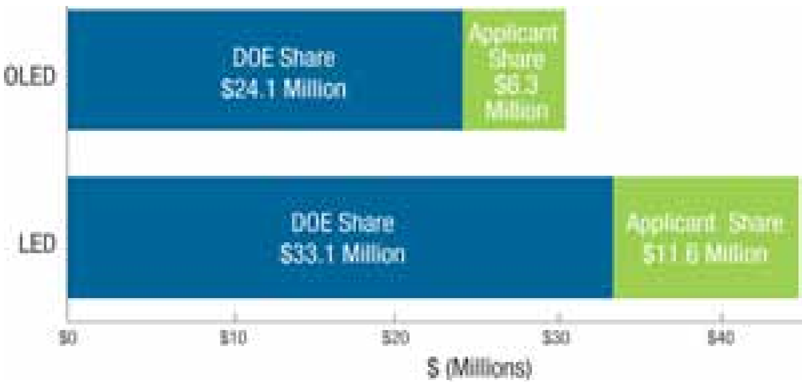


Figure 6-1: SSL R&D Project Funding

Brodrick reported that 57% of the total portfolio funds 27 projects in Core Technology, while 43% is invested in 17 Product Development projects. Among the 27 Core Technology research projects, 16 are LED projects, with 10 researching LED internal quantum efficiency (IQE), 3 researching substrates and growth, 2 studying phosphors/down converters, and 1 studying light extraction. Of the 11 OLED Core Technology research projects, 3 are studying charge injection, 3 are researching OLED materials and structures, 2 are researching transparent conductive oxides, and of the remaining 3, 1 is studying OLED fabrication, 1 degradation/lifetime, and 1 light extraction.

Among the 17 Product Development research projects, the 10 investigating LED-related areas (Figure 6-2) include 6 researching packaging, 2 researching optical coupling and modeling, 1 studying thermal design, and 1 studying manufactured materials. Of the 7 OLED Product Development research projects (Figure 6-3), 3 are studying light extraction, 2 are researching packaging, and 2 are researching materials and structures.

DOE funds SSL research in partnership with industry (37 percent to corporations and 24 percent to small businesses), universities (23 percent), and national labs (16 percent). Since DOE began funding research projects in 2000, a total of 90 patents have been applied for or awarded. See Appendix C for a fact sheet containing additional information on SSL patents resulting from DOE-funded research.

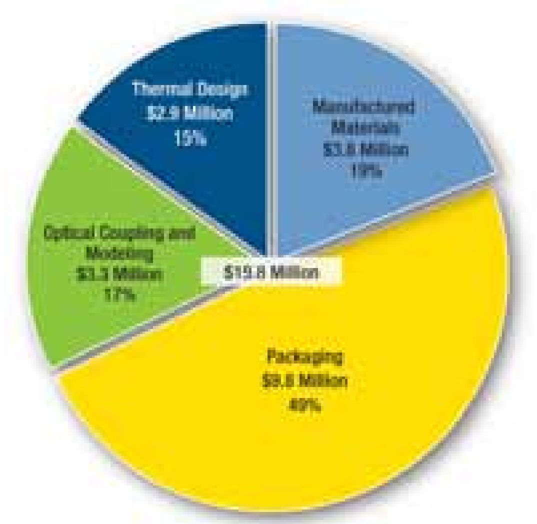


Figure 6-2: LED Product Research

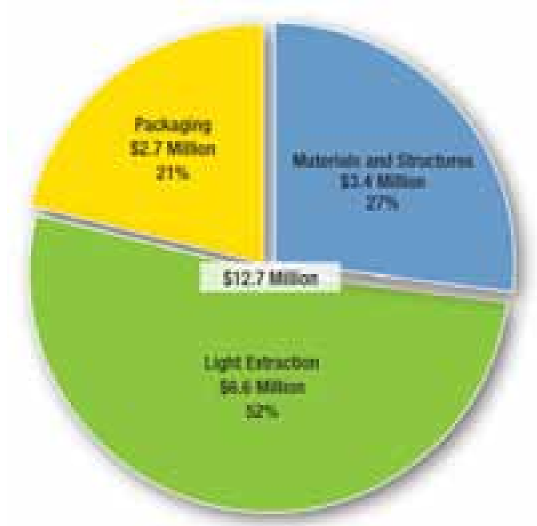


Figure 6-3: OLED Product Research

Brodrick concluded his talk by presenting special awards to seven project teams, for significant achievements in 2008:

- Rensselaer Polytechnic Institute
- Eastman Kodak
- General Electric Global Research
- University of Florida
- Cree, Inc.
- Universal Display Corporation
- Philips Color Kinetics

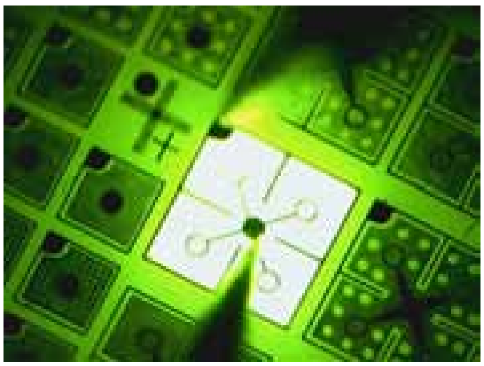
Jim Brodrick, fourth from right, with R&D awardees (left to right): Christian Wetzel (RPI), Yuan-Sheng Tyan (Eastman Kodak), Anant Setlur (GE Global Research), Franky So (U. of Florida), Monica Hansen (Cree), Mike Hack (UDC), and Kevin Dowling (Philips Color Kinetics).

6.2 Reports on Selected DOE-Funded R&D Projects (Invited Talks)

James Brodrick, U.S. Department of Energy

SSL R&D Project Managers Joel Chaddock, Brian Dotson, and Ryan Egidi from the National Energy Technology Laboratory introduced a series of invited talks on significant DOE-funded 2008 project achievements and projects of interest for 2009.

Closing the "Green Gap" in LED Materials
Christian Wetzel, Rensselaer Polytechnic Institute



RPI research on deep green LEDs

Christian Wetzel of Rensselaer Polytechnic Institute discussed his team's efforts to close "the green gap"—that is, to increase the efficiency of green LEDs. Currently, most LEDs rely on a mixture of blue LED and yellow phosphors. However, for a full color spectrum, efficient greens are essential, but at 550 nanometers (nm), our eye's most sensitive wavelength, this has been tricky, and the "green gap" refers to this fact of performance lag. According to Wetzel, a white LED lamp with greater color balance and unprecedented efficiency could be achieved if the "green gap" were solved, and an efficient green were available for the manufacture of a product.

Wetzel first took a moment to discuss critical die performance and wafer yield aspects of the RPI team's optimization approach to the active layer of the GaInN/GaN quantum wells. "The prime challenge lies in the combination of extending the wavelength from 470 nm blue to 525 nm green while maintaining the emission power level—commonly a steep decrease in power is observed." Wetzel explained that blue LEDs grown on sapphire are rather tolerant to craters, surface roughness, and inhomogeneities. However, such defects are highly detrimental to green LEDs. By use of the more expensive bulk GaN substrate, light output power in the 546–560 nanometer range can be increased about 5 times, just by the avoidance of craters alone. Even better gains can be expected once also the remaining dislocations can be avoided as well.

RPI researchers have also studied the effect of piezoelectric polarization on the LED's efficiency, its performance droop, and its role in the green gap. They've found that the differences in polarization fields in the *c*-, *a*-, and *m*-plane devices have a big impact on wavelength emission. LED powers from non-polar, green emitting structures are currently less than 1 mW, but there is no more wavelength shift with current variation. Further power improvements are expected through better p-type doping and optimized junction placement. This recent development of non-polar LEDs will help RPI to unravel the role of piezoelectric polarization in the green gap. According to Wetzel, "Good quality bulk GaN pays off. The exciting news in the non-polar devices is the wavelength is much more stable."

The result is an epitaxial crystal growth optimization scheme that leads to high performance 525 nm green. On the basis of this achievement it will be possible to optimize the device design and to overcome the performance limitations such as typically experienced low quantum efficiency. Although there are fundamental issues still to be resolved, the team concludes that reduced threading dislocations and improved polarization control will play a huge role in closing the green gap.

Optimizing OLED Architecture for Maximum Efficiency and Color Quality
Yuan-Sheng Tyan, Eastman Kodak Company

Yuan-Sheng Tyan began the next session by describing Eastman Kodak Company's research to optimize OLED architecture for maximum efficiency and color quality. To date, the team has demonstrated a hybrid fluorescent/phosphorescent OLED device with an efficacy of 56 lm/W, color coordinates within the 4,000K tolerance quadrangle, and a CRI of 83.6. This is the highest efficacy ever reported for OLED devices that meet DOE's SSL ENERGY STAR color requirements for LED lighting. This achievement, Tyan stated, has met and exceeded the original project goal of demonstrating 50 lm/W power efficiency and 10,000 hours lifetime (T50) at 1,000 cd/m^2.

When DOE's ENERGY STAR color requirements were published, he added, the team took on the additional objective of meeting those specifications. "These color requirements have made our tasks much more challenging and interesting," he continued, "because color and efficacy of emitters are highly related. It would be much easier to get high efficacy numbers if we did not have to adhere to the color requirements. To get the right color, sometimes we had to sacrifice the efficacy and even tune down the EQE. Some other times, we ruled out a device architecture or a material altogether because it would not get the color right."

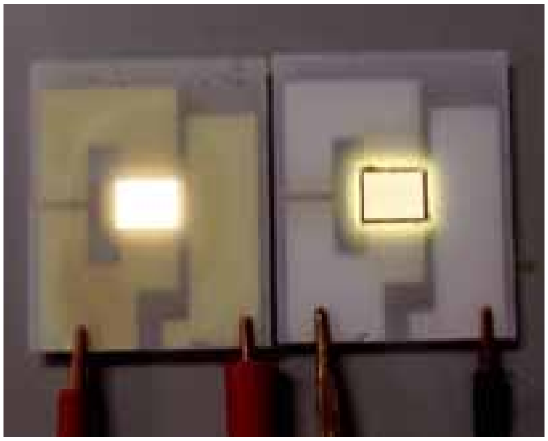
To pursue these project goals, the team developed strategies for their technical approach, agreeing to work simultaneously on four areas:

1. Employ low-voltage materials and architecture for a direct impact on efficacy
2. Increase IQE through fluorescent and hybrid fluorescent/phosphorescent white-emitting layers
3. Use a stacked structure
4. Address light extraction enhancement using extraction enhancement layers.

The fourth area in particular, Tyan noted, was key to the team's achievement of the breakthrough performance. The team succeeded in developing an internal enhancement structure (IES) that enhances light out put by more than 130%. "That is among the best ever reported," Tyan said. "Furthermore, the IES was a flat enhancement structure that can be applied to large area lighting devices, contrasting to some solid enhancement schemes that are only useable for small devices."

"Because OLED offers diffuse non-glare light naturally, it does not suffer much fixture losses," Tyan pointed out as he compared the OLED performance with the CALiPER and

NLPIP test results. “At 56 lm/W, OLED is already competitive against other lighting technologies at the luminaire level.”



The device to the left has IES in the icon area, and the device to the right has no extraction enhancement. In both devices, an external enhancement structure (EES) was applied to the area outside of the active icon. The icon at left is much brighter than the one at right, demonstrating the effectiveness of the IES in extracting light. The device to the right has a halo around the icon area because light is trapped in the glass substrate, which is extracted into the air by the EES surrounding the icon area. The device to the left has no halo because the IES was effective in extracting light within the icon area, leaving much less trapped light in the substrate to be extracted by the EES.

“Finally,” Tyan concluded, “thanks to the DOE support, the OLED field has made significant advances in recent years. DOE’s ENERGY STAR program is key to the commercial success of the SSL products. We have seen progress toward meeting these requirements. This trend should continue.”

Using Advanced Phosphor Systems for Warm, Efficient LEDs
Anant Setlur, General Electric Global Research

Anant Setlur of General Electric Global Research described how his team, which includes the University of Georgia (UGA) and GE Lumination, is working to develop efficient phosphor platforms to enable efficient, customer-driven solid-state lighting.

4 W Vio™ product—Vio platform is a testing vehicle for new phosphors in this program and one potential path for commercialization.

Overall efficacy and color goals for this program are “to achieve high-quality light with good CRIs and low color temperatures in LEDs.” Apart from maximizing the phosphor efficiency, the team is also accounting for the lumen equivalent (LER) of new phosphors and blends as it works to discover new materials. In this aspect, the team’s main goal is to develop high-efficiency green, yellow, and orange phosphors that do not quench at high temperatures. Once there are materials that have the potential to meet the spectral and efficiency requirements, optimization begins, and more samples are made to test these phosphors in representative LED packages, such as the 4 W Vio™, to understand their potential for high-quality LED lighting products.

Another aspect of GE’s research is to understand the fundamentals of LED phosphor quenching, leading to decisions on whether something is physically possible within a given composition. This work is being done in collaboration with researchers at UGA to understand the effects of chemistry on phosphor performance and ultimate phosphor efficiency limits. For example, when screening new phosphors with fast decay times, the team is determining if quenching is through non-radiative level crossing, activator photoionization, or energy transfer to lattice defects. This work involves numerous spectroscopic measurements and analysis, but it gives the team critical guidance towards the next steps in optimization.

Using these tools and framework for materials discovery, GE has developed new green and orange phosphors using a combination of crystal and combinatorial chemistry, resulting in two filed patents. However, even within optimized phosphors, one additional goal is to ensure that the phosphor is not a weak link in the overall lamp reliability. In this regard, Setlur emphasized the importance of reliability testing early and often, because it is difficult to predict reliability. The initial results for the new GE phosphors are encouraging in that the new green phosphors have passed >3,000 hours and the orange phosphors have passed 10,000 hours without efficiency losses or color shifts. In the final year of this 3-year program, additional optimization and blend development will be combined with iterative feedback from the lamp tests. Initial blends of the new GE green phosphor and phosphors in GE Lumination's portfolio have been used to make lamps with CCT<3000 K and CRI>90 that have an efficacy of 62 lm/W. Additional testing is under way for different CCT/CRI combinations at GE Lumination, and the team hopes to move towards new high efficacy, high color quality LED lighting products using their new phosphors.

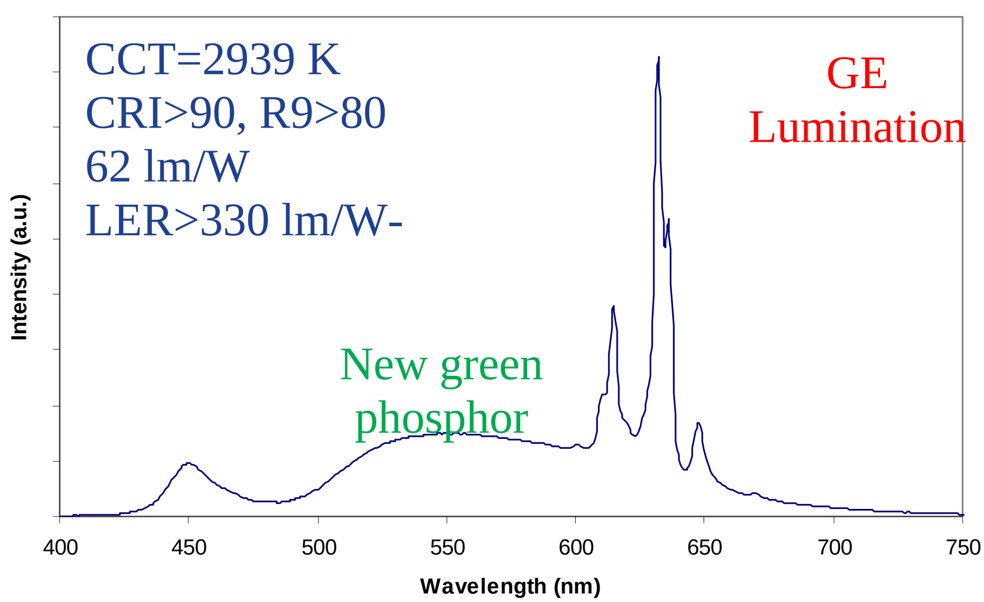


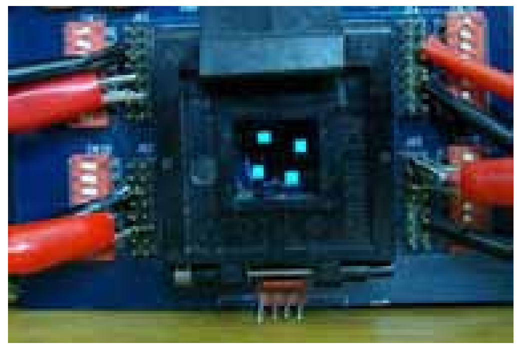
Figure 6-4: Initial high CRI, low CCT lamp using new phosphors developed within this program

Achieving Record Efficiency Blue OLEDs with Charge Balance
Franky So, University of Florida

Franky So presented the University of Florida's (UF) research to achieve record efficiency with blue OLEDs by controlling the charge balance. He reported that the UF research team has demonstrated a blue phosphorescent OLED with a peak power efficiency of 50 lm/W and a peak external quantum efficiency (EQE) exceeding 20 percent at a luminance of 1,000 cd/m^2, using no external light extraction techniques. This accomplishment is believed to be the world record in blue OLED efficiency. Wall-plug efficiency (W/W) reached 17 percent at 100 cd/m^2 and 14 percent at 1,000 cd/m^2.

So outlined the three main areas of research focus:

1. Demonstration of high-efficiency blue OLEDs
2. Demonstration of OLED devices with integrated microcavity structure
3. Demonstration of efficient down-conversion (from blue to white) using phosphors



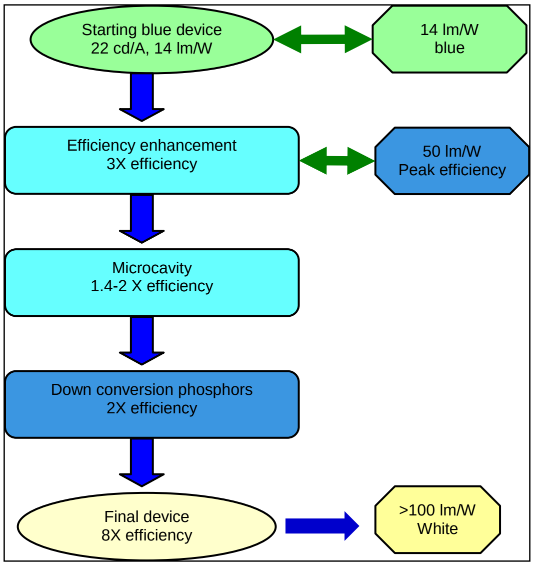
UF research on blue OLEDs

At the start of their work three years ago, efficiency was 14 lm/W, and the team set a goal to achieve white efficiency of 100 lm/W.

Blue OLEDs are important in the creation of white light suitable for solid-state general illumination applications, So continued, but high-efficiency blue OLEDs with good lifetime and stability have represented a significant technical hurdle. Most phosphorescent OLEDs—including this particular type of blue small molecule—possess an inherent imbalance of charge carriers that limits IQE. Charge balance is key because a high concentration of exciton quenching leads to very low efficiency. An imbalance in carrier transport results when charge accumulation at interface leads to exciton quenching, and/or carrier transport materials with low triplet energies lead to exciton quenching.

With charge transport in organic materials, So stated, electronic states are highly localized and charge transport is very limited by hopping. As a result, carrier mobility is very low (10^{-6}–10^{-3} cm^2/Vs) and there is insensitivity to impurities and defects. The ideal, he noted, is to have balance transport with recombination happening in the middle, away from the interface. Through their investigation of charge balance, the UF team has demonstrated very high-efficiency blue OLEDs using a unique charge carrier material with special electrical properties.

The team found that the use of a bathocuproine (BCP) exciton blocking layer improved conversion efficiency. "We know that BCP is a material with low triple energy, so we knew we could improve device performance by creating higher mobility and higher triple



Last steps—microcavity and down-conversion phosphors

energy," So said. "We were thus not only able to increase efficiency but were also able to shift peak efficiency at higher luminance level. By incorporating the new electron transfer material and doping it, we were able to increase efficiency further."

The team will continue to exploit certain light extraction techniques and special down-converting phosphors that will produce white light from the high-efficiency blue OLEDs developed in their lab. "Our challenge now," So concluded, "is to incorporate this OLED with microcavity structure and down-conversion phosphors. We hope in a few months to be able to demonstrate something even better."

Demonstrating the Next Wave of LED Chips and Packaging Improvements
Monica Hansen, Cree, Inc.

Monica Hansen described how Cree, Inc. has been working to bring chip performance improvements to a finished, packaged product. Over the course of this project, Cree has mapped well to DOE's MYPP, with its cool white XLamp® products at about 122 lumens now being used in lighting solutions. Hansen noted that performance has doubled since the product was first introduced in 2006 (Figure 6-5). Cree's XLamp family, available in volume production, provides lighting class LEDs in various form factors for integration into solid-state lighting (SSL) applications. The XLamp XR series provides the cost and color point for many mainstream lighting applications; the MC provides 4 times the light in the same package size as the XR series; and the XP series provides the same light as the XR series but in an 80% smaller package.

The goal of this project is to create a novel 120 lm/W low-cost SSL lamp module suitable for commercial SSL luminaires that emits at a 4100 K color temperature. Using the EZ Bright® chip as baseline technology, Cree incorporated a photonic crystal (PC) element to demonstrate 52% external quantum efficiency (EQE) at 350 mA (455 nm, 1 mm^2 chip). This was a scalable process developed on 3" wafers that achieved comparable efficiency performance to Cree's benchmark, the EZBright LED.

To improve package efficiency, Cree reduced existing package optical losses and designed a lamp module around the specifics of the new chip design and project goals. The prototype 4-chip lamp modules demonstrated an efficacy of 102 lm/W at 4125 K with a color rendering index (CRI) of 73. Overall conversion efficiency at 4100 K improved to ~65% (compared to ~57% for the baseline package), and scaled performance from the single chip package to 4-chip modules.

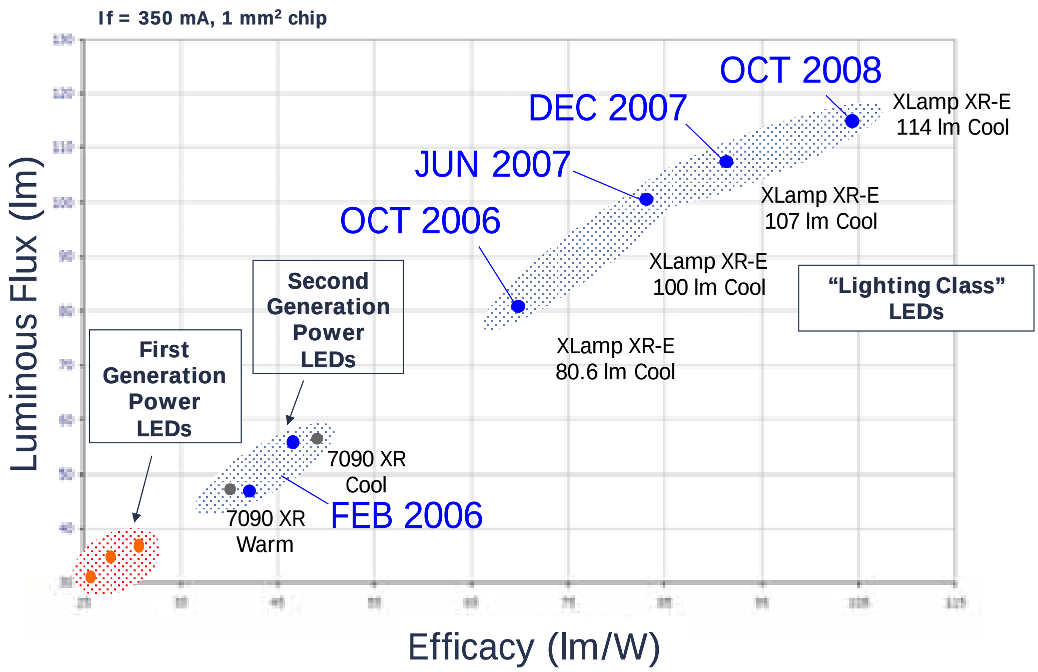


Figure 6-5: Cree XLamp® Performance Gains in 2006–08; the XLamp performance has doubled since the product was first introduced in 2006. XLamp XR-E LEDs are available with a luminous flux of 122 lumens (since December 2008).

Hansen emphasized that additional improvement in PC quality for better light extraction is still needed, and the company is working to manage the tradeoff between LED operating voltage and EQE. She also stated that PC LED reliability has not yet been tested, and that an optimized phosphor/chip integration process is needed for the new chip design to improve the overall package performance.

Cree has met all project milestones to date and developed a three-tiered commercialization plan for chips, components, and luminaires that anticipates manufacturing and selling LED modules to Cree LED Lighting Solutions and other OEM manufacturers for integration into lighting systems.

Hansen concluded by noting Cree product installations in 2008, including the Water Cube and Bird's Nest at Beijing Olympic venues, several LED cities using XLamp products in outdoor lighting, and recessed downlights for the Sheraton Hotel in Greensboro, NC, which have resulted in up to 82% energy savings.

Pushing the Envelope for White OLED Efficiencies
Mike Hack, Universal Display Corporation

UDC white OLED demonstration

Universal Display Corporation (UDC) has successfully demonstrated a world record-breaking white OLED with a power efficacy of 102 lm/W at 1000 cd/m^2 using its proprietary, high-efficiency phosphorescent OLED technology. The research team achieved these results through the combination of phosphorescence IQE of nearly 100 percent, novel outcoupling efficiency enhancements, and low voltage operation through highly conductive transport layers and device engineering. Their achievement represents a significant milestone for OLED technology, demonstrating performance that surpasses the power efficacy of incandescent bulbs with less than 15 lm/W and fluorescent lamps at 60–90 lm/W.

This WOLED light source offers a white emission with a CRI of 70 and a CCT of 3,900K and highlights the potential of white OLEDs to offer significant energy savings and environmental benefits. Through the use of UDC's phosphorescent OLED technology, power-efficient white OLEDs have the potential to reduce energy consumption dramatically and to lower the amount of by-product heat, which creates additional energy and environmental burdens. Combining important "green" features with a very thin, lightweight and durable form factor, white OLEDs offer significant new lighting design opportunities.

In discussing UDC's research, Mike Hack observed that "OLEDs represent a diffused form of light that is really quite different." Reviewing comparisons of various forms of lighting technologies, from incandescent through fluorescent, to LEDs and OLEDs, he commented, "For the last few years at UDC, we've been exploring how OLED lighting can 'take off.' We've been asking, 'What are the various infrastructure requirements for having large-area diffused panels as opposed to the current 60W light bulb technology we have today?' The trend to large-area panels and the change in the way we look at using light in buildings and ceilings could be very important in the future. Therefore, what we like most about OLEDs are the form factors." Hack added, "We can make flexible or conformable lighting, or transparent lighting panels with unique architectural and design features that cannot be matched by traditional lighting today."

UDC's current success incorporates progress achieved through a focus on four key elements of WOLED research that all must work together to achieve maximum power savings: IQE, outcoupling efficiency or EQE, device voltage, and lifetime. UDC has achieved approximately 100% IQE through its breakthrough with phosphorescence and continues to make EQE improvements with the development of several novel technologies that further enhance outcoupling efficiency and significantly reduce the absorption losses incurred when light waveguides in the substrate. Low voltage operation is obtained by incorporating highly conductive transport layers and by designing devices to improve charge injection and recombination in the emissive layer.

“The specific technology we’ve been developing at UDC focuses on phosphorescent OLEDs. We are of course working in the display arena at UDC,” Hack continued. “The energy efficiency of phosphorescent OLEDs is ideal for mobile devices, key for AMOLED TVs, and critical for lighting. These OLEDs are also environmentally friendly and provide better total product life cycle through more benign production and disposal. They are economical and versatile, with prospective cost savings and compatibility with multiple manufacturing methods and active-matrix backplanes.

