Arnold Schwarzenegger
Governor

LIGHTING CALIFORNIA'S FUTURE: ADVANCED ENERGY-EFFICIENT LED LIGHTING FOR RESIDENTIAL AND COMMERCIAL APPLICATIONS

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Lighting California's Future: Advanced Energy-Efficient LED Lighting for Residential and Commercial Applications is the final report for the project Lighting California's Future Program (Contract Number 500-06-035) conducted by Architectural Energy Corporation. The information from this project contributes to PIER Buildings End-Use Energy Efficiency Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at (916) 654-4878.

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Abstract

Lighting California's Future (LCF) was a $3.7 million California Energy Commission Public Interest Energy Research Program project focused on lighting technologies for buildings. The project on Advanced LED (light-emitting diode) Lighting for Residential and Commercial Applications sought to develop an LED light for use in residential and commercial buildings. The LED-based light developed in this project would be based on the Lighting Research Center's (LRC) patent-pending SPE™ (Scattered Photon Extraction) technology, which has been shown to significantly improve the efficiency and light output of current generation LED technology. This final report presents information about the development of the SPE technology into a downlight product. This product has the potential to save California 5,450 gigawatt hours annually.

Keywords: Solid-state lighting, LED, light-emitting diode, downlight, SPE, scattered photon extraction, energy efficiency

Executive Summary

Introduction

Lighting California's Future was a $3.7 million California Energy Commission Public Interest Energy Research Program focused on lighting technologies for buildings. The program, which began in May 2007, featured nine technical projects and a market connection project. One of the technical projects featured the Advanced Light-Emitting Diode (LED) Lighting for Residential and Commercial Applications.

Purpose

This project sought to develop an LED-based light for use in residential and commercial buildings. The LED lighting module is based on the Lighting Research Center's patent-pending SPE ™ (Scattered Photon Extraction) technology, a technique that has been shown to significantly improve the efficiency and light output of current generation LED technology. The project team included the Lighting Research Center, which is part of Rensselaer Polytechnic Institute of Troy, New York. The purpose was to develop an advanced, energy-efficient LED lighting system for wall-wash and other accent lighting applications in residential and commercial buildings.

Objectives

Specific objectives were:

- Reduce lighting energy use in the selected application by 50 percent to 70 percent over current state-of-the-art lighting technologies.
- Be cost-effective to purchase, install, use, and maintain.
- Allow for easy and cost-effective control in response to occupancy and daylight.
- Respond easily to the need for reduced power requirements during times of peak electric demand.

Project Outcomes

An analysis of both the residential and commercial downlighting markets indicated that one of the fastest growing luminaire types in each category is the recessed downlight (Lithonia, 2008). In the United States, the current residential downlight market exceeds $400 million per year, and the commercial downlight market exceeds $537 million per year (Lithonia, 2008). About $250 million of this market is for fixtures with an initial cost greater than $65 per unit (Lithonia, 2008). Products sold in the specification-grade market segment are selected primarily based upon the product's performance (Lithonia, 2008). This market is an attractive segment for a light source that can show performance improvements over currently available light source technologies. The most common lamp type used in commercial downlights is the CFL (compact fluorescent light). However, recent testing of CFL downlights showed that these downlights are, on average, only 44 percent efficient (National Lighting Product Information Program, 2008). Also, a growing trend in commercial and residential downlights is consumer preference for downlights with smaller openings, generally four inches (Lightolier, 2007), which typically cannot accommodate CFLs.

The LRC determined that the development of highly efficient, small-aperture, specification-grade, recessed downlight fixtures geared toward the commercial lighting market would be the best course of action for this project. This would allow for the highest impact on energy savings in the shortest amount of time, especially in California where lighting and energy conservation trends tend to push the market toward more efficient, environment friendly products. Based on the market analysis and knowledge of competing products, the LRC project team focused on the commercial downlight market, currently served primarily by 32 watt (W) CFL downlight products. The LED lighting system would have a target effectiveness of 100 lumens per watt (lm/W), exceeding current incandescent, LED, ceramic metal halide, and CFL technologies. Lumens are defined as "a measure of the amount of light available from a light source equivalent to the light emitted by one candle."

The LRC intended and started to work with a major manufacturer, Lightolier, throughout this project. During the early stages of the project, however, the manufacturing partner was not able to continue as part of the team due to a change in the company's ownership. In response to this change in logistics, the goal of the project shifted to producing a sufficient prototype to conduct a field demonstration to survey end users' opinions on the SPE-based LED downlights. In parallel, the LRC continuously sought partnerships with other companies that eventually did not materialize.

To carry out a field demonstration, the target specifications of the SPE-based LED downlight were adjusted to reflect the most likely retrofit scenario in a commercial application, while being consistent with the overarching energy efficiency goals of the project. The final specification for the SPE-based LED downlight was selected so that it could be installed to replace either a 75 W incandescent or a 26-32 W CFL 6-inch downlight, and included:

- Photometric (light measurement)
  - 600-1000 lm
  - Color Rendering Index of 85 at 3000 to 3500 Kelvin (K). Color Rendering Index is to help indicate how colors will appear under different light sources. Degrees K is a scale used to measure the color of the light output.
  - Beam distribution: general downlight
- Electrical
  - Preferably dimmable
- Mechanical/thermal
  - 5-inch to 6-inch diameter
- Non-insulation contact rated (this means the light fixture should be installed in a space that does not contain insulation to prevent overheating).

The economics of the design were always considered but not optimized during this project. The experience and capabilities that a manufacturing partner can offer are needed to achieve specific manufacturing costs and sales prices.

The development process of this project included working iteratively on the following activities:

- Characterization of several commercial phosphors, types of lenses, and types of blue LEDs.
- Optical modeling to achieve a target quality of color between 3000 K and 4000 K with optimum efficiency that achieves a higher color rendering index.
- Experimental verification of optical models.

