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Governor

LIGHTING CALIFORNIA'S FUTURE: ADVANCED LED DOWNLIGHTING SYSTEM

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Managed By:
Architectural Energy Corporation

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Public Interest Energy Research (PIER) Program
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DISCLAIMER

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Preface

The California Energy Commission 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 LED Downlighting System is the final report for the Lighting California's Future project (Contract Number 500-06-035) conducted by Architectural Energy Corporation and California Lighting Technology Center. The information from this project contributes to PIER's Building End-Use Energy Efficiency 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 was the California Energy Commission's $3.7 million Public Interest Energy Research Program focused on lighting technologies for buildings. The goal of the Advanced LED Downlighting System project was to design, develop, demonstrate, and commercialize an advanced light-emitting diode downlight system, retooling the traditional downlight and optimizing it for light-emitting diode sources while maintaining the features and functionality that have made downlights popular. This report describes the design and development activities with information on additional technology prototype revisions conducted to recharacterize the downlights using light-emitting diode sources currently available. The California Lighting Technology Center worked with various manufacturers to develop several versions of an integrated prototype with an indirect LED source. The prototype has been demonstrated at the California Lighting Technology Center facility and is looking for a commercialization partner. Once commercialized, this product can save California money by lowering maintenance costs due to longer product life and result in energy savings up to 75 percent compared to incumbent compact fluorescent lamp downlights.

Keywords: Solid-state lighting, LED, light emitting diode, indirect downlight, energy efficiency

Executive Summary

Introduction

Lighting California's Future was the California Energy Commission's $3.7 million Public Interest Energy Research Program focused on lighting technologies for buildings. The Advanced LED Downlighting System project focused on the design, development, demonstration, and commercialization of an advanced light-emitting diode downlight system, retooling the traditional downlight and optimizing it for light-emitting diode sources while maintaining the features and functionality that have made downlights popular. The energy savings potential of such a technology is very high for both business and home applications. Estimates indicate light-emitting diode downlights could save 80 percent as compared to incumbent technologies. Energy savings—combined with other technology benefits, such as long life, dimmability, and reduced recycling requirements—make light-emitting diode sources optimal choices for energy-efficient lighting research and development.

Project Objectives

Based on market research of existing downlight products, the project team identified performance criteria for a new, advanced light emitting diode downlighting system. Performance objectives included compliance with ENERGY STAR® requirements for downlights, maximization of system efficacy and optical efficiency using an indirect optical design, and optimization of controllability through creation of a plug-and-play, dimmable system with multiple downlights serviced by a single power supply.

Project Outcomes

The original intent of the project was to develop and commercialize a light-emitting diode downlighting system that would meet project objectives. Although the product was not selected for commercialization by industry partners, the project work resulted in:

- Developing of performance specifications for an advanced light-emitting diode downlighting system
- Developing of several indirect optical designs, which showed promise to meet the performance goals
- Completing prototype fabrication and testing demonstrated viability of the indirect optical design concept
- Making recommendations for increased optical and system performance for future indirect downlight system development

Conclusions and Recommendations

The California Lighting Technology Center and its manufacturing partners worked together to determine the commercial feasibility of the indirect downlight concept. Partners decided to commercialize a more traditional light-emitting diode downlight system using lessons learned during the design process of the indirect downlight project. The net result of this project was a market offering of a reliable, efficient light-emitting diode downlight module, suitable for new construction and retrofit applications, that provides significant energy savings over equivalent incandescent technology.

The California Lighting Technology Center continues product development and research on indirect downlight concepts and other light distribution designs. In particular, the California Lighting Technology Center recommends that manufacturers pursue emerging next-generation optical coating and films to improve optical efficiency, which allow indirect designs to achieve the system efficacies necessary to compete with traditional downlights.

Benefits to California

Once commercialized, this product can save California money by lowering maintenance costs due to longer product life and result in energy savings up to 75 percent compared to incumbent compact fluorescent lamp downlights.