“Of course, lifetime is also critical, and through outcoupling enhancement, we believe we have already achieved lifetimes from 14,000 to 24,000 hours. The message is we are getting close to commercial performance targets. Over the last five years, we in this industry have seen tremendous improvements, reflected in our work as well as in the work of other research teams who’ve presented today,” Hack concluded. “Clearly what we need to do now is make panels, so we can start making OLED luminaires and really get serious about commercial products. Our work now is to translate the high efficiencies we’re getting at the pixel level into panels and then into luminaires.”

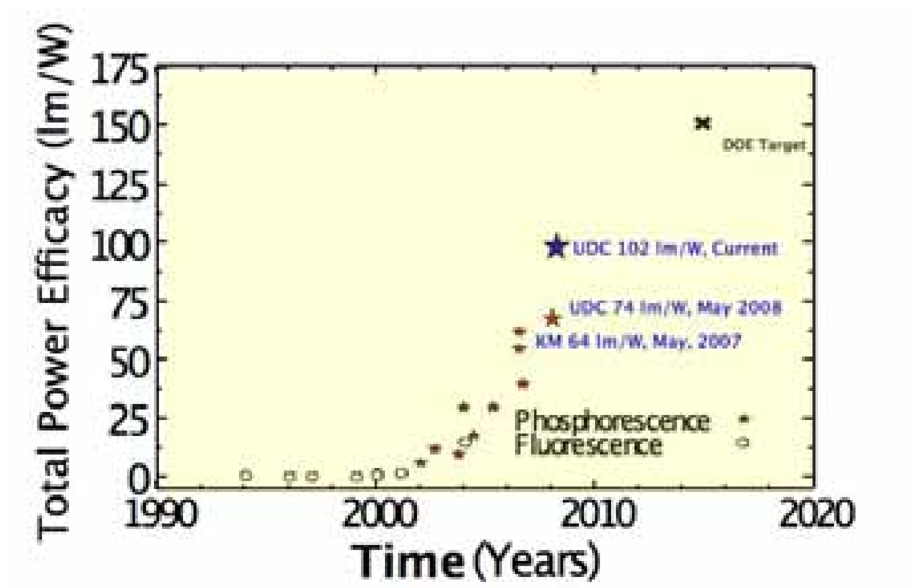


Figure 6-6: WOLED PHOLED Progress

Improving the Efficacy and Performance of an Integrated LED Luminaire
Kevin Dowling, Philips Color Kinetics

Kevin Dowling of Philips Color Kinetics reviewed the team goals for this project: to develop a high-efficiency light source equivalent to a 60W Edison-base A-lamp that will achieve substantial benchmarks in efficacy, cost, lifetime and performance. Specifically, this program targeted 800 lumens in output, at a 90 CRI, with an efficacy of 80 lm/W.

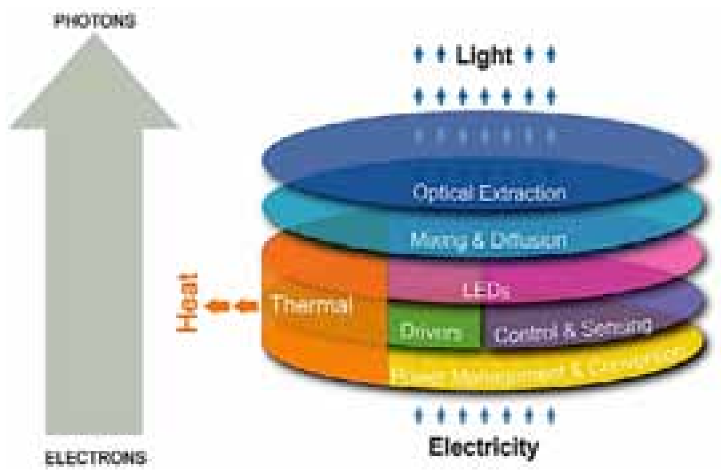


Figure 6-7: Philips Color Kinetics Systems Approach

The team not only aims to improve efficacy and LED performance, but to deliver on a market need using a systems approach. Dowling stated, “We see the system as the product—like an iPod—the consumer is not just buying hardware, but a whole experience.” To ensure product development was in sync with the market, the team began by visiting a retail store, and examining what a lighting designer needs to light merchandise. This brought more focus on light output, beam angle, uniformity, and designing a product to meet those specifications.

One approach was to use large numbers of small die. This provides optical uniform light output, lower electrical currents, lower cost LED drivers, lower thermal and power density, potentially lower packaging cost, and overall efficiency improvements. On the downside, yield is potentially lower due to the higher parts count. The team also used a hybrid LED approach, using a mix of phosphor coated dye (blues plus reds) and direct emissions (red), and developed a selective phosphor coating process. This resulted in good color temperature.

The overall configuration appears in Figure 6-8—the lens is in lower right, followed by the module, copper slug, cage, secondary optic, base, power supply, converters, and the screw base.

Figure 6-8: Overall configuration of integrated LED luminaire

Thermal management is one of the most challenging aspects of a replacement lamp, and Philips found new ways to create multiple generations without having to repeatedly die cast parts. The team uses a tightly coupled system with an eye toward the inter-related combination of thermal, optical, electrical, mechanical, control and more. The team uses this system model and carefully analyzes all design elements with a ripple effect through system. They also created an output-based feedback control mechanism that accounted for the different thermal characteristics between red chips and blue chips, resulting in no color change in the light output.

Question and Answer Session
In the Q&A session, one attendee asked, "Why pursue a screw based source?" Dowling acknowledged the difficulty of trying to shoehorn a lot into a small space in an archaic form which evolved over many decades. He said Philips is thinking about other forms—one possibility is whole new base, as existing bases have no thermal management capability.

6.3 Poster Session for All DOE-Funded R&D Projects

In the evening, a Poster Session and Reception for all DOE SSL projects provided additional opportunities to share research results, identify needs, and build relationships. The following list gives the poster topics and presenters.

LED Project Posters

Photoluminescent Nanofibers for High Efficiency Solid-State Lighting Phosphors
Lynn Davis, Research Triangle Institute

Novel Heterostructure Designs for Increased Internal Quantum Efficiencies in Nitride LEDs
Robert Davis, Carnegie Mellon University

High Extraction Luminescent Materials for Solid State Lighting
Christopher Summers, PhosphorTech Corporation

Affordable High-Efficiency Solid-State Downlight Luminaires with Novel Cooling
Mehmet Arik, GE Global Research

Phosphor Systems for Illumination Quality Solid State Lighting Products
Anant Setlur, GE Global Research

Fundamental Studies of Higher Efficiency III-N LEDs for High-Efficiency High-Power Solid-State Lighting
Russell Dupuis, Georgia Institute of Technology

High Quality Down Lighting Luminaire with 73% Overall System Efficiency
Robert Harrison, Osram Sylvania Development Inc.

Efficient White SSL Component for General Illumination
James Ibbetson, Cree, Inc.

LED Chips and Packaging for 120 LPW SSL Component
James Ibbetson, Cree, Inc.

Low-Cost Substrates for High-Performance Nanorod Array LEDs
Timothy Sands, Purdue University

Epitaxial Growth of GaN Based LED Structures on Sacrificial Substrates
Ian Ferguson, Georgia Institute of Technology

An Integrated Solid-State LED Luminaire for General Lighting
Kevin Dowling, Philips Color Kinetics

100 LPW 800 LM Warm White LED for Illumination
Decai Sun, Philips Lumileds Lighting, LLC

High-Efficiency Nitride-Based Photonic Crystal Light Sources
James Speck, University of California, Santa Barbara

GaN-Ready Aluminum Nitride Substrates for Cost-Effective, Very Low Dislocation Density III-Nitride LEDs
Tim Bettles, Crystal IS, Inc.

Enhancement of Radiative Efficiency with Staggered InGaN Quantum Well Light Emitting Diodes
Nelson Tansu, Lehigh University

High Performance Green LEDs by Homoepitaxial MOVPE
Christian Wetzel, Rensselaer Polytechnic Institute

Multicolor, High Efficiency, Nanotextured LEDs
Jung Han, Yale University

Novel Defect Spectroscopy of InGaN Materials for Improved Green LEDs
Andrew Armstrong, Sandia National Laboratories

Innovative Strain-Engineered InGaN Materials for High-Efficiency Deep-Green Light Emission
Michael Coltrin, Sandia National Laboratories

Improved InGaN Epitaxial Quality by Optimizing Growth Chemistry
J. Randall Creighton, Sandia National Laboratories

OLED Project Posters

Application of Developed APCVD Transparent Conducting Oxides and Undercoat Technologies for Economical OLED Lighting
Gary Silverman, Arkema, Inc.

Charge Balance in Blue Electrophosphorescent Devices
Asanga Padmaperuma, Pacific Northwest National Laboratory

High Stability Organic Molecular Dopants for Maximum Power
Daniel Gaspar, Pacific Northwest National Laboratory

Multi-Faceted Scientific Strategies Towards Better Solid-State Lighting of Phosphorescent OLEDs
Mohammad Omary, University of North Texas

High Quantum Efficiency OLED Lighting Systems
Joe Shiang, GE Global Research

Materials Degradation Analysis and Development to Enable Ultra Low Cost, Web-Processed White P-OLED for SSL
Devin McKenzie, Add-Vision Inc.

Low Cost, High Efficiency Polymer OLEDs Based on Stable p-i-n Device Architecture
Devin McKenzie, Add-Vision Inc.

High Efficiency Microcavity OLED Devices With Down-Conversion Phosphors
Franky So, University of Florida

OLED Lighting Device Architecture
Yuan-Sheng Tyan, Eastman Kodak Company

Novel High Work Function Transparent Conductive Oxides for Organic Solid State Lighting Using Combinatorial Techniques
Joseph Berry, National Renewable Energy Laboratory

Development of High Efficacy, Low Cost Phosphorescent OLED Lighting Ceiling Luminaire System
Mike Hack, Universal Display Corporation

WOLEDs Containing Two Broad Emitters
Mike Hack, Universal Display Corporation

High Efficacy Phosphorescent SOLED Lighting
Mike Hack, Universal Display Corporation

Efficient Large Area WOLED Lighting
Mike Hack, Universal Display Corporation

High Efficiency Organic Light Emitting Devices for General Illumination
Paul Shnitser, Physical Optics Corporation

High Quality Low Cost TCOs
Anthony Burrell, Los Alamos National Laboratory

High Efficiency Long Lifetime OLEDs With Stable Cathode Nanostructures
Samuel Mao, Lawrence Berkeley National Laboratory

Investigation of Long-Term OLED Device Stability via Transmission Electron Microscopy Imaging of Cross-Sectioned OLED Devices
Gao Liu, Lawrence Berkeley National Laboratory

For an overview of all current DOE-funded SSL R&D projects, including a brief description, partners, funding level, and proposed timeline, see the 2009 SSL Project Portfolio on the DOE SSL Web site at www.ssl.energy.gov/projects.html.

6.4 A Fresh Look at Priorities—Updates to the DOE SSL R&D Roadmap

Fred Welsh, Radcliffe Advisors

Fred Welsh provided an overview of proposed updates to Chapter 4 of the DOE SSL Multi-Year Program Plan (MYPP). "Chapter 4 spells out how to reach DOE's goals and presents the technical content of the DOE roadmap—the R&D agenda—for SSL for the coming year," Welsh noted. He explained that overarching performance targets are currently focused in four areas: conversion efficiencies independent of spectrum; overarching device targets for efficacy, lifetime, and cost; luminaire targets; and detailed, specific subtask metrics and targets.

As the strategic plan for SSL, the MYPP guides R&D solicitations by establishing priorities and interim goals for specific efforts, providing a record of progress, and increasing transparency of competitive processes and monitoring procedures. The MYPP is updated annually, with close participation from many partners, including the Next Generation Lighting Industry Alliance (NGLIA), the National Energy Technology Laboratory (NETL), DOE managers, and participants in the annual R&D Workshop.

Welsh reported that, in 2008, impressive progress continued on both OLED and LED efficacies, with no signs of slowing, but new issues emerged more prominently including color quality, cost, and lifetime. While there are more good luminaires on the market, he added, problems remain with inaccurate claims and poor reliability. LED prices continue to decrease but remain a barrier to deployment, with estimates not yet firm on competitive first-cost targets. "As a result," Welsh continued, "you'll see some specific changes that are quite different this year from previous years." These proposed MYPP updates include a completely revised R&D task structure, with increased emphasis on luminaire performance issues and product development in general, as well as manufacturing, lifetime, and quality. This year, only modest changes were made to the efficacy targets for LEDs and OLEDs, while price targets were updated, based on replacement lamps.

Metric	2008	2010	2012	2015
Efficacy- Lab (lm/W)	144	160	176	200
Efficacy- Commercial Cool White (lm/W)	108	147	164	188
Efficacy- Commercial Warm White (lm/W)	64	97	114	138
OEM Lamp ($/klm)	169	101	61	28

Figure 6-9: LED Device Performance Track

Metric	2008	2010	2012	2015
Efficacy- Lab (lm/W)	58	99	150	150
Efficacy- Commercial (lm/W)	N/A	44	76	150
OEM Device Price- ($/klm)	N/A	72	27	10
OEM Device Price- ($/m^2)	N/A	216	80	30
Device Life- Commercial Product (1000 hours)	N/A	11	25	40

Figure 6-10: OLED Device Performance Track

Welsh concluded by reviewing DOE's "wish list" for 2009, which includes "an OLED light in the general market at better than 25 lumens per watt (lm/W) and 500 lumens, at a reasonable cost; commercially available LED devices above 100 lm/W; replacement lamp cost at under $135 per kilo-lumen (klm); indoor LED luminaires above 80 lm/W with more than 1 klm of output; and, finally, much more consistency in color quality and in reliability of the products—that is really essential." In the interval since the workshop, DOE has incorporated comments and feedback into a final MYPP, published in March 2009 on the SSL Web site at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf.

6.5 SSL Workshop—Breakout Group Discussions

On Wednesday and Thursday of the SSL workshop, three sessions were dedicated to discussing the Department's SSL R&D subtasks. Discussions were convened in four separate breakout groups — three on LEDs and one on OLEDs. Each breakout group had approximately 50 participants representing universities, national laboratories, manufacturers, distributors, and end-users. DOE scheduled these breakout sessions to solicit input on the selection of subtasks for R&D funding for the next one to two years.

Prior to the breakout sessions, all workshop participants were given a draft copy of the 2009 SSL Multi-Year Program R&D technical chapter as well as a list of LED or OLED subtasks. The subtask list represented potential funding opportunities as identified by the DOE and technical committees. Participants were asked to review these documents and prioritize the subtasks prior to the breakout sessions.

At the initiation of the breakout sessions, a call of hands was conducted to gauge which subtasks the group believed to be the most important. The three LED breakout groups and the OLED group were asked to conduct concurrent reviews on their respective Core Technology and Product Development R&D priorities. All of the ideas, issues, and topics discussed in each of the four breakout groups are captured in Appendix C of this workshop report, grouping the discussion into LEDs and OLEDs.

The Department's approach for engaging participants in the prioritization process proceeded as follows:

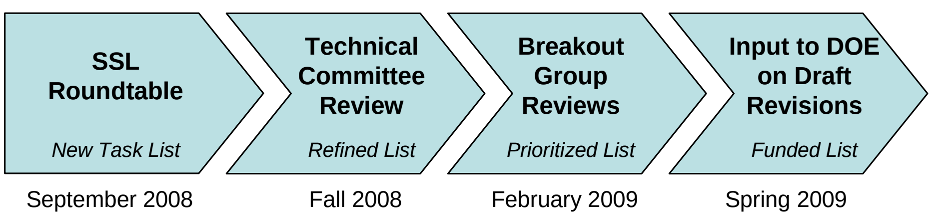


Figure 6-11: Linear Representation of SSL R&D Subtasks Discussion and Prioritization

The Department's review of its SSL R&D subtasks began several months before the San Francisco workshop, at a DOE SSL roundtable session held in Washington, D.C. At this roundtable the existing task structure, from past Multi-Year Program Plans (MYPPs), was substantially revised due to continuing progress in the technology. Further refinement occurred through a series of conference calls with members of DOE SSL technical committees in the fall of 2008. In the breakout sessions in San Francisco, participants focused on prioritizing this list, and identifying any areas where they felt further revisions were necessary. Each of the four breakout groups was given the same general charge, centered on three critical steps:

1. Prioritize the core technology and product development subtasks proposed by the DOE, and suggest additional subtasks for the priority lists.
2. Modify or suggest metric/status/target/resources required values for each subtask.
3. Edit description of subtasks if needed.

The original version of the breakout session materials that was provided to the workshop participants is included in Appendix B of this report. Appendix C summarizes the discussion in the breakout groups pertaining to the R&D priority subtasks. The discussion summary is organized to be consistent with DOE's R&D portfolio: 1) LED Core Technology, 2) LED Product Development, 3) OLED Core Technology, and 4) OLED Product Development. Under each subtask heading is a summary table including the title and a short description of the subtask, and the proposed metrics, targets, and status coming into the workshop. Following each table is a recap of the group discussion regarding the metrics, status, and priorities. *Note: After receiving input from participants at the SSL workshop, DOE defined new R&D priorities based on the new task structure. Tables with the final prioritized subtasks appear in the final version of the 2009 MYPP (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf). In the published version, tasks were renumbered to avoid confusion with the task structure of previous reports. The first digit of each subtask has changed from 1–4 to A–D.*

7. Designing SSL for Market

7.1 What Architects and Designers Want from SSL

Avraham Mor, Lightswitch Architectural

Avraham Mor of Lightswitch Architectural kicked off the final day of the workshop by offering some bold insights on the challenges of specifying today's LED lighting products. Mor was among the lighting designers who participated in DOE's 2008 Lighting Designers Roundtable, and he began his talk by noting his appreciation for DOE's efforts to bring together lighting designers, researchers, and a broad range of other industry representatives to foster such productive information exchanges.

Mor reminded attendees that LED product parts differ greatly from the simple bulb, filament, and base parts of an incandescent lamp. "LED system parts are different from existing technologies," Mor asserted. "When it comes to LEDs, where are the parts and pieces—where are the things we're used to replacing? As a lighting designer, I specify every fixture that goes into a building, but when it comes to LEDs, it's much less clear to me what I can actually specify. This is a major problem for us as designers."

Avi Mor (standing) with panelists (left to right): Jeff Dross (Kichler Lighting), Frank Shum (Luximo), Tim O'Sullivan (Cree), and Ruth Taylor (PNNL).

Showing several LED products that his firm has specified, Mor observed, "This product is amazing—very beautiful, small. But the LED sits in the bottom, there are two wires running up into the top, and this is connected to a junction box with a driver. So what happens when this doesn't work anymore? I have to hire an electrician, on a scaffold, to come out, pull out that whole thing, throw it out, and install a new one. There are manufacturers building products that can be pulled out of the ceiling but the technology is moving so fast, we don't know if we can support that platform. You have to create a platform that you will stand behind as long as possible, because I don't want to get sued when they have to break open the drywall to replace the inside of the fixture."

While lighting designers want to have innovative solutions to offer clients, Mor also advised a thorough comparison using test data, and noted that data sheets often compare poorly with actual performance. "Ultimately," he stated, "LM-79 testing information is required—we need this information, we need it publicized and listed on cut sheets."

In conclusion, Mor outlined his firm's list of essential questions to ask your SSL luminaire manufacturer/representative when considering specification of SSLs:

Testing

- Is there an LM-70 testing report for the luminaire?
- Has the luminaire been thoroughly heat tested?

Policies

- What is the process to replace defective LEDs in their luminaire?
- Do they have a written binning policy for each LED type used in their luminaire?
- Is there a written end of life policy?

Warranties

- Are all parts (including luminaire, driver with enclosure, and LEDs) provided by the manufacturer and covered by their warranty?
- Does their written warranty include materials and labor when replacing defective product?
- Is there a policy for replacing luminaires where colors do not match?

7.2 Panel 3: Recognizing Quality in the Marketplace

Ruth Taylor, Pacific Northwest National Laboratory

Ruth Taylor of Pacific Northwest National Laboratory described how DOE's national design competitions recognize the best-of-the-best quality SSL products on the market, and offer valuable insights on the rapidly developing SSL market. Taylor first offered perspectives from the judging of the new commercial lighting competition, Next Generation Luminaires™.

Although the Next Generation Luminaires competition winners were not yet announced at the time of the workshop, Taylor provided lessons learned from the judging process. In this first-ever commercial LED design competition, DOE asked for white light, general illumination products for the commercial market. The goal was to find complete luminaires that were specifiable, market-ready products. There was also an emerging products category that allowed for submission of prototypes.

All entries required photometric testing. The judging was both quantitative and qualitative, with both playing an important role in ensuring that winning products were ready. DOE received 68 product submissions, with 30% linear LEDs and 25% downlights. *(Note: The 2009 winners were announced at Strategies in Light on February 19, 2009. Twenty-two products were recognized as market-ready; three of these were recognized as "Best in Class": GE Lighting, Immersion™ jewelry case lighting; Journée Lighting, AZARA track mounted luminaires; and Winona Lighting, STEP03 indoor/outdoor step lighting. Five products were recognized as "Emerging Products." For details on the winning products, visit www.ngldc.org.)*

Taylor then turned to the Lighting for Tomorrow competition, introducing a panel of speakers representing the 2008 SSL winners of this residential lighting design competition.

7.3 Lighting for Tomorrow Winner—Design Pro Series™ LED Cabinet Lighting

Jeff Dross, Kichler Lighting

Kichler's Design Pro Series kitchen undercabinet lighting

Jeff Dross of Kichler Lighting, whose winning product was the Design Pro Series Undercabinet System, first described why the company got involved in LED lighting. Kichler is known for making fashionable, durable lights and accessories rather than technological advances but found that customers sought lighting solutions not available with conventional lighting sources. A Kichler customer needed a small underwater light with long lamp life, which involved learning the complexities of landscape lighting. Kichler created LED cabinet lighting, noting that the increasingly popular European cabinets couldn't use the industry standard 1" undercabinet lighting. LEDs provided benefits that allowed a thinner profile 1/2" and 3/8" thick product, so despite the concerns about cost and lifetime, Kichler created a product that was well received by the design community.

It wasn't all smooth sailing. Kichler encountered problems with packaged driver and circuitry solutions, along with a lack of knowledge about the technology at independent product testing and certification organizations. Dross noted that Kichler seeks tighter binning, as color variations are unacceptable to customers. He also discussed his company's frustration with two ENERGY STAR specifications issued by DOE and EPA. Kichler is following the DOE specifications, but as Dross stated, "The ability to continue to [ignore EPA's spec] becomes tainted when sub-standard product is introduced and placed on the shelf alongside mine. When that occurs, I am guilty by association. It then becomes more beneficial for me to back away from ENERGY STAR."

Looking ahead, Dross said that industry will need to educate the consumer, who lacks understanding about how lumen output differs from wattage, and what color temperature and Color Rendering Index (CRI) are. He reminded the audience that most consumers think, "If you need more light, you simply increase the wattage of the light bulb." Working with ENERGY STAR and Lighting for Tomorrow has been a positive experience for Kichler, and Dross stated his belief that the long range value for both programs will lie in the end consumer realizing that there is viable energy-efficient lighting available.

7.4 Lighting for Tomorrow Winner—LR4 Recessed Downlights

Tim O'Sullivan, Cree LED Lighting Solutions

Tim O'Sullivan from Cree LED Lighting Solutions described how the company used an integrated systems approach and started with the end user perspective to create the winning LR4 downlight. This approach involved optimized design of the LEDs, electronics, power supply and driver, mechanical design, thermal management, and optics. O'Sullivan emphasized that Cree, which won a 2007 Lighting for Tomorrow award for the LR6 downlight, didn't simply reduce the LR6 to make this product. The number of LEDs differs, the power factor changed, and there is a deeper recess of LEDs, which created different thermal challenges. In addition, Cree sought to make a dimmable light that is field replaceable without an electrician. O'Sullivan emphasized that "total system optimization is critical to maximize performance."

O'Sullivan also described how the team used color mixing, a proprietary combination of yellow with red, with active color management, to deliver up to 70 lm/W of light with a 92+ CRI and CCT of 2700–3500 K. The results were then shown in several current installations. He stated the importance of not wasting electrons or photons, and that optical mixing can be used to create a smooth appearance. He stressed that thermal management is critical, because heat kills LEDs, and then provided a checklist for others seeking to create a good quality of light. Other key lessons learned by the Cree team are to avoid wasting LED potential, to consider and optimize every thermal interface, from the LED chip to the environment.

A Cree residential installation, Stanford Court, demonstrates how colors "pop" with the LR4.

Among the key questions on Cree's checklist:

- ENERGY STAR qualified?
- What are the delivered lumens?
- What is the real Input Power?
- Do you have photometric reports and IES files?
- Have light output and color characteristics been validated by independent testing labs?
- Whose LEDs to you utilize?
- What is the CRI at each color temperature?
- How do you ensure color consistency among fixtures built today or a year from now? Over the life of a product?
- Does the thermal management system keep the LED junction temperature below specified maximums in all applications?

O'Sullivan closed by explaining that the Lighting for Tomorrow competition addresses most of the concerns users have, so winning provides a company with great credibility and exposure. The competition shows that SSL luminaires are viable today. He added that the Cree team uses the competition as a motivation by asking, "Is that good enough to win Lighting for Tomorrow?"

On the University of Notre Dame campus, a conference room outfitted with Cree products produced an 84% energy savings. Because the university generates its own power, this is particularly significant.

7.5 Lighting for Tomorrow Winner—Cylindrium™ LED Desk/Task Light

Frank Shum, Luximo

Finally, Frank Shum from Luximo discussed the approach his small startup company took to create the winning Cylindrium Desk/Task Light, noting that he was inspired by the 2007 winning desk lamp from Finelite. By utilizing lighting industry contacts at the 2008 R&D workshop, Shum found himself well-connected, and excited by the possibilities that Lighting for Tomorrow offered. In just 8 weeks, Shum and his partner created their winning desk/task lamp. Shum stated that "lighting is more about lumens, lumens per watt. Design is important, but together they form an experience,"adding that the "best lamp is one you can't see. The one you don't notice."

Luximo Cylindrium desk/task light

With this philosophy in mind, Shum used DOE CALiPER reports to examine LEDs currently on the market. The team found that the easiest piece was the LEDs—the challenges were finding a power supply manufacturer and the right switch to meet the competition's off state power requirements. Still, the team sought to find the perfect marriage between the technical and aesthetic worlds and create a product with no wires: "Instead of hiding the heat sink, let's make it beautiful."

The team spent a lot of time modeling, but to create a winning product in a short time frame, iterations to get the thermals right were not possible—they had to get it right in one try. With competition and ENERGY STAR requirements in hand driving their technical choices, the duo sought a manufacturer that could meet their lm/W requirements. The result is the Cylindrium desk/task light: a product with recessed LEDs in a slender design that is only possible with LEDs. Though the product is not yet available on the market, Luximo is currently seeking manufacturing and agent sourcing.

Question and Answer Session
One participant commented that he is looking for better bin sorting. He asked the panel for help understanding and conveying it to the lighting community. Another attendee asked the Kichler representative about what it would take to untether the outdoor light, and whether Kichler had considered a solar cell on top of the light. Dross responded that Kichler has not found solar options that work well, stating that landscape lighting is a virtually untapped market, with only 3–4% penetration, but that Kichler engineers regulated lumen output with variable input, which isn't feasible with solar at this time. Dross added that Kichler is continuing to look at alternatives, including solar and long life batteries.

8. Next Steps

Moving forward, the Department of Energy will continue to work closely with the SSL R&D community, manufacturers, energy efficiency organizations, utilities, and standards generating organizations to speed energy efficient SSL technologies from lab to market.

In March 2009, DOE released the final version of the updated *Multi-Year Program Plan FY'09–FY'15; Solid-State Lighting Research and Development*. Significant updates include revised definitions of components of a solid-state lighting luminaire to comply with IES standards, a greater emphasis on luminaire issues in product development for both LEDs and OLEDs, revised task structure and new priorities for core and product development tasks for both LEDs and OLEDs, and an updated list of technical, cost, and market barriers. The updated plan is available for download at www.ssl.energy.gov/techroadmaps.html.