With the components available toward the end of the project, the LRC team achieved SPE-based LEDs with luminous efficiencies of up to 106 lm/W, 118 lm at 350 milliamps (mA) and 4793 K, and up to 114 lm/W, 69 lm at 200 mA and 4020 K. These SPE-based LEDs had an average efficacy of 96 lm/W when operated at 350 mA and produced an average of 109 lm, average CRI = 74 (CRI describes how well the light renders colors in objects) at an average correlated color temperature = 4100 K. Correlated color temperature describes the relative color appearance of a white light source, indicating whether it appears more yellow/gold or more blue, in terms of the range of available shades of white. During the final iteration, the LRC team created over one hundred SPE lenses for use in seven prototype downlights intended for a field evaluation. The final set of lenses was created at a correlated color temperature of ~4100 K to account for the changes in color temperature resulting from the integration of the lenses inside the downlight. With these lenses, the resulting correlated color temperature of the downlights was 3500 K on average, as intended.

During the luminaire development and evaluation stage, the LRC carefully evaluated the performance of the prototype luminaires built and modified the luminaire design as needed, conducted further testing, and developed a final design for the SPE-based LED downlight system. The final prototype minimized the use of metal to reduce weight and the cost of the design without compromising the thermal performance. The design performed well enough to keep the LED junction temperature (the temperature at the heart of an LED device) as low as 44°Celsius when the LEDs are operated at a current of 175 mA (~8 W LED power, ~700 lm) inside an insulated contact environment. Such junction temperature can be translated into an estimated life of 50,000 hours, according to the LED manufacturer.

The final system had a nominal aperture of 6 inches and produced similar light output to a 75 W small diameter incandescent reflector lamp or a 26 W CFL downlight, but with only 9.5 W of input power. The SPE downlight features an efficient driver with three additional settings if a higher light output is desired (up to 1036 lm). The driver is dimmable and has power factor correction to improve system efficiency and capacity. The correlated color temperature is nominally 3500 K, a neutral white suitable for many commercial and hospitality applications. The design of the SPE LED downlight affords a sufficiently low LED operating temperature to achieve a target life of 50,000 hours. The one-part reflector and trim is housed in a traditional 6-inch housing that can be installed from below the ceiling (suitable for remodeling jobs and requires a ceiling opening of 7 $^{1}/_{8}$-inches). The average performance characteristics of the seven prototypes produced are:

- Lumen output 720 lm at 9.5 W
- System efficacy 76 lm/W
- CRI of 75 at 3500 K
- Life (L_{70}) rating 50,000 hrs (junction temperature = 44 °C)

- Light distribution general diffuse
- Installation labor costs are the same as comparable CFL or incandescent luminaires

At this time, the location for the field test has not been determined. The research team is evaluating three potential sites.

Conclusions

Overall, this project demonstrated the potential of the SPE technology in terms of energy efficiency, light output, and life at the luminaire level. In general, the remote-phosphor approach to creating white LED-based luminaires seems very promising and a viable option for luminaire manufacturers looking for a different product with high energy efficiency performance.

Appropriate applications include commercial lobbies, offices, conference rooms, hospitality lobbies, reception areas, corridors, and general open areas. Based on the performance measured by the LRC team, it is expected that a production version of the SPE-based downlight would be ENERGY STAR®-rated.

Recommendations

To further this project the research team recommends that product development be continued, a manufacturing partner should be found to participate in product commercialization, and several field test sites should be selected for installation and monitoring of the SPE downlight.

Benefits to California

The primary market for the new LED lighting system is ambient and accent lighting applications in retail and hospitality buildings. Based on one percent market penetration and energy savings potential of 20 percent, electric consumption savings of 15 GWh and demand savings of 2.6 MW could be achieved. This estimate is conservative for two reasons: LED recessed downlights have quickly gained market share and, if replacing incandescents bulbs rather than CFLs, the energy efficiency improvement is greater than 20 percent.

1.0 Introduction

Lighting California's Future was a $3.7 million California Energy Commission Public Interest Energy Research Program focused on lighting technologies for buildings. The program, which was managed by Architectural Energy Corporation, featured nine technical projects and a cross-cutting market connection project. The goal of LCF was to help meet California's growing needs for energy efficiency and demand response by creating energy-efficient, advanced lighting technologies, products, systems, and implementation tools and bring them to market for the benefit of California's citizens.

The project on Advanced LED Lighting for Residential and Commercial Applications sought to develop an LED (light-emitting diode) luminaire for use in residential and commercial buildings. The LED lighting module is based on the Lighting Research Center's (LRC) patent-pending Scattered Photon Extraction (SPE™) technology, which has been shown to significantly improve the efficacy and light output of current generation LED technology. The project team included the LRC, which is part of Rensselaer Polytechnic Institute.

This LED lighting system (lamp, driver, and luminaire) has a target efficacy of 100 lumens per watt (lm/W), exceeding current incandescent, LED, compact fluorescent lamp (CFL), and many ceramic metal halide luminaire systems. The luminaire resulting from this project is expected to lower energy use in residential and commercial buildings in California and reduce peak energy demand. Additionally, the LED module is expected to improve the reliability of lighting products by significantly improving lamp life, compared with existing incandescent and CFL technologies. Longer lamp life also will reduce the impact of disposal on the waste stream and the environment.

1.1. Background

Commercial white LEDs combine a short-wavelength light-emitting semiconductor with a phosphor to produce white light. The scattering nature of most phosphors, however, causes more than half of the light, or photons, generated by the phosphor to divert back toward the semiconductor die, where much of it is absorbed and lost. This scattering reduces the LED's overall light output, luminous efficacy, and life.

LRC researchers developed a Scattered Photon Extraction (SPE) method to improve the light output and efficacy of white LEDs. The SPE method combines optimally shaped optics and placement of the phosphor away from the die. This configuration allows light traveling back toward the die to escape through the sides of the optics, generating 30 to 60 percent more light output (lumens) and luminous efficacy (lumens per electrical watt) than typical white LEDs. The new SPE-based LEDs are able to achieve an efficacy of more than 100 lumens per watt (lm/W). Moreover, moving the phosphor layer away from the die improves LED life. Figure 1 illustrates the concept.