Introduction

1.1. Background

The energy savings potential of light emitting diodes (LED) is very high, and many market sectors have experienced increased penetration of white-light LED luminaires into applications dominated by incandescent, fluorescent, and high intensity discharge (HID) sources. The residential and commercial downlight market is one niche application that is expected to see exceptional growth of LED products. One study estimates the energy savings potential of LEDs for these applications to be more than 80 billion kilowatt hours per year, assuming 100% market saturation, and the benefits go beyond energy savings[1]. LEDs are dimmable, have long life spans, minimal recycling requirements, reduced radiated heat, and are highly directional. All of these characteristics make the LED an optimal technology for energy-efficient luminaire research and development.

The goal of the Advanced LED Downlighting System Project was to design, develop, demonstrate, and commercialize an advanced light emitting diode downlight system, retooling the traditional downlight and optimizing it for LED sources while maintaining the features and functionality that have made downlights popular.

The California Lighting Technology Center (CLTC) was the primary technical leader on this project. Two manufacturers also involved in this project were Samsung Electronics and Philips Capri Lighting.

1.2. Project Objectives

Performance objectives included compliance with ENERGY STAR® requirements for downlights, maximization of system efficacy and optical efficiency using an indirect optical design, and optimization of controllability through creation of a plug-and-play, dimmable system with multiple downlights serviced by a single power supply.

1.3. Benefits to California

Estimates show that an average California home contains approximately three recessed downlights and that these luminaires account for 15% of all lighting energy use in the residential sector. This amount is expected to grow by 0.5% annually[2]. Energy-efficiency improvements to this important market sector will create significant energy savings for California. While similar statistics are not available for California's commercial sector, nationwide estimates show more than 800 million installed units, accounting for approximately 103 billion kilowatt hours (kWh) of energy use. Energy-efficient LED downlights are estimated to deliver 80% energy savings over these baselines.

1.4. Report Organization

The organization of the remainder of this report is as follows:

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1 Navigant Consulting. *Energy Savings Estimates of Light-Emitting Diodes in Niche Lighting Applications*. September 2008.

2 California Energy Commission. *Lighting Efficiency Technology Report – Volume 1 California Baseline*. September 1999.

Section 2.0 – Project Approach summarizes the methods used to design and develop an advanced LED downlighting system.

Section 3.0 – Project Outcomes describes the results of the project work.

Section 4.0 – Conclusions and Recommendations presents the conclusions drawn from the project research and the CLTC team's recommendations for future work.

2.0 Project Approach

Researchers from the CLTC partnered with manufacturing partners Samsung Electronics and Philips Capri Lighting to develop the advanced LED downlighting system. The following table shows the responsible parties for each task within the project.

Table 1. Task responsibility matrix

Task	Responsible Partner
Conduct market review to determine price points and cost constraints	CLTC
Develop product performance specification	CLTC
Design system components: optical assembly, power supply, driver	CLTC/Samsung Electronics /Philips Capri Lighting
Develop and test initial prototype	CLTC
Evaluate and refine initial prototype	CLTC/Philips Capri Lighting
Develop prototype of final design	CLTC
Demonstrate performance of prototype	CLTC/Philips Capri Lighting
Conduct project-level market connections activities (see the Final Report for Project 11, Market Connections)	CLTC

Source: California Lighting Technology Center

2.1. Market Review

The project team completed a comparison of traditional downlight systems to develop the energy and cost characteristics necessary for a competitive LED system. Table 2. Downlight product provides a comparison of technologies for a standard residential kitchen, an application appropriate for the type of LED downlight system under development. This analysis showed that a competitive LED downlight system should deliver approximately 650 lumens and have an installed cost of $120. Calculations are based on initial lamp lumens, $0.12 per kilowatt hour electricity cost, and 3.5 hours of operation per day.