Also in March DOE announced the competitive selection of 14 projects for SSL R&D, in response to the SSL Core Technology and Product Development funding opportunity announcements. The new selections represent the fifth round in a series seeking to examine high-priority research and development activities that will advance the state-of-the-art SSL used for general illumination applications. The selections have a total value of $26 million. For more details on the selections, visit www.ssl.energy.gov/fundopps_032709.html.

In April 2009, DOE hosted an SSL Manufacturing Workshop in Fairfax, Virginia, to solicit industry input regarding the underlying issues that influence SSL product quality and cost. Workshop attendees explored opportunities, goals, and methods for a potential new manufacturing initiative designed to reduce product costs, ensure product quality and consistent performance, accelerate introduction of OLED products, and encourage and strengthen U.S. manufacturing of SSL products. A follow-up workshop will be held June 24–25 in Vancouver, Washington. More details will be available soon on the DOE SSL Web site.

DOE anticipates issuing competitive solicitations for SSL Core Technology Research and Product Development (Round 6) by mid 2009. Another solicitation for SSL Manufacturing is expected for 2009. In September, DOE's Small Business Innovation Research (SBIR) Program (http://sbir.er.doe.gov/sbir/) will issue its annual solicitation, which includes topics related to solid-state lighting.

8.1 Market Introduction Activities

The number of ENERGY STAR-qualified products continues to grow. At the time of the workshop, 7 products had been qualified; as of April 2009, the total increased to 49 (26 residential, 23 commercial), and many more are in the submission queue. To view a current listing of qualified products, visit www.energystar.gov/led.

DOE's CALiPER program continues to test commercially available LED products, providing unbiased information on product performance. Round 8 reports are expected to be finalized in May and published in June. Previous reports, as well as test results on over 150 products, are available by request at www.ssl.energy.gov/caliper.html.
The DOE Gateway Demonstration Program will continue to showcase high-performance SSL products in commercial and residential applications. DOE recently published the GATEWAY report on parking lot lighting at a Raley's supermarket in California. Learn more at www.ssl.energy.gov/gatewaydemos.html.

National design competitions also showcase energy-efficient SSL products. At the Strategies in Light conference in February 2009, DOE announced the first winners in the inaugural Next Generation Luminaires™ competition. Twenty-two products were recognized as market-ready; three of these were recognized as "Best in Class": GE Lighting, Immersion™ jewelry case lighting; Journée Lighting, AZARA track mounted luminaires; and Winona Lighting, STEP03 indoor/outdoor step lighting. Five products were recognized as "Emerging Products." For details on the winning products, visit www.ngldc.org.

The L Prize™ competition will heighten awareness of high-performance SSL products even further. The competition specifies significant prizes for the development of high-performance products in three categories: a 60 W incandescent replacement, a PAR 38 halogen replacement, and a 21st Century Lamp. L Prize partners stand ready to support the winning products through incentives, promotions, and education. To date, more than 23 utilities and efficiency programs in 29 states have signed on as L Prize partners. Learn more at www.lightingprize.org.

In July, DOE will host "Voices for Efficiency 2009" in Chicago, Illinois. Co-hosted by the Midwest Energy Efficiency Alliance, this workshop focuses on market introduction issues and provides a forum for Federal, State, and private-sector organizations to work together to shape markets for high-performance SSL products. More details on the workshop will soon be posted at www.ssl.energy.gov.

To stay apprised of DOE SSL program activities, progress, and events, register for ongoing updates at www.ssl.energy.gov/registration/registration.aspx.

9. Appendices

APPENDIX A: Workshop Attendee List

APPENDIX B: LED/OLED Breakout Session Workshop Materials

APPENDIX C: Breakout Group Discussions

APPENDIX D: DOE SSL Program Fact Sheets

- Guiding Technology Advances from Laboratory to Marketplace
- Operational Plan for DOE Solid-State Lighting Research and Development
- Solid-State Lighting Patents Resulting from DOE-Funded Projects
- Guiding Market Introduction of High Efficiency, High Performance SSL Products
- CALiPER Program Supports Unbiased Testing, Promotes Consumer Confidence
- ENERGY STAR® Criteria for Solid-State Lighting Products
- GATEWAY Demonstrations Showcase LED Product Performance
- SSL Quality Advocates Support Accuracy in LED Product Information
- Standards Development Increases Market Confidence in SSL Performance
- Lighting for Tomorrow: Competition Recognizes Innovative, Energy-Efficient Residential Lighting Design
- Next Generation Luminaires: Competition Recognizes Innovative, Energy-Efficient Commercial Lighting Luminaires
- L Prize: The Race to Replace the Common Light Bulb
- L Prize: Competition Requirements Set the Bar High
- L Prize: Program Partners Leverage Know-How and Market Pull

APPENDIX A: Workshop Attendee List

2009 DOE SOLID-STATE LIGHTING WORKSHOP
Transformations in Lighting
February 3–5, 2009
San Francisco, CA

Bob Adams
Chips & Wafers

Bunmi Adekore
LZ, Inc.

Jerine Ahmend
SDG&E

Scott Alberts
DCM

David Alexander
Pacific Gas & Electric

Diane Allard
Akoya

Steven Allen
Osram Sylvania

Kenneth E. Anderson
Task Lighting Corp

Linda Anderson
Task Lighting Corp

Brian Appleton
16500 Inc.

Mehmet Arik
GE Global Research Center

Andrew Armstrong
Sandia National Laboratories

Mariane Ayoub
Sixteenfivehundred

Edward Bailey
Brillia Lighting

Karen Baker
OptoLum, Inc.

James Norman Bardsley
Bardsley Consulting

Patrick Barker
LED Green Power

Tom Barnett
Masco Corp.

Jay Bartek
Task Lighting Corp

Bryan Beatenbough
EfficientLights LLC

Jim Beck
Optoelectronix Inc.

Chuck Berghoff
Optoelectronix Inc.

Rolf Bergman
Rolf Bergman Consulting

Joseph Berry
National Renewable Energy Laboratory

Tim Bettles
Crystal IS, Inc.

Vrinda Bhandarkar
Strategies Unlimited

Unnat Bhansali
University of Texas at Dallas

Robert Biefeld
Sandia National Laboratories

Bryed Billerbeck
Finelite, Inc.

Dave Bisbee
Sacramento, Municipal Utility District

Juan Carlos Blacker
Portland Energy Conservation, Inc.

Chris Blain
Camelbak Products

Erwin Blancaflor
City of Hercules

Stephen Bland
SB Consulting

Ken Blow Jr.
ISG Illumination Systems, LLC

Ken Blow Sr.
ISG Illumination Systems, LLC

Andrew Bobel
Neptun Light, Inc

Chris Bohler
Cooper Lighting

David Bonfante
CAL Lighting

Ellen Bossert
Philips Color Kinetics

Scott Boyd
Brilliant Associates

Michael Bremser
Permlight

Steve Briggs
GE Lumination

James Brodrick
U.S. Department of Energy

Marco Bron
Philips Lighting Company

Richard J. Bronson
Indak Manufacturing, Inc

Richard Brown
Architectural Media Design

James Brug
Hewlett-Packard Laboratories

Dallas Buchanan
A.L.P. Lighting Components, Inc.

Diana Burk
Navigant Consulting, Inc.

Anthony Burrell
Los Alamos National Laboratory

Mike Burton
ThinkEquity LLC

Bob Busse
Nanosys, Inc.

Jamey Butteris
Hubbell Lighting, Inc.

John Cannon
City of San Jose

Julian Carey
LUXIM

John Castner
Consolidated Electrical Distributors (CED)

Bruce Cervone
Advanced Optoelectronics, Inc.

Joel Chaddock
National Energy Technology Laboratory

Paul Chalmer
NCMS

Michael Chan
Digital Lighting Inc

Dong-Soo Chang
Innovatech

Jianping Chen
Add-Vision, Inc.

Kenan Chen
Advanced Optoelectronics, Inc.

Liang Chen
Applied Materials, Inc.

Charu Chibber
Dialight Corporation

Nicholas Chintala
GE Lighting Systems

Weng Onn Choong
Digital Lighting Incorporated

Kelvin Chuk
Architectural Area Lighting, Inc

Dan Chwastyk
Navigant Consulting

John Clancy
MaxLite

Terry Clark
Finelite, Inc.

Ilkan Cokgor
Intematix

Steve Cole
Great Basin Lighting Inc.

Michael Coltrin
Sandia National Laboratories

Daniel Cook
Energy Solutions

Keith Cook
Philips Lighting

Robert Costa
City of Pleasant Hill

M. George Craford
Philips Lumileds

Steven Crimi
Light Emotions Design LLC

John Curran
LED Transformations, LLC

Lou Dadok
Philips Lumileds

David Dai
Arkema Inc.

Anand Daniel
Flybridge Capital Partners

Leslie Davis
Silverman and Light

Lynn Davis
RTI International

Robert Davis
Carnegie Mellon University

Daryl DeJean
Pacific Gas & Electric

T.J. de Jony
Exclara

Olivier Delesalle
Bayer MaterialScience

Steven Denbaars
University of California Santa Barbara

Andrea Denver
Pacific Gas & Electric

Jameson Detweiler
Summalux

Tushar Dayagude
mSilica, Inc.

Vijay Dhingra
Echelon Corp

Kathy Diehl
Environmental Protection Agency

Brian Dotson
National Energy Technology Laboratory

Kevin Dowling
Philips Color Kinetics

Jeffrey Dross
Kichler Lighting

Robert Dubrow
Nanosys Inc.

Gerald Duffy
GE Lumination

Ben Duggan
OptoElectronix

Andrzej Duljas
Sea Gull Lighting

Marshall Dunbar
Beta Kramer Lighting

Dan Dungan
Indak Manufacturing, Inc

Frederic Dupont
Soitec USA, Inc.

Russell Dupuis
Georgia Institute of Technology

Cy Eaton

John Ebert
SC Solutions

Ryan Egidi
National Energy Technology Laboratory

Eric Eisele
Drexel University

Nayla El-haber
Dicon Fiberoptics

Phil Elizondo
Xicato

Chris Elsass
Agile

Waqidi Falicoff
LPI

Allen Fann
Action Media Technology

Dave Farnsworth
Bright Innovation

Richard Fassler
Power Integrations

Donna Feehan
City of Lafayette

William Feehery
DuPont

William Fenwick
Georgia Institute of Technology

Ian Ferguson
Georgia Institute of Technology

Paul Fini
Inlustra Technologies

Jeannine Fisher
Finelite, Inc.

Emilio Fontana
Roal Electronics USA, Inc.

Parry Forcier
BioLED

Larry French
Auerbach Glasow French

Ted Gailhouse
PECI

Francisco Galvez
Los Angeles Dept. of Water & Power

Samir Gandhi
Advance Color Lighting, Inc

Dennis Garcia
Boyd Lighting Company

Chris Garlington
Communities By Design

Karl Gaskins
Raytheon Missiles Company

Dan Gaspar
Battelle

Richard Gaughan
Freelance Science Writer

Kevin Gauna
California Lighting Technology Center

Mark Gaynor
Boyd Lighting Company

Thomas Geist
EPRI

Lijian Geng
CAO Group Inc.

Zach Gibler
Lighting Science Group Corp.

Cailey Gibson
Clinton Climate Initiative

David Ginley
National Renewable Energy Laboratory

Kevin Givens
Relume Technologies, Inc.

David Goggin

Kelly Gordon
Pacific Northwest National Laboratory

Timerie Gordon
Nielson Architects

Bud Grandsaert
IMS

Derek Greenauer
D&R International

Ira Greenberg
Keystone Technologies

Garrett Grega
Philips Lighting Company

Joel Gregowski

Gordon Grice
Echelon Corp.

Mark Gross
Battelle

Mahima Gupta
Navigant Consulting

Michael Hack
Universal Display Corporation

Douglas Hagen
B-K Lighting/TEKA Illumination

Ryan Haley
EfficientLights LLC

Caterina Hall
InteLED

Mark Hamann
Comed

Rick Hamburger
Philips Lumileds

Mark Hand
Acuity Brands

Kathleen Hannon
San Francisco Department of the Environment

Monica Hansen
Cree

Shatil Haque
Philips Lumileds

Gerard Harbers
Xicato Inc

Don Hargreaves
Carmanah Technologies Corp.

Robert Harrison
Osram Sylvania

Jason Hartlove
Nanosys Inc.

Elizabeth Hastings
Stanford University

Eric Haugaard
Beta Lighting

Jim Haussener
City of Vallejo

Andrew Hawryluk
Ultratech

Rudi Hechfellner
Philips Lumileds Lighting

Brian Hedayati
Maxim Integrated Products

Kurt Hendrickson
H.E. Williams

Doug Highbridge
USAI

Wah Hing Leung
Light Engine

David Hinman
DPL Inc.

Peter Hochstein
Relume Technologies

Robert Hojnacke
American Bright Optoelectronics Corp.

Mari Holcomb
Philips Lumileds Lighting Company

Richard Holmberg
Carmanah Technologies Corporation

Mark Homan
Relume Technologies, Inc.

Alex Hong
Digital Lighting Inc.

Noah Horowitz
NRDC

Evelyn Hu
Harvard University

Joe Hu
City of Oakland

Daniel Huang
Enplas USA

Li Huang
Carnegie Mellon University

Tyler Huebner
ICF International

Matt Huffaker
City of Walnut Creek

Bette Hughes
Akoya

James Ibbetson
Cree

Ilia Ivanov
Oak Ridge National Laboratory

Mark Jackson
Blue Dolphin Design

Jianzhong Jiao
OSRAM Opto Semiconductors

Greg Jobe
City of San Jose - Public Works

Karl Johnson
CA Institute for Energy & Environment

Megan Johnson
Energy Solutions

Barry Johnston
CM Global, LLC

Robert Jorgenson
LPI

James Kaentje
SmithGroup, Inc.

Patricia Kane
Studio Pk Interiors, Inc

Rahul Kapoor

Adam Karbaf
Fulham Company, Inc.

Richard Karney
U.S. Department of Energy

Sandeep Karwa
Alcoa

Hamid Kashani
Leotek

Thomas Katona
Decegy Consulting

Caroline Kay
B-K Lighting/TEKA Illumination

Shawn Keeney
LED Transformations, LLC

Bill Kennedy
Toyoda Gosei Co., Ltd.

Kandy Kernes
Lighting Science Group Corp.

John Kerr
Lawrence Berkeley National Laboratory

Mike Kim
Synergy Micro Technologies

Suhan Kim
Lawrence Berkeley National Laboratory

Bruce Kinzey
Pacific Northwest National Laboratory

Jay Koch
Redwood Systems

Robert Koenig
Clinton Climate Initiative

Jason Koman
Clinton Foundation

Gary Kowalczyk
Hilux LED Solutions

Kiran Kumar
Carmanah Technologies Corp.

Simon Kuppens
Philips Lighting B.V.

Brandon Kwak
Synergy Micro Technologies

Denise Kwan
Lion Group

Phil Kwan
Lion Group

Bruce Lamin
Echelon Corp.

Josh Lampl
Lightwave Photonics, Inc.

Susan Larson
Neo-Neon International

Troy Larson
Lighting Systems

Ken Lau
Powerlux Corp.

Melinda LaValle
CAL Lighting

Pierrette LeBlanc
Natural Resources CANADA

Marc Ledbetter
Pacific NW National Laboratory

Kanghee Lee
Fawoo Technology

Kidgeon Lee
Innovatech

Sangmin Lee
Fawoo Technology

David Leonard
Redwood Systems

Rob Leonard
Orb Optronix

Leslie Levine
Consultant

Todd Lewis
Omega Pacific Electrical Supply, Inc.

Jane Li
JD Greentech-global

Bing Liang
Handson Technologies, Inc.

Eric Lind
Lutron Electronics Co., Inc

Andrew Lindstrom
GE Lighting Systems

Robert Lingard
Pacific Northwest National Laboratory

Jonathan Linn
Northeast Energy Efficiency Partnerships

Alice Liu
Philips Lumileds Lighting

Deang Liu
Lawrence Berkeley National Laboratory

Gao Liu
Lawrence Berkeley National Laboratory

Heng Liu
Bridgelux

Russell Liu
Global Green Energy

Jonathan Livingston
Livingston Energy Innovations

Leonard Livschitz
LedEngin Inc.

Rochelle Lockridge
3M Company

Ed Macias
Kim Lighting

John Devin MacKenzie
Add-Vision

Samuel Mao
Lawrence Berkeley National Laboratory

Karen Marchese
Akoya

Thomas Marchok
Intel Capital

Celine Marcipan
16500 Inc.

Robert Marken
The Cypress Funds, LLC

John Martin
International Association of Lighting Designers

Vladimir Maslov
Action Media Techonlogy

Elison Matioli
University of California Santa Barbara

Mary Matteson Bryan
Pacific Gas & Electric

Deanna Matthews
Carnegie Mellon University

H. Scott Matthews
Carnegie Mellon University

Matt Maurer
Synergy Micro Technologies

Lawrence Mazer
Exclara Inc.

Mark McClear
Cree

Michael McClear
Relume Technologies

Thomas McClellan
LED Green Power, Inc.

Jeff McCullough
Pacific Northwest National Laboratory

Dal McGinnis
CAL Lighting

Kelly McGroddy
Xicato

Chad McSpadden
H.E. Williams

Oliver Meissner
The Consilio Group

Jacob Melby
Carnegie Mellon University

Jonathan Melman
Intematix Corporation

Hisham Menkara
PhosphorTech

Steve Mesh
Pacific Gas & Electric

Charly Meyer
DiCon Fiberoptics

Melese Michael
Oznium.com

Aaron Miller
Orb Optronix

Greg Miller
Carmanah Technologies

Erik Milz
Philips Lumileds

Andrew Minor
University of California, Berkeley

Jerry Mix
Watt Stopper/Legrand

Jing Mo
Seoul Semiconductor

Laura Moorefield
Ecos

Avraham Mor
Lightswitch Architectural

Lorenza Moro
SRI International

John Morreale
Iluumitex, Inc

G R Mortenson
QuNano

Greg Murphy
MaxLite

Mic Murphy
Energy Federation, Inc.

Shyam Nagrani
mSilica, Inc

Brantley Natter
Michigan Industrial Manufacturing

Jamie Natter
Michigan Industrial Manufacturing

Jeff Nause
Cermet, Inc.

Nazzi Nazeri
Lighting Systems

Peter Ngai
Acuity Brands Lighting

Harry Niedecken
WirlNet

Frederick Nobile
Yokohama Electron Co., Ltd.

David Noland
Capri Omega Lighting

Cedric Novenario
City of Livermore, CA

Arto Nurmikko
Brown University

Chris Nyel
Leotek

John Nylander
InteLED

Wes Okubo
City of Santa Clara

Susan June Olson
Radiance

Mohammad Omary
University of North Texas

William Ong
Sooner Cap

Nora Onofrio
Architectural Area Lighting

Bill Orner
Optoelectronix

Richard Osborne
Loop Lighting

Tim O'Sullivan
Cree LED Lighting

Jose Pacheco
City of Hercules

Asanga Padmaperuma
Battelle

Erik Page
Erik Page & Associates

Mia Paget
Pacific Northwest National Laboratory

Terrance Pang
Energy Solutions

Steve Paolini
Telelumen LLC

Konstantinos Papamichael
California Lighting Technology Center

Kitae Park
Samsung Information System America

Brett Parker
Heatron, Inc.

Nag Patibandla
Applied Materials, Inc

Morgan Pattison
SSLS, Inc.

Rich Payne
City of Walnut Creek

Dennis Pearson
Tempo Industries

Qibing Pei
University of California, Los Angeles

David Pelka
InteLED

Bruce Pelton
California Lighting Technology Center

John Perkins
National Renewable Energy Laboratory

Michael Petagna
ROAL Electronics

Edward Petrow
Lincoln Technical Services, Inc.

Christiane Poblenz
Kaai, Inc.

Jason Pomante
Arkema Inc

Lisa Porter
Carnegie Mellon University

Andy Poster
Republic Intelligent Transportation Services

Matt Price
Nth Power LLC

Mark Pugh
Xicato

Alex Qiao
NN-Labs

Jeff Quinlan
Acuity Brands

Mark Raissen
Optiled

David Ramer
Renaissance Lighting, Inc.

Douglas Ramsey
Alcoa

George Rasko
ASIC Advantage

Nidhi Rastogi
Instapower

William Ratcliffe
General LED

Padmanabha Ravilisetty
SRI International

Meredith Reed
Army Research Laboratory

Kristian Reyes
Lighting Systems

Michael Reznikov
Physical Optics Corporation

Michael Riebling
Hadco

Kate Ringe-Welch
National Grid

Tom Riordan
Exclara, Inc

John Rivera
D&R International Ltd.

Allen Rogers
Illumination Unlimited USA Inc.

Christopher Rooks
Ecos Consulting

Kevin Russell
Tempo Industries

Larry Sadwick
InnoSys, Inc.

Robert Sagebiel
Arrow Electronics - Lighting Group

Connie Samla
Sacramento Municipal Utility District

Marci Sanders
D&R International

Susan Sanderson
Rensselaer Polytechnic Institute

Vince Santini
LSI Industries

Pat Sapinsley
Good Energies

Thomas Schuller
H.E. Williams

Michael Schwartz
Optiled

Thor Scordelis
PG&E Emerging Technology

Keith Scott
Bridgelux

Michael Seaman
California Energy Commission

Ed Selbe
NUR Lighting Corporation

Ron Senger
City of Los Angeles

Christopher Sequeira
Navigant Consulting, Inc.

Anant Setlur
GE Global Research

Jordan Shackelford
Energy Solutions

Mehdi Shafaghi
Los Angeles Department of Water and Power

Eddie Shaw
Duke Energy

Nasir Sheikh
Sharp Labs of America

Joseph Shiang
General Electric

Joon Ho Shin
Add-Vision Inc.

Paul Shnitser
Physical Optics Corporation

Jay Shuler
Philips Lumileds

Frank Shum
Luximo

Olin Sibert
Cybrite, Inc

Dennis Siemiet
Ilumisys

Johannes Sillevis Smitt
Philips Lumileds Lighting

Gary Silverman
Arkema Inc.

Jerry Simmons
Sandia National Labs

Kenneth Simons
Rensselaer Polytechnic Institute

John Simpson
Oak Ridge National Laboratory

Franky So
University of Florida

John Sofranac
Pacific Gas & Electric

Margaret Song
Cape Light Compact

Joe Spangler
Ecos Consulting

James Speck
University Of California, Santa Barbara

Simon Speight
ISG Illumination Systems, LLC

Patrick Spicer
Wellmade Lighting Products

Eric Stach
Purdue University

J. Chad Stalker
Luminus

Ron Steen
Xicato

Lee Stevens
Emerging Technologies Associates, Inc

Jeremy Stieglitz
Redwood Systems

Lauren Stoller
Lazard Capital Markets

John Stone
Boyd Lighting Company

Matthew Stough
Osram Sylvania

Todd Straka
Intertek

Pete Strasser
International Dark-Sky Association

Thomas Struhs
Dialight Corporation

Laura Stuchinsky
City of San Jose

Joerg Student
Luximo

Christopher Summers
PhosphorTech

Decai Sun
Philips Lumileds Lighting

Rickson Sun
IDEO

Suresh Sunderrajan
NN-Labs, LLC

Yon Sung
MaxLite

Shiva Swaminathan
City of Palo Alto

Aijaz Taj
Lights of America

Fatima Taj
Lights of America

Hiroyuki Takai
Sharp Corporation

Christine Tam
City of Palo Alto

Steven Tam
City of Richmond

Ford Tamer
Khosla Ventures

Jinke Tang
University of Wyoming

Nelson Tansu
Lehigh University

Eric Taub
The New York Times

Ruth Taylor
Pacfic Northwest National Laboratory

John Teodecki
RS Consultants, LLC

Marc Theobald
EMCOR Energy Services

Matt Thomas
Illumitex, Inc

Ethan Thorman
SuperBulbs

Larry Thrall
Envirolight LED

Paul Thurk
ARCH Venture

Andrew Timmerman
Fairfield Crystal Technology

Mike Trainor
A&M Studios

Ralph Tuttle
Cree, Inc.

Yuan-Sheng Tyan
Eastman Kodak Company

Anand Upadhyay
Philips

Craig Updyke
NGLIA/NEMA

Guy Vaccaro

Joe Vaccher
Eugene Water & Electric Board

Steven Van Slyke
Eastman Kodak

Jeff Varenkamp
Carmanah Technologies

Jan Vetrovec
Aqwest LLC

John Vetrovec
Aqwest LLC

Katerina Vetrovec
Aqwest LLC

Paul Vrabel
Sea Gull Lighting

Jim Wagner
Republic Intelligent Transportation Services

Peter Wagner
SSL DRIVERS

Bill Wakefield
Hilux

Stan Walerczyk
Lighting Wizards

Terrence Walsh
Tempo Industries, Inc.

Jack Wang
Leotek

Shaoping Wang
Fairfield Crystal Technology

Charles Warren
Alcoa Inc.

Michael Weaver
Universal Display Corporation

Ronald Weber
Tyco Electronics

Yajun Wei
Philips Lumileds Lighting Company

Claude Weisbuch
University of California, Santa Barbara

Richard Weiss
Hymite

Fred Welsh
Radcliffe Advisors, Inc.

Scott Wentworth
City of Oakland

Christian Wetzel
Rensselaer Polytechnic Institute

Regina Wheeler
City of Menlo Park

Glen Whitehead
Ecos Consulting

Mark Whitney
Portland General Electric

Dean Wigger
Wigger Works

Dennis Willing
Lighting Systems, Inc.

Kevin Willmorth
Lumenique LLC

Matthew Wilson
White & Lee LLP

Richard Wilson
CDT Ltd

Klaas Wisniewski
AIXTRON Inc

Weeky Wong
Optiled

George Woodbury
Republic Intelligent Transportation Services

Sonny Wu
GSR Ventures

Jiangeng Xue
University of Florida

John Yang
American Bright Optoelectronics Corp.

Michael Yang
Varian Semiconductor

Barry Young
OLED Association

John Yriberri
Xicato Inc.

David Yu
eldoLED America, Inc.

Regan Zane
University of Colorado at Boulder

Hanim Zhao
Sierra Solar Power

Lihua Zhao
Hewlett-Packard

Ming Zhu
Intel Corporation

Aaron Zude
SEMI

APPENDIX B: LED/OLED Breakout Session Workshop Materials

DOE Solid State Lighting Research and Development Workshop

San Francisco, CA February 3-5, 2009

Breakout Preparation Materials

Welcome to the 2009 Solid State Lighting Workshop. One of the primary goals of the Workshop is to help DOE to identify and target funding for critical tasks on the path to practical solid state lighting. The outcome of this work will be published in the 2009 edition of the SSL Multi-Year Program Plan (MYPP) and used by DOE to determine appropriate foci of upcoming R&D solicitations.

This document contains materials to assist in the process of refining and prioritizing R&D tasks. In preparation for the Workshop, we ask you to familiarize yourself with this material and do the "Homework Assignment" described below. The materials provided here are the result of a pre-planning effort that began with two R&D Roundtables held in Washington, DC in September of 2008. The Roundtables provided an opportunity for experts in SSL to present their views as to important research and development topics that should be candidates for R&D funding. The task structure used in past versions of the MYPP was first developed in 2003, and has been only slightly modified since then. Because of the rather remarkable progress that has been made in SSL under DOE's program, it was clear that it was time to revisit that structure and determine anew the tasks we need to perform going forward. Following the Roundtables there ensued a series of weekly teleconferences during which participants defined and refined the task descriptions that follow. Although there are some similarities to the previous structure, and certain constraints on defining Core versus Product Development work, the structure is essentially new.

We are providing three Views of the proposed new task structure. The first, the *Core/Product Development(PD) View* will be familiar. It is separated by Core and PD pretty much the same as you have seen in past MYPPs, grouped into several general Technology Categories, and showing a task number, name, description, metric, status, and target.

