Cree® XLamp® MK-R LED MR16 Reference Design

TABLE OF CONTENTS

Introduction 1
Design approach/objectives 2
The 6-step methodology 2
1. Define lighting requirements 2
2. Define design goals 5
3. Estimate efficiencies of the optical, thermal & electrical systems 5
4. Calculate the number of LEDs 7
5. Consider all design possibilities 7
6. Complete the final steps: implementation and analysis 8
Conclusion 10
Bill of materials 11

INTRODUCTION

The compact MR16 form factor, with limited space for drive electronics and thermal dissipation, presents a difficult challenge for an LED-based design. Built on Cree's revolutionary SC³ Technology™ platform, the Cree XLamp MK-R LED enables that challenge to be met by a high-lumen-output, high-light-quality lamp.

Building on Cree's reference designs of MR16 replacement lamps using XLamp MT-G, XM-L EasyWhite™, XP-E and XB-D LEDs, this design demonstrates the possibility of

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employing the XLamp MK-R LED as the light source of a 50-watt equivalent MR16 replacement lamp for use as an indoor spotlight.[1]

DESIGN APPROACH/OBJECTIVES

In the "LED Luminaire Design Guide"[2] Cree advocates a six-step framework for creating LED luminaires and lamps. All Cree reference designs use this framework, and the design guide's summary table is reproduced below.

Step	Explanation
1. Define lighting requirements	• The design goals can be based either on an existing fixture or on the application's lighting requirements.
2. Define design goals	• Specify design goals, which will be based on the application's lighting requirements. • Specify any other goals that will influence the design, such as special optical or environmental requirements.
3. Estimate efficiencies of the optical, thermal & electrical systems	• Design goals will place constraints on the optical, thermal and electrical systems. • Good estimations of efficiencies of each system can be made based on these constraints. • The combination of lighting goals and system efficiencies will drive the number of LEDs needed in the luminaire.
4. Calculate the number of LEDs needed	• Based on the design goals and estimated losses, the designer can calculate the number of LEDs to meet the design goals.
5. Consider all design possibilities and choose the best	• With any design, there are many ways to achieve the goals. • LED lighting is a new field; assumptions that work for conventional lighting sources may not apply.
6. Complete final steps	• Complete circuit board layout. • Test design choices by building a prototype luminaire. • Make sure the design achieves all the design goals. • Use the prototype to further refine the luminaire design. • Record observations and ideas for improvement.

Table 1: Cree 6-step framework

THE 6-STEP METHODOLOGY

The goal of this design is an LED-based 50-watt equivalent retrofit MR16 lamp that shows the performance available from the XLamp MK-R LED.

1. DEFINE LIGHTING REQUIREMENTS

Table 2 shows a ranked list of desirable characteristics to address in an MR16 lamp reference design.

1 Cree XLamp MT-G MR16 Reference Design, Application Note AP62, www.cree.com/xlamp_ref/mtg_mr16
Cree XLamp XM-L EZW MR16 Reference Design, Application Note AP71, www.cree.com/xlamp_ref/xml_ezw_mr16
Cree XLamp XP-E MR16 Reference Design, Application Note AP76, www.cree.com/xlamp_ref/xpe_mr16
Cree XLamp XB-D MR16 Reference Design, Application Note AP95, www.cree.com/xlamp_ref/xbd_mr16

2 LED Luminaire Design Guide, Application Note AP15, www.cree.com/xlamp_app_notes/luminaire_design_guide

Importance	Characteristics	Units
Critical	Light intensity - center beam candle power (CBCP)	candelas (cd)
	Beam angle - full width half maximum (FWHM)	degrees (°)
	Illuminance distribution	footcandles (fc)/lux (lx)
	Power	watts (W)
	Luminous flux	lumens (lm)
	Efficacy	lumens per watt (lm/W)
	Form factor	
Important	Price	$
	Lifetime	hours
	Operating temperature	°C
	Correlated color temperature (CCT)	K
	Color rendering index (CRI)	100-point scale
	Manufacturability	

Table 2: Ranked design criteria for an MR16 lamp

Table 3 summarizes the ENERGY STAR® requirements for all integral LED lamps.[3]