Table 2. Downlight product comparison

	Standard incandescent (BR30)	4-pin CFL* downlight system	LED downlight system
Total # of downlights	10	8	10
Delivered lumens per downlight	620	850**	650
Power per downlight (Watts)	65	28	12
Materials cost per downlight	$20	$38	$90
Installation cost per downlight	$30	$30	$30
Total kitchen lamp lumens	6,200	6,800	6,500
Total kitchen power (Watts)	650	224	120
Total initial installed cost	$500	$544	$1,200
Operating cost per year	$99.65	$34.34	$18.40
Additional initial cost vs. incandescent	NA	$44	$700
Annual savings vs. incandescent	NA	$65.31	$81.25
Simple payback (additional initial cost vs. incandescent/annual savings vs. incandescent)	NA	0.67	8.62
Color rendering index (CRI)	100	~82	~92

Source: California Lighting Technology Center staff calculations

* Compact fluorescent lamp

**Assumes 50% luminaire efficiency. Luminaire efficiency taken from the following source: Davis, Roberts, and Welhong Chen. 1995. Specifier Reports, "CFL Downlights," Vol. 3 No. 2, page 29. August 1995

2.2. Performance Specifications

Based on research to characterize existing downlight products on the market, the project team identified performance criteria for a new, advanced LED downlight that would meet ENERGY STAR downlight requirements, provide appropriate visual comfort, and reduce glare for residential use. The team aimed to meet ENERGY STAR because it is an industry-accepted certification that consumers trust. In addition, many rebate and incentive programs require ENERGY STAR certification for program participation. The team felt these incentives would be vital in creating a cost-effective, competitive LED system.

The following are the ENERGY STAR photometric requirements for recessed downlights.

Minimum Light Output

- Aperture ≤ 4.5" : 345 lumens (initial)
- Aperture > 4.5" : 575 lumens (initial)

Zonal Lumen Density Requirement

- Luminaire shall deliver a minimum of 75% of total lumens (initial) within the 0-60° zone (bilaterally symmetrical).

Minimum Luminaire Efficacy

- 35 lumens/Watt (lm/W)

Allowable Correlated Color Temperatures (CCTs)

- 2,700 Kelvin (K), 3,000 K and 3,500 K for residential products
- No restrictions for commercial products

Building from the ENERGY STAR foundation, the team identified a set of initial performance criteria for the LED downlight system. Initial specifications sought to achieve the maximum level of energy efficiency, optical efficiency, and controllability. In particular, the power supply was conceptualized to include multiple control channels capable of accepting control signals for various types of controllers such as occupancy sensor, photosensors, and scene controllers. These optional features would be coupled with a dimming driver to achieve the multiple light levels anticipated to result from these control scenarios.

Optical System

- Utilize an indirect design to reduce brightness and increase visual comfort
- Meet ENERGY STAR criteria for total lumen output and efficacy

Power Supply

- Utilize switch mode power supply (SMPS) technology (see the section on Task 7.2, Power Supply Design and Development, for details on this technology)
- Electrical efficiency > 87%
- Operate up to 10 downlights
- Meet Underwriters Laboratory safety standard 1598 for luminaires
- Meet Federal Communications Commission Class B (residential use) electromagnetic compatibility standard for radio frequency
- Total harmonic distortion < 10%
- Power factor > 90
- Optional low-voltage control inputs
- Optional digitally addressable control inputs
- Optional occupancy sensor input
- Optional manual dimmer input
- Optional scene controller input
- Optional timer input
- Optional photosensor input
- Withstand insulation contact at 55° Centigrade ambient temperature

Driver

- Electrical efficiency > 94%
- Operate up to 2 downlights
- Accept maximum input of 48 volts (V)
- Produce maximum output of 700 milliampere (mA)
- Drive 14 LEDs @ 700 mA maximum
- Have current follow voltage from 48V-32V

- Off state if voltage < 32V

2.3. System Design

The CLTC focused on design optimization and development for each of the three key components of an LED downlight: optical system, power supply, and driver. All potential designs utilized an indirect approach, whereby LED emitters were shielded from direct view and their light was directed into the downlight housing where it was reflected back out of the aperture. Figure 1 is a rendering of the indirect cross design. This was the design selected by the project team for prototype fabrication and testing.