Next is a *Technology View*. This is essentially the same information, but sorted by Technology Category. This View allows one to see related Core and PD tasks grouped together. This View also contains some footnotes to further clarify the material and some discussion points for the breakout sessions.

Third is a *Planning View*. Here we are attempting to get some idea of the resources needed to reach proposed milestones for 2010 and 2012 (see last page of the Planning View). You will receive more information at the Workshop, but what we will be trying to do is to scope the effort (staff-years) that would be required by competent researchers working on a specific task to make "sufficient progress" so as to enable the program as a whole to meet the relevant milestone.

Homework Assignment

1. A preliminary prioritization (refer to "My Priority" on the *Core/PD View*). Please identify your top 5 Core tasks (rank 1(top) to 5) and do the same for PD. We will take an initial canvass at the beginning of the breakouts.
2. For each of your prioritized tasks, edit or add to the metric, the status in 2008, and the target for 2015. At the Workshop, once the whole group has reached a priority recommendation, we will ask that they fill in these parameters.
3. Give some thought to the resource needs for your top tasks. What would you be proposing to DOE if you were to respond to a solicitation for one of them?

The DOE appreciates your participation and we hope you will enjoy the Workshop. We'll see you in San Francisco!

LED Tasks – Core/PD View

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
1.	**1.0**	**Emitter Materials Core**						
1.	1.1		Alternative substrates	Explore alternative practical substrate materials and growth for high quality epitaxy so that device quality can be improved.	Performance potential improvement over conventional			
1.	1.2		Emitter materials research	Focus on the development of efficient green and deep red emitters with low droop and minimal thermal sensitivity and continue improvement in blue LEDs	IQE across the visible spectrum at high current densities	20% green (540 nm),75% red, 80% blue	90% for all three colors	
1.	1.3		Down converters	High-efficiency wavelength conversion materials for improved quantum yield, optical efficiency, and color stability. Explore novel approaches to conversion.	Quantum Yield; Scattering Losses; Color Stability	95% at 450 nm.; 10%	90% across visible spectrum; 10%	
1.	**2.0**	**Device Materials and Architecture Core**						
1.	2.1		Light extraction approaches	Devise improved methods for raising chip level extraction efficiency and LED system optical efficiency. Photonic crystal structures or resonant cavity approaches would be included.	Chip Extraction Efficiency (χ); Phosphor Conversion Efficiency	16% green (540 nm), 38% red (610 nm), 64% blue; 65%	81% for all three colors; 73%	
1.	2.2		Novel emitter materials and architectu	Devise alternative emitter geometries and emission mechanisms in manufacturable configurations that show genuine improvement over existing approaches. (Possible examples: quantum dots, monolithic integrated RGB, 360 degree emitters, etc.)	EQE	64%	81%	
1.	**3.0**	**Device Packaging Core**						
1.	3.4		Thermal control research	Simulation of solutions to thermal management issues at the package or array level. Innovative thermal management solutions.	Thermal Resistance (junction to case)		5ºC per Watt	
1.	**4.0**	**LED Fabrication Core**						
1.	4.4		Manufacturing simulation	Develop manufacturing simulation approaches that will help to improve yield and quality of LED products.				
1.	**5.0**	**Optical Components Core**						
1.	5.1		Optical component materials	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.	Transmission across visible spectrum, lifetime		> 90% transmission	

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
1.	**6.0**	**Luminaire Integration Core**						
1.	6.2		Thermal components research	Research and develop novel thermal materials and devices, that can be applied to solid state lighting products	LED source junction temperature maintenance			
1.	6.3		System reliability methods	Develop models, methodology, and experimentation to determine the lifetime of the integrated SSL luminaire and all of the components. Includes investigation of accelerated testing.				
1.	**7.0**	**Electronic components Core**						
1.	7.4		Driver electronics	Develop advanced solid state electronic materials and components that enable higher efficiency and longer lifetime for control and driving of LED light sources	Driver efficiency; lifetime at operating temperature	85%	90%	
1.	7.5		Electronics reliability research	Develop designs that improve and methods to predict the lifetime of electronics components in the SSL luminaire	Accuracy of predictive model vs. long term actual results or potential lifetime improvement for a novel design approach.			

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
2.	**1.0**	**Emitter Materials Product Development**						
2.	1.1		Substrate development	Develop low cost, high quality substrates that enable epitaxial growth of high quality emitting material.	Cost of Substrate ($/klm); Defect Density			
2.	1.2		Semiconductor materials	Improve IQE at optimal wavelengths for producing white light across the visible spectrum (red: 610nm; green: 540nm). Improve droop and thermal sensitivity	IQE across the visible spectrum at high current densities	20% green (540 nm),75% red (610 nm), 80% blue	90% for all three colors	
2.	1.3		Phosphors	Optimize phosphors for LED white light applications, including color uniformity, color maintenance, thermal sensitivity and stability.	Quantum Yield; Scattering Losses; Color Stability	95% at 450 nm; 10%	90% across visible spectrum; 10%	
2.	**2.0**	**Device Materials and Arch. PD**						
2.	2.3		Electrical	Reduce the operating voltage of LED chips or arrays by increasing lateral conductivity or architectural improvements or package design, etc.	Operating Voltage			
2.	**3.0**	**Device Packaging Product Development**						
2.	3.1		LED package optics	Beam shaping or color mixing at the LED package or array level.	Optical/Fixture Efficiency	80%	95%	
2.	3.2		Encapsulation	Develop a thermal/photo resistant encapsulant that exhibits long life and has a high refractive index.	% of original transmission per mm	85-90% (at 150°C and 10-15 kHrs)	95% (at 150oC junction temp. and 50 kHrs)	
2.	3.4		Emitter thermal control	Demonstrate an LED or LED array that maximizes heat transfer to the package so as to improve chip lifetime and reliability.	Thermal Resistance (junction to case)		5ºC per Watt	
2.	3.5		Environmental sensitivity	Develop and extensively characterize a packaged LED with significant improvements in lifetime associated with the design methods or materials.	Mean Time to Failure		50 kHrs	
2.	3.6		Package architecture	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.				

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
2.	4.0	**LED Fabrication Product Development**						
2.	4.1		Yield and manufacturability	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.				
2.	4.2		Epitaxial growth	Develop and demonstrate growth reactors capable of growing state of the art LED materials at low-cost and high reproducibility with improved materials use efficiency.				
2.	4.3		Manufacturing tools	Develop improved tools and methods for die separation, chip shaping, and wafer bonding, and testing equipment for manufacturability at lower cost.				
2.	5.0	**Optical Components Product Dev**						
2.	5.1		Light utilization	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.	Useful light output from luminaire/total light generated by LED source	80%	95%	
2.	5.2		Color maintenance	Ensure luminaire optical components maintain the LED source color quality over the life of the luminaire	Color maintenance within X-step MacAdam Ellipse over time			
2.	5.3		Diffusion and beam shaping	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.	Optical loss measured as part of the luminaire optical system, lifetime			

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
2.	**6.0**	**Luminaire Integration Product Development**						
2.	6.1		Luminaire mechanical design	Integrate all aspects of LED based luminaire design: thermal, mechanical, optical, and electrical. Design must be cost effective, energy efficient and reliable.				
2.	6.2		Thermal	Design integrated thermal management techniques to protect the LED source, maintain the luminaire efficiency and color quality and be low cost.	Tj in steady state operation. Must be below appropriate level for design lifetime.			
2.	6.3		Optimizing system reliability	Optimize and verify overall luminaire reliability. Includes system reliablity analysis to determine failure mechanisms and improve.	Mean time to failure (either catastrophic or lumen depreciation below 70%)		40 kHrs	
2.	**7.0**	**Electronic components PD**						
2.	7.1		Color maintenance	Develop LED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in LED output over time and temperature, and degradation of luminaire components.	Color shift over the life of the luminaire; efficiency of control electronics			
2.	7.2		Color tuning	Develop efficient electronic controls that allow a user to set the color point of the luminaire.	Efficiency of control electronics; off-state power consumption; accuracy of color setting			
2.	7.3		Smart controls	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.	Efficiency of control electronics; off-state power consumption; power saved			
2.	7.4		Electronics component research	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	Driver efficiency; lifetime at operating temperature; cost	85%	90%	

LED Tasks – Technology View

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	1.0	**Emitter Materials**							
2.	1.1		Substrate development	Develop low cost, high quality substrates that enable epitaxial growth of high quality emitting material.	Cost of Substrate ($/klm); Defect Density			Defect density is not directly correlated to enabling epitaxial growth for all substrates; need other metrics	
1.	1.2		Emitter materials research	Focus on the development of efficient green and deep red emitters with low droop and minimal thermal sensitivity and continue improvement in blue LEDs	IQE across the visible spectrum at high current densities	20% green (540 nm),75% red, 80% blue	90% for all three colors	What are specific wavelengths for blue and "deep" red? How should we define "high" for current density?	IQE status and projections assume pulsed measurements at 350 mA drive currents with a 1x1mm2 chip and Tj = 25oC.
2.	1.2		Semiconductor materials	Improve IQE at optimal wavelengths for producing white light across the visible spectrum (red: 610nm; green: 540nm). Improve droop and thermal sensitivity	IQE across the visible spectrum at high current densities	20% green (540 nm),75% red (610 nm), 80% blue	90% for all three colors	Are the statuses of 1.1.2 and 2.1.2 the same or different?	
1.	1.3		Down converters	High-efficiency wavelength conversion materials for improved quantum yield, optical efficiency, and color stability. Explore novel approaches to conversion.	Quantum Yield; Scattering Losses; Color Stability	95% at 450 nm.; 10%	90% across visible spectrum; 10%		Quantum Yield is measured at a pumped wavelength of 450 nm.
2.	1.3		Phosphors	Optimize phosphors for LED white light applications, including color uniformity, color maintenance, thermal sensitivity and stability.	Quantum Yield; Scattering Losses; Color Stability	95% at 450 nm; 10%	90% across visible spectrum; 10%		
	2.0	**Device Materials and Architecture**							
1.	2.1		Light extraction approaches	Devise improved methods for raising chip level extraction efficiency and LED system optical efficiency. Photonic crystal structures or resonant cavity approaches would be included.	Chip Extraction Efficiency (χ); Phosphor Conversion Efficiency	16% green (540 nm), 38% red (610 nm), 64% blue; 65%	81% for all three colors; 73%		
1.	2.2		Novel emitter materials and architectu	Devise alternative emitter geometries and emission mechanisms in manufacturable configurations that show genuine improvement over existing approaches. (Possible examples: quantum dots, monolithic integrated RGB, 360 degree emitters, etc.)	EQE	64%	81%		IQE status and projections assume pulsed measurements at 350 mA drive currents with a 1x1mm2 chip and Tj = 25oC.
2.	2.3		Electrical	Reduce the operating voltage of LED chips or arrays by increasing lateral conductivity or architectural improvements or package design, etc.	Operating Voltage				

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	3.0	**Device Packaging**							
2.	3.1		LED package optics	Beam shaping or color mixing at the LED package or array level.	Optical/Fixture Efficiency	80%	95%		
2.	3.2		Encapsulation	Develop a thermal/photo resistant encapsulant that exhibits long life and has a high refractive index.	% of original transmission per mm	85-90% (at 150°C and 10-15 kHrs)	95% (at 150oC junction temp. and 50 kHrs)		This target may change to 185oC as efficiency goals are met and cost becomes a higher priority.
1.	3.4		Thermal control research	Simulation of solutions to thermal management issues at the package or array level. Innovative thermal management solutions.	Thermal Resistance (junction to case)		5ºC per Watt		
2.	3.4		Emitter thermal control	Demonstrate an LED or LED array that maximizes heat transfer to the package so as to improve chip lifetime and reliability.	Thermal Resistance (junction to case)		5ºC per Watt		
2.	3.5		Environmental sensitivity	Develop and extensively characterize a packaged LED with significant improvements in lifetime associated with the design methods or materials.	Mean Time to Failure		50 kHrs		
2.	3.6		Package architecture	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.					
	4.0	**LED Fabrication**							
2.	4.1		Yield and manufacturability	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.					
2.	4.2		Epitaxial growth	Develop and demonstrate growth reactors capable of growing state of the art LED materials at low-cost and high reproducibility with improved materials use efficiency.					
2.	4.3		Manufacturing tools	Develop improved tools and methods for die separation, chip shaping, and wafer bonding, and testing equipment for manufacturability at lower cost.					
1.	4.4		Manufacturing simulation	Develop manufacturing simulation approaches that will help to improve yield and quality of LED products.					

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	5.0	**Optical Components**							
1.	5.1		Optical component materials	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.	Transmission across visible spectrum, lifetime		> 90% transmission		
2.	5.1		Light utilization	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.	Useful light output from luminaire/total light generated by LED source	80%	95%		
2.	5.2		Color maintenance	Ensure luminaire optical components maintain the LED source color quality over the life of the luminaire	Color maintenance within X-step MacAdam Ellipse over time			How many steps, and what period of time?	
2.	5.3		Diffusion and beam shaping	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.	Optical loss measured as part of the luminaire optical system, lifetime				
	6.0	**Luminaire Integration**							
2.	6.1		Luminaire mechanical design	Integrate all aspects of LED based luminaire design: thermal, mechanical, optical, and electrical. Design must be cost effective, energy efficient and reliable.					
1.	6.2		Thermal components research	Research and develop novel thermal materials and devices, that can be applied to solid state lighting products	LED source junction temperature maintenance				
2.	6.2		Thermal	Design integrated thermal management techniques to protect the LED source, maintain the luminaire efficiency and color quality and be low cost.	Tj in steady state operation. Must be below appropriate level for design lifetime.				
1.	6.3		System reliability methods	Develop models, methodology, and experimentation to determine the lifetime of the integrated SSL luminaire and all of the components. Includes investigation of accelerated testing.					
2.	6.3		Optimizing system reliability	Optimize and verify overall luminaire reliability. Includes system reliablity analysis to determine failure mechanisms and improve.	Mean time to failure (either catastrophic or lumen depreciation below 70%)		40 kHrs	What should the performance target be, as it is for the entire luminaire?	

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	7.0	**Electronic components**							
2.	7.1		Color maintenance	Develop LED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in LED output over time and temperature, and degradation of luminaire components.	Color shift over the life of the luminaire; efficiency of control electronics				
2.	7.2		Color tuning	Develop efficient electronic controls that allow a user to set the color point of the luminaire.	Efficiency of control electronics; off-state power consumption; accuracy of color setting				
2.	7.3		Smart controls	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.	Efficiency of control electronics; off-state power consumption; power saved				
1.	7.4		Driver electronics	Develop advanced solid state electronic materials and components that enable higher efficiency and longer lifetime for control and driving of LED light sources	Driver efficiency; lifetime at operating temperature	85%	90%		
2.	7.4		Electronics component research	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	Driver efficiency; lifetime at operating temperature; cost	85%	90%		
1.	7.5		Electronics reliability research	Develop designs that improve and methods to predict the lifetime of electronics components in the SSL luminaire	Accuracy of predictive model vs. long term actual results or potential lifetime improvement for a novel design approach.				

LED Tasks – Planning View

C/PD	a.b	Cat.	Subtask	Metric	2008	Resources('10)	Resources ('12)
1.	**1.0**	**Emitter Materials Core**					
1.	1.1		Alternative substrates	Performance potential improvement over conventional			
1.	1.2		Emitter materials research	IQE across the visible spectrum at high current densities	20% green (540 nm),75% red, 80% blue		
1.	1.3		Down converters	Quantum Yield; Scattering Losses; Color Stability	95% at 450 nm.; 10%		
1.	**2.0**	**Device Materials and Architecture Core**					
1.	2.1		Light extraction approaches	Chip Extraction Efficiency (χ); Phosphor Conversion Efficiency	16% green (540 nm), 38% red (610 nm), 64% blue; 65%		
1.	2.2		Novel emitter materials and architectu	EQE	64%		
1.	**3.0**	**Device Packaging Core**					
1.	3.4		Thermal control research	Thermal Resistance (junction to case)			
1.	**4.0**	**LED Fabrication Core**					
1.	4.4		Manufacturing simulation				
1.	**5.0**	**Optical Components Core**					
1.	5.1		Optical component materials	Transmission across visible spectrum, lifetime			
1.	**6.0**	**Luminaire Integration Core**					
1.	6.2		Thermal components research	LED source junction temperature maintenance			
1.	6.3		System reliability methods				
1.	**7.0**	**Electronic components Core**					
1.	7.4		Driver electronics	Driver efficiency; lifetime at operating temperature	85%		
1.	7.5		Electronics reliability research	Accuracy of predictive model vs. long term actual results or potential lifetime improvement for a novel design approach.			

C/PD	a.b	Cat	Subtask	Metric	2008	Resources('10)	Resources ('12)
2.	**1.0**	**Emitter Materials Product Development**					
2.	1.1		Substrate development	Cost of Substrate ($/klm); Defect Density			
2.	1.2		Semiconductor materials	IQE across the visible spectrum at high current densities	20% green (540 nm),75% red (610 nm), 80% blue		
2.	1.3		Phosphors	Quantum Yield; Scattering Losses; Color Stability	95% at 450 nm; 10%		
2.	**2.0**	**Device Materials and Arch. PD**					
2.	2.3		Electrical	Operating Voltage			
2.	**3.0**	**Device Packaging Product Development**					
2.	3.1		LED package optics	Optical/Fixture Efficiency	80%		
2.	3.2		Encapsulation	% of original transmission per mm	85-90% (at 150°C and 10-15 kHrs)		
2.	3.4		Emitter thermal control	Thermal Resistance (junction to case)			
2.	3.5		Environmental sensitivity	Mean Time to Failure			
2.	3.6		Package architecture				
2.	**4.0**	**LED Fabrication Product Development**					
2.	4.1		Yield and manufacturability				
2.	4.2		Epitaxial growth				
2.	4.3		Manufacturing tools				

C/PD	a.b	Cat.	Subtask	Metric	2008	Resources('10)	Resources ('12)
2	5.0	Optical Components Product Dev					
2	5.1		Light utilization	Useful light output from luminaire/total light generated by LED source	80%		
2	5.2		Color maintenance	Color maintenance within X-step MacAdam Ellipse over time			
2	5.3		Diffusion and beam shaping	Optical loss measured as part of the luminaire optical system, lifetime			
2	6.0	Luminaire Integration Product Development					
2	6.1		Luminaire mechanical design				
2	6.2		Thermal	Tj in steady state operation. Must be below appropriate level for design lifetime.			
2	6.3		Optimizing system reliability	Mean time to failure (either catastrophic or lumen depreciation below 70%)			
2	7.0	Electronic components PD					
2	7.1		Color maintenance	Color shift over the life of the luminaire; efficiency of control electronics			
2	7.2		Color tuning	Efficiency of control electronics; off-state power consumption; accuracy of color setting			
2	7.3		Smart controls	Efficiency of control electronics; off-state power consumption; power saved			
2	7.4		Electronics component research	Driver efficiency; lifetime at operating temperature; cost	85%		

Milestone	Year	Milestone Target
Milestone 1	FY08	80 lm/W, < $25/klm, 50,000 hrs device
Milestone 2	FY10	> 140 lm/W cool white device; >90 lm/W warm white device; < $10/klm
Milestone 3	FY12	126 lm/W luminaire that emits ~1000 lumens
Milestone 4	FY15	< $2/klm device

Assumption: CRI > 80, CCT < 5000°K, T_j = 125°C

OLED Tasks – Core/PD View

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
3.	**1.0**	**Materials and Device Architectures Core**						
3.	1.1		Novel device architectures	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.	EQE; Voltage; L70	36% EQE including light extraction enhancements; L50=20kHrs	EQE 74% for all colors including outcoupling enhancements; 2.8 V; 40 kHrs	
3.	1.2		Novel materials	Organic materials or contact materials to increase IQE, reduce voltage and improve device lifetime. Explores novel materials that can be used to emit highly efficient blue light with the ultimate goal of generating highly efficient white light. The materials should be inherently stable against moisture and temperature.	IQE; Voltage; L70; EQE without extraction enhancement; L70 & voltage @ 1mA/cm^22; CCT; CRI	29% EQE; L50=20khrs; 3900K, 70 CRI; 100% IQE	IQE=100% across visilble spectrum; 2.8 V; 40 khrs; blue deep enough that it is capable of generating CCT >2800K	
C/PD	1.3		Device Modeling	Developing software simulation tools to model the performance of OLED devices using detailed material characteristics.				
3.	1.4		Material degradation	Understand and evaluate the degradation of materials during device operation.	L70	L50=20 kHrs	50 kHrs	
3.	1.5		Thermal characterization of materials and devices	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.				
3.	**2.0**	**Substrate and Electrode Core**						
3.	2.2		Electrode research	Develop a novel transparent electrode with low resistivity to serve as a lower cost replacement for ITO with the same or better performance. This electrode should be inherently stable against moisture and temperature. Areas of research may include p-type and n-type degenerate electrodes, two-material electrodes, electrodes that reduce current spreading, flexible electrodes, or other low-voltage electrodes.	Ohms/Square; Transparency absorption over the visible spectrum	Non-ITO electrode: 40 Ohms/Square; 75-80% Transparency	Non-ITO electrode: < 10 Ohms/Square; 92% Transparency	
3.	**3.0**	**Fabrication Core**						
3.	3.1		Fabrication technology research	Develop new practical techniques for organic materials deposition, device fabrication, or encapsulation. Could also include developing a physical, chemical, or optical model for fabrication of OLED devices.	Capital Cost; Operating Cost; Material Use; Deposition Rate; Uniformity			

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
3.	**4.0**	**Luminaire Integration Core**						
3.	4.3		Optimizing system reliability	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.				
3.	**5.0**	**Electronic Components Core**						
3.	**6.0**	**Panel Architecture Core**						
3.	6.3		Light extraction approaches	Devise new optical and panel designs for improving OLED panel light extraction.	Light Extraction Efficiency	40%	76%	

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
4.	**1.0**	**Materials and Device Arch. Product Dev**						
4.	1.1		Practical implementation of materials and device architectures	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.	Efficacy; L70; Lumen Output; CRI; CCT	102 lm/W; L50=20khrs; 70 CRI	> 100 lm/W Efficacy; 70 = 40 kHrs; 50 Lumens; 90 CRI	
4.	1.5		Device failure	Understand the failure modes of an OLED at the device level.	L70	L50=20 kHrs	50 kHrs	
4.	**2.0**	**Substrate and Electrode Product Dev**						
4.	2.1		Substrate	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.	$/m^2; Water Permeability; Oxygen Permeability	Glass: $4/m2 w/o TCO, no water permeability; Flexible: $100/m2, 10-6 g/m2-day Water Permeability	< $6/m^2 (cost includes substrate plus TCO/equivalent); 10-6 g/m2-day Water Permeability including TCO or equivalent	
4.	2.2		Low-cost electrodes	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.	Ohms/Square; Transparency absorption over the visible spectrum; $/m^2	Non-ITO electrode: 40 Ohms/Square; 85% Transparency	Non-ITO electrode: < 10 Ohms/Square; 92% Transparency; Cost < $6/m^2	
4.	**3.0**	**Fabrication Product Dev**						
4.	3.1		Panel manufacturing technology	Produce an OLED panel using low cost, integrated manufacturing technologies that have a short TAC time and the ability to scale to large areas.	Capital Cost; Material Use; Deposition Rate; Uniformity; Total Actual Cycle Time (TAC)	5 min/m^2	1 min/m^2/capital cost	
4.	3.2		Quality control	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.				

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
4.	**4.0**	**Luminaire Integration Product Dev**						
4.	4.1		Light utilization	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.	Useful light output from luminaire/total light generated by OLED panel	90%	95%	
4.	4.1		Luminaire mechanical design	Integrate all aspects of OLED based luminaire design: thermal, mechanical, optical, and electrical into a cost effective, long life, energy saving, and marketable luminaire. All components should be as robust as the OLED.	Efficacy; Lifetime; Cost			
4.	4.2		Thermal	Design integrated thermal management techniques to extract heat from the luminaire in a variety of environments and operating conditions. Thermal management should maintain the OLED source temperature as well as enhance the luminaire color and efficiency performance.	Lifetime; Case Temperature			
4.	4.3		System reliability methods	Develop models, methodology, and experimentation to determine the lifetime of the integrated OLED luminaire and all of the components				
4.	4.3		Electrical interconnects	Develop standard connections for integration of OLED panels into the luminaire.				
4.	**5.0**	**Electronic Components Product Dev**						
4.	5.1		Color maintenance	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.	Color shift over the life of the luminaire and efficiency of control electronics			
4.	5.2		Smart controls	Develop integrated lighting controls and sensors that save energy over the life of the luminaire.	Efficiency of control electronics; off-state power consumption; power saved			
4.	5.3		Driver electronics	Develop efficient, long life OLED driver electronics and power converters that efficiently convert line power to acceptable input power of the OLED source(s) and maintain their performance over the life of the fixture. These can include energy-saving functionality such as daylight and occupancy sensors and communication protocols for external lighting control systems.	Conversion efficiency; component lifetime; cost; color maintenance at low light levels			

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	My Priority
4.	**6.0**	**Panel Architecture Product Dev**						
4.	6.1		Large area	Investigate barriers unique to the fabrication of OLED panels (assemblies of devices). Demonstrate a high efficiency OLED panel with good thermal performance, employing low cost designs and materials and with the potential for large scale manufacturing. Demonstrate that the panel reduces conductive (I*R) losses, defect density, or shorting density and increases color and luminance uniformity of light.	Lumen Output; Color; X-step MacAdam Ellipse away from Planckian locus		> 500 lumens	
4.	6.2		Panel packaging	Investigate 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 fields should also be considered. Demonstrate a high-efficiency OLED panel that employs such a packaging design and exhibits improved lifetime.	Light Extraction Efficiency; Panel Operating Lifetime; Panel Shelf Life			
4.	6.3		Panel outcoupling	Demonstrate manufacturable approaches to fabricate OLED panels with improved light extraction efficiency.	Light Extraction Efficiency			
4.	6.4		Panel reliability	Analyze and understand failure mechanisms of OLED panels and demonstrate a packaged OLED panel with significant improvements in lifetime.				
4.	6.5		Mechanical design	Integrate all aspects of OLED based luminaire design: thermal, mechanical, optical, and electrical. The design must be cost effective, energy efficient and reliable.				