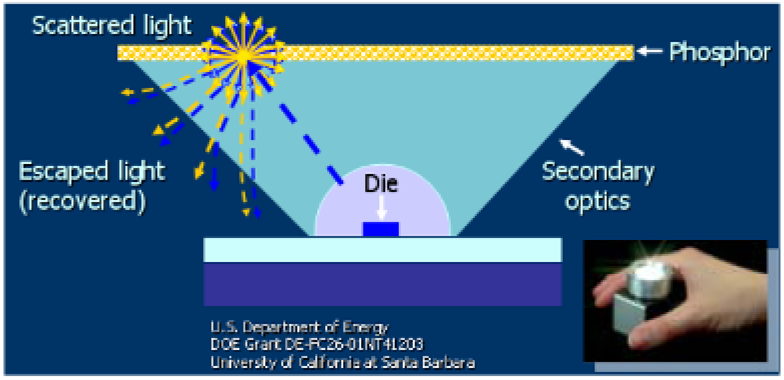

Figure 1. SPE technology recovers most of the backscattered light before it reaches the semiconductor die.
Source: Lighting Research Center

This PIER project was needed to move this technology to the product development stage and closer toward commercialization, where it can provide significant energy benefits. Luminaire developers and manufacturers were unlikely to undertake the research and development necessary on their own due to the high cost of LED components, their lack of knowledge concerning LED operation, and the relatively small market penetration of LED systems for general illumination. This project was needed to make it economically feasible and to bring together the research abilities, skills, and expertise needed to undertake it in an effective manner.

1.2. Project Objectives

The goal of this project was to develop an advanced, energy-efficient LED lighting system for wall-wash and other accent lighting applications in residential and commercial buildings.

Specific objectives were:

- Reduce lighting energy use in the selected application by 50 percent to 70 percent over current state-of-the-art lighting technologies.
- Be cost-effective to purchase, install, use, and maintain.
- Allow for easy and cost-effective control in response to occupancy and daylight.
- Respond easily to the need for reduced power requirements during times of peak electric demand.

1.3. Benefits to California

The major benefit of this project is reduced energy consumption, lower peak demand, and therefore lower energy costs for California ratepayers. Lighting uses a significant amount of energy in commercial and residential buildings in California. This highly efficient LED lighting system may reduce energy consumption in a large portion of existing buildings and new construction. As lighting designs for new buildings become more sophisticated, lighting designers are using downlighting, wall-washing, and accent lighting techniques to improve visual interest, visual comfort, and apparent brightness of spaces. It is important that highly efficient, flexible luminaire options be available to ensure that this lighting is applied more efficiently and effectively; otherwise, it can result in significant energy waste. The LED system from this project is controllable, so it can be linked with photosensors, occupancy sensors, or other building control strategies to save the maximum amount of energy and lower peak electric demand.

The LED system is also a more environmentally sustainable technology, significantly reducing the negative environmental impacts of lamp disposal. LEDs do not contain mercury, a material toxic to humans and animals, which is found in fluorescent lamps. LEDs provide effective lighting for more than 50,000 hours, which reduces the number of lamps disposed over time. This is 50 times the life of most incandescent technologies, 10 times the life of many CFL technologies, and more than twice the life of most linear fluorescent technologies. It also is important to note that the LED lighting system from this project will not only provide more efficient lighting, but will also reduce the heat that is radiated into a building compared with current incandescent, fluorescent, and metal halide technologies. This reduction of heat will provide a commensurate reduction in the energy used by a building's ventilation and air conditioning systems. The energy saved by the widespread use of this lighting system has the potential to significantly reduce emissions from California power plants.

Based on available market data, the LRC estimates that wall-wash and accent lighting applications account for between 5 percent and 20 percent of total lighting energy in California, depending on the application type. This would represent the total potential market for the products developed through this project. As shown above, the LED lighting product developed in this project will reduce energy use in these applications by between 50 percent and 70 percent, depending on the lighting technology being replaced.

The primary market for the new LED lighting system is ambient and accent lighting applications in retail and hospitality buildings. Based on one percent market penetration and energy savings potential of 20 percent, electric consumption savings of 15 GWh and demand savings of 2.6 MW could be achieved. This estimate is conservative for two reasons: LED recessed downlights have quickly gained market share and, if replacing incandescents bulbs rather than CFLs, the energy efficiency improvement is greater than 20 percent.

1.4. Commercialization Potential

The LRC hopes to develop a partnership with a major manufacturer that will license the SPE technology and move the system design to commercialization. Originally, the LRC intended to collaborate with Lightolier, a company that has a highly effective marketing strategy and distribution chain in California, excellent name recognition, and a reputation among lighting specifiers and end users of producing high-quality products that provide excellent long-term value. Lightolier has the expertise and experience needed to engineer, produce, and bring a luminaire to market in the most cost-effective manner possible. However, Lightolier was purchased by Phillips during the early stages of this PIER project. The impact of this acquisition was a change in direction by Lightolier. As a result, the Lightolier/LRC collaboration did not materialize and the LRC-developed LED commercialized downlight was not realized.

There are two main market barriers to be overcome before this LED lighting system will reach commercialization and any significant market penetration. The first market barrier is the luminaire's projected initial cost. This issue was to be addressed as part of the project development efforts. The SPE technology to be incorporated into the product allows for the production of a luminaire that will use 50 percentto 70 percent less energy than the most efficient luminaires available. The LED system within the luminaire lasts two to ten times longer than competing state-of-the-art technologies. The SPE technology is likely to be more cost-effective to produce than current white LED products, thus bringing down the overall product cost. These production cost reductions, coupled with reduced maintenance and energy costs provided by the product, allows for a reasonable rate of return for end users who purchase the LED lighting system. The payback period could be further enhanced if electric utilities in California offer financial incentives to the individual consumer to purchase and install the product.

The second market barrier to be overcome is a general reluctance of the lighting specification and end-use communities to accept new and unproven technologies. One of the recommendations is for the LRC to seek further funding, once this project is completed, for a full-scale demonstration and evaluation of the product in a "real world" application.

Once the LED lighting system is fully developed, the LRC intends to work closely with the ENERGY STAR® program to ensure that the product meets ENERGY STAR® specifications. Having the ENERGY STAR® designation will assist with the product's market penetration in the residential sector.