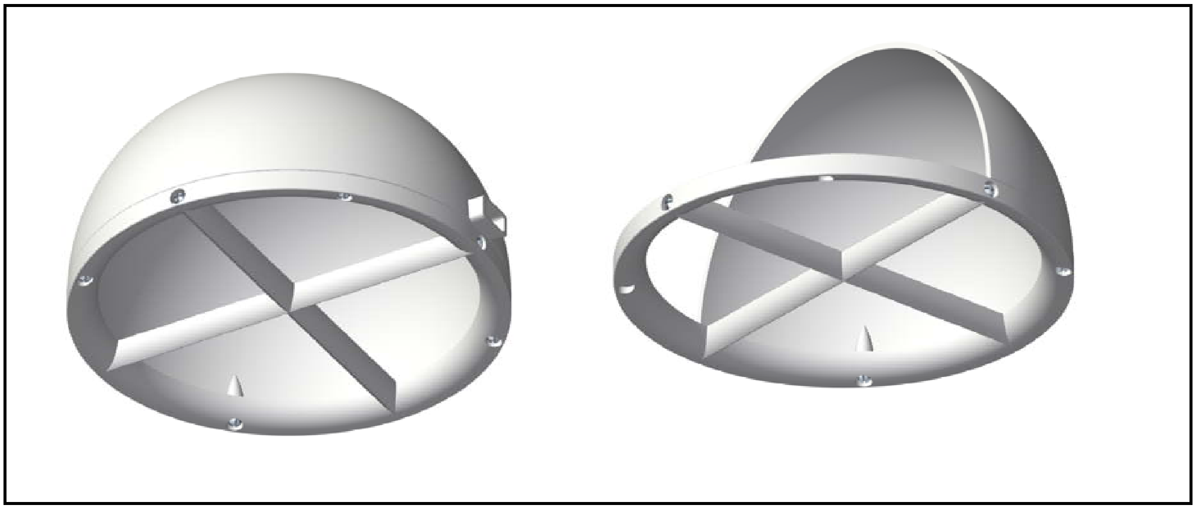


Figure 1. Indirect cross design

Source: California Lighting Technology Center

Figure 2 shows the visual comfort analysis results for the indirect cross concept. The indirect cross was shown to have an optical efficiency of 64% and a maximum brightness of 10,790 cd/m2. These results indicate that the indirect cross provides superior optical efficiency and visual comfort.

The indirect optical design approach reduced the visual discomfort and glare commonly associated with LED sources used in direct lighting designs. Additional considerations included analysis of LED emitters and thermal design to ensure LEDs operated within manufacturer recommendations.

Based on the emitter analysis results, the team determined that a higher color rendering index (CRI) value would be needed to meet ENERGY STAR criteria. Based on a survey of available LED providers, the project team determined that a Cree product would be the best choice for the LED. The team focused on the XR-E emitter family and compared the P2 and P3 output groups. With the goal of meeting ENERGY STAR criteria for the downlight, the team compared the downlight’s output in lumens per watt (lm/w) and plotted the results against the associated drive current required. From the P2 and P3 analysis, the project team concluded that the higher-output (P3) LEDs are preferable. Although these LEDs were more expensive, economies of scale in producing the downlights could reduce costs to some extent.

The project team verified that the thermal performance of the prototypes. The team gathered thermal data for three downlight prototypes over a 96-hour period by fitting fixtures with a thermocouple for each LED. The second prototype performed best and met project requirements. Temperatures generally ranged from 80° to 90° celsius.