OLED Tasks – Technology View

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	1.0	**Materials and Device Architectures**							
3.	1.1		Novel device architectures	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.	EQE; Voltage; L70	36% EQE including light extraction enhancements; L50=20kHrs	EQE 74% for all colors including outcoupling enhancements; 2.8 V; 40 kHrs		
4.	1.1		Practical implementation of materials and device architectures	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.	Efficacy; L70; Lumen Output; CRI; CCT	102 lm/W; L50=20khrs; 70 CRI	> 100 lm/W Efficacy; 70 = 40 kHrs; 50 Lumens; 90 CRI		CRI and CCT metrics are useful only if color point is <0.005 distance away from black-body locus in CIE color space.
3.	1.2		Novel materials	Organic materials or contact materials to increase IQE, reduce voltage and improve device lifetime. Explores novel materials that can be used to emit highly efficient blue light with the ultimate goal of generating highly efficient white light. The materials should be inherently stable against moisture and temperature.	IQE; Voltage; L70; EQE without extraction enhancement; L70 & voltage @ 1mA/cm^22; CCT; CRI	29% EQE; L50=20khrs; 3900K, 70 CRI; 100% IQE	IQE=100% across visilble spectrum; 2.8 V; 40 khrs; blue deep enough that it is capable of generating CCT >2800K	Is 29% EQE too high? What is the headroom for improvement?	CRI and CCT metrics are useful only if color point is <0.005 distance away from black-body locus in CIE color space.
0	1.3		Device Modeling	Developing software simulation tools to model the performance of OLED devices using detailed material characteristics.					
3.	1.4		Material degradation	Understand and evaluate the degradation of materials during device operation.	L70	L50=20 kHrs	50 kHrs		
3.	1.5		Thermal characterization of materials and devices	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.					
4.	1.5		Device failure	Understand the failure modes of an OLED at the device level.	L70	L50=20 kHrs	50 kHrs		

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	2.0	**Substrate and Electrode**							
4.	2.1		Substrate	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.	$/m^2; Water Permeability; Oxygen Permeability	Glass: $4/m2 w/o TCO, no water permeability; Flexible: $100/m2, 10-6 g/m2-day Water Permeability	< $6/m^2 (cost includes substrate plus TCO/equivalent); 10-6 g/m2-day Water Permeability including TCO or equivalent		
3.	2.2		Electrode research	Develop a novel transparent electrode with low resistivity to serve as a lower cost replacement for ITO with the same or better performance. This electrode should be inherently stable against moisture and temperature. Areas of research may include p-type and n-type degenerate electrodes, two-material electrodes, electrodes that reduce current spreading, flexible electrodes, or other low-voltage electrodes.	Ohms/Square; Transparency absorption over the visible spectrum	Non-ITO electrode: 40 Ohms/Square; 75-80% Transparency	Non-ITO electrode: < 10 Ohms/Square; 92% Transparency		
4.	2.2		Low-cost electrodes	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.	Ohms/Square; Transparency absorption over the visible spectrum; $/m^2	Non-ITO electrode: 40 Ohms/Square; 85% Transparency	Non-ITO electrode: < 10 Ohms/Square; 92% Transparency; Cost < $6/m^2	What should an appropriate cost target be?	
	3.0	**Fabrication**							
3.	3.1		Fabrication technology research	Develop new practical techniques for organic materials deposition, device fabrication, or encapsulation. Could also include developing a physical, chemical, or optical model for fabrication of OLED devices.	Capital Cost; Operating Cost; Material Use; Deposition Rate; Uniformity				
4.	3.1		Panel manufacturing technology	Produce an OLED panel using low cost, integrated manufacturing technologies that have a short TAC time and the ability to scale to large areas.	Capital Cost; Material Use; Deposition Rate; Uniformity; Total Actual Cycle Time (TAC)	5 min/m^2	1 min/m^2/capital cost		
4.	3.2		Quality control	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.					

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	4.0	**Luminaire Integration**							
4.	4.1		Light utilization	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.	Useful light output from luminaire/total light generated by OLED panel	90%	95%		
4.	4.1		Luminaire mechanical design	Integrate all aspects of OLED based luminaire design: thermal, mechanical, optical, and electrical into a cost effective, long life, energy saving, and marketable luminaire. All components should be as robust as the OLED.	Efficacy; Lifetime; Cost				
4.	4.2		Thermal	Design integrated thermal management techniques to extract heat from the luminaire in a variety of environments and operating conditions. Thermal management should maintain the OLED source temperature as well as enhance the luminaire color and efficiency performance.	Lifetime; Case Temperature				
3.	4.3		Optimizing system reliability	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.					
4.	4.3		System reliability methods	Develop models, methodology, and experimentation to determine the lifetime of the integrated OLED luminaire and all of the components					
4.	4.3		Electrical interconnects	Develop standard connections for integration of OLED panels into the luminaire.					
	5.0	**Electronic Components**							
4.	5.1		Color maintenance	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.	Color shift over the life of the luminaire and efficiency of control electronics				
4.	5.2		Smart controls	Develop integrated lighting controls and sensors that save energy over the life of the luminaire.	Efficiency of control electronics; off-state power consumption; power saved				
4.	5.3		Driver electronics	Develop efficient, long life OLED driver electronics and power converters that efficiently convert line power to acceptable input power of the OLED source(s) and maintain their performance over the life of the fixture. These can include energy-saving functionality such as daylight and occupancy sensors and communication protocols for external lighting control systems.	Conversion efficiency; component lifetime; cost; color maintenance at low light levels				

C/PD	a.b	Cat.	Subtask	Description	Metric	2008	2015 Target	Discussion Points	Footnotes
	6.0	**Panel Architecture**							
4.	6.1		Large area	Investigate barriers unique to the fabrication of OLED panels (assemblies of devices). Demonstrate a high efficiency OLED panel with good thermal performance, employing low cost designs and materials and with the potential for large scale manufacturing. Demonstrate that the panel reduces conductive (I*R) losses, defect density, or shorting density and increases color and luminance uniformity of light.	Lumen Output; Color; X-step MacAdam Ellipse away from Planckian locus		> 500 lumens		
4.	6.2		Panel packaging	Investigate 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 fields should also be considered. Demonstrate a high-efficiency OLED panel that employs such a packaging design and exhibits improved lifetime.	Light Extraction Efficiency; Panel Operating Lifetime; Panel Shelf Life				
3.	6.3		Light extraction approaches	Devise new optical and panel designs for improving OLED panel light extraction.	Light Extraction Efficiency	40%	76%		
4.	6.3		Panel outcoupling	Demonstrate manufacturable approaches to fabricate OLED panels with improved light extraction efficiency.	Light Extraction Efficiency				
4.	6.4		Panel reliability	Analyze and understand failure mechanisms of OLED panels and demonstrate a packaged OLED panel with significant improvements in lifetime.					
4.	6.5		Mechanical design	Integrate all aspects of OLED based luminaire design: thermal, mechanical, optical, and electrical. The design must be cost effective, energy efficient and reliable.					

OLED Tasks – Planning View

C/PD	a.b	Cat.	Subtask	Metric	2008	Resources('10)	Resources('12)
3.	**1.0**	**Materials and Device Architectures Core**					
3.	1.1		Novel device architectures	EQE; Voltage; L70	38% EQE including light extraction enhancements; L50=20kHrs		
3.	1.2		Novel materials	IQE; Voltage; L70; EQE without extraction enhancement; L70 & voltage @ 1mA/cm^22; CCT; CRI	29% EQE; L50=20khrs; 3900K, 70 CRI; 100% IQE		
3.	1.3		Device Modeling				
3.	1.4		Material degradation	L70	L50=20 kHrs		
3.	1.5		Thermal characterization of materials and devices				
3.	**2.0**	**Substrate and Electrode Core**					
3.	2.2		Electrode research	Ohms/Square; Transparency absorption over the visible spectrum	Non-ITO electrode: 40 Ohms/Square; 75-80% Transparency		
3.	**3.0**	**Fabrication Core**					
3.	3.1		Fabrication technology research	Capital Cost; Operating Cost; Material Use; Deposition Rate; Uniformity			
3.	**4.0**	**Luminaire Integration Core**					
3.	4.3		Optimizing system reliability				
3.	**5.0**	**Electronic Components Core**					
3.	**6.0**	**Panel Architecture Core**					
3.	6.3		Light extraction approaches	Light Extraction Efficiency	40%		

C/PD	a.b	Cat.	Subtask	Metric	2008	Resources('10)	Resources('12)
4.	1.0	**Materials and Device Arch. Product Dev**					
4.	1.1		Practical implementation of materials and device architectures	Efficacy; L70; Lumen Output; CRI; CCT	102 lm/W; L50=20khrs; 70 CRI		
4.	1.5		Device failure	L70	L50=20 kHrs		
4.	2.0	**Substrate and Electrode Product Dev**					
4.	2.1		Substrate	$/m^2; Water Permeability; Oxygen Permeability	Glass: $4/m2 w/o TCO, no water permeability; Flexible: $100/m2, 10-6 g/m2-day Water Permeability		
4.	2.2		Low-cost electrodes	Ohms/Square; Transparency absorption over the visible spectrum; $/m^2	Non-ITO electrode: 40 Ohms/Square; 85% Transparency		
4.	3.0	**Fabrication Product Dev**					
4.	3.1		Panel manufacturing technology	Capital Cost; Material Use; Deposition Rate; Uniformity; Total Actual Cycle Time (TAC)	5 min/m^2		
4.	3.2		Quality control				
4.	4.0	**Luminaire Integration Product Dev**					
4.	4.1		Light utilization	Useful light output from luminaire/total light generated by OLED panel	90%		
4.	4.1		Luminaire mechanical design	Efficacy; Lifetime; Cost			
4.	4.2		Thermal	Lifetime; Case Temperature			
4.	4.3		System reliability methods				
4.	4.3		Electrical interconnects				

C/PD	a.b	Cat.	Subtask	Metric	2008	Resources(*10)	Resources(*12)
4.	**5.0**	**Electronic Components Product Dev**					
4.	5.1		Color maintenance	Color shift over the life of the luminaire and efficiency of control electronics			
4.	5.2		Smart controls	Efficiency of control electronics; off-state power consumption; power saved			
4.	5.3		Driver electronics	Conversion efficiency; component lifetime; cost; color maintenance at low light levels			
4.	**6.0**	**Panel Architecture Product Dev**					
4.	6.1		Large area	Lumen Output; Color; X-step MacAdam Ellipse away from Planckian locus			
4.	6.2		Panel packaging	Light Extraction Efficiency; Panel Operating Lifetime; Panel Shelf Life			
4.	6.3		Panel outcoupling	Light Extraction Efficiency			
4.	6.4		Panel reliability				
4.	6.5		Mechanical design				

Milestone	Year	Milestone Target
Milestone 1	FY08	25 lm/W, < $100/klm, 5,000 hrs
Milestone 2	FY10	> 45 lm/W
Milestone 3	FY12	< $30/klm
Milestone 4	FY15	> 100 lm/W

Assumptions: CRI > 80, CCT < 2700-4100K and luminance = 1,000 cd/m^2, and total output ≥ 500 lumens for an OLED panel. All milestones assume continuing progress in the other overarching parameters - lifetime and cost.

APPENDIX C: Breakout Group Discussions

Appendix C of this report summarizes the discussion in the breakout groups pertaining to the R&D priority subtasks. The discussion summary is organized to be consistent with DOE's R&D portfolio: 1) LED Core Technology, 2) LED Product Development, 3) OLED Core Technology, and 4) OLED Product Development. Under each subtask heading is a summary table including the title and a short description of the subtask, and the proposed metrics, targets, and status coming into the workshop. Following each table is a recap of the group discussion regarding the metrics, status, and priorities. *Note: After receiving input from participants at the SSL workshop, DOE defined new R&D priorities based on the new task structure. The final descriptions and priorities are published in the 2009 MYPP, available for download at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf. In the published version, tasks were renumbered to avoid confusion with the task structure of previous reports. The first digit of each subtask has changed from 1–4 to A–D.*

The subtasks listed below were the main topics of discussion during the breakout groups.

LED Core Technology Subtask List

1.1.1	Alternative substrates
1.1.2	Emitter materials research
1.1.3	Down converters
1.2.1	Light extraction approaches
1.2.2	Novel emitter materials and architectures
1.3.4	Thermal control research
1.4.4	Manufacturing simulation
1.5.1	Optical component materials
1.6.2	Thermal components research
1.6.3	System reliability methods
1.7.4	Driver electronics
1.7.5	Electronics reliability research

LED Product Development Subtask List

2.1.1	Substrate development
2.1.2	Semiconductor materials
2.1.3	Phosphors
2.2.3	Electrical
2.3.1	LED package optics
2.3.2	Encapsulation
2.3.4	Emitter thermal control
2.3.5	Environmental sensitivity
2.3.6	Package architecture
2.4.1	Yield and manufacturability
2.4.2	Epitaxial growth
2.4.3	Manufacturing tools

2.5.1 Light utilization
2.5.2 Color maintenance
2.5.3 Diffusion and beam shaping
2.6.1 Luminaire mechanical design
2.6.2 Thermal
2.6.3 Optimizing system reliability
2.7.1 Color maintenance
2.7.2 Color tuning
2.7.3 Smart controls
2.7.4 Electronics component research

OLED Core Technology Subtask List

3.1.1 Novel device architectures
3.1.2 Novel materials
3.1.3 Modeling
3.1.4 Material degradation
3.1.5 Thermal characteristics of materials and devices
3.2.2 Electrode research
3.3.1 Fabrication technology research
3.4.3 Optimizing system reliability
3.6.3 Light extraction approaches

OLED Product Development Subtask List

4.1.1 Practical implementation of materials and device architectures
4.1.5 Device failure
4.2.1 Substrate
4.2.2 Low-cost electrodes
4.3.1 Panel manufacturing technology
4.3.2 Quality control
4.4.1 Light utilization
4.4.2 Luminaire mechanical design
4.4.3 System reliability methods
4.4.4 Thermal
4.4.5 Electrical interconnects
4.5.1 Color maintenance
4.5.2 Smart controls
4.5.3 Driver electronics
4.6.1 Large area
4.6.2 Panel packaging
4.6.3 Panel outcoupling
4.6.4 Panel reliability
4.6.5 Mechanical design

LED General Discussion

Three groups discussed the LED subtasks. In all groups, there was a large representation from LED luminaire manufacturers followed by researchers and device manufacturers. These groups agreed that the most important subtasks were ones which accelerated the market acceptance of LED products. There was general consensus that the most significant barriers to market acceptance were cost reduction and system reliability, and therefore subtasks related to these two factors were deemed highest priority. Two groups independently came to the same conclusion that the LED chip remains the highest cost component of a luminaire, and therefore research should be focused on subtasks which improve LED chip efficiency. The third group, with a heavy representation from the manufacturing industry, countered that the lack of standardization is the driver of costs, and government research should instead focus on subtasks which promote standardization of components.

The rest of the general conversation focused on mixed topics in the three groups. One group had an extended conversation concerning the DOE's role in research and development. Multiple participants commented on the need for a greater government role in core technology research and a decreased role in product research. One participant supported this sentiment by pointing out that the further along one is on the value chain, the more the end user drives market decisions, and thus the less impact the DOE can have.

A second group discussed the implications of an extended LED lifetime. Based on the fact that LED-related technology has consistently progressed quicker than expected, one member mentioned that the speed of technology development may lead to the rapid obsolescence of products that are designed for high lifetimes (such as 100 kHrs). Thus, such products may not be kept for their entire useful lifetimes, which would potentially negate the investment into increasing product lifetimes. As a counter, other members of the group suggested that a goal of high lifetimes allows developers more flexibility to trade off LED lifetime and other issues such as those related to cost, heat dissipation, and power consumption.

The final group was concerned that the milestones did not focus on the quality of light emitted by the luminaire. For example, although many devices have met milestone 1 (with an efficacy of 80 lm/W and a price of $25/klm), the color of these devices is not suitable (70 CRI). Reliability testing was also considered an important obstacle to achieving market adoption. Improved reliability testing methods would allow organizations to develop more reliable LED luminaires.

<u>LED Core Technology Discussion</u>

Task 1.1: LED Emitter Materials Core Technology

1.1.1 Alternative substrates		
Short Descriptor: *Explore alternative practical substrate materials and growth for high-quality epitaxy so that device quality can be improved.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Performance potential improvement over conventional		

<u>Priority:</u>
One group believed that alternative substrates should be a priority. The group noted that investment in this subtask is a high risk, high reward scenario, precisely the type that the DOE targets. The group concluded that there is a high potential in alternative substrates to positively impact both the cost and efficiency of LEDs. However, participants in another group decided that this subtask should not be prioritized because certain alternative substrates, such as silicon, appear to not be as efficient as existing substrates. On top of this, there were concerns in that group that the necessary funding for this subtask would be too costly.

<u>Metric:</u>
It was determined that IQE improvement is the proper metric for this subtask.

<u>Status:</u>
One group believed that the appropriate status of IQE was 20% for green, 75% for red, and 80% for blue.

1.1.2 Emitter Materials Research		
Short Descriptor: *Focus on the development of efficient green and deep red emitters with low droop and minimal thermal sensitivity and continue improvement in blue LEDs.*		
Metric	**Status (2008)**	**Program Target (2015)**
• IQE across visible spectrum at high current densities	20% green (540nm), 75% red, 80% blue	90% for all colors

<u>Priority:</u>
All three breakout groups discussed subtask 1.1.2. Two groups were in support of emitter materials as a prioritized task and one group was against. The supporters believed that core research into emitter materials would greatly improve the efficiency of the LED device. Several participants noted that the efficiency of green LEDs is lagging and fundamental research is needed before efficient products can be manufactured. One participant noted that the result of making green LEDs more efficient would be a lower cost and a higher efficiency RGB LED system.

<u>Metric:</u>
There was a consensus approval of IQE as the metric for this subtask.

Status:
The groups agreed that the green LED is lacking behind the red and blue LEDs. The DOE proposed status was deemed acceptable.

Target:
The groups agreed that the appropriate target is 90% for red, blue, and green LEDs. One group commented that the gap between the green LED status and its target was quite sizable and would require a large amount of resources.

Resources:
There was a discrepancy between the resources the breakout groups deemed necessary. One group believed this subtask would require an average amount of resources. A second group believed that this subtask would require a large amount of resources.

1.1.3 Down Converters		
Short Descriptor: *High-efficiency wavelength conversion materials for improved quantum yield, optical efficiency, and color stability. Explore novel approaches to conversion.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Quantum Yield	95% at 450 nm	90% across visible spectrum
• Scattering Losses	10%	10%
• Color Stability		

Priority:
Down converters were selected as a high priority by two of the LED groups. One group stressed that improved performance of phosphors would be critical to meeting long-term DOE milestones. This group identified lifetime, color control, and conversion efficiency as the key issues where further research is necessary.

Metric:
A collection of metrics was proposed including:

1. Quantum yield – One group proposed that this metric be referenced to a warm white phosphor mix and a cool white phosphor mix instead of individual wavelengths. A second group believed that a pumped wavelength of 540 nm and a phosphor temperature of 150°C be specified for this metric.
2. Scattering losses – Similar to quantum yield, it was proposed that this metric be referenced to a warm white phosphor mix and a cool white phosphor mix instead of individual wavelengths.
3. Temperature stability – The units for this metric were proposed to be the percentage drop in quantum yield at operating temperature versus ambient temperature.
4. Color stability – The units for this metric were proposed to be $\Delta u^* v^*$ over the lifetime, where u^* and v^* are coordinates in the CIE 1976 (CIELUV) color space.

Status:
Statuses were determined for three of the four proposed metrics. The current quantum yield is 80% for warm white and 95% for cool white. Scattering losses were determined to be 10%, and the current color stability is a Δu^*v^* of 0.012 over the lifetime of the device.

Target:
One group discussed the targets for this subtask. This group believed that the quantum yield target should be 90% for warm white and 95% for cool white and the scattering losses target should be 10%. The group acknowledged that both the cool white target and the scattering losses target have already been met. The group also noted that the temperature stability target should be less than a 10% drop at 150°C for both warm and cool white devices, and the color stability target should be Δu^*v^* of less than 0.007 over the device lifetime.

Resources:
Although multiple targets have already been accomplished, more work needs to be conducted to develop down converters that exhibit high color stability and more efficient warm white down converters. Therefore, both groups agreed that a moderate amount of staff resources would be needed to achieve the program targets for this task.

Task 1.2: LED Device Materials and Architectures Core Technology

1.2.1 Light Extraction Approaches		
Short Descriptor: *Devise improved methods for raising chip level extraction efficiency and LED system optical efficiency. Photonic crystal structures or resonant cavity approaches would be included.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Chip Extraction Efficiency (χ)	16% green (540 nm), 38% red (610 nm), 64% blue	81% for all three colors
• Phosphor Conversion Efficiency	65%	73%

Priority:
This subtask was discussed by all three of the breakout groups. Two groups were in support of light extraction approaches as a prioritized subtask and one group was against. Many participants stressed the importance of the extraction of "useful" light from the whole system instead of just the LED. One participant pointed out that better control of the distribution would lead to significant efficiency gains. The group that did not want to prioritize this subtask believed that chip extraction efficiency is fairly advanced and therefore does not need to be made a research priority. However, several participants in this group stated that additional gains could be made in phosphor conversion efficiency and photonic crystals.

Metric:
The only metric that was discussed thoroughly was chip extraction efficiency. The groups differed on whether this metric would be appropriate. Supporters felt that it was the best method of measuring improvements in light extraction approaches. Critics did not argue this point, but instead suggested that the current levels of chip extraction efficiency were sufficient.

Status:
The consensus was that the chip extraction efficiency had improved greatly. One group believed it had improved to 80% for red, green, and blue. A second group agreed that this is the case for blue and green, however they believed that 55% is the status for red's efficiency.

Target:
An appropriate target was determined to be 90% for red, green, and blue.

Resources:
The groups designated medium resources to complete this subtask.

1.2.2 Novel Emitter Materials and Architectures		
Short Descriptor: *Devise alternative emitter geometries and emission mechanisms in manufacturable configurations that show genuine improvement over existing approaches. (Possible examples: quantum dots, monolithic integrated RGB, 360 degree emitters, etc.)*		
Metric	**Status (2008)**	**Program Target (2015)**
• EQE	64%	81%

Priority:
One of the three groups stated that novel emitter materials and architectures should be a high priority subtask. The group's reasoning behind this decision was that the efficiency of LEDs is key to not only reaching DOE's efficacy milestones but also in reducing the cost of LEDs. For example, LEDs using quantum dots could be more efficient than LEDs using phosphors.

Metric:
The group agreed with the DOE metric.

Status:
The group agreed with the DOE status.

Target:
The group also agreed with the DOE program target.

Resources:
The belief that reaching this target would require a small amount of resources was commonly held within the group.

Task 1.3: LED Device Packaging Core Technology

1.3.4 Thermal Control Research		
Short Descriptor: *Simulation of solutions to thermal management issues at the package or array level. Innovative thermal management solutions.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Thermal Resistance (junction to case)		5°C per watt

Priority:
Multiple participants in one group stated that they would like to hear more DOE discussion and see more DOE funding towards thermal management. One participant explained that "standardization would perhaps give the greatest boost towards increased efficiency; and one of the first steps to standardization is improving thermal management." Ultimately the group with these members believed that this subtask was the single most important subtask. This task was not discussed in the other two groups.

Metric:
Participants agreed with the DOE-given metric of thermal resistance, junction to case.

Status:
There was an agreement that the current status of thermal resistance is about 5°C per watt.

Target:
Because the current status of thermal resistance was determined to be 5°C per watt, participants felt that an appropriate target for 2015 is under 1°C per watt.

Resources:
This was seen as an accomplishable target with a low amount of resources required.

Task 1.5: LED Optical Components Core Technology

1.5.1 Optical Component Materials		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Transmission across visible spectrum		>90% transmission
• Lifetime		

Priority:
Only one of the groups felt that this subtask should be considered high priority. Although this subtask did not have the widespread support of the other subtasks in this group, the majority of those who voted to prioritize this task stated that it was their number one priority. In particular, some members stated that research must be done into how polycarbonate materials, acrylic materials, as well as adhesives degrade due to long-term ultraviolet and near-ultraviolet light exposure from LED emitters.

Metric:
There was general agreement with the DOE-given metrics of transmission across the visible spectrum and lifetime. However, several participants stated that the metric should specify the transmission across 350 nm to 750 nm, assuming a 1 optical watt per mm^2 device. Participants also suggested that lifetime should be in kHrs using L_{70}.

Target:
As for targets, the groups decided that a transmission greater than 90% and an L_{70} of 100kHrs are appropriate.

Resources:
The groups believed that a low amount of resources is required to complete this subtask.

Task 1.6: LED Luminaire Integration Core Technology

1.6.2 Thermal Components Research		
Short Descriptor: *Research and develop novel thermal materials and devices that can be applied to solid state lighting products.*		
Metric	**Status (2008)**	**Program Target (2015)**
• LED source junction temperature maintenance improvement		

Priority:
Two of the LED groups rated this subtask as a high priority. These groups believed that the subject matter required attention but this specific subtask was too general, as there are multiple components where improvements can occur. After discussion, one group decided that it should be up to the researchers to choose their components of interest, as long as their research supports the overall objective of improving luminaire thermal performance. A participant in another group suggested that DOE look at the work NASA has conducted on thermal materials. He went on to note that many of the materials used in space are similar in composition and have similar performance requirements as LED materials.

Metric:
The group that felt researchers should choose their components of interest supports the use of LED source junction temperature maintenance improvement as a metric. They went on to further define this metric by stating that it should be measured as ΔT_j in Kelvin.

Status:
The metric that was chosen is a relative metric based on improvement in junction temperature. This metric requires a baseline value. The baseline was decided to be the 2008 status. Because a multitude of components could be researched, statuses for each were not determined.
Target:
Based on the baseline, an appropriate target for 2015 was determined to be a 25% improvement in $\Delta T_{j.}$

Resources:
A medium amount of staff hours would be acceptable to achieve the 25% improvement in $\Delta T_{j.}$

1.6.3 System Reliability Methods		
Short Descriptor: *Develop models, methodology, and experimentation to determine the lifetime of the integrated SSL luminaire and all of the components. Includes investigation of accelerated testing.*		
Metric	**Status (2008)**	**Program Target (2015)**

Priority:

Two groups decided that this task should be prioritized. One of these groups noted that improving system reliability methods might lead to improved efficiency. Although this sentiment was universally agreed upon, there was concern about how to improve these methods. Participants believed the subtask needed to be defined in a manner which would allow a variety of luminaires to be tested. One group proposed that the subtask focus on identifying the failure mechanisms and researching the physics behind the luminaire failures. A second group suggested looking at the flat-screen television industry, as it has existing system reliability methods that could be modified and applied to LED luminaires.

Metric:

In order to predict an LED system's reliability, a testing model is necessary. The accuracy of that model would then be the metric DOE research would improve. One group defined the accuracy metric as being the ratio of model predicted lifetime to actual lifetime.

Status:

Currently there is no model that measures the system reliability. One participant stated that IES LM-80 contains the only current information on LED lighting system reliability.

Target:

In order for the model to be useful, one group determined that a necessary accuracy target should be 99% at 6,000 hours and 90% at 50,000 hours.

Resources:

All groups which discussed this subtask agreed that a low amount of resources is needed to reach the system reliability methods target.

Task 1.7: LED Electronic Components Core Technology

1.7.4 Driver Electronics		
Short Descriptor: *Develop advanced solid state electronic materials and components that enable higher efficiency and longer lifetime for control and driving of LED light sources.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Driver efficiency	85%	90%
• Lifetime at operating temperature		

Priority:
There were mixed opinions concerning whether this subtask should be prioritized amongst the groups. One group agreed that this is a priority subtask, and in this group there was the consensus opinion that the current status given by the DOE, a driver efficiency of 85%, does not represent marketable products. Another group disagreed. A participant in this group summed up their reasoning by stating “the efficiencies and lifetimes of the driver electronic materials are actually quite good when compared to the other components of the LED device.”

Metric:
The driver efficiency and lifetime at operating temperature were deemed to be the appropriate metrics. More specifically, it was suggested that the metric of plug-to-chip driver efficiency be measured at 120 volt and 6 watts with a 70% power factor correction at the 20% dimming level.

Status:
One group believed that the 2008 statuses of the metrics were as follows: a plug-to-chip driver efficiency of 50% at the 20% dimming level, and a 40kHrs lifetime at operating temperature.

Target:
The 2015 targets agreed upon are 80% driver efficiency at the 20% dimming level, and 100kHrs lifetime at operating temperature.

Resources:
The single group that believed this task was a priority believed that a medium amount of resources would be required to reach the 2015 target. Further discussion resulted in an agreement that any additional gains in driver efficiency above the target would require extensive resources.

LED Product Development Discussion

Task 2.1: LED Emitter Materials Product Development

2.1.2 Semiconductor Materials		
Short Descriptor: *Improve IQE at optimal wavelengths for producing white light across the visible spectrum (red: 610nm; green: 540nm). Improve droop and thermal sensitivity.*		
Metric	**Status (2008)**	**Program Target (2015)**
• IQE across the visible spectrum at high current densities	20% green (540 nm), 75% red (610 nm), 80% blue	90% for all three colors

Priority:
The LED groups brought up the similarity of this subtask with subtask 1.1.2, “Emitter Materials Research,” and recommended that the distinction between the two be emphasized. Most groups believed that since the subtasks’ targets were the same, and since emitter materials for LEDs require significant progress, the DOE should focus on conducting core technology research on this topic. One group recognized the value of the product development aspect of this topic and believed this subtask should be prioritized.

Metric:
The groups agreed with the DOE-given metric.

Status:
One group believed it was important to note that the wavelength for blue light be defined as 455 nanometers. Apart from this addition, the group agreed with the DOE-given status.

Target:
The groups agreed with the DOE-given target.