Characteristic	Requirements
CCT and Duv	Lamp must have one of the following designated CCTs (per ANSI C78.377-2008) consistent with the 7-step chromaticity quadrangles and Duv tolerances below. Nominal CCT / Target CCT (K) and Tolerance / Target Duv and Tolerance: 2700 K / 2725 ± 145 / 0.000 ± 0.006 3000 K / 3045 ± 175 / 0.000 ± 0.006 3500 K / 3465 ± 245 / 0.000 ± 0.006 4000 K / 3985 ± 275 / 0.001 ± 0.006
Color maintenance	The change of chromaticity over the minimum lumen maintenance test period (6,000 hours) shall be within 0.007 on the CIE 1976 (u′, v′) diagram.
CRI	Minimum CRI (R_a) of 80. R_9 value must be greater than 0.
Allowable lamp bases	Must be a lamp base listed by ANSI.
Power factor	Lamp power < 5 W and low voltage lamps: no minimum power factor is required Lamp power > 5 W: power factor must be $\geq$ 0.70 Note: Power factor must be measured at rated voltage.
Minimum operating temperature	-20 °C or below
LED operating frequency	≥ 120 Hz Note: This performance characteristic addresses problems with visible flicker due to low frequency operation and applies to steady-state as well as dimmed operation. Dimming operation shall meet the requirement at all light output levels.
Electromagnetic and radio frequency interference	Must meet appropriate FCC requirements for consumer use (FCC 47 CFR Part 15)
Audible noise	Class A sound rating
Transient protection	Power supply shall comply with IEEE C62.41-1991, Class A operation. The line transient shall consist of seven strikes of a 100 kHz ring wave, 2.5 kV level, for both common mode and differential mode.
Operating voltage	Lamp shall operate at rated nominal voltage of 120, 240 or 277 VAC, or at 12 or 24 VAC or VDC.

Table 3: ENERGY STAR requirements for all lamps

3 ENERGY STAR® Program Requirements for Integral LED Lamps Eligibility Criteria – Version 1.4, Table 4 www.energystar.gov/ia/partners/product_specs/program_reqs/Integral_LED_Lamps_Program_Requirements.pdf

Table 4 summarizes the ENERGY STAR requirements for replacement MR16 lamps.[4]

Criteria Item	ENERGY STAR Requirements
Definition	Directional lamp means a lamp having at least 80% light output within a solid angle of Π sr (corresponding to a cone with angle of 120°)
Minimum luminous efficacy	Lamp diameter < 20/8 inch: 40 lm/W Lamp diameter > 20/8 inch: 45 lm/W
Color spatial uniformity	The variation of chromaticity within the beam angle shall be within 0.006 from the weighted average point on the CIE 1976 (u', v') diagram.
Maximum lamp diameter	Not to exceed target lamp diameter
Maximum overall length (MOL)	Not to exceed MOL for target lamp
Minimum center beam intensity PAR and MR16 lamps	
MR16 lamps	Link to online tool at www.energystar.gov/ia/products/lighting/iledl/IntLampCenterBeamTool.zip
Lumen maintenance	> 70% lumen maintenance (L_{70}) at 25,000 hours of operation
Rapid-cycle stress test	Cycle times must be 2 minutes on, 2 minutes off. Lamp will be cycled once for every 2 hours of L_{70} life.

Table 4: ENERGY STAR requirements for MR16 lamps

As shown in Figure 1, we used the ENERGY STAR Center Beam Intensity Benchmark Tool to determine that a 50-W equivalent MR16 lamp with an 18° beam angle needs to provide CBCP of 3,838 cd.

ENERGY STAR® Integral LED Lamp Center Beam Intensity Benchmark Tool

MR-16 Lamps

Target Halogen Lamp Parameters

Enter Nominal Lamp Wattage: **50** watts
Enter Nominal Beam Angle*: **18** degrees

Minimum Center Beam Intensity: 3838 cd

Term	Coefficient		Watts	Beam Angle		Predicted Log CBCP	Log CBCP Two-sigma Lower Bound		Predicted CBCP	CBCP Two-sigma Lower Bound
Intercept	8.2926932		50	18		8.749	8.253		6302	3838
Watts	0.0685006									
Beam Angle	-0.109284									
$Watts^2$	-0.000514									
$Beam Angle^2$	0.0008734									
Root Mean Square Error	0.247998									

*Nominal beam angle per ANSI C78.379-2006: American National Standard for electric lamps-- Classification of the Beam Patterns of Reflector Lamps.
See Section 4.1 Nominal beam angle classifications, and section 4.3 Beam angle tolerance of PAR and R lamps.