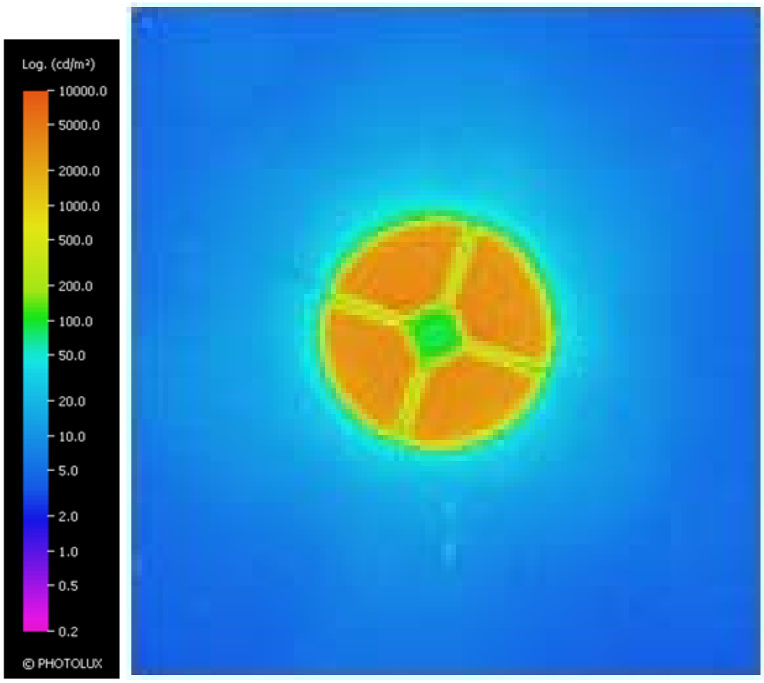


Figure 2. Indirect cross visual comfort analysis

Source: California Lighting Technology Center

The team refined the power supply and driver design several times in order to achieve optimal operating conditions. The initial design housed the drivers separately, but the final design housed them together with the power supply in a single unit for ease of installation. A prototype driver was supplied by Samsung Electronics. This unit was tested to ensure it performed in line with project requirements. The project team validated the electrical efficiency, power factor, harmonic distortion, and other characteristics of the initial power supply provided by Samsung Electronics. Following a test of the initial unit, the team changed the final product specification to reflect 600 mA constant current to increase system performance. The final product performed as documented below:

- Voltage @ output of driver with open 0 – 10 V signal : ~ 55 volts direct current (DC)
- Current through 16 LEDs with open 0 – 10 V signal : ~ 606 mA DC
- Voltage with 0 – 10 V signal – Dimmer switch full up position: ~ 55 volts DC
- Current with 0 – 10V signal – Dimmer switch full up position: ~ 606 mA DC

- Comparable results seen on 4 different driver units

Samsung Electronics also provided four additional drivers for use in the project. The CLTC team tested these units to verify the drivers' performance relative to the final performance specifications and to ensure repeatability of results. Each module served two downlights. The driver utilized with pre-production prototypes was a single-channel unit with 24V DC input and 60V/0.6A output.

2.4. Prototype Fabrication and Testing

The manufacturing partner for this project, Philips Capri Lighting, wanted a lighting system that would fit into standard existing downlight housings to ensure ease of retrofit installations, so the design was constrained to fit a 6.5"-diameter housing. As a result, the cross heat sink size was reduced from original designs to leave room for the optic in the existing housing. In the first pre-production prototypes provided by Philips Capri Lighting, the thermal design did not meet either the manufacturer's requirements for thermal performance or ENERGY STAR performance criteria. In order to meet these requirements, different LEDs were selected for the final design, which also had lower source efficacy. In addition, the team fine-tuned the heat sink design to meet the thermal specifications. The following figures show the initial and final indirect downlights. These units utilized the power supply and driver described in Section 2.2.