The LRC research team has identified a need to develop a specification-grade, highly efficient small aperture downlight (4" diameter) producing at least 1000 lumens to compete with compact fluorescent-based luminaires in size and light output, and with ceramic metal halide-based luminaire in life, cost, and dimming features. The primary market for the new LED lighting system is ambient and accent lighting applications in retail and hospitality (i.e., hotel, restaurant) industries and institutional (i.e., assisted living, dormitory) applications. For example, large retailers such as Macy's, Kohl's, Nordstrom, and Sears are continuously evaluating new lighting technologies that improve the sales floor environment while reducing maintenance and energy costs in their retail stores. These companies are such large purchasers of lighting equipment that they often work directly with manufacturers and have great influence over the new product development process. Downlights, wall-washers, and accent lighting are a substantial part of this market. A specification-grade LED product, which competes in price and performance with the incumbent technologies (ceramic metal halide, CFL, and incandescent), reduces required ceiling aperture, is dimmable and controllable by occupancy sensors, and has great potential to be preferentially specified in retail building design.

1.5. Report Organization

The report organization steps through the approach, outcomes, conclusions, and recommendations for the further development of the SPE technology into a viable LED product that may benefit California's citizens.

2.0 Project Information

2.1. Project Approach

The LRC intended to work with a major manufacturer throughout this project. The project team's goal was to research various downlight applications and define the best markets for potential product development. After the market analysis, the LRC planned to further develop the SPE technology. With the manufacturing partner, the LRC planned to develop the LED system, which would include the LED light system, driver, and housing, and target an efficacy of 100 lumens per watt (lm/W). Prototype systems would have been produced, tested, and refined. Market connection activities promoting the research were planned throughout the course of the project.

During the early stages of the project, however, the manufacturing partner was not able to continue as part of the team, and a field evaluation was considered as an additional task.

Key tasks to be accomplished using this approach are listed in Table 1.

Table 1. Project Tasks

Task 1. In-depth Market Analysis
Task 2. Further Development of SPE Technology
Task 3. LED Luminaire Development and Prototyping
Task 4. LED Luminaire Evaluation and Final Prototype Development
Task 5. Project-level Market Connections Activities

Source: Lighting Research Center

Outcomes associated with each task will be described in the next section.

2.2. Project Outcomes

2.2.1. In-depth Market Analysis

The LRC project team conducted an analysis of the market in California and determined the most appropriate product(s) to develop, based on the analysis. A brief summary follows.

Lighting accounts for approximately 9 percent of energy consumption in residential buildings and 36 percent of energy consumption in commercial buildings in the United States (EIA, 1996). In California, lighting accounts for almost 18 percent of energy consumption in residential buildings and 30 percent of energy consumption in commercial buildings during peak demand (UC Davis, 2004).

Table 2. Market data

Sector	Lighting Electricity Use (terawatt-hours)	Total Electricity Use (terawatt-hours)	Lighting as Percentage of Sector Total
Residential	340	1034	9.1%
Commercial	94	938	36.3%

Source: Energy Information Administration

As shown in Table 2, the majority of the electricity used for lighting in the United States is used in commercial buildings. It is estimated that more than 60 percent of lighting energy consumption is attributable to the commercial sector, with 20 percent used by residential lighting, and approximately 16 percent in the industrial sector (Atkinson et al., 1995).

The major source of illumination in the residential sector is the incandescent lamp, accounting for approximately 87 percent of the energy consumed by lighting in homes (Navigant, 2002). Each U.S. home contains an average of 30 luminaries, and the combined sales of residential luminaires from both new construction and remodeling is approximately 165 million units per year (Jennings et al., 1997). Recessed downlights are increasingly more popular in new homes and account for total sales of approximately 20 million per year. (Banwell and Figueiro, 2002) Recent surveys show that new homes now have an average of 23 recessed downlights (Navigant, 2002). Downlights in homes are estimated to consume approximately 15 percent to 20 percent of total lighting energy (Vorsatz, 1997). In contrast, commercial lighting energy consumption is dominated by the fluorescent lamp, which accounts for 77 percent of the energy consumed by lighting (Navigant, 2002). Of these, approximately 12 percent are compact fluorescent lamps (CFLs), which are typically used in downlight luminaires (Navigant, 2002). Considering that downlights, accent lights, and wall-wash luminaires using incandescent lamps are found in 60 percent of all commercial office buildings (EIA, 1998) and that some low-wattage high-intensity discharge (HID) sources are also used in commercial downlight luminaires, it is estimated that approximately 15 percent to 18 percent of total lighting energy in commercial buildings is attributable to downlight luminaires.

An analysis of both the residential and commercial downlighting markets indicates that one of the fastest growing luminaire types in each category is the recessed downlight (Lithonia, 2008). In the United States, the current residential downlight market exceeds $400 million per year, and the commercial downlight market exceeds $537 million per year (Lithonia, 2008). About $250 million of this market is for specification-grade fixtures with an initial cost greater than $65 per unit (Lithonia, 2008). Products sold in the specification-grade market segment are selected primarily based upon the product's performance (Lithonia, 2008). This market is an attractive segment for a light source that can show performance improvements over currently available light source technologies.

The most common lamp type used in commercial downlights is the CFL. Recent testing of CFL downlights showed that these downlights are, on average, only 44 percent efficient (NLPIP, 2008). A growing trend in commercial and residential downlights is consumer preference for downlights with smaller apertures, generally four inches (Lightolier, 2007). Because the distribution of CFLs does not realistically allow for a downlight with an aperture size less than six inches, a growing trend in commercial downlights is to use low-wattage ceramic metal halide lamps (Lightolier, 2007). These lamps, however, have several drawback including higher cost, non-dimmability, poor lamp-to-lamp color consistency, and lengthy startup time.

The LRC determined that the development of highly efficient, small aperture, specification-grade, recessed downlight fixtures geared toward the commercial lighting market would be the best course of action for this project. This would allow for the highest impact on energy savings in the shortest amount of time, especially in California where lighting and energy conservation trends tend to push the market toward more efficient, environmentally friendly products.