Figure 1: ENERGY STAR Center Beam Intensity Benchmark Tool output for 50-W equivalent MR16 lamp with 18° beam angle

4 Ibid., Table 7C

2. DEFINE DESIGN GOALS

The aim of this project is a 50-W equivalent MR16 indoor spotlight with an 18° beam angle using the XLamp MK-R LED. Table 5 shows the design goals for this project.

Characteristic	Unit	Minimum Goal	Target Goal
CBCP - 18° beam angle	cd	3,838	4,000
Light output	lm	500	> 500
Power	W	7	< 7
Efficacy	lm/W	80	> 80
CCT	K	3,000	3,000
CRI	100-point scale	80	> 80
Power factor		0.8	> 0.8

Table 5: Design goals

3. ESTIMATE EFFICIENCIES OF THE OPTICAL, THERMAL & ELECTRICAL SYSTEMS

We used Cree's Product Characterization Tool (PCT) tool to determine the drive current for the design.[5] For the 500-lumen target, we estimated 90% optical efficiency and 85% driver efficiency. We also estimated a solder-point temperature of 70 °C.

LED 1

Model Cree XLamp MK-R {EZW}

Flux G2 [780] **Tsp (°C)** 70

Price $ -

Current (A)	SYS lm tot	SYS lm/W	SYS W	SYS # LED
0.350	782.2	84.1	9.3039	2
0.400	879.7	82.2	10.6962	2
0.450	974.5	80.5	12.1011	2
0.500	533.3	78.9	6.7589	1
0.550	577.8	77.3	7.4722	1
0.600	621.2	75.8	8.191	1
0.650	663.2	74.4	8.9139	1
0.700	704.1	73	9.6416	1

Figure 2: PCT view of the number of LEDs used and drive current

The PCT shows that, at 500 mA, a single XLamp MK-R LED provides light output that exceeds the design goal.

Thermal Requirements

About 75% of the input power will be converted to heat, which the heat sink must be able to dissipate. In addition, the heat sink in this design must serve as the mechanical housing for the other lamp components. We selected a

5 PCT is available at pct.cree.com

commercially available aluminum heat sink with 36 fins that fits the compact MR16 form factor. The heat sink is part of a kit, shown in Figure 3, that also includes a metal optic-locking ring and plastic driver-housing cap.[6]

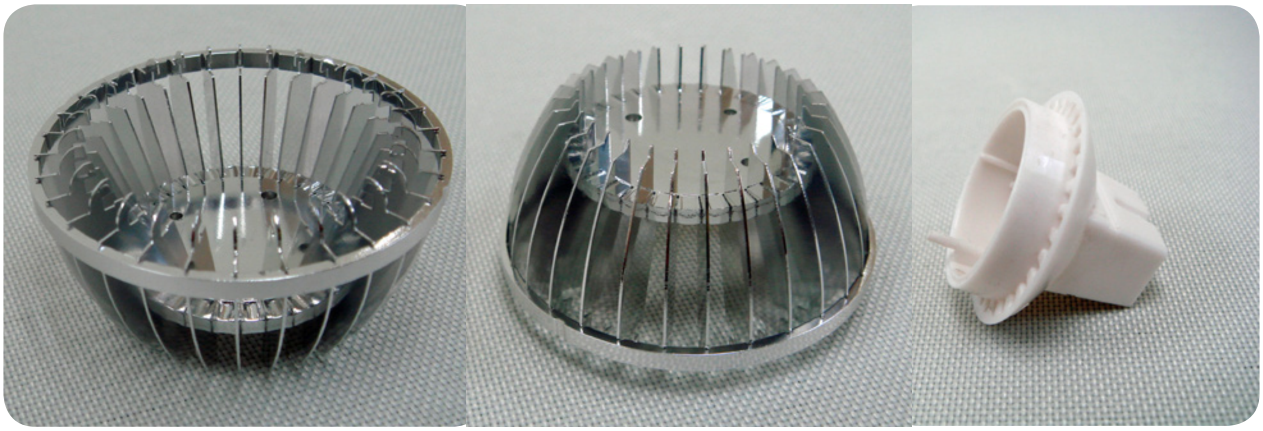


Figure 3: Heat sink/housing kit components

Cree performed thermal simulation of the design and found the estimated solder point temperature to be 75.5 °C. Figure 4 shows the thermal simulation of the solder point temperature.