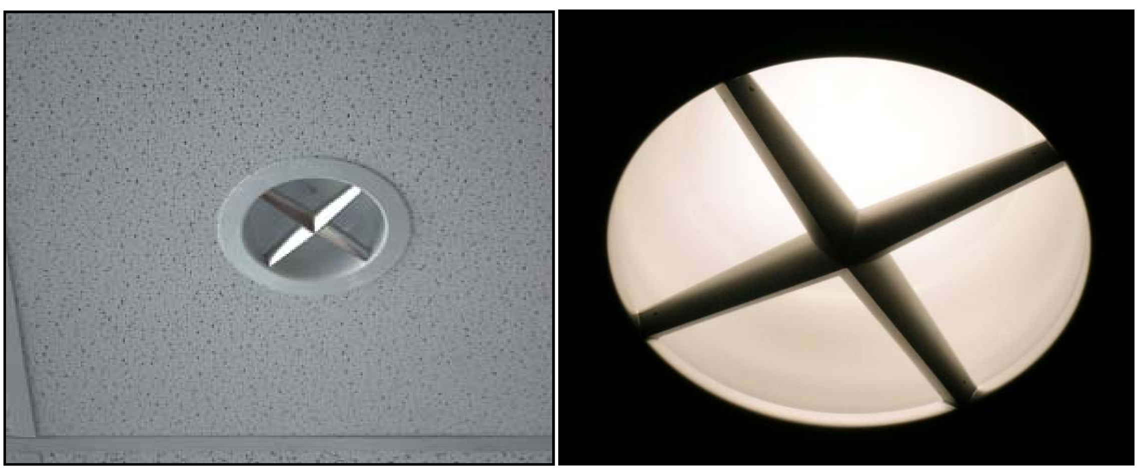


Figure 3. First prototype produced by Philips Capri Lighting, based on CLTC design (left) and final indirect downlight (right)

Source: California Lighting Technology Center

Table 3. Final indirect cross downlight performance test results

Source Lumen Output	825.0 lumens
Luminaire Lumen Output	486.8 lumens
Fixture Efficiency	59%
CRI	85.1

CCT	3,060 K
Power	16.2 W
Luminaire Efficacy	30.0 lm/W

Source: California Lighting Technology Center

Additional design work was conducted at the end of the project to update the indirect downlight concept light engine. The original design incorporated Cree XR-E LEDs but during this project Cree released two new LEDs that are interchangeable electrically but offer increased performance over the XR-E. These are the XP-E and the XP-G. The fixture below shows the redesigned circuit board for the XP LEDs.

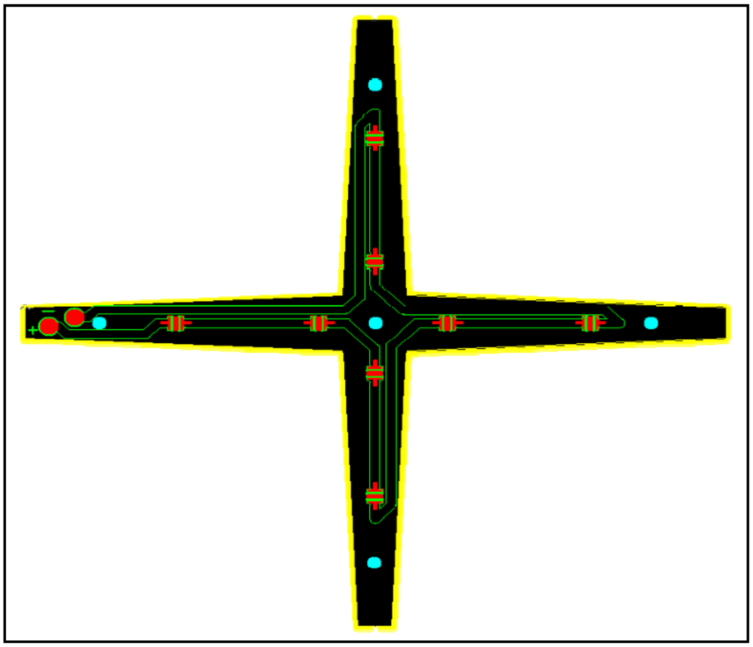


Figure 4. Final circuit board design

Source: California Lighting Technology Center

The CLTC selected a high-quality thermal interface material with low thermal impedance to optimize heat dissipation away from the high powered Cree XP LEDs. This material utilized a thick 2 oz. copper layer to optimize power transfer and heat mitigation throughout the cross-design heat sink. The aluminum base layer, as opposed to typical double sided board stock that utilizes a fiberglass core, also contributed to optimal thermal performance of the revised design.