Based on the above market analysis and knowledge of competing products, the LRC project team would focus on the commercial downlight market, currently served primarily by 32-watt

CFL downlight products. The LED lighting system would have a target efficacy of 100 lumens per watt (lm/W), exceeding current incandescent, LED, ceramic metal halide, and CFL technologies. This technology is particularly well-suited to commercial lighting applications because it will:

- Reduce lighting energy use by 50 percent to 70 percentcompared to traditional incandescent and CFL technologies.
- Provide significantly longer life (5 to 10 times) than other available lighting technologies.
- Far exceed the requirements of the ENERGY STAR® specifications for lighting products.
- Allow for much more compact and flexible designs for targeted lighting products.
- Be easily dimmed, allowing for flexible and demand responsive lighting.
- Be cost effective to purchase, install, use, and maintain.

2.2.2. Further Development of SPE Technology

LRC researchers exploited the SPE technology to produce a downlight suitable for commercial use. In general, the development process included working iteratively on the following activities:

- Characterization of several commercial phosphors, types of lenses, and types of blue LEDs. During this task, the LRC team identified and procured the most efficient blue LEDs and phosphors available. Upon arrival of new components, the LRC team measured the excitation and emission characteristics of the different phosphors, the optical and electrical characteristics of the LEDs, and the optical properties of the secondary lenses. Several batches of products in each category were analyzed over the course of the project.
- Optical modeling to determine the phosphor density needed to achieve a target chromaticity between 3000 K and 4000 K with optimum luminous efficacy and color rendering properties. During this task, the LRC used LightTools modeling software to determine the best combination to achieve the photometric targets of the downlight. The information gathered during the characterization of the different SPE components was used to define the optical modeling parameters.
- Experimental verification of optical models. During this task and over the duration of the project, the LRC created several hundred SPE lenses with different phosphor mixes at different densities. Similarly, several test printed circuit boards were created and populated with several different bins of blue LEDs. The SPE lenses and LED boards were characterized individually and then matched together and characterized as modules. The characterization of the LED modules was conducted at different current values to determine the trade-offs between light output, luminous efficacy, and operating temperature.

Before finalizing the design of the SPE-based LED downlight, the LRC team produced several LED module prototypes. Figure 2 shows two of the initial models, one in a 5 inch diameter and one in a 2-inch diameter.

With the components available toward the end of the project, the LRC team achieved SPE-based LEDs with luminous efficacies of up to 106 lm/W (118 lm at 350 mA and 4793 K) and up to 114 lm/W (69 lm at 200 mA and 4020 K). These SPE-based LEDs had an average efficacy of 96 lm/W when operated at 350 mA and produced an average of 109 lm (average CRI = 74 at and average CCT = 4100 K). During the final iteration, the LRC team created over one hundred SPE lenses for use in seven prototype downlights intended for a field evaluation. The final set of lenses was created at a CCT of ~4100 K to account for the changes in color temperature resulting from the integration of the lenses inside the downlight. With these lenses, the resulting CCT of the downlights was 3500 K on average, as intended. As higher efficacy (amount of light produced by a lamp) blue LEDs become readily available, SPE-based luminaires will produce the same target light output but at a reduced input power. As an added benefit, the operating temperature of the LEDs will also decrease accordingly.

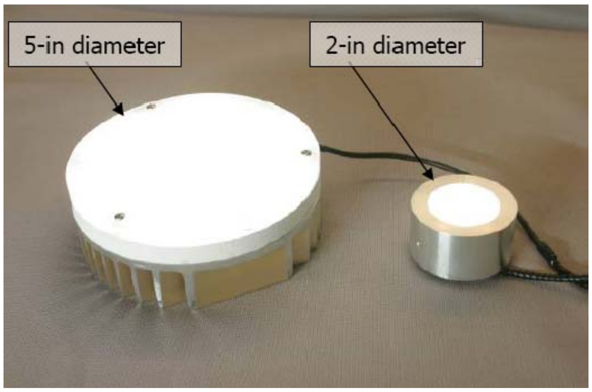

Figure 2. Two of the initial LED module prototypes featuring SPE technology.
Source: Lighting Research Center

2.2.3. LED Luminaire Development and Prototyping

The LRC developed a series of highly efficient prototype luminaires. The SPE technology was configured by the research team to take the best advantage of the optical and operational qualities of the prototype in trying to achieve the target performance. At the same time, the LRC team worked iteratively to develop the LED downlight. LRC researchers approached the electrical (driver), thermal and mechanical (housing), and optical (housing, reflector) elements of the luminaire in parallel to account for all the interactions among each of these components. LRC researchers characterized the performance (overall light output, color, and efficiency) of the final prototypes.

During the first few months of the project, the LRC worked together with Lightolier as a manufacturing partner. During this time, the LRC and Lightolier developed the target specifications for the SPE-based LED downlight based on the market analysis and Lightolier’s specific goals for a line of LED luminaires that would have the following target product specifications:

- Photometric
    - 1000 lm
    - CRI of 85 at 3000 K to 3500 K
    - Three beam spreads (for different ceiling heights)

    - 50 degree cut-off (the angle from straight down to the position where the light source is not directly seen
- Electrical
    - Dimmable
    - Compatible with occupancy sensors, photosensors, and load shedding controls
    - Capable of being used in emergency circuits or have its own battery back-up
- Mechanical/thermal
    - 4-inch diameter
    - Ideally less than 5-inch height, but not more than 6-inch height
    - Non-IC rated (light fixture is to be installed in a space that does not contain insulation)
- Economical
    - Target material costs $50
    - Target selling price less than comparable ceramic metal halide luminaire

However, as mentioned, the partnership between the LRC and Lightolier could not continue as expected after Philips's acquisition of the Genlyte Group, which includes Lightolier. In response to this change in logistics, the goal of the project shifted from producing a sufficient prototype to carry out a field demonstration to survey end users' opinions on the SPE-based LED downlights. In parallel, the LRC continuously sought partnerships with other companies, but none materialized.

In order to carry out a field demonstration, the target specifications of the SPE-based LED downlight were adjusted to reflect the most likely retrofit scenario in a commercial application, while being consistent with the overarching energy-efficiency goals of the project. The final specification for the SPE-based LED downlights was selected so that the SPE-based downlight could be installed to replace either a 75 W incandescent or a 26-32 W CFL 6-inch downlight, and include:

- Photometric
    - 600-1000 lm
    - CRI of 85 at 3000 K to 3500 K
    - Beam distribution: general downlight
- Electrical
    - Preferably dimmable
- Mechanical/thermal
    - 5-inch to 6-inch diameter
    - Non-IC rated ((light fixture is to be installed in a space that does not contain insulation)

It is worth emphasizing that the economics of the design were always considered but not optimized during this project. The experience and capabilities that a manufacturing partner can offer are needed to achieve specific manufacturing costs and sales prices. The following sections offer more details on how each one of the specifications were addressed.