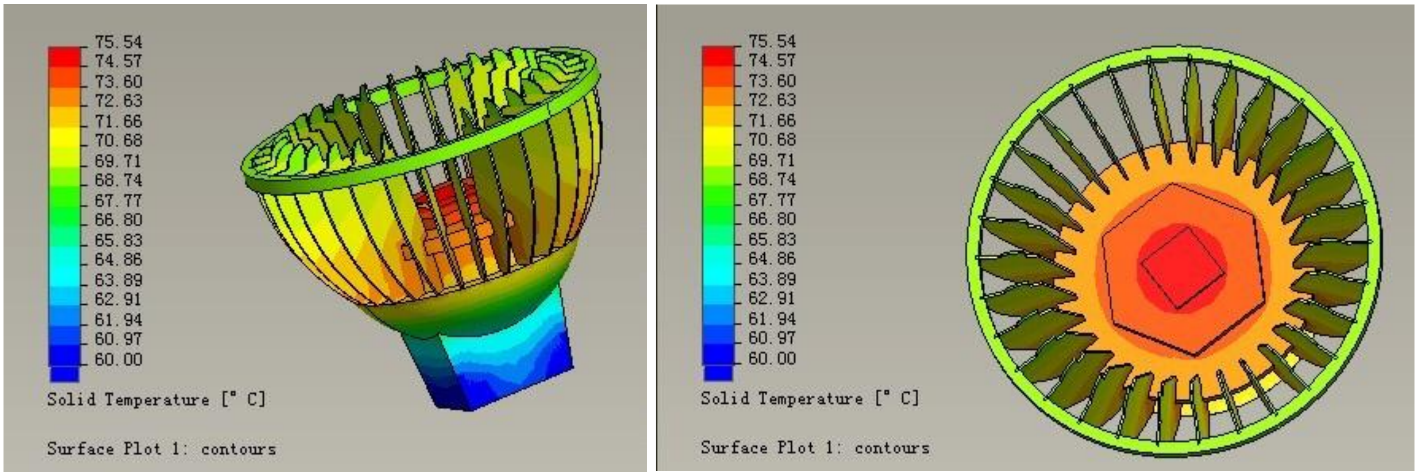


Figure 4: Thermal simulation of MK-R MR16

Driver

The driver for this MR16 lamp must be located inside the lamp housing. We used a custom constant-current driver, shown in Figure 5, that fits within the MR16 form factor and matches the design's current and voltage range.[7]

6 Model MR16-HS-MTG-W1, TaiSun Precision Parts, www.hztaisun.com
7 SZ-WND, www.sz-wnd.com

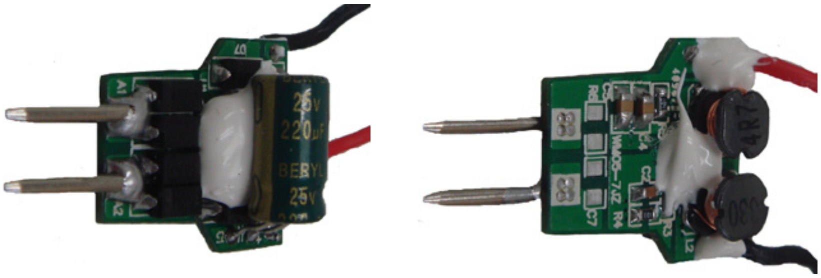


Figure 5: Top and bottom views of MK-R MR16 driver

Secondary Optics

Although many different lens optics are available for an MR16 spotlight, this design uses a total internal reflection (TIR) optic designed for the Cree XLamp MT-G LED that is also suitable for the MK-R LED.[8]

Figure 6: Top and bottom views of MK-R MR16 optic

4. CALCULATE THE NUMBER OF LEDS

Using Cree's PCT, we determined that only one XLamp MK-R LED is needed to produce sufficient light to meet the 500-lm design goal.

5. CONSIDER ALL DESIGN POSSIBILITIES

This is only one of the many ways to design an LED-based MR16 lamp. This reference design aims to show that the XLamp MK-R LED enables an MR16 lamp offering superior performance.

The MK-R LED offers a wide range of color temperatures. As highlighted in Table 6, we selected a warm white LED for this MR16 lamp design. By selecting an LED from a mid-level flux bin, we ensured that this design meets its goals using an LED that is readily available.