Resources:
In order to accomplish the target by 2015, one group believed that the most attention and resources should be devoted to it.

2.1.3 Phosphors		
Short Descriptor *Optimize phosphors for LED white light applications, including color uniformity, color maintenance, thermal sensitivity, and stability.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Quantum Yield	95% at 450 nm	90% across visible spectrum
• Scattering Losses	10%	10%
• Color Stability		

Priority:
This subtask was selected as the number one priority by two of the three breakout groups. The participants in these groups valued the fact that the phosphor can not only increase the efficiency of the LED, but improve the color and quality of the LED as well. These improvements lead to reduced costs and increase market adoption of LEDs. One participant noted that color quality is especially important in the retail sector. Some participants warned that it will take extensive time to put new materials into pilot scale production.

Metric:
Two groups thought that the metrics in this task needed clarification. One group suggested that the quantum yield metric be measured at a pumped wavelength of 540nm and a phosphor temperature of 150°C. Another group believed that quantum yield as well as scattering losses should be measured in percentages and be referenced to a warm white phosphor mix and a cool white phosphor mix instead of individual wavelengths. This group also thought it necessary to add temperature stability to the list of metrics. The proposed unit for temperature stability was the percentage drop in quantum efficiency at operating temperature versus ambient temperature. The proposed unit for color stability was Δu^*v^* over the lifetime of a device, where u^* and v^* are coordinates in the CIE1976 (CIELUV) color space.

Status:
Drawing upon their discussion on the proposed metrics, one group selected the quantum yield status to be 80% for warm white phosphor mix and 95% for cool white phosphor mix. This

group determined that scattering losses were currently at 10% and color stability is a Δu^*v^* of 0.012.

Target:
The targets chosen were as follows: quantum yield of 90% for warm white phosphor mix and 95% for cool white phosphor mix, scattering losses of 10%, temperature stability of less than 10% drop at 150°C for cool and warm white devices, and color stability of Δu^*v^* less than 0.007 over the device lifetime. According to the group's discussion concerning the current status, two of these targets have been accomplished – scattering losses and quantum yield for warm white phosphor mix.

Resources:
The breakout groups determined that the Phosphors subtask would require a medium to high amount of resources. One group added that in order to spur innovation, the DOE resources should go to many organizations.

Task 2.3: LED Device Packaging Product Development

2.3.4 Emitter Thermal Control		
Short Descriptor *Demonstrate an LED or LED array that maximizes heat transfer to the package so as to improve chip lifetime and reliability.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Thermal Resistance (junction to case)		5ºC per watt

Priority:
Emitter thermal control is one of two subtasks which all three LED breakout groups believed should be a priority. There was a general agreement that increasing thermal conductivity will increase the device efficacy, its reliability, and the current density. Even with the wide support there was discussion concerning whether a product development subtask is needed to improve thermal resistance. Several participants believed that the completion of the core subtasks, thermal control research and thermal component research, would adequately fix the problem. Other participants believed that the problem of getting the heat from the junction to the case has been solved.

Metric:
The junction to case thermal resistance was the agreed upon metric, however most groups believed this metric needed clarification. Several participants believed DOE should specify that thermal resistance be measured for a single chip because thermal resistance changes depending on whether a chip or full array is being measured. Participants also suggested that DOE specify that thermal resistance be measured for chips in bulk production, so as to avoid measurement of a prototype chip.

Status:
The proposed status of thermal resistance from the three groups ranged from 10°C per watt to 5°C per watt. One group noted that a majority of chips are near the top of that range, while there are a few advanced chips on the market at 5°C per watt.

Target:
Because several chips already have a thermal resistance of 5°C per watt, a more ambitious target was deemed necessary. The groups provided a range of targets from less than 5°C per watt to less than 1°C per watt. One group suggested that the target must be reached with no extra costs.

Resources:
There was a wide range of current statuses and targets discussed amongst the groups. Accordingly, the range of resources needed was equally as wide. The breakout groups touched every part of the spectrum, stating that the resources needed could be low, medium, or high depending on the target pursued.

2.3.6 Package Architecture		
Short Descriptor: *Demonstrate a packaged chip or multi-chip product employing practical, low-cost designs, materials, or methods for improving light outcoupling and removing heat from the chip to produce a product with high total lumen output efficiently.*		
Metric	**Status (2008)**	**Program Target (2015)**

Priority:
Although only one group believed that package architecture be a prioritized subtask, the vast majority of participants in this group were in support of prioritizing this subtask. These participants commented that this was one of the few subtasks where cost concerns of the product were explicitly stated in the descriptor. The dissenters believed that demonstration of a packaged chip product is outside the scope of the DOE’s work, and should be left to manufacturers.

Metric:
Several ideas for a metric were tossed around. The two which received the most support were cost per lumen and the lumens per watt per dollar.

Status:
That status of cost per lumen varies greatly between devices. Participants felt that the best technologies cost approximately 3 cents per lumen.

Target:
A 2015 target of 1 cent per lumen was proposed.

Resources:
Participants agreed that decreasing the cost per lumen by two-thirds would be difficult and require a high amount of resources.

Task 2.4: LED Fabrication Product Development

2.4.2 Epitaxial Growth		
Short Descriptor: *Develop and demonstrate growth reactors capable of growing state of the art LED materials at low-cost and high reproducibility with improved materials use efficiency.*		
Metric	**Status (2008)**	**Program Target (2015)**

Priority:
One of three groups believed this subtask should be prioritized. Participants felt that in order for LEDs to achieve market penetration they must be low cost and reproducible. Other groups disagreed. One participant stated that funding expensive manufacturing techniques (like growth reactor development) would not be wise as those funding dollars could achieve bigger gains in other research areas. Another participant stated that funding improved manufacturing techniques would not help the industry as a whole move forward, as many manufacturers are hesitant to share information on their techniques.

Task 2.5: LED Optical Components Product Development

2.5.1 Light Utilization		
Short Descriptor: *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	**Status (2008)**	**Program Target (2015)**
• Useful light output from the luminaire/total light generated by the LED source	80%	95%

Priority:
One group listed light utilization as a high priority subtask. The impetus for this rating was the belief that increasing the efficiency of the luminaire is a major method of lowering the cost of the luminaire. This group also felt that this subtask should be combined with subtask 2.5.3, Diffusion and Beam Shaping, and added that the description should then address the issue of uniformity in light output.

Metric:
Many participants felt that the pattern of the beam should be specified in the metric. For example, a narrow beam pattern often results in more fixture losses than a wider beam pattern. Uniformity was also discussed as a key metric. One participant noted that the DOE ENERGY STAR had developed a metric for uniformity that could be adopted for this task. Another participant added that uniformity could be described as a certain minimum/maximum ratio within the beam angle.

Status:
Participants felt that 80% was the appropriate current status for fixture useful light output to total light generated by the LED source. The group decided that current fixture efficiencies were as follows: 80% at wide distribution, 50% at medium distribution, and 30% at narrow distribution.

Target:
Participants felt that the DOE-given target of 95% for fixture efficiency was unrealistic for many luminaires, as LED luminaires must mix light with different colors to achieve uniform light output. This target, 95% fixture efficiency, was believed to be appropriate only for a subset of simple luminaires. Finally, the participants settled on the following targets based on the three categories of beam distribution: 95% at wide distribution, 75% at medium distribution, and 60% at narrow distribution.

Resources:
The group believed that accomplishing the targets would require a high amount of resources.

Task 2.6: LED Luminaire Integration Product Development

2.6.2 Thermal		
Short Descriptor: *Design integrated thermal management techniques to protect the LED source, maintain the luminaire efficiency and color quality, and be low cost.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Junction temperature in steady state operation		

Priority:
The thermal subtask received a priority rank from all three LED breakout groups. Increasing the thermal conductivity was seen as a necessary task in order to increase the device efficacy and reliability. There was also the feeling that to date this subtask has not been adequately explored by researchers, and thus the potential gains are large.

Participants discussed the numerous challenges associated with this subtask, which include:

1. Scope of subtask is extensive, as the temperature performance of all components in a luminaire needs to be addressed.
2. Efficiencies need to be maintained at high temperatures.
3. Research for this subtask could border on sensitive intellectual properties issues.
4. Research findings could be product design specific, and may not be applicable to different designs.

Metric:
The groups debated the proper metric for the thermal subtask. Two of the groups settled on the junction temperature in steady state operation. This metric was chosen because it is easy to measure and because it is also used in the Illuminating Engineering Society's LM-80. The third group discussed using thermal resistance, junction temperature, and in-situ measurements but ultimately dismissed these metrics because they were believed to be either hard to measure or not

meaningful. The group ultimately decided that the percentage lumen loss per degree ambient temperature over package device utilized (LLPD) would be an appropriate metric.

Status:
For junction temperature, the groups selected a current status of 90°C at 25 kHrs. A wide range of LLPDs are believed to be on the market currently. One participant guessed the average value to be around 50%.

Target:
There were two proposed junction temperature targets. The first was a specific target selected as 200°C at 25 kHrs. The second was a floating target. This target calls for research to simply continue to minimize the difference between thermal junction and ambient temperature.

Concerning the LLPD metric, participants felt that limiting the reduction of lumen output due to thermal effects as compared to the packaged device to 10% would indicate that the luminaire sufficiently dissipated the heat away from the LED device.

Resources:
Determining the amount of resources needed to accomplish this subtask was difficult for the breakout groups. Not only do different targets result in different resources needed, but the components which most need improvement are unknown. Based on the junction temperature targets, the groups believed a medium to high amount of resources was necessary.

2.6.3 Optimizing System Reliability		
Short Descriptor: *Optimize and verify overall luminaire reliability. Includes system reliability analysis to determine failure mechanisms and improve.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Mean time to failure (either catastrophic or lumen depreciation below 70%)		40 kHrs

Priority:
There was much discussion in the groups concerning whether this subtask should be prioritized. Participants almost unanimously agreed that improving the reliability of LED systems was important. Points were made that most customers care about how long the LED luminaires will last and that the failure to solve the problem of system reliability could derail the industry. However, multiple participants believed that the system reliability subtask should not be a high priority, as effective solutions vary significantly amongst applications and each manufacturer should devote their own resources to conducting this research. In the end, two of the three breakout groups listed this as a high priority subtask.

Metric:
Two groups accepted the DOE-given metric or mean time to failure. The definition of failure was set at L_{70}. One group debated whether or not other metrics, such as a metric related to color

shift, should be added, but dismissed these alternate metrics as lesser representations of systems reliability.

Status:
The groups believed that the current status was between 40kHrs and 50kHrs.

Target:
The groups agreed that an appropriate target for mean time to failure should be 100kHrs. Several participants brought up an alternate target of maintaining the mean time to failure at 50kHrs, but increasing the performance from L_{70} to L_{85}.

Resources:
A medium amount of resources was deemed necessary to reach the lifetime target.

Task 2.7: LED Electronics Components Product Development

2.7.3 Smart Controls		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Efficiency of control electronics		
• Off-state power consumption		
• Power saved		

Priority:
There was one group that believed research on smart controls required federal funding, as this group was predominantly composed of members of the luminaire manufacturing sector. These participants went on to claim there is also a need to resolve issues of compatibility and standards for smart controls and perhaps these issues should be added to the subtask's description. The other groups believed that lighting controls products should not receive funding, as the market for this technology is not currently developed. Participants in these groups added that progressive manufacturers and entrepreneurs will work on this task without DOE funding.

Metric:
The metrics selected for this subtask were plug-to-chip efficiency, off-state power consumption, and power saved versus a specific baseline. The plug-to-chip efficiency should be based on a 6 watt driver with 70% power factor correction.

Status:
It was decided that the current status of plug-to-chip efficiency is 50% at the 20% dimming level. The groups were unable to determine current statuses of the other proposed metrics.

Target:
An appropriate target for plug-to-chip efficiency was determined to be 80% at the 20% dimming level.

Resources:
A low amount of resources was determined necessary to accomplish the smart controls target.

2.7.4 Electronics Components Research		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Driver efficiency	85%	90%
• Lifetime at operating temperature		
• Cost		

Priority:
Two groups believed the electronics components research subtask to be a priority. These groups believed it would be less expensive and easier to raise the efficiency of the LED driver than to raise the efficiency of the LED device. There was limited concern that increasing the lifetime of LED luminaires would be futile as the lights would become obsolete prior to failure due to technology advances.

Metric:
The three DOE-given metrics were deemed appropriate. However, one group noted that plug-to-chip driver efficiency should be measured at 120 volts and 25 watts. One group stressed the necessity of a driver being able to operate LEDs regardless of drive current requirements. In order to do so, standardization of components is needed in the long term and additional flexibility is needed in the short term. Because of this, flexibility was added as a metric.

Status:
A range for plug-to-chip driver efficiency of 70% to 85% was proposed by the groups. One participant stated that a range is necessary, as the efficiency depends heavily on the drive current and voltage requirements of the LED.

Target:
A range of 90% to 95% was proposed for the plug-to-chip driver efficiency target. A range of 50kHrs to 100kHrs was proposed for the lifetime target. A cost target was not determined.

Resources:
According to the groups, accomplishing the electronics components research subtask's targets would require the greatest amount of resources.

OLED General Discussion

The participants in the OLED group were primarily university or national laboratory researchers with just a few participants who represented manufacturers. Over the course of the breakout sessions there were several discussions that occurred. One discussion regarded whether the ultimate OLED product will be based on a larger area at low brightness device or small area at high brightness device. Most participants supported the former but acknowledged that research is important for both avenues. Another discussion regarded the somewhat low support for the luminaire-related product development tasks. While these subtasks initially received nearly zero support, when a proposal was made to group these subtasks into one subtask—"Design a Manufacturable OLED Luminaire with 500 Lumens"—there was significant support.

OLED Core Technology Discussion

Task 3.1: OLED Materials and Device Architectures Core Technology

3.1.1 Novel Device Architectures		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**
• EQE	40% EQE including light extraction enhancements	EQE 76% for all colors including outcoupling enhancements
• Voltage		2.8 V
• Lumen depreciation lifetime	L_{50}=20khrs	L_{70}=40 kHrs

Priority:
After discussion concerning the description of this subtask, the OLED breakout group decided that novel device architectures needed to be a high priority of the DOE. There was concern that the scope of the subtask was too broad, but in the end participants felt this was appropriate for a core technology subtask.

Metric:
The OLED breakout group, in general, felt that EQE, voltage, and L_{70} were the appropriate metrics. One participant commented that the lighting industry more often uses L_{80} or L_{85} and DOE should consider changing the metric in the future.

Status:
The group agreed with the DOE-given statuses for EQE and lumen depreciation lifetime. No status was established for the voltage metric.

Target:
The group agreed with the DOE-given targets for EQE and lumen depreciation lifetime. Because the voltage of the device is highly dependent on the device structure and materials, the group felt that the voltage target should be modified to read "close to bandgap."

3.1.2 Novel Materials		
Short Descriptor: *Organic materials or contact materials to increase IQE, reduce voltage and improve device lifetime. Explores novel materials that can be used to emit highly efficient blue light with the ultimate goal of generating highly efficient white light. The materials should be inherently stable against moisture and temperature.*		
Metric	**Status (2008)**	**Program Target (2015)**
• IQE		IQE=100% across visible spectrum
• Voltage		2.8 V
• Lumen depreciation lifetime	L_{50}=20kHrs	L_{70}=40 kHrs
• EQE without extraction enhancement	29%	blue deep enough that it is capable of generating CCT >2800K
• L_{70} & voltage @ 1mA/cm2		
• CCT	3900K	
• CRI	70 CRI	

Priority:
This subtask received the greatest support for the core technology subtasks. However, several recommendations were made to modify the descriptor. The OLED breakout group felt that the descriptor should more clearly indicate that the ultimate goal of the subtask is to achieve highly efficient white light. The current descriptor focuses on blue light as the only path towards accomplishing this goal; instead it should allow for research in alternate paths. In addition, the group felt that the last sentence of the descriptor, "The materials should be inherently stable against moisture and temperature," overlapped with subtask 3.1.5, Thermal Characteristics of Materials and Devices, and should be removed. Finally, there were several members who emphasized that the major barrier associated with this task is developing materials that have the potential for large-scale, low-cost production and processing.

Metric:
The OLED group felt that the metrics should be limited to voltage, lumen depreciation lifetime, and EQE without extraction enhancement. They believed IQE should be eliminated as it is not a directly measurable quantity. There was concern that all the metrics were not applicable to all materials that may be investigated under this subtask.

Status:
The group did not establish statuses for this subtask. They felt that the ongoing lack of standardized testing for OLEDs has led to highly suspect numbers for given statuses. In terms of efficiency, all the milestones have already been met if the academic literature is to be believed. However, these devices often have extremely short operating lifetimes. The group therefore found itself unable to define a consistent set of values that they felt were representative of the current status.

Target:
The OLED breakout group believed that the target for EQE without extraction should be 20–30% across the visible spectrum. Similar to the novel device architectures subtask, the group agreed that the voltage target should be changed to “close to bandgap.” The OLED group felt that the lifetime target of L_{70} of 40 kHrs was appropriate. There was some disagreement over the importance of a deep blue, since that is only required for a cool white lamp, which is generally acknowledged to be undesirable for most commercial applications.

3.1.3 Modeling		
Short Descriptor: *Developing software simulation tools to model the performance of OLED devices using detailed material characteristics.*		
Metric	**Status (2008)**	**Program Target (2015)**

Priority:
This subtask received no support, as it was believed to be encompassed by subtask 3.1.1, Novel Device Architectures.

3.1.4 Material Degradation		
Short Descriptor: *Understand and evaluate the degradation of materials during device operation.*		
Metric	**Status (2008)**	**Program Target (2015)**
• L_{70}	L_{50} = 20 kHrs	L_{70} = 50 kHrs

Priority:
While there was a large amount of support for this subtask, and general agreement that it should be prioritized, the OLED group ultimately neglected Material Degradation due to inability to determine an appropriate metric. The group agreed that there is a critical need for research in this area and it should be a priority of the basic science program.

3.1.5 Thermal Characterization of Materials and Devices		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**

Priority:
Participants in the OLED group felt that this subtask overlapped with subtask 3.1.2, Novel Materials, and therefore “thermally insensitive materials” should be eliminated from the descriptor. In addition, some participants felt that thermal management is more related to the luminaire rather than the device. However, others argued that thermal management of the device may become important as OLEDs get very large.

Task 3.2: OLED Substrate and Electrode Core Technology

3.2.2 Electrode Research		
Short Descriptor: *Develop a novel transparent electrode with low resistivity to serve as a lower cost replacement for ITO with the same or better performance. This electrode should be inherently stable against moisture and temperature. Areas of research may include p-type and n-type degenerate electrodes, two material electrodes, electrodes that reduce current spreading, flexible electrodes, or other low-voltage electrodes.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Ohms/square	75 Ohms/square	< 10 Ohms/square
• Transparency absorption over the visible spectrum	85% Transparency	92% Transparency

Priority:
This subtask received a large amount of support from the OLED group. The group suggested that the last sentence of the subtask descriptor should be modified to read, “Areas of research may include p-type and n-type degenerate electrodes, two-material electrodes, electrodes that reduce IR loss, and flexible electrodes.”

Metric:
The OLED group believed that ohms per square is the appropriate metric. However, they believed that “transparency over the visible spectrum” should be changed to “absorption over the visible spectrum.” There was also considerable discussion around whether roughness should be included as a metric. In the end the group decided that it should not be included since there was difficulty determining how to measure roughness, as it is highly dependent on the device in which you incorporate the electrode. In addition there was discussion regarding whether efficiency and voltage should be included as metrics. These metrics were seen as being true indicators of how well the electrode is operating in the device. However, they were left out

because some participants believed that forcing researchers to incorporate their electrodes into devices may impede research under this subtask.

Status:
The OLED group believed that the status should reflect the performance of ITO at 10 ohms per square and absorption over the visible spectrum of less than 1%.

Target:
The target, like the status, should reflect the current performance of ITO.

Task 3.3: OLED Fabrication Core Technology

3.3.1 Fabrication Technology Research		
Short Descriptor: *Develop new practical techniques for organic materials deposition, device fabrication, or encapsulation. Could also include developing a physical, chemical or optical model for fabrication of OLED devices.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Capital cost		
• Operating cost		
• Material use		
• Deposition rate		
• Uniformity		

Priority:
While initial polling resulted in this subtask receiving a large amount of support, during subsequent discussion some participants questioned whether there were really any new fabrication methods to be developed. Others emphasized the importance of developing new fabrication methods that allow for lower cost production. The group ultimately agreed that the descriptor should include the phrase “Shows the potential for scalability and lowering costs.” In addition, the OLED group agreed that it was unnecessary to address modeling in the descriptor.

Metric:
The OLED group believed that the only appropriate metrics were material use and uniformity. They felt that capital cost and operating cost were metrics that were more applicable to product development tasks. Also, though some members were in favor of using a metric similar to deposition rate or throughput, many felt that it may be too difficult to determine such a metric in a core technology research project.

Status:
The OLED group believed the current status of fabrication technology was less than 5% material utilization and a uniformity of less than 5% over the device area.

Target:
For targets, the OLED group chose a material utilization of greater than 50% and a uniformity of less than 10% variation over a six inch square.

OLED Product Development Discussion

Task 4.1: OLED Materials and Device Architecture Product Development

4.1.1 Practical Implementation of Materials and Device Architectures		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Efficacy	102 lm/W	> 100 lm/W
• L_{70}	L_{50} = 20 kHrs	L_{70} = 40 kHrs
• Lumen Output		50 lumens
• CRI	70 CRI	90 CRI
• CCT		

Priority:
This subtask did not receive widespread support on initial polling. There was also confusion regarding the descriptor. Participants did not feel that “pixel-sized” was appropriate for this subtask and recommended it be deleted. They argued that the 50 lumen requirement was more important.

Task 4.2: OLED Substrate and Electrode Product Development

4.2.1 Substrate		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Cost per m^2	Glass: $4/m^2 w/o TCO Flexible: $100/m^2	< $6/m^2 (cost includes substrate plus TCO equivalent)
• Water Permeability	Glass: no water permeability Flexible: 10-6 g/m^2-day water permeability	10-6 g/m^2-day water permeability including TCO or equivalent
• Oxygen Permeability		

Priority:
This subtask received significant support as a high priority among initial polling. Further discussion resulted in most participants believing that the real barriers regarding substrates only exist in developing flexible substrates. They noted that OLEDs can be fabricated on residential soda-lime glass, which is already a fairly low cost. Therefore, the group agreed that this task should focus on flexible substrates with the potential for roll-to-roll processing.

Metric:
The OLED group agreed with the established metrics.

Status:
Statuses of the metrics were not established.

Target:
Participants felt that the targets should be a cost of less than $4 per m^2 and a water permeability of less than 10-6 g per m^2-day.

4.2.2 Low-Cost Electrodes		
Short Descriptor: *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.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Ohms/square	Non-ITO electrode: 75 Ohms/square	Better that ITO: < 10 Ohms/square
• Transparency absorption over the visible spectrum	85% Transparency	92% Transparency
• Cost per m^2		<$6/m^2$

Priority:
This task received a large amount of support as a high priority. Participants emphasized that scalability and low cost were the most important factors in this task. Therefore, they recommended renaming the subtask to "Scalable Low-Cost Electrodes." Some participants emphasized that stability of the electrode was important not only in operation but also during processing.

Metric:
The OLED group generally agreed with the established metrics. However, they did suggest deleting transparency as a metric. They also discussed adding a volume attribute to the cost metric.

Status:
The OLED group believed that the status of this task should reflect the cost and performance of ITO. They therefore established the status as 10 ohms per square, less than 1% absorption, and a cost of $100 per m^2.

Target:
Participants felt that the targets should be less than 10 ohms per square, less than 1% absorption over the visible spectrum, and a cost less than $20 per m^2 scalable to 30,000 m^2 per month.

Task 4.3: OLED Fabrication Product Development

4.3.1 Panel Manufacturing Technology		
Short Descriptor: *Produce an OLED panel using low-cost, integrated manufacturing technologies that have a short TAC time and the ability to scale to large areas.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Capital cost		
• Material use		
• Deposition rate	5 minute / m^2	1 minute / m^2
• Uniformity		
• Total Actual Cycle Time (TAC)		

Priority:
The OLED group was in consensus that this subtask should be the DOE's high priority. Some participants felt that the capital cost of manufacturing equipment has prevented an OLED product from being released in the marketplace. Others indicated that operational costs were also important and getting the production up to a large scale was a significant barrier. Ultimately, the group decided that a cost analysis should be required as part of this subtask. They also recommended that the descriptor be modified to emphasize that the manufacturing technology does not yet exist.

Metric:
Participants felt that the most appropriate metrics would be cost per klm and klm per month. This would allow for several approaches to OLED structures, such as large and dim OLEDs or small and bright OLEDs.

Status:
The OLED group did not assign a status to this subtask, as they believed there is no technology that currently exists that can be used to manufacture OLEDs on a large scale.

Target:
The OLED group felt that $20 per klm and 100,000 klm per month were appropriate targets for this task. However, one participant did feel that the cost target was unattainable. This participant felt that instead of a cost target based on an OLED lamp replacement, the cost target should be based on the luminaire replacement.

Task 4.5: OLED Electronic Components Product Development

4.5.3 Driver Electronics		
Short Descriptor: *Develop efficient, long life OLED driver electronics and power converters that efficiently convert line power to acceptable input power of the OLED source(s) and maintain their performance over the life of the fixture. These can include energy-saving functionality such as daylight and occupancy sensors and communication protocols for external lighting control systems.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Conversion efficiency		
• Component lifetime		
• Cost		
• Color maintenance at low light levels		

<u>Priority:</u>
The OLED group did not believe that this subtask needed to be prioritized at this time. Participants felt that because it is difficult to predict what an OLED product would look like, it is premature to prioritize the driver.

Task 4.6: OLED Panel Architecture Product Development

4.6.1 Large Area		
Short Descriptor: *Investigate barriers unique to the fabrication of OLED panels (assemblies of devices). Demonstrate a high-efficiency OLED panel with good thermal performance, employing low-cost designs and materials and with the potential for large scale manufacturing. Demonstrate that the panel reduces conductive (I*R) losses, defect density, or shorting density and increases color and luminance uniformity of light.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Lumen Output		> 500 lumens
• Color		
• X-step MacAdam Ellipse away from Planckian locus		

<u>Priority:</u>
This subtask received significant support upon initial polling. However, upon further discussion the OLED group felt that many of the barriers associated with large area panels had to do with the manufacturing. The group felt that this subtask was actually subsumed by subtask 3.3.1,

Fabrication Technology Research, and did not believe that this subtask needed to be prioritized at this time.

4.6.2 Panel Packaging		
Short Descriptor: *Investigate 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 fields should also be considered. Demonstrate a high-efficiency OLED panel that employs such a packaging design and exhibits improved lifetime.*		
Metric	**Status (2008)**	**Program Target (2015)**
• Light extraction efficiency		
• Panel operating lifetime		
• Panel shelf life		

Priority:
This subtask received support for being a high priority task. Some participants questioned whether this subtask would be more appropriate in the core technology section. Therefore the OLED group recommended including in the descriptor that research should go to “scaling up known packaging solutions.”

Metric:
Participants felt that the metrics of this subtask should be cost per m^2, water and oxygen permeability, and shelf life.

Status:
The OLED group did not assign a status to this subtask, as they believed that there is no scaled packaging technology that currently exists.

Target:
The OLED group felt that the targets should be less than \$4 per m^2 for cost, 10-6g/m^2-day for permeability, and greater than 10 years for shelf life.