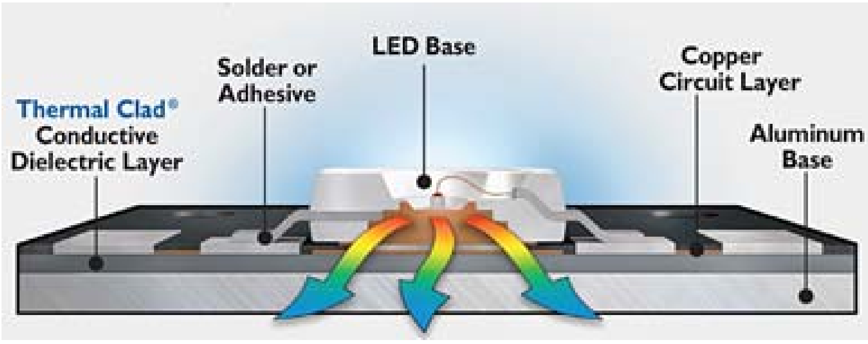


Figure 5. LED heat dissipation and chip schematic
Source: The Berquist Compant

Following selection of the thermal insulation material, the CLTC determined the minimum trace width required for the circuits based on a maximum operating current of 700 mA and material properties of the insulation. The trace width required was found to be 2 mm. This value was verified by calculating the voltage drop across the circuit board, which is dependent on the trace width and was found to be negligible compared to the voltage draw of the eight LEDs contained in the design. While these changes did not increase the overall optical efficiency of the design, they did increase the light engine efficacy and total light output.

2.5. Prototype Demonstration

The CLTC fabricated several prototypes using the final design and installed these units in local area displays. Four units are currently on display at the CLTC facility. These units are part of a kitchen vignette, which is used to demonstrate the lighting quality and energy savings of next-generation downlights. Visitors to the facility can compare the indirect downlights to other LED and fluorescent products, also installed in the display. The units have drawn interest from manufacturers, lighting designers, and home owners regarding their availability.

Figure 6. Indirect downlight prototypes on display at CLTC

Source: California Lighting Technology Center

3.0 Project Outcomes

The primary outcomes of this project are as follows:

- Developed performance specifications for an advanced LED downlighting system
- Identified challenges of using an indirect approach to mitigate the visual discomfort often associated with LED luminaires
- Developed several indirect optical designs, which showed promise to meet the performance goals
- Refined and selected promising designs for full prototype development
- Completed prototype testing and identified additional issues that should be addressed prior to commercialization
- Demonstrated pre-production prototypes to show validity of the indirect concept for LED downlights
- Recommended increased optical and system performance for future indirect downlight system development

4.0 Conclusions and Recommendations

4.1. Conclusions

The CLTC and Phillips Capri Lighting worked together to determine the feasibility of manufacturing the indirect downlight concept. After exhausting all viable options, it was determined that manufacturing and cost constraints would result in a downlight system that would not meet the performance specification. Because of this, Capri decided it would be best to commercialize a more traditional LED downlight system utilizing lessons learned during the design process of the indirect downlight project. The net result of this project was Philips Capri Lighting offering a reliable, efficacious LED downlight module (CRL6K-14) that provides significant energy savings over equivalent incandescent technology. The specification sheet provided by Philips Capri Lighting may be found in attachment A.

4.2. Recommendations

The California Lighting Technology Center continues product development and research on indirect downlight concepts and other light distribution designs. These designs have the ability to mitigate the visual discomfort commonly associated with LED luminaires. In particular, CLTC recommends that manufacturers pursue emerging next-generation optical coating and films to improve optical efficiency, which allow indirect designs to achieve the system efficacies necessary to compete with traditional downlights.

4.3. Benefits to California

Once commercialized, this product can save California money by lowering maintenance costs due to longer product life and result in energy savings up to 75 percent compared to incumbent compact fluorescent lamp downlights.

Glossary

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

Acronym	Definition
AEC	Architectural Energy Corporation
C	Celsius
CCT	Correlated color temperature
Commission	California Energy Commission
CLTC	California Lighting Technology Center
CFL	Compact fluorescent lights
CRI	Color rendering index
DC	Direct current
FC	Footcandles
GW	Gigawatt
HID	High intensity discharge
K	Kelvin temperature
kcd/m2	Kilocandelas per square meter
LED	Light-emitting diode
LM	Lumens
lm/W	Lumens a Watt
LPD	Lighting Power Density
kW	Kilowatt
kWh	Kilowatt-hour
mA	Milliamps
MW	Megawatt
MWh	Megawatt Hour
PIER	Public Interest Energy Research
SMPS	Switch Mode Power Supply
Vdc	Volts direct current
V	Volts
W	Watts
W/sqft	Watts per square foot