Photometric Characteristics

The photometric needs of the prototype were addressed initially with the further development of the SPE-based modules. Figure 3 shows the progress in light output and luminous efficacy of some of the first prototypes built during the initial development phase. The results from this phase were instrumental in determining the number and type of LEDs and the type and mix of phosphors to achieve a balance between light output, efficacy, life, and color properties.

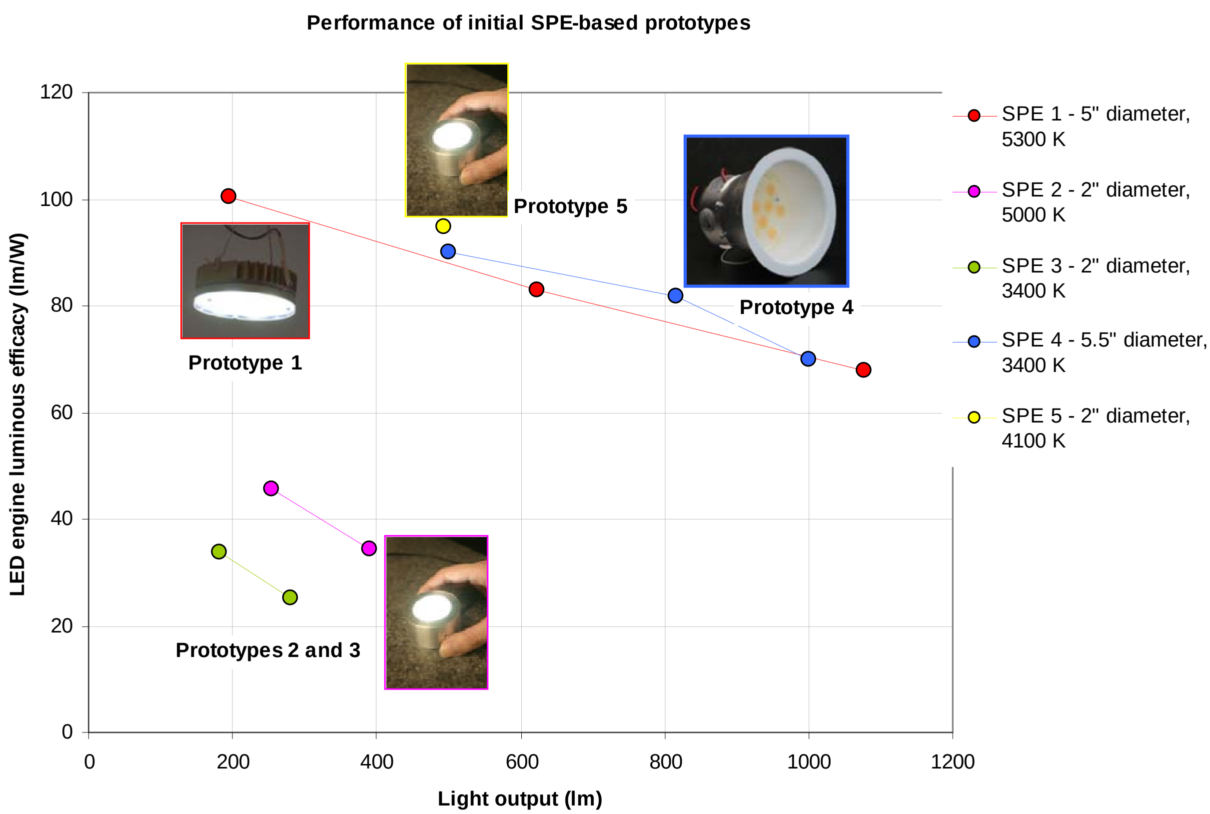

Figure 3. Light output and luminous efficacy of the initial SPE-based LED prototypes.
Source: Lighting Research Center

Electrical Characteristics

During this task, the LRC team specified the requirements needed for the driver (driver is a self-contained power supply that has outputs matched to the electrical characteristics of your LED) to be used in the final prototype. Several commercially available drivers were evaluated in terms of efficiency and their ability to drive the LED module at a current of approximately 175 mA. This current value was determined as the target to produce comparable light output from the LED downlight as compared to a 75 W incandescent downlight. Custom drivers capable of providing the required currents were procured from a manufacturer offering efficiencies higher than typical products. The average efficiency for the drivers ranged from 85 percent to 88 percent, values that are higher than those offered by most commercial products (~75 percent to 80 percent). Because a manufacturing partnership did not materialize, it was not possible to explore additional features of the driver such as load shedding. However, the driver samples produced for this project are dimmable and can be further optimized to increase efficiency and power factor correction.

Mechanical and Thermal Characteristics

The LRC team conducted several studies to determine the best thermal management strategy. LRC researchers analyzed the conductive, convective, and radiative properties of housings of different materials and geometries using specialized commercial software (Fluent). As in other tasks, the approach was iterative and included laboratory evaluations to determine some of the critical coefficients needed for the thermal modeling. Once the models were completed and validated experimentally, LRC researchers were able to enhance the conductive and radiative heat transfer of the housing by tailoring the material properties. Figure 4 shows an image of the computer modeling process where eventually the operating temperature of the LEDs can be estimated based on the electrical power dissipated by the LEDs, the materials, dimensions and geometry of the housing, and the application conditions (either IC or non-IC for purposes of experimentation). For ease of installation of the downlights in a field demonstration, the LRC team selected a commercially available outer housing. It is worth emphasizing that the thermal management of the LEDs is not dependent in any way on this outer housing (Figure 5).