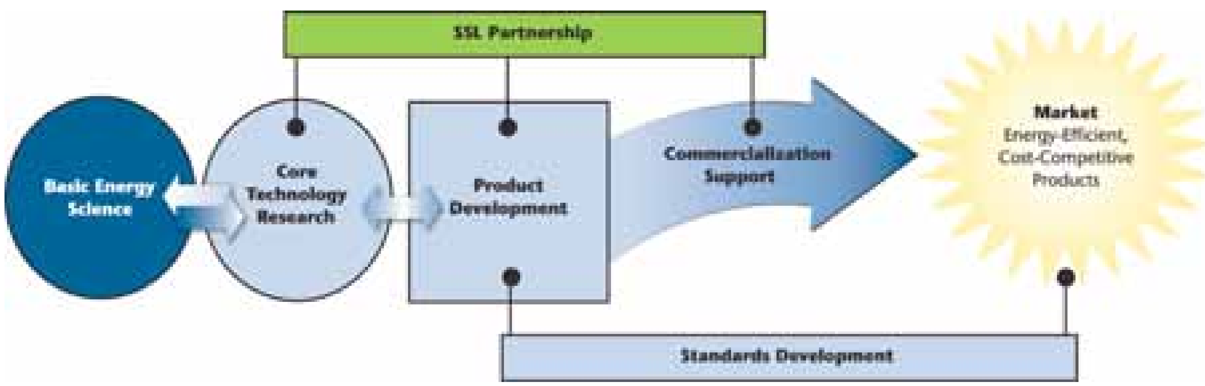
APPENDIX D: DOE SSL Program Fact Sheets

Guiding Technology Advances from Laboratory to Marketplace

The U.S. Department of Energy's solid-state lighting (SSL) portfolio draws on the Department's long-term relationships with the SSL industry and research community to guide SSL technology from laboratory to marketplace. DOE's comprehensive approach includes Basic Energy Science, Core Technology Research, Product Development, Commercialization Support, an SSL Partnership, and Standards Development.

Basic Research Advances Fundamental Understanding. Projects conducted by the Basic Energy Sciences program focus on basic scientific questions that underlie DOE mission needs. These projects target principles of physics, chemistry, and the materials sciences, including knowledge of electronic and optical processes that enable development of new synthesis techniques and novel materials.www.science.doe.gov/bes

DOE SOLID-STATE LIGHTING PORTFOLIO



- DOE's **Basic Energy Sciences** program conducts basic research to advance fundamental understanding of materials behavior. Project results often have multiple applications, including SSL.
- **Core Technology Research** projects focus on applied research for technology development, with particular emphasis on meeting efficiency, performance, and cost targets.
- **Product Development** projects focus on using the knowledge gained from basic or applied research to develop or improve commercially viable materials, devices, or systems.
- To ensure that these investments lead to SSL technology commercialization, DOE has drawn on its ongoing relationships with the SSL industry and research community to develop appropriate **Commercialization Support** strategies.
- The **SSL Partnership** provides input to enhance the manufacturing and commercialization focus of DOE's SSL portfolio.
- In addition, DOE is working with the National Electrical Manufacturers Association (NEMA), the Next Generation Lighting Industry Alliance (NGLIA), and other standards-setting organizations to accelerate the **Standards Development** process.

Core Technology Research Fills Knowledge Gaps. Conducted primarily by academia, national laboratories, and research institutions, Core Technology Research involves scientific research efforts to seek more comprehensive knowledge or understanding about a subject. These projects fill technology gaps, provide enabling knowledge or data, and represent a significant advance in our knowledge base. They focus on applied research for technology development, with particular emphasis on meeting technical targets for performance and cost. www.netl.doe.gov/ssl/project.html

Product Development Utilizes Knowledge Gains. Conducted primarily by industry, Product Development is the systematic use of knowledge gained from basic or applied research to develop or improve commercially viable materials, devices, or systems. Technical activities focus on a targeted market application with fully defined price, efficacy, and other performance parameters necessary for the success of the proposed product. Project activities range from product concept modeling through development of test models and field-ready prototypes. www.netl.doe.gov/ssl/project.html

Commercialization Support Activities Facilitate Market Readiness. To ensure that DOE investments in Core Technology Research and Product Development lead to SSL technology commercialization, DOE has also developed a national strategy to guide market introduction of SSL for general illumination (www.netl.doe.gov/ssl/comm_support.html). Working with the SSL Partnership and other industry and energy organizations, DOE is implementing a full range of activities, including:

- Testing of commercially available SSL products for general illumination.
- Technology demonstrations showcasing high-performance products in commercial and residential applications and providing real-world experience and data on performance and cost effectiveness.
- Technology procurement programs that encourage manufacturers to bring high-quality, energy-efficient SSL products to the market, and that link these products to volume buyers.
- ENERGY STAR® designation for SSL technologies and products.
- Design competitions for lighting fixtures and systems using SSL.
- Technical information resources on SSL technology issues, test procedures, and standards.
- Coordination with utility, regional, and national market-transformation programs.

SSL Partnership Provides Manufacturing and Commercialization Focus. Supporting the DOE SSL portfolio is the SSL Partnership between DOE and NGLIA, an alliance of for-profit lighting manufac-turers. DOE's Memorandum of Agreement with NGLIA, signed in 2005, details a strategy to enhance the manufacturing and commercialization focus of the DOE portfolio by utilizing the expertise of this organization of SSL manufacturers. www.nglia.org

The SSL Partnership (www.netl.doe.gov/ssl/partnership.html) provides input to shape DOE R&D priorities, and accelerates implementation of SSL technologies by:

- Communicating SSL program accomplishments.
- Encouraging development of metrics, codes, and standards.
- Promoting demonstration of SSL technologies for general lighting applications.
- Supporting DOE voluntary market-oriented programs.

Standards Development Enables Meaningful Performance Measurement. LEDs differ significantly from traditional light sources, and new test procedures and industry standards are needed to measure their performance. DOE provides national leadership and support for this effort, working closely with the Illuminating Engineering Society of North America (IESNA), NEMA, NGLIA, the American National Standards Institute (ANSI), and other standards-setting organizations to accelerate the standards development process, facilitate ongoing collaboration, and offer technical assistance. New national standards and rating systems for SSL products began taking effect in 2008. www.netl.doe.gov/ssl/standards_dev.html

Operational Plan for DOE Solid-State Lighting Research and Development

The U.S. Department of Energy (DOE) supports domestic research, development, demonstration, and commercial application of advanced solid-state lighting (SSL) technologies that are significantly more energy efficient than current lighting technologies. Guided by a Government-industry partnership, the mission is to create a new U.S.-led market for high efficiency, general illumination products through the advancement of semiconductor technologies—to save energy, reduce costs, and enhance the quality of the lighted environment. DOE has set aggressive targets for SSL research and development (R&D): By 2025, develop advanced SSL technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost competitive. DOE is targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum.

DOE has structured an operational plan for SSL R&D (Figure 1) that features two concurrent, interactive pathways. **Core Technology Research** is conducted primarily by academia, national laboratories, and research institutions. **Product Development** is conducted primarily by industry. Although the pathways and participants described here are typical, some crossover does occur. For example, a product develop-ment project may include focused, short-term applied research, as long as its relevance to a specific product is clearly identified and the industry organization abides by the solicitation provisions. For more details about the SSL R&D pathways, see DOE's SSL website at www.netl.doe.gov/ssl/project.html. The operational structure also includes innovative intellectual property provisions and an SSL Partnership that provides significant input to shape Core Technology Research and Product Development priorities.

OPERATIONAL PLAN FOR SSL R&D (Figure 1)

This document provides an overview of the high-level structure of the DOE SSL R&D program. More detailed program documents, such as annual solicitations and cooperative agreements, take precedence over information in this document.

SSL Partnership. In 2004, DOE competitively selected an SSL Partnership composed of manufacturers and allies that are individually or collaboratively capable of manufacturing and marketing the desired SSL products. Members must comply with pertinent DOE guidelines on U.S.-based research and product development. One key function of the SSL Partnership is to provide input to shape Core Technology Research and Product Development priorities. As SSL technologies mature, identified research gaps are filled through Core Technology Research — allowing the SSL industry to continue the product develop-ment process, while much-needed breakthrough technologies are created in parallel. Partnership members confer among themselves and communicate technical guidance to DOE program managers, who in turn use this feedback and input from DOE workshop participants to shape DOE SSL R&D solicitations.

Core Technology Research. Core Technology Research provides the focused research needed to advance SSL technology — research that is typically longer-term in nature and not the focus of sustained industry investment. DOE funds these research efforts primarily at universities, national laboratories, and other research institutions through one or more competitive solicitations. Core Technology Research supports the SSL program by providing problem-solving research to overcome technical barriers. Participants in the Core Technology Research program perform work subject to what is termed an "exceptional circumstance" to the Bayh-Dole Act, and any resultant intellectual property is open, with negotiated royalties, to all Partnership members with a non-exclusive license. Core Technology Research projects are subject to peer review by DOE.

Product Development. DOE solicits proposals from interested companies (or teams of companies) for product development, demonstrations, and market conditioning. DOE expects these proposals to include comprehensive work plans to develop a specific SSL product or product family. Since the ultimate goal is to manufacture energy-efficient, high-performance SSL products, each work plan should address the abilities of each participant or manufacturer throughout the development process. These offerors must not only have all the technical requirements to develop the desired SSL technology, but must also have reasonable access to manufacturing capabilities (substantially in the U.S.) and targeted markets identified to quickly move their SSL product from the industry laboratory to the marketplace. Product Development projects are subject to peer review by DOE.

Timeline. Figure 2 details the high-level timeline for the SSL R&D operational plan. Each year, DOE expects to issue at least three competitive solicitations: Core Technology Research, Core Technology Research Call to DOE/Federal Laboratories, and SSL Product Development. A number of annual meetings are held to provide regular DOE management and review checks, and to keep all interested parties adequately informed. More specifically, they:

- Provide a general review of progress on the individual projects (open meeting).
- Review/update the R&D plan for upcoming "statement of needs" in future solicitations (open meeting).
- Provide a peer review of DOE SSL R&D projects, at DOE's discretion.
- Provide individual project reviews by DOE.

R&D OPERATIONAL PLAN PROCESS (Figure 2)

Solid-State Lighting Patents Resulting from DOE-Funded Projects

As of December 2008, 22 solid-state lighting (SSL) patents have been awarded to research projects funded by the U.S. Department of Energy (DOE). This achievement demonstrates the value of DOE SSL projects to private companies and indicates notable progress toward commercialization. Since December 2000, when DOE began funding SSL research projects, a total of 90 patent applications have been sub-mitted, ranging from large businesses (44) and small businesses (16) to universities (26) and national laboratories (4). The table below provides specific patent information.

Primary Research Organization	Title and/or Number of Patent Applications (Titles in bold indicate patents that were granted.)
Agiltron, Inc.	Two patent applications filed.
Boston University	Formation of Textured III-Nitride Templates for the Fabrication of Efficient Optical Devices Formation of Textured III-Nitride Templates for the Fabrication of Efficient Optical Devices Nitride LEDs Based on Flat and Wrinkled Quantum Wells Optical Devices Featuring Textured Semiconductor Layers
Cree, Inc.	**Light Emitting Diode with Porous SiC Substrate and Method for Fabricating** Light Emitting Diode with High Aspect Ratio Sub-Micron Roughness for Light Extraction and Methods of Forming Light emitting diode with high aspect ratio submicron roughness for light extraction and methods of forming Light emitting diode package element with internal meniscus for bubble free lens placement One other patent application filed.
Dow Corning	Four patent applications filed.
Eastman Kodak	**Ex-Situ Doped Semiconductor Transport Layer** Doped Nanoparticle-Based Semiconductor Junction Three other patent applications filed.
Fairfield Crystal Technology	Method and Apparatus for Aluminum Nitride Monocrystal Boule Growth
GE Global Research	**Light-Emitting Device with Organic Electroluminescent Material and Photoluminescent Materials** **Luminaire for Light Extraction from a Flat Light Source** **Mechanically Flexible Organic Electroluminescent Device with Directional Light Emission** **Organic Electroluminescent Devices and Method for Improving Energy Efficiency and Optical Stability Thereof** **Series Connected OLED Structure and Fabrication Method** **Organic Electroluminescent Devices having Improved Light Extraction** **Electrodes Mitigating Effects of Defects in Organic Electronic Devices** Hybrid Electroluminescent Devices OLED Area Illumination Source Eight other patent applications filed.
Georgia Tech	One patent application filed.

Research Corporation	
International Technology Exchange	One patent application filed.
Light Prescriptions Innovators	**Optical Manifold for Light-Emitting Diodes** **Optical Manifold for Light-Emitting Diodes** Two other patent applications filed.
Maxdem Incorporated	Polymer Matrix Electroluminescent Materials and Devices
Nanosys	Nanocrystal Doped Matrices
OSRAM Opto Semiconductors, Inc.	**Integrated Fuses for OLED Lighting Device** Novel Method to Generate High Efficient Devices, which Emit High Quality Light for Illumination Novel Method to Generate High Efficient Devices, which Emit High Quality Light for Illumination OLED with Phosphors Polymer and Small Molecule Based Hybrid Light Source Polymer Small Molecule Based Hybrid Light Source
Pacific Northwest National Laboratory	Organic Materials with Phosphine Sulphide Moieties having Tunable Electric and Electroluminescent Properties Organic Materials with Tunable Electric and Electroluminescent Properties
Philips Electronics North America	High Color-Rendering-Index LED Lighting Source using LEDs from Multiple Wavelength Bins Three other patent applications filed.
PhosphorTech Corporation	**Light Emitting Device having Selenium-Based Fluorescent Phosphor** **Light Emitting Device having Silicate Fluorescent Phosphor** **Light Emitting Device having Sulfoselenide Fluorescent Phosphor** **Light Emitting Device having Thio-Selenide Fluorescent Phosphor**
Sandia National Laboratory	**Cantilever Epitaxial Process** One other patent application filed.
Universal Display Corporation	**Binuclear Compounds** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** Stacked OLEDs with a Reflective Conductive Layer One other patent application filed.
University of California, San Diego	Rare-earth activated nitrides for solid state lighting applications Two additional patent applications filed.
University of California, Santa Barbara	**Plasmon Assisted Enhancement of Organic Optoelectronic Devices** Silicone Resin Encapsulants for Light Emitting Diodes Five other patent applications filed.
University of North Texas	One patent application filed.
University of Southern California	Fluorescent Filtered Electrophosphorescence Fluorescent Filtered Electrophosphorescence OLEDs utilizing macrocyclic ligand systems Materials and architectures for efficient harvesting of singlet and triplet excitons for white light emitting OLEDs Organic vapor jet deposition using an exhaust Phenyl and fluorenyl substituted phenyl-pyrazole complexes of Ir Low Index Grids (LIG) to Increase Outcoupled Light From Top or Transparent OLED Three additional patent applications filed.

Guiding Market Introduction of High Efficiency, High Performance SSL Products

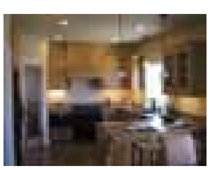
The U.S. Department of Energy (DOE) has developed a comprehensive national strategy to guide market introduction of solid-state lighting (SSL) for general illumination. DOE's commercialization support plan draws on key partnerships with the SSL industry, research community, standards setting organizations, energy efficiency groups, utilities, and others, as well as lessons learned from the past. Commercialization support activities are closely coordinated with research progress to ensure appropriate application of SSL products, and avoid buyer dissatisfaction and delay of market development. DOE's role is to:

- Help consumers, businesses, and government agencies differentiate good products and applications.
- Widely distribute objective technical information.
- Coordinate SSL commercialization activities among federal, state, and local organizations.
- Communicate performance targets to industry.

DOE SSL Pathways to Market

SSL Quality Advocates. DOE's SSL Quality Advocates program is a voluntary pledge program to assure that LED lighting, as it reaches the market, is represented accurately. Participation in SSL Quality Advocates is open to all who manufacture, sell, and recommend the best in LED lighting. Those who take the pledge become part of a growing community of SSL Quality Advocates across the lighting supply chain committed to supporting continuous improvement of SSL product quality. www.netl.doe.gov/ssl/qualityadvocates.html

ENERGY STAR for SSL. ENERGY STAR® is a voluntary energy efficiency labeling program identifying products that save energy, relative to standard technology. The DOE ENERGY STAR program for SSL launched in September 2008, and the first labeled products are expected on the market in early 2009. The ENERGY STAR label on SSL luminaires provides consumers with confidence that these products meet efficiency and performance criteria established by DOE in collaboration with industry stakeholders. www.netl.doe.gov/ssl/energy_star.html



GATEWAY Technology Demonstration. Demonstrations showcase high performance LED products for general illumination in a variety of commercial and residential applications. Demonstration results provide real-world experience and data on state-of-the-art SSL product performance and cost effectiveness. Performance measurements include energy consumption, light output, color consistency, and interface/control issues. The results connect DOE technology procurement efforts with large-volume purchasers and provide buyers with reliable data on product performance. www.netl.doe.gov/ssl/techdemos.htm

CALiPER. DOE's testing program provides unbiased information on the performance of a widely representative array of commercially available SSL products for general illumination. Test results guide DOE planning for R&D, design competitions, technology procurement activities, and ENERGY STAR®; furnish objective product performance information to the public; and inform the development and refinement of standards and test procedures for SSL products. www.netl.doe.gov/ssl/comm_testing.htm

LPrize. The L Prize™ competition aims to accelerate development and adoption of SSL products to replace the common light bulb. The DOE L Prize challenges industry to develop replacement technologies for two of today's most widely used and inefficient products: 60W incandescent lamps and PAR 38 halogen lamps. It also calls for development of a 21st Century Lamp that delivers ultra-high efficiency and performance. www.lightingprize.org

Lighting for Tomorrow. The Lighting for Tomorrow competition recognizes innovative, attractive, energy-efficient residential lighting design. Sponsored by DOE, the American Lighting Association (ALA), and the Consortium for Energy Efficiency, the competition was launched in 2002 with an initial focus on CFL fixtures. In 2006, a category for solid-state lighting was added. Winners are announced at the annual ALA conference. www.lightingfortomorrow.com

Next Generation Luminaires. The Next Generation Luminaires™ competition recognizes excellence in the design of energy-efficient LED commercial lighting lumi-naires. Sponsored by DOE, the Illuminating Engineering Society of North America, and the International Association of Lighting Designers, the competition was launched in May 2008. Winners are announced at the annual Strategies in Light conference. www.ngldc.org

Technical Support for Standards. DOE provides national leadership and support for the development of new test procedures and standards for SSL, working closely with the Illuminating Engineering Society of North America, the National Electrical Manufacturers Association, the Next Generation Lighting Industry Alliance, the American National Standards Institute, and other organizations to accelerate the standards development process, facilitate ongoing collaboration, and offer technical assistance. The first national standards and rating systems for SSL products were issued in 2008, and more will follow. www.netl.doe.gov/ssl/standards_dev.html

TINSSL. DOE's Technical Information Network for Solid-State Lighting (TINSSL) increases awareness of SSL technology, performance, and appropriate applications. A coalition of representatives from energy efficiency organizations and utilities participate in monthly meetings to share information and updates, working closely with DOE to produce SSL outreach materials and support outreach events and activities. TINSSL members include the Consortium for Energy Efficiency, Northeast Energy Efficiency Partnerships, Northwest Energy Efficiency Alliance, Midwest Energy Efficiency Alliance, Pacific Gas & Electric, Southern California Edison, and Energy Trust of Oregon. www.netl.doe.gov/ssl/technetwork.htm

CALiPER Program Supports Unbiased Testing, Promotes Consumer Confidence

Solid-state lighting (SSL) technologies are changing and improving rapidly as a growing stream of new products is introduced to market. Industry groups, standards-setting organizations, and the U.S. Department of Energy (DOE) are moving quickly to develop and implement needed standards and test procedures for SSL products. At the same time, there is a need for reliable, unbiased product performance information in the dynamic early years of a developing market.

DOE's Commercially Available LED Product Evaluation and Reporting (CALiPER) Program addresses that need. CALiPER test results guide DOE planning for R&D, technology demonstration, procurement, and ENERGY STAR® initiatives; convey objective product performance information to the public; and inform the development and refinement of standards and test procedures for SSL products.

Launched in October 2006, CALiPER supports testing of a widely representative array of SSL products available for general illumination, using industry-approved test procedures. Guidelines for selecting products for testing ensure that the overall set of tests delivers insights across a range of lighting applications, product categories, and performance characteristics, a mix of manufacturers and devices, and variations in geometric configurations that may affect testing and performance. In addition, CALiPER testing measures variability across units and establishes benchmarking data with respect to other light source technologies and LED thermal management.

Testing Procedures and Methods

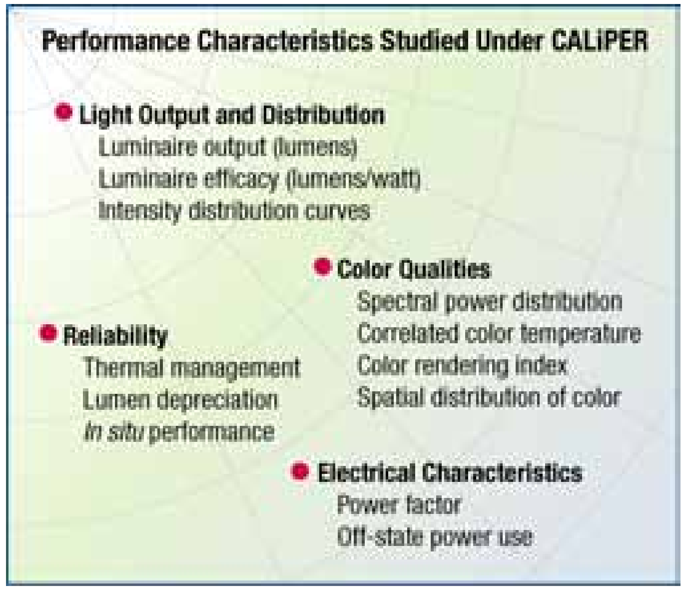
Products selected for the CALiPER Program are purchased and sent to qualified independent lighting testing laboratories. All luminaires are tested with both spectroradiometry and goniophotometry, along with temperature measurements (taken at the hottest accessible spots on the luminaire) and off-state power consumption. Standardized procedures are used for the tests, including the LM-79 standard for electrical and photometric measurement of SSL products, issued by the Illuminating Engineering Society of North America (IESNA) in April 2008.

Why CALiPER?

- Solid-state lighting is different from traditional sources.
- Existing standards and test procedures are not appropriate for evaluating SSL products.
- New standards and test procedures for evaluating LED-based luminaires (light source and fixture) are now available.
- CALiPER results help industry develop and implement a new way of testing.
- CALiPER results support DOE planning.
- Credible performance information is needed to avoid early buyer dissatisfaction and delay of market development.

Manufacturers of tested products are given the opportunity to comment on test results prior to report completion. Testing results, summaries, and analysis are then distributed via the DOE SSL website.

- **Detailed Test Reports** are distributed in the public interest for noncommercial, educational purposes only.
- **Summary Reports** provide detailed analysis of the test results for all products included in each round of testing.
- **Benchmark Reports** help users better compare LED products with conventional lighting technologies.



Results

CALiPER testing to date has revealed a wide range of performance, from poor to excellent. Some SSL products tested deliver light output and efficacies that equal or exceed comparable incandescent and CFL products. Others perform poorly and do not produce enough light output for their intended application to be considered a suitable replacement for any similar product in use today.

The great divergence in applications and performance characteristics highlights the need for buyers to consider the performance of each product separately and to require clear and accurate luminaire perfor-mance information from manufacturers. While some manufacturers are publishing credible values for luminaire output and efficacy, there is often wide disparity between performance claims in marketing literature and actual tested luminaire performance. The need for reliable standards, credible testing, and accurate information — both for manufacturers and the public — is clear.

Next Steps

Ongoing CALiPER testing shows notable improvement in each round of testing, underscoring the significant potential of SSL and the rapid pace of technology advances. Luminaire manufacturers continue to integrate improvements in component efficiencies and new LED chips, which lead to improvements in overall luminaire efficacy and color quality.

Analysis of CALiPER test results and feedback from lighting manufacturers, efficiency programs, and utilities guide DOE planning for the CALiPER program as well as GATEWAY demonstrations and SSL R&D priorities. In November 2007, DOE hosted a CALiPER Roundtable to solicit input on test results and procedures, and additional testing needs for SSL. DOE has also established a guidance committee — including representatives from energy efficiency programs, utilities, the lighting design community, and key trade groups — to guide CALiPER program improvements and serve as a direct communications channel with stakeholders. To learn more about the CALiPER Program and guidance committee, or to download the Roundtable report, see www.netl.doe.gov/ssl/CALiPER-Program.htm.

ENERGY STAR® Criteria for Solid-State Lighting Products

ENERGY STAR is a voluntary labeling program designed to help consumers identify energy-efficient, cost-effective products on the market. To earn the label, a manufacturer's product must meet strict efficiency and performance criteria established by the U.S. Department of Energy (DOE). The ENERGY STAR program for solid-state lighting (SSL) luminaires went into effect in September 2008 with the goal of ensuring that only high-quality, efficient SSL products bear the label.

The ENERGY STAR label is a highly valued and widely recognized mark of energy efficiency. As part of its national strategy to accelerate market introduction of high-efficiency SSL products, DOE developed ENERGY STAR criteria, which employs a transitional, two-category approach:

- **Category A** addresses near-term applications, where SSL technology can already be applied to provide good lighting performance and energy efficiency.
- **Category B** establishes a future efficacy target for all applications, which will take effect approximately three years after the initial effective date of the ENERGY STAR SSL criteria.

Category A covers indoor and outdoor residential and non-residential lighting applications of many types, including undercabinet lights, portable desk/task, recessed downlights, ceiling- and surface-mounted lights, and several types of outdoor luminaires. These applications were chosen on the basis of their suitability for solid-state lighting, given the current state of SSL technology. Because this technology continues to advance quickly, DOE adds new applications to Category A regularly.

Category B will cover innovative SSL systems applications of all types. This category encompasses a much wider range of future applications that will emerge as the technology matures further, and serves as a target for lighting manufacturers as they develop products over the next several years. SSL products will be able to qualify under Category B approximately three years after the effective date of the criteria.

Once Category B goes into effect, Category A will be dropped. This transitional approach recognizes the rapid pace of SSL technology development, yet allows early participation of a limited range of products for lighting applications in Category A that take advantage of SSL's unique attributes.

DOE intends to periodically review and amend the criteria to parallel technology advances and ensure that criteria remain up-to-date. For example, DOE has recently expanded Category A to include ceiling-mounted luminaires, cove lighting, wall wash, and several other residential and commercial applications. Outdoor area and roadway lighting, parking garage lighting, and other outdoor applications will be added to Category A in early 2009. In addition, DOE has initiated a public stakeholder review and comment process for new criteria covering integrated LED replacement lamps.

For more information on DOE's ENERGY STAR program for solid-state lighting, or to view the complete criteria, see www.energystar.gov/sslpartners.

Key Stakeholders in Criteria Development

DOE worked closely with key industry stakeholders in developing the new ENERGY STAR criteria and the testing procedures upon which the criteria are based, including the Next Generation Lighting Industry Alliance (NGLIA), Illuminating Engineering Society of North America (IESNA), and American National Standards Institute (ANSI). DOE also received extensive advice and useful comments from individual lighting companies, electric utilities, energy efficiency organizations, and others.

General Requirements

The principal energy efficiency metric used in the criteria is luminaire efficacy (net light output from the fixture divided by the input power). In April 2008, IESNA completed the LM-79 standard for electrical and photometric measurement of SSL products, which specifies a standard test method for measuring the photometric properties of SSL luminaires, allowing calculation of luminaire efficacy. In September 2008, IESNA completed the LM-80 standard for measuring the lumen maintenance of LEDs under various temperature conditions. Both LM-79 and LM-80 are integral to the ENERGY STAR criteria for SSL. LM-79 is the basis for CALiPER testing and is used to evaluate products for GATEWAY demonstrations.

To streamline the product qualification process, DOE has developed a Manufacturer's Guide for Qualifying Solid-State Lighting Luminaires and an online product submittal tool that allows manufac-turers to upload the necessary information and test data required for qualifying their products. To learn more about these tools and other resources for manufacturers, visit www.energystar.gov/sslpartners.

Finding Qualified Products

The ENERGY STAR criteria for SSL focus on lighting applications and products that have advanced to a point where performance is equal to or better than traditional lighting technologies, based on light output, luminaire efficacy, and cost. The ENERGY STAR website offers additional tools and resources to assist consumers in finding and selecting qualified products, including a Buyer's Guide for Selecting LED Products, a Qualified Products List, and Frequently Asked Questions. To learn more, see www.energystar.gov/led.