Attachment A

CRL6K

6" Capri Recessed LED Retrofit

Remodel

Catalog Number:____________________

Type:____________________

Project:____________________

The Capri CRL6K Retrofit LED Series provides the latest in LED technology in an easy to install module that mounts into a variety of Capri 6" recessed housings in minutes. The all-in-one unit comes complete with a medium base socket adapter that screws into the existing incandescent socket. cETL listed and suitable for use in IC and non-IC applications.

Features

- Energy-saving long life LED technology produces lumens approximately equal to a 65W BR30 lamp.
- Energy efficient - Consumes only 14 watts of energy.
- Long life LEDs designed to perform up to 50,000 hours with 70% lumen maintenance.
- LED module mounts easily with torsion springs into incandescent housings and screws into existing medium base sockets with provided adapter.
- Wide selection of finishing trims, reflectors and baffles, in a variety of finishes to complement any decor.
- Frosted lens provides soft comfortable light.
- Dimmable with AC line dimmers.
- cETL listed for IC and non-IC applications.

CATALOG SYSTEM AND OPTIONS

SAMPLE CATALOG NUMBER: CRL6K-14-30K-CRL6R-CLR

HOUSING		WATTAGE		COLOR TEMPERATURE	VOLTAGE	REFLECTOR	STYLE	REFLECTOR
CRL6K	-	14	-	30K	____	CRL6	____	____
CRL6K 6" LED Retrofit Kit		14 14 watt		30K 3000 Kelvin	BLANK 120 Volt	CRL6 6" LED Retrofit Trim Insert	R Reflector B[1] Baffle	WHT White BLK Black CLR Clear GLD Gold

Footnotes:
1. Baffle available in white or black only.

SPECIFICATIONS

1. **Die-Cast Heat Sink** - Large, yet lightweight die-cast aluminum heat sink helps dissipate heat generated by LEDs to ensure long LED life; up to 50,000 hours with 70% lumen maintenance.

2. **Lower Trim Casting** - Die-cast aluminum lower trim assembly works in conjunction with the die-cast heat sink to help dissipate heat.

3. **LED Module** - Unique 4-cluster LED module with ceramic board provides light output comparable to a 65W BR30 lamp. Available in 3000K CCT.

4. **LED Driver** - High efficiency, UL1310 class 2 driver is fully potted and dimmable with a typical AC line dimmer. See dimming chart for compatible dimming systems.

5. **Mixing Chamber** - Deep mixing chamber is lined with Miro™ 5 optical material for maximum brightness and efficiency.

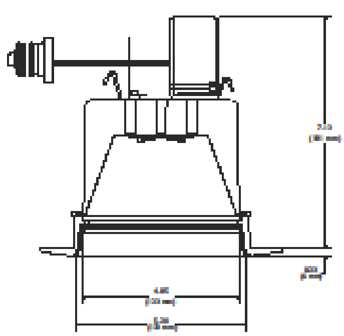
6. **Lens** - frosted lens works in conjunction with the mixing chamber to deliver high brightness while minimizing glare to provide comfortable, quality illumination.

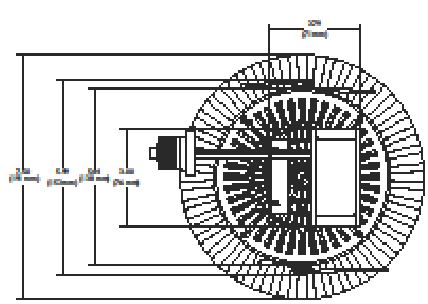
7. **Socket Bracket** - convenient bracket to mount existing incandescent bracket.

8. **Finishing Trims** - A variety of trims snap into the trim casting for a wide choice of appealing looks. Available in smooth reflectors or baffles in clear, gold, white, or black finishes.

9. **c/ETL listed** for Damp Locations and Through Branch Circuit Wiring 4 in/4 out.

DIMENSIONS





REV. 05/10

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