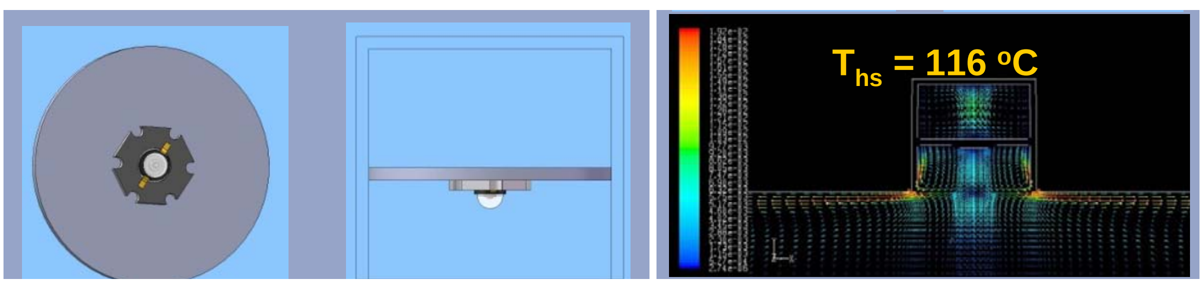

Figure 4. Sample images from the computer thermal modeling process to determine the optimum housing properties.

Source: Lighting Research Center

Economic Considerations

Although the LRC team kept the economics of the SPE-based downlight as a high priority, it was not possible to develop a design that was optimized for the initial economic targets of the project. In this area, the understanding of all variables involved and the expertise of a manufacturing partner are critical to achieve the production costs and selling price.

After several iterations, the LRC team produced an initial SPE-based downlight, shown in Figure 5. The thermal performance of this prototype was as expected; however, in the interest of increasing the light output and system luminous efficacy, the LRC took this design and refined it in one last step.

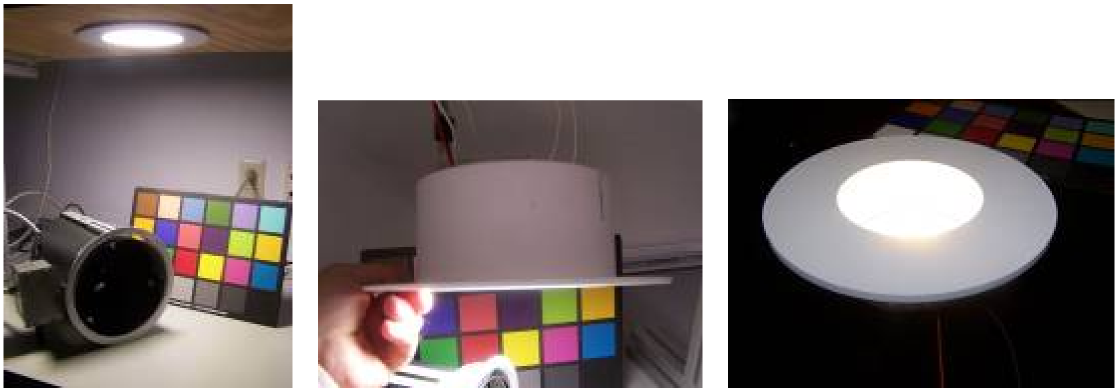

Figure 5. Housing (painted white) developed during this task to serve as initial LED housing, heat sink, and secondary reflector. The picture on the left shows the commercial outer housing selected to install the SPE-based downlight in a field demonstration.

Source: Lighting Research Center

2.2.4. LED Luminaire Evaluation and Final Prototype Development

The LRC carefully evaluated the performance of the prototype luminaires and modified the luminaire design as needed, conducted further testing, and developed a final design for the SPE-based LED downlight system. The final prototype minimized the use of metal to reduce weight and cost of the design without compromising the thermal performance. The design performed well to keep the LED junction temperatures as low as 44 °C when the LEDs are operated at a current of 175 mA (~8 W LED power, ~700 lm) with the fixture in contact inside with insulation. Such junction temperature can be translated into an estimated life of 50,000 hours, according to the LED manufacturer.

The final system has a nominal aperture of 6 inches and produces similar light output to a 75W BR40 or a 26W CFL downlight, but with only 9.5W of input power. The SPE downlight features an efficient driver with three additional settings if a higher light output is desired (up to 1036 lm). The driver is dimmable and has power factor correction (>0.95 at full load). The correlated color temperature of the SPE LED-based downlight is nominally 3500 K, a neutral white suitable for many commercial and hospitality applications. The design of the SPE LED downlight affords a sufficiently low LED operating temperature to achieve a target life of 50,000 hours. The one-part reflector and trim is housed in a traditional 6-inch housing that can be installed from below the ceiling (suitable for remodeling jobs; requires a ceiling opening of 7 $^{1}/_{8}$-inch). Figure 6 shows two images of the final prototype, and Figure 7 shows the seven prototypes produced.

Figure 6. Final housing design developed to reduce optical losses while maintaining the satisfactory thermal performance of previous prototypes.

Source: Lighting Research Center

The average performance characteristics of the seven prototypes produced are:

- Lumen Output 720 lm at 9.5W
- System Efficacy 76 lm/W
- CRI of 75 at 3500 K
- Life (L_{70}) rating 50,000 hrs (junction temperature = 44 °C)
- Light Distribution General diffuse
- Installation labor costs are the same as comparable CFL or incandescent luminaires

Appropriate applications are commercial lobbies, offices, conference rooms, open areas and hospitality lobbies, reception areas, corridors, and general open areas. Based on the performance measured by the LRC team, it is expected that a production version of the SPE-based downlight would be ENERGY STAR-rated.

Figure 7. The seven SPE-based LED downlight prototypes on a table (left), and six of them installed in an open area lab at the Lighting Research Center (right).

Source: Lighting Research Center

Figure 8 shows a comparison between the light output and luminaire efficacy among the SPE-based prototypes and several commercial products. The SPE-based prototypes has much higher efficacy than other similar products commercially available.