GATEWAY Demonstrations Showcase LED Product Performance

The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Technology Demonstration GATEWAY Program features high-performance SSL products for general illumination in a variety of commercial and residential applications. Results provide real-world experience and data on product performance and cost effectiveness, and connect DOE technology procurement efforts with large-volume purchasers. Performance measures include energy consumption, light output, color consistency, and installation/interface/ control issues.

Demonstration in Oakland, California, with Beta LED streetlights (foreground) and HPS streetlights (background) Photo: Beta LED

How to Participate

DOE seeks to assemble demonstration teams that match host sites with appropriate products and partners. DOE GATEWAY demonstrations are open to all participants, subject to certain eligibility parameters. Demonstration teams typically include a product manufacturer, a host site, and an energy efficiency organization or local utility where applicable.

- **Manufacturers** provide products for demonstration and may assist in site selection and installation.
- **Host sites** provide locations for demonstrations, assistance with installation and evaluation/ measurement, and a willingness to participate in demonstration-related activities such as tours and webcasts.
- **Energy efficiency organizations and utilities** provide contacts with potential host site organizations and assist with related outreach and promotional activities.

Potential participants are encouraged to submit expressions of interest using the application forms available at www.netl.doe.gov/ssl/techdemos.htm. Team members are not restricted to a single team or a particular project. A large hosting organization might demonstrate products from more than one manufacturer, or a single manufacturer might participate with multiple products designed for different applications and locations.

Sharing Results

Results from DOE GATEWAY demonstrations enable participants to evaluate and refine their lighting requirements before making large-scale purchasing decisions. Demonstration project results are shared through the DOE SSL website, workshops, webcasts, and other demonstration-related activities.

DOE is also interested in working with team members, host site organizations, and other entities to form “user groups” to share information among users with similar needs. Participants in these user groups can join or initiate procurement efforts for high efficiency applications using information gained from demonstration projects, which can result in large-scale purchases and/or promotion of featured products.

Other Ways to Participate

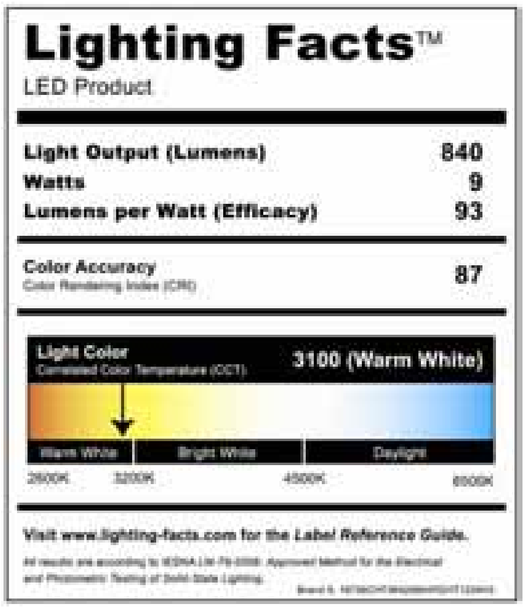
For parties conducting their own demonstrations and interested in widely sharing results, or for demonstrations already underway, DOE has developed the GATEWAY Demonstration Registry and Reporting Template. Demonstrations conducted using the template or meeting its requirements will be incorporated into the Registry and the results will be widely shared. Learn more at www.netl.doe.gov/ ssl/techdemos.htm.

DOE TECHNOLOGY DEMONSTRATION PROCESS

- **Initial Screening:** Applications are screened; prospective products and host sites deemed eligible are informed of their eligibility or asked for additional information.
- **Participant Team Identification:** Host sites and other team members are identified to carry out the actual demonstration of products.
- **Laboratory Testing:** Concurrent with team identification, testing of sample products is conducted to establish or verify important measures of performance.
- **Installation:** Products are installed with appropriate pre- and post-measurements; demonstration steps are carried out, including any publicity and education events.
- **Evaluation:** DOE’s Pacific Northwest National Laboratory evaluates the results, including energy and cost savings and related economic analyses, as well as qualitative occupant and user responses to the installed LED light source.
- **Results Reporting:** Results of successful demonstrations are widely publicized; results from long-term testing are released as they become available. While no sales of demonstrated products are assured, DOE expects large-scale product purchases or promotions by demonstration team members will also occur at this stage for products that have performed to buyers’ satisfaction.

SSL Quality Advocates Support Accuracy in LED Product Information

For the solid-state lighting (SSL) market to grow, consumers must have confidence that the product they are buying is well designed and performs to their expectations. Sponsored by the U.S. Department of Energy (DOE), SSL Quality Advocates is a voluntary pledge program to assure that LED lighting is represented accurately as it reaches the market. SSL Quality Advocates pledge to use the Lighting Facts™ label (below) to document the performance of products they manufacture, sell, distribute, or promote, based on industry-standard testing.



Similar to a nutrition label, the Lighting Facts Label provides a quick summary of product performance data. Luminaire manufacturers who take the SSL Quality Advocates pledge agree to use the label to disclose performance results in five areas — lumens, efficacy, watts, correlated color temperature (CCT) and color rendering index (CRI) — as measured by the new industry standard for testing photometric performance, IESNA LM-79-2008. Additional metrics related to reliability, product consist-ency, construction, and other parameters may be considered in future editions of the label. By introducing transparency to the lighting supply chain, the Lighting Facts label will guard against exaggerated claims and help ensure a satisfactory experience for lighting buyers.

Importance of Quality

Today's marketplace features an increasing number of LED products for everyday lighting purposes, from desk lamps to outdoor lighting. While many of these products deliver on their performance claims, independent testing conducted through the DOE CALiPER test program[1] reveal that some do not. Concerns include low light output, lifetimes that are shorter than reported, and poor or inconsistent color quality. Such shortcomings could discourage consumers from accepting SSL lighting technology, much as quality problems in the early days of compact fluorescent lighting (CFL) slowed market acceptance of these products.

[1] The CALiPER program conducts independent testing of commercially available LED products. Learn more at www.netl.doe.gov/ssl/comm_testing.htm.

The SSL Quality Advocates program and the Lighting Facts label were jointly developed by DOE and the Next Generation Lighting Industry Alliance as a foundation for successful commercialization of solid-state lighting, a technology with the potential to cut lighting energy use by 50 percent. The SSL Quality Advocates program showcases LED luminaire manufacturers who commit to testing products and reporting performance results according to industry standards, and gives lighting buyers, designers, and energy efficiency programs the essential information to evaluate and select products[2] for their specific projects and for promotion to clients and consumers.

How to Participate

Companies or organizations are invited to take the SSL Quality Advocates Pledge at www.lighting-facts.com. Participating manufacturers agree to follow the guidelines for reporting luminaire performance and to use the Lighting Facts label on product packaging or in product literature. Others in the supply chain — buyers, contractors, lighting designers, distributors, retailers, utilities, and efficiency organizations — may also become SSL Quality Advocates by agreeing to look for and use products that bear the label.

The Lighting Facts label complements the ENERGY STAR® program for LED lighting launched by DOE in 2008. While both of these voluntary programs are designed to make energy-efficient purchasing decisions easier and more transparent, they take different approaches:

- ENERGY STAR was designed with consumers in mind. It sets a minimum performance level for qualifying products to help consumers choose the most efficient products. The ENERGY STAR label can only be applied to a limited group of qualifying LED lighting products for general illumination.
- The Lighting Facts label is an industry tool to help retailers and other buyers choose wisely. It provides essential information to evaluate product performance against manufacturer claims. Armed with this information, retailers and other industry stakeholders can keep poor-performing products from ever reaching their shelves.

Taking the SSL Quality Advocates Pledge establishes a manufacturer as an industry leader in support of accurate reporting and disclosure, and continual improvement of LED product quality.

[2] The Lighting Facts label may appear only on LED lighting products, including self-contained replacement lamps and full luminaire products; it does not apply to packaged LED devices or to LED indicator applications such as flashlights, nightlights, and holiday lighting.

Standards Development Increases Market Confidence in SSL Performance

Like traditional lighting products, LED-based luminaires sold in the United States rely on industry-developed standards and test methods to characterize their performance and safety. The use of national standards and test methods is critical to user design and bolsters consumer confidence that products meet Federal standards. However, the unique attributes of LEDs, or light-emitting diodes, necessitate some modifications and additions to the existing standards for lighting products.

Until recently, the lack of sufficient standards for solid-state lighting (SSL) generated a great deal of confusion and frustration in the market. Variations in testing methods and terminology from one manufacturer to another made it difficult to compare new LED products to traditional sources.

The U.S. Department of Energy (DOE) has been working closely with a network of standards-setting organizations to accelerate the development and implementation of needed SSL standards. DOE hosts ongoing workshops to foster coordination and collaboration on related efforts, attended by major standards groups: American National Standards Institute (ANSI), Illuminating Engineering Society of North American (IES), National Electrical Manufacturers Association (NEMA), National Institute of Standards and Technology (NIST), Underwriters Laboratories Inc. (UL), Commission Internationale de l'Eclairage (CIE), CSA International, and International Electrotechnical Commission.

Recent Releases

Four new standards for LEDs were released in 2008, reflecting the hard work of these organizations and their commitment to SSL market growth:

- **IESNA LM-79-2008, Approved Method for the Electrical and Photometric Testing of Solid-State Lighting Devices,** enables the calculation of luminaire efficacy (net light output from the luminaire divided by the input power and measured in lumens per watt). Luminaire efficacy is the most reliable way to measure LED product performance, measuring luminaire performance as a whole instead of relying on traditional methods that separate lamp ratings and fixture efficiency. LM-79 helps establish a foundation for accurate comparisons of luminaire performance, not only for solid-state lighting but for all sources.[3]

- **IESNA LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources,** supports an assessment of expected LED lifetime by defining a method of testing lamp depreciation. Unlike traditional filament-based sources, which usually fail completely, LEDs don't typically fail; they simply fade over time, which is referred to as lumen depreciation. LM-80 establishes a standard method for testing lumen depreciation.
- **ANSI C78.377-2008**, **Specifications for the Chromaticity of Solid-State Lighting Products,** specifies recommended color ranges for white LEDs with various correlated color temperatures. Color range and color temperature are metrics of critical importance to lighting designers.[4]
- **IESNA RP-16 Addendum a, Nomenclature and Definitions for Illuminating Engineering,** provides industry-standard definitions for terminology related to solid-state lighting.

All of these standards are integral to or referenced by the DOE ENERGY STAR® criteria for solid-state lighting; products qualifying[5] for the ENERGY STAR label must be tested to these standards. They are also fundamental to DOE's CALiPER testing and evaluation of products for GATEWAY demonstrations.

Future SSL Standards

The releases of LM-79, LM-80, C78.377-2008, and RP-16(a) are the first tangible results of an accelerated, collaborative standards development process. There also have been significant developments on additional standards:

- **ANSI C82-SSL1,** "LED Drivers," will specify operational characteristics of power supplies and drivers for solid-state lighting products.
- **UL 8750,** "LED Safety," will specify minimum safety requirements for solid-state lighting components, including LEDs and LED arrays, power supplies, and control circuitry.[6]
- **TM-21,** "Method for Estimation of LED Life," will provide one method of applying LM-80-type test data to extrapolate an expected life of an LED product.

Over time, these and other standards will remove the guesswork about comparative product performance, making it easier for lighting manufacturers, designers, and specifiers to select the best product for an application. As industry experts continue the painstaking work of standards development, they are contributing to a growing body of information that will help support solid-state lighting innovation, as well as market adoption and growth.

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[3] Electronic copies of LM-79, LM-80, and RP-16(a) may be purchased online through the Illuminating Engineering Society store at www.iesna.org/shop.

[4] The C78.377 standard is available for hard copy purchase or as a free download from NEMA at www.nema.org/stds/ANSI-ANSLG-C78-377.cfm#download. Hard copies can also be purchased from ANSI at www.webstore.ansi.org.

[5] To learn more about the ENERGY STAR qualification process, visit www.netl.doe.gov/ssl/energy_star.html.

[6] UL customers can obtain the outline for free (with login) at www.ulstandards.com. Others can purchase the outline at www.comm-2000.com.

Competition Recognizes Innovative, Energy-Efficient Residential Lighting Design

Lighting for Tomorrow encourages technical innovation and recognizes and promotes excellence in the design of energy-efficient residential lighting fixtures. Organized by the American Lighting Association, the U.S. Department of Energy, and the Consortium for Energy Efficiency, the design competition stimulates the market for attractive, energy-efficient residential lighting fixtures that use a fraction of the electricity of standard incandescent fixtures.


Kichler's Design Pro Series kitchen undercabinet lighting

By encouraging manufacturers to develop the next generation of innovative, attractive — and energy-efficient — residential lighting fixtures, Lighting for Tomorrow increases market acceptance and awareness of the growing opportunities in energy-efficient lighting. The competition focus extends to marketing, promotion, and sales through primary distribution channels for both new construction and renovation markets.

Lighting for Tomorrow was launched in 2002, with an initial focus on CFL fixtures. In 2006, a category for solid-state lighting was added and now, over three dozen energy efficiency organizations in the U.S. and Canada pledge their support to the competition, with the number growing each year.


Luximo Cylindrium desk/task light

2008 Solid-State Lighting Winners

In 2008, a total of 56 entries were submitted in the solid-state lighting category. Among the winners, Kichler's Design Pro Series™ LED Cabinet Lighting won in the kitchen undercabinet category with its innovative, ultra-thin unit that provides even light distribution and excellent color quality. In the desk/task light category, Luximo took top honors with its elegantly designed Cylindrium™ — a high-efficiency LED task lamp with superior light quality, high light output, and even color distribution. Cree LED Lighting Solutions was the winner in the recessed downlight category, with a versatile 4-inch can offering an unprecedented combination of output, efficacy, beautiful color, and affordability.


Cree LR4 recessed downlights

For more details or purchasing information on these and the other winning products, visit www.lightingfortomorrow.com.

Lighting for Tomorrow 2009

The 2009 Lighting for Tomorrow competition was launched at the Dallas International Lighting Market in January 2009. The 2009 competition categories include:

- **Near-term applications:** Undercabinet, portable desk/task, downlights, outdoor porch/path/step lighting, surface- and pendant-mounted downlights, ceiling-mounted luminaires with diffusers, residential cove lighting, surface-mounted luminaires with directional heads, and outdoor pole/arm-mounted decorative luminaires capable of meeting ENERGY STAR® criteria for solid-state lighting, Category A.
- **Other applications:** Additional fixture types not included in the ENERGY STAR® criteria such as wall sconces, table/floor lamps, torchieres, chandeliers, pendant uplights, and landscape lighting.

Judging Criteria

Designs are evaluated on the basis of potential market impact, innovation, and functionality. Specifically in the LED category, judging criteria include lighting quality (color appearance, color rendering, illuminance levels, and distribution), application efficiency, thermal management, and aesthetic appearance.

Bonus points will be given for innovative designs that take advantage of unique LED attributes, fixtures eliminating off-state power consumption, indoor entries capable of dimming, and outdoor entries that are dark-sky friendly. Lighting for Tomorrow judges are drawn from across the lighting industry, creating a diverse panel of experts who sell, design, evaluate, and write about residential lighting design.

Timeline

The deadline for entries in the 2009 competition is April 24. Winners will be announced in September at the ALA Annual Conference in Palos Verdes, CA. Winners gain further visibility and recognition as they are showcased at DOE and industry events, and in various publications. They also become eligible for promotion by energy efficiency programs across the U.S. and Canada.

For complete guidelines and rules for the 2009 competition, see www.lightingfortomorrow.com.

2009 Timeline

- January 2009: **Competition Announced**
- March 2009: **Intent to Submit Forms Due**
- April 2009: **Entries Due**
- May 2009: **Judging**
- September 2009: **Winners Announced**

Competition Recognizes Innovative, Energy-Efficient Commercial Lighting Luminaires

The Next Generation Luminaires™ Solid-State Lighting (SSL) Design Competition seeks to encourage technical innovation and recognize and promote excellence in the design of energy-efficient LED com-mercial lighting luminaires. Organized by the Department of Energy (DOE), Illuminating Engineering Society of North America (IESNA), and the International Association of Lighting Designers (IALD), the competition encourages manufacturers to develop innovative commercial luminaires that are energy-efficient and provide high lighting quality and consistency, glare control, lumen maintenance, and luminaire appearance needed to meet specification lighting requirements.

Background

Since 2002, DOE has co-sponsored a national lighting fixture design competition (called Lighting for Tomorrow) in partnership with industry and energy efficiency organizations. The competition focuses on residential lighting, demonstrating that energy-efficient (fluorescent) lighting can be beautiful and decorative. In 2006, an LED category was added to Lighting for Tomorrow to encourage well-designed residential LED luminaires in specific applications.

Ongoing advances in SSL technology and the growing number of product introductions signal an opportunity to encourage, recognize, and promote LED luminaires suitable for the commercial specifi-cation market, implicitly differentiating them from LED products that will not meet the needs of lighting designers, specifiers, and users.

The Next Generation Luminaires competition recognizes the rapid changes and advancements in white LED technology for general illumination. LEDs, when incorporated into well-designed luminaires, are now appropriate for a growing number of lighting applications. Entries will be accepted in the following categories:

Market-Ready Luminaires

The Market-Ready category is for luminaires that are in or near production and ready for specification. Emphasis should be on quality and practicality of the luminaire for real-world lighting applications in the commercial specification market. Acceptable entries include, but are not limited to, under-cabinet shelf-mounted lights, portable desk/task lights, recessed downlights, cove lighting, valance lighting, pendants, wall washers, wall sconces, accent lighting, refrigerated and non-refrigerated retail display case lighting, exterior architectural lights, facade lighting, street and area lighting, and pedestrian pathway lighting.

Emerging Products
The Emerging Products category encourages new, innovative ideas for application of white LEDs to solve lighting design problems. It is open to products that are not yet market-ready, but a working prototype must be provided. Luminaires as well as LEDs and LED systems designed for integration into furniture, equipment, or architectural or structural elements are eligible.

For complete guidelines and rules for the 2008 competition, see www.ngldc.org.

Participants

The competition is open to LED, lighting, lighting system, and luminaire manufacturers, including LED device and system manufacturers in conjunction with their luminaire manufacturing partners.

Judging Criteria

Designs are evaluated on the basis of color appearance, color rendering, appropriate illuminance and luminance levels, application efficiency, thermal management, and aesthetic appearance and style. Bonus points are awarded for innovative designs that eliminate off-state power consumption, outdoor entries that are dark-sky friendly, and entries that address application modularity and serviceability/replacement issues.

Next Generation Luminaires judges are drawn from across the architectural lighting design community, creating a diverse panel of experts who design, specify, evaluate, research, and write about commercial SSL luminaires.

2008–2009 Timeline

- May 2008: **Call for Entries Begins**
- July 31, 2008: **Intent to Submit Forms Due**
- September 26, 2008: **Entries Due**
- November 2008: **Judging**
- February 2009: **Winners Announced**

L•PRIZE™
Bright Tomorrow Lighting Prizes

The Race to Replace the Common Light Bulb

The Bright Tomorrow Lighting Prize (L Prize™) competition is the first government-sponsored technology competition designed to spur lighting manufacturers to develop high-quality, high-efficiency solid-state lighting products to replace the common light bulb. It aims to substantially accelerate America's shift from inefficient, dated lighting products to innovative, high-performance products.

The Energy Independence and Security Act (EISA) of 2007 directed the U.S. Department of Energy (DOE) to establish the L Prize competition. The legislation challenges industry to develop replacement technologies for two of today's most widely used and inefficient technologies: 60W incandescent lamps and PAR 38 halogen lamps. It also calls for development of a 21st Century Lamp that delivers more than 150 lm/W. The competition will award winning products with a cash prize, plus opportunities for federal purchasing agreements, partner program promotions, and other incentives.

Competition Requirements Set the Bar High

L Prize submissions must meet strict technical specifications to ensure compliance with the general requirements outlined in the legislation. Additional details are also specified for quality, performance, and mass manufacturing. To download the complete competition requirements, see www.lightingprize.org.

60W Incandescent Replacement Lamp	PAR 38 Halogen Replacement Lamp	21st Century Lamp
• More than 90 lm/W • Less than 10 watts • More than 900 lumens • More than 25,000 hour life • More than 90 CRI • Between 2700–3000 K CCT	• More than 123 lm/W • Less than 11 watts • More than 1,350 lumens • More than 25,000 hour life • More than 90 CRI • Between 2700–3000 K CCT	• To be defined in a future L Prize announcement

The competition also includes a rigorous evaluation process for proposed products, designed to detect and address product weaknesses before market introduction, to avoid problems with long-term market acceptance. Comprehensive product evaluation will include performance and lumen depreciation testing conducted by independent laboratories, field assessments conducted in collaboration with utilities and other partners, and stress testing under extreme conditions. This multi-step evaluation process is designed to provide a high level of confidence in the performance and energy efficiency of the winning products.

Partners Leverage Know-How and Market Pull

A growing number of utilities and energy efficiency organizations from coast to coast have signed on with DOE as L Prize partners. These program partners have agreed to play an important role in evaluating and promoting the winning L Prize products, developing markets and providing access to more than 100 million customers from Los Angeles to Cape Cod. These organizations participate in bi-monthly planning meetings, working with DOE to develop region-specific plans for field assessments and product promotion.

L Prize Partners

Cape Light Compact
Commonwealth Edison
DTE Energy
Efficiency Vermont
Energy Trust of Oregon
Eugene Water and Electric Board
Midwest Energy Efficiency Alliance (covers 9 states)
Northeast Energy Efficiency Partnerships (covers 8 states)
NSTAR Electric
NV Energy
Pacific Gas & Electric
Puget Sound Energy
Sacramento Municipal Utility District
San Diego Gas & Electric
Seattle City Light
Southern California Edison
Wisconsin Energy Conservation Corporation

Field assessments of submitted products will provide valuable information on energy use, lighting system performance, reliability, customer acceptance, and cost-effectiveness in real-world conditions. Product promotions may include incentives paid directly to manufacturers or to consumers, collaborative market-ing and educational campaigns, retailer partnerships, and demonstrations. To learn more, see www.lightingprize.org.

Opportunities for Recognition

The L Prize competition offers significant opportunities for recognition. All competitors and program partners will be in the media spotlight, both on the L Prize website and in national, trade, and regional publications.

L•PRIZE™

Bright Tomorrow Lighting Prizes

Competition Requirements Set the Bar High

The L Prize competition is designed to spur development of high-quality solid-state lighting products capable of replacing today's most widely used and inefficient products: 60W incandescent lamps and PAR 38 halogen lamps. The Energy Independence and Security Act of 2007 directed the U.S. Department of Energy (DOE) to establish the competition and outlined general competition requirements. To draw on lessons learned from past lighting market introduction experiences, DOE worked with several California utilities to tap their expertise in developing a comprehensive technology competition program.

The L Prize technical specifications comply with the general requirements outlined in the legislation, with additional details specified for quality, performance, and mass manufacturing. The competition requirements are designed to ensure that the winning products deliver excellent lighting quality. To view the complete competition requirements, see www.lightingprize.org.

Why Compete?

- Opportunities to be recognized as the best of the best
- Immediate market potential for sales
- Program partner promotions, incentives, marketing
- Intense media spotlight
- Automatic ENERGY STAR® qualification
- Cash prize (first winner in each category)

Requirement	60-Watt Incandescent Replacement	PAR 38 Halogen Replacement
Efficacy	More than 90 lm/W	More than 123 lm/W
Light Output	More than 900 lumens	More than 1,350 lumens
Wattage	Less than 10 watts	Less than 11 watts
Lifetime	More than 25,000 hour life	
Color Rendering Index (CRI)	More than 90	
Correlated Color Temperature (CCT)	2700–3000 K	
Form Factor	Same lamp form factor as incumbent technology	
Beam Distribution	Same beam distribution characteristics as incumbent technology	
Dimming	Products must be compatible with at least three widely available residential dimmers, and must be continuously dimmable to at least 20% of maximum light output	

Competition Process

- **Intent to Submit.** To participate in the L Prize competition, interested manufacturers must provide a letter of intent to submit.

- **Entry Package.** Manufacturers must then submit a complete entry package that includes the required **technical information**, **product samples**, and a **commercial manufacturing plan** describing their capability for mass production and distribution of proposed products.

- **Evaluation Part 1.** Samples of proposed products will undergo **performance testing** at independent laboratories such as those participating in the DOE CALiPER program.

- **Evaluation Part 2.** The L Prize technical review committee will assess the provided technical information, test results, and **manufacturing capabilities**.
  - Products that meet the competition requirements will then undergo at least 6,000 hours of **lifetime testing**.
  - At the same time, DOE and program partners will coordinate **field assessments**, using criteria established through the DOE GATEWAY demonstration program to evaluate energy use, lighting system performance, reliability, customer acceptance, and cost effectiveness.
  - DOE and partners will also conduct **stress testing**, subjecting products to extreme conditions such as high temperatures, humidity, frequent switching, voltage fluctuation, and electromagnetic interference.

- At key stages in the process, DOE may request additional information or follow up with submitters regarding the product or information provided.

Selection of Winners

Entries will be accepted for each product category until a winner is declared, or until 24 months have elapsed since the first award in that category, whichever comes first. In each category, the first entrant to successfully meet the full competition requirements will receive all prizes. Up to two additional entrants may be eligible for program partner promotions.

L•PRIZE™

Bright Tomorrow Lighting Prizes

Program Partners Leverage Know-How and Market Pull

Partners are key to the success of the L Prize competition. Utilities and energy efficiency programs from coast to coast have joined the U.S. Department of Energy (DOE) to promote super-efficient, solid-state lighting products to replace today's most common light bulbs. L Prize partners assist DOE in evaluating potential L Prize products through field assessments and provide ready-made markets for winning products.

New technologies are almost always more expensive when first brought to market, due to low volumes and high development costs. By joining together to represent significant demand, the U.S. government and L Prize partners drive sales volumes up and prices down far more quickly than would otherwise be possible.

Why Partner?

- Confidence in performance and consistency of winning products
- Reduced risk through intensive product evaluations
- Opportunities for hands-on field testing
- Save time learning about new LED technologies
- Sure, effective route to energy savings

West	Central	East
Energy Trust of Oregon, Inc.; EWEB; NV Energy; Pacific Gas and Electric Company; Puget Sound Energy; SDG&E; Seattle City Light; SMUD; Edison	ComEd; DTE Energy; MEEA; WECC	Cape Light Compact; Efficiency Vermont; NSTAR

L Prize Product Evaluation

Products entering the L Prize competition are evaluated in a multi-step process designed to provide a high level of confidence in their performance and energy efficiency. Photometric and electrical testing of proposed products is conducted by independent laboratories, such as those participating in the DOE CALiPER test program.

Program partners play a critical role in the evaluation process by conducting field assessments of proposed products. Field assessments use criteria established by the DOE GATEWAY demonstration program and include:

- Installation in host customer facilities, such as homes, commercial spaces, or outdoor locations.
- Installation in utility technology demonstration facilities.
- Focus group testing with retailers, builders, and/or consumers.

L Prize field assessments:

- Evaluate **energy use** of the products when installed in-situ.
- Characterize the **lighting system performance** as compared to the existing technology.
- Evaluate **reliability** and **customer acceptance** of the products during the test period.
- Evaluate criteria for **cost-effective deployment** through an energy efficiency program.

Field assessment results provide valuable input for the ultimate selection of winners.

L Prize Product Promotion

Program partners play an important role in promoting and developing markets for the winning L Prize products. A large amount of quantitative and qualitative data is available to support promotion of the winning products via:

- **Product incentives** paid directly to manufacturers or to consumers
- Collaborative **marketing and promotion**
- **Partnerships** with local, regional, and/or national retailers
- **Demonstrations and promotions** with local homebuilders, commercial developers, hospitality chains, local governments, schools, universities, etc.

Join Us

For more information on becoming a program partner, contact lprize@pnl.gov.