8 Model 10755, Carclo plc, www.carclo-optics.com/index.html

Color	CCT Range	Base Order Codes Min. Luminous Flux @ 700 mA			2-Step Order Code		4-Step Order Code	
		Group	Flux (lm) @ 85 °C	Flux (lm) @ 25 °C*	Chromaticity Region		Chromaticity Region	
80-CRI EasyWhite	5000 K	H2	900	1044	50H	MKRAWT-00-0000-0D0HH250H	50F	MKRAWT-00-0000-0D0HH250F
		G4	840	974		MKRAWT-00-0000-0D0HG450H		MKRAWT-00-0000-0D0HG450F
	4500 K	H2	900	1044	45H	MKRAWT-00-0000-0D0HH245H	45F	MKRAWT-00-0000-0D0HH245F
		G4	840	974		MKRAWT-00-0000-0D0HG445H		MKRAWT-00-0000-0D0HG445F
	4000 K	H2	900	1044	40H	MKRAWT-00-0000-0D0HH240H	40F	MKRAWT-00-0000-0D0HH240F
		G4	840	974		MKRAWT-00-0000-0D0HG440H		MKRAWT-00-0000-0D0HG440F
	3500 K	H2	900	1044	35H	MKRAWT-00-0000-0D0HH235H	35F	MKRAWT-00-0000-0D0HH235F
		G4	840	974		MKRAWT-00-0000-0D0HG435H		MKRAWT-00-0000-0D0HG435F
	3000 K	G4	840	974	30H	MKRAWT-00-0000-0D0HG430H	30F	MKRAWT-00-0000-0D0HG430F
		G2	780	905		MKRAWT-00-0000-0D0HG230H		MKRAWT-00-0000-0D0HG230F
	2700 K	G2	780	905	27H	MKRAWT-00-0000-0D0HG227H	27F	MKRAWT-00-0000-0D0HG227F
		F4	730	847		MKRAWT-00-0000-0D0HF427H		MKRAWT-00-0000-0D0HF427F

Table 6: MK-R order codes

6. COMPLETE THE FINAL STEPS: IMPLEMENTATION AND ANALYSIS

Using the methodology described above, we determined a suitable combination of components and drive conditions to meet the design goals. This section describes how Cree assembled the MR16 lamp and shows the results of the design.

Prototyping Details

1. We verified the component dimensions to ensure a correct fit.
2. Following the recommendations in Cree's Soldering and Handling Application Note for the MK-R LED, with an appropriate solder paste and reflow profile, we reflow soldered the LEDs to the metal core printed circuit board (MCPCB) and cleaned the flux residue with isopropyl alcohol (IPA).[9]
3. We applied a thin layer of thermal conductive compound[10] to the back of MCPCB and attached it to the heat sink/housing with screws.
4. We fed the driver output wires through the through-holes in the heat sink and soldered the wires to the MCPCB terminal pads.
5. We tested the connection by applying power to the LEDs and verified the LEDs lit up.
6. We fit the LED driver into the driver housing/lamp base and snapped it into the heat sink. Adhesive can also be used to secure the base to the heat sink.
7. The heat sink holds the optics holder in place. We inserted the optics holder onto the front side of the heat sink and snapped the TIR lens into the optics holder.

9 Cree XLamp MT Family & MK-R LED Soldering and Handling, Application Note AP75, www.cree.com/xlamp_app_notes/MT_SH
10 Arctic Silver, www.arcticsilver.com/arctic_silver_thermal_adhesive.htm
Refer to Cree's Chemical Compatibility application note for compounds that are safe to use with Cree LEDs.
Cree XLamp LED Chemical Compatibility Application Note, AP63, www.cree.com/products/pdf/XLamp_Chemical_Comp.pdf

8. We performed final testing.

Results

Thermal Results

Cree verified the board temperature with a thermocouple to confirm that the thermal dissipation performance of the heat sink is sufficient. Based on the measured solder point temperature of 78.9 °C, the junction temperature (T_J) can be calculated as follows.

$T_J = T_{SP}$ + (LED power * LED thermal resistance)
T_J = 78.9 °C + (7 W * 1.7 °C/W)
T_J = 90.8 °C

Optical and Electrical Results

We obtained the results in Table 7 by testing the MK-R MR16 lamp in a 1.5-meter sphere after a 60-minute stabilization time.[11] As the table shows, the lamp exceeds the 500-lm light-output target using just 7 W of power. The MR16 lamp also meets the ENERGY STAR efficacy, CCT and CRI requirements.

The XLamp MK-R LED footprint is 38% smaller than the footprint of the MT-G LED that was used in Cree's initial MR16 lamp reference design. The MK-R's smaller optical source size facilitates a beam angle that is 33% narrower than that of the MT-G MR16 lamp. Used in a retail application, the MK-R MR16 is even more capable of highlighting merchandise.