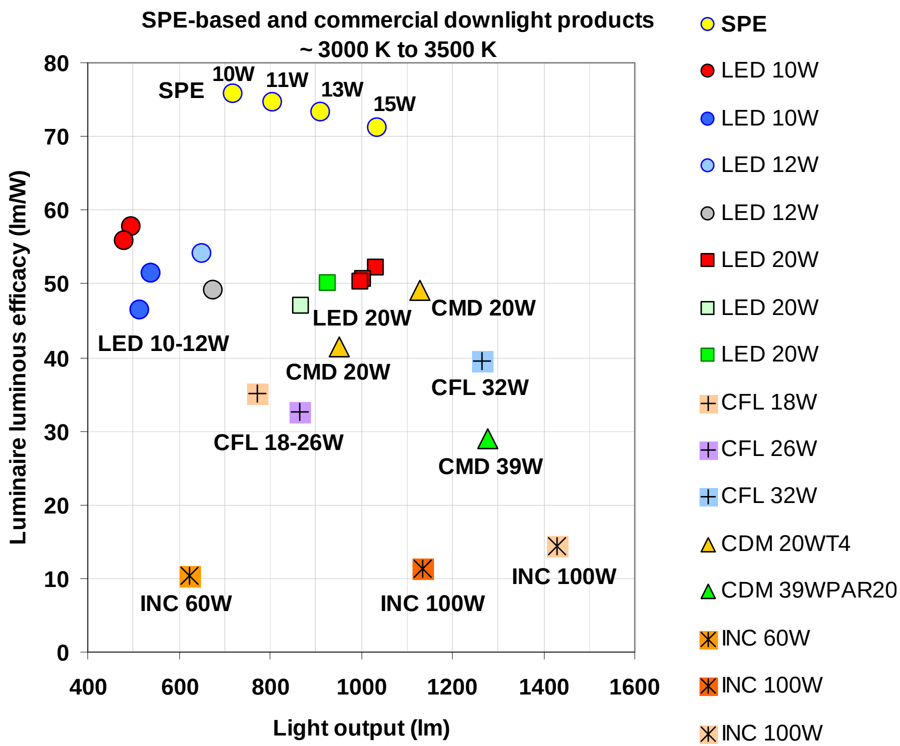

Figure 8. Light output and luminaire efficacy of SPE-based LED downlight prototypes and similar downlights in the market.
Source: Lighting Research Center

The final step in the evaluation of the SPE-based LED downlight design was a photometric test conducted by an independent laboratory. The measurements reported by the independent laboratory showed very strong agreement (within 3 percent) with the LRC's evaluation. Figure 9 shows the results of the intensity distribution portion of the test for the SPE-based downlight. The intensity distribution indicates the direction of the light in both tabular and polar graph formats and shows a broad distribution. In general the intensity distribution is needed to predict light levels at different locations based on the geometry of a given application. In this case, the plot shows a wide, diffuse light source that would be useful for general illumination (as opposed to a narrow distribution more suitable for accent lighting purposes). This information can be further used to inform a range of other lighting metrics.

Intensity (Candlepower) Summary at 25℃

Vertical Angle	Mean Cd
	LRC-SPE-DOWNLIGHT LED Recessed Can Retrofit
0	231
5	230
10	228
15	225
20	220
25	214
30	207
35	197
40	185
45	171
50	154
55	135
60	115
65	93
70	70
75	46
80	25
85	7
90	0

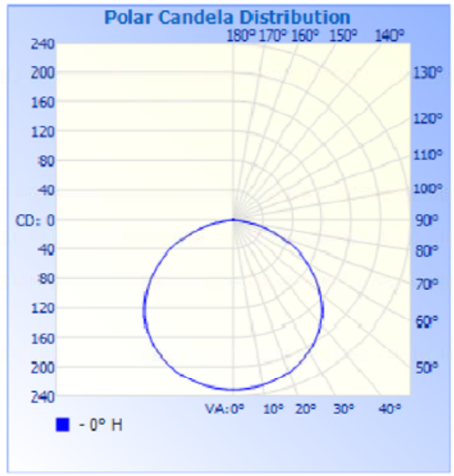

Figure 9. Intensity distribution of the SPE-based downlight as reported by an independent testing laboratory.

Source: Lighting Research Center

Field Test Summary

A field evaluation of the final prototype units was discussed as an additional step, though it was not part of the original scope of work. A field test may be pursued in the future with additional funding.

2.2.5. Market Connection Activities

The LRC has collaborated with the New Buildings Institute to produce preliminary specification sheets of the SPE-based downlight for media distribution. Additionally, the LRC has presented an invited paper on the topic of remote-phosphor LEDs and LED systems during the Ninth International Conference on Solid State Lighting in San Diego (August 3-5, 2009).

2.3. Conclusions and Recommendations

2.3.1. Conclusions

This research project provided several conclusions:

- This project demonstrated the potential of the SPE technology in terms of energy efficiency, light output, and life at the luminaire level.
- In general, the remote-phosphor approach to creating white LED-based luminaires seems very promising and a viable option for luminaire manufacturers looking for a different product with high energy efficiency performance.

2.3.2. Recommendations

Recommendations based on the results of this project are as follows:

- Continue with product development.
- Find a manufacturing partner to participate in product commercialization.
- Submit the commercialized downlight as a candidate product for the Utilities' Emerging Technologies Program.

- Find, install, and monitor several field test sites. Create case studies based on the test site results.

Glossary

Specific terms and acronyms used throughout this work statement are defined as follows:

Acronym	Definition
AEC	Architectural Energy Corporation
BR Bulb	Bulged reflector bulb
CCT	Correlated color temperature
Commission	California Energy Commission
CFL	Compact Fluorescent Lights
CRI	Color rendering index
DR	Demand response
FC	Footcandles
GW	Gigawatt
IC rated	Insulation contact-rated
IES	Illuminating Engineering Society
K	Kelvin temperature
LED	Light emitting diode
LM	Lumens
LPD	Lighting power density
LRC	Lighting Research Center
kW	Kilowatt
kWh	Kilowatt-hour
M&V	Measurement and Verification
mA	Milliamps
MW	Megawatt
MWh	Megawatt hour
N/A	Not available
NLPIP	National Lighting Product Information Program
RPI	Rensselaer Polytechnic Institute
IOU	Investor-owned utility
PIER	Public Interest Energy Research
SMUD	Sacramento Municipal Utility District
SPE™	Scattered photon extraction
Title 24	California Non-Residential Energy Efficiency Building Standards
TOU	Time of use (electricity rate)
UCC.1	Uniform Commercial Code (Financing Statement)
Vdc	Volts direct current
W	Watts
W/sqft	Watts per square foot

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