The alert reader will notice that the CBCP of the MK-R MR16 lamp makes this a 49.1-W equivalent lamp, just shy of the 50-W equivalence goal. We suggest two ways to reach the 50-W CBCP target.

1. Use an XLamp MK-R LED from a higher flux bin. There are several alternatives from which to choose.
2. Operate the lamp at a higher current. The PCT results in Figure 2 suggest that increasing the current to 550 mA could provide sufficient light output to reach the CBCP goal. The thermal results of the MK-R MR16 indicate that there is ample thermal headroom to allow this.

Characteristic	Unit	Result
CBCP	cd	3778
Light output	lm	565
Power	W	7
Efficacy	lm/W	81
CCT	K	3102
CRI	100-point scale	82
Power factor		0.85

Table 7: MK-R MR16 lamp steady-state results

11 Testing was performed at Cree's Shenzhen Technology Center.

We also tested the intensity distribution of the MK-R MR16 lamp.[12] Figure 7 shows an even intensity distribution for the 18° beam angle.

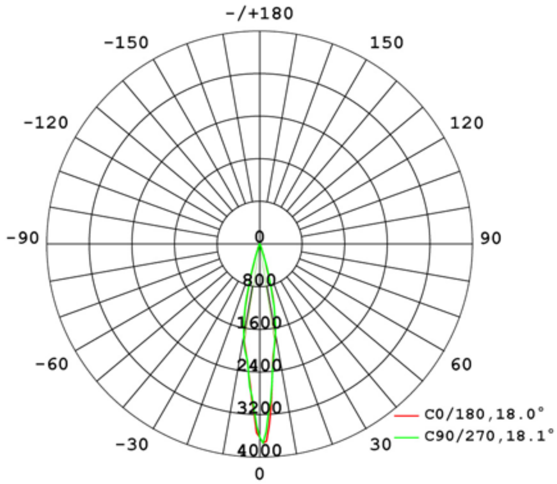


Figure 7: Angular luminous intensity distribution of MK-R MR16 lamp - 18° beam angle

Table 8 shows the illuminance of the MK-R MR16 lamp at various distances from the light source.

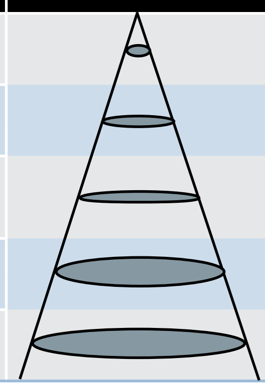
Height		Illuminance					Diameter	
		Eavg	Emax	Eavg	Emax			
1 m	3.3 ft	222.4 fc	356.8 fc	2,394 lx	38,411 lx		30.5 cm	1.0 ft
2 m	6.6 ft	55.6 fc	89.2 fc	598.5 lx	960.1 lx		60.9 cm	2.0 ft
3 m	9.8 ft	24.7 fc	39.6 fc	266.0 lx	426.7 lx		91.4 cm	3.0 ft
4 m	13.1 ft	13.9 fc	22.3 fc	149.6 lx	240.0 lx		121.8 cm	4.0 ft
5 m	16.4 ft	8.9 fc	14.3 fc	95.8 lx	153.6 lx		152.31 cm	5.0 ft

Table 8: MK-R MR16 illuminance – 18° beam angle

CONCLUSION

This reference design illustrates the excellent performance of an MR16 lamp based on the Cree XLamp MK-R LED. The narrow beam angle and CBCP of this MR16 lamp make it particularly effective at attracting attention to merchandise in retail applications. Optimized for directional lighting applications, the lighting-class performance of the Cree XLamp MK-R LED makes it a compelling design option for an LED-based MR16 lamp.

12 Testing was performed in a type A goniometer at Cree's Shenzhen Technology Center. An IES file for the MR16 lamp are available at www.cree.com/xlamp_app_notes/MK-R_MR16_ies.

BILL OF MATERIALS

Component	Order Code/Model Number	Company	Web Link
Driver		SZ-WND	www.sz-wnd.com
Heat sink/housing, base, optic holder	MR16-HS-MTG-W1	TaiSun Precision Parts	www.hztaisun.com
LED	MKRAWT-00-0000-0D0HG230F	Cree, Inc.	www.cree.com/XLamp/MKR
Optic	10755	Carclo, plc	www.carclo-optics.com/index.html
Thermal epoxy	ASTA-7G	Arctic Silver, Inc.	www.arcticsilver.com/arctic_silver_thermal_ adhesive.htm

Table 9: Bill of materials for MK-R MR16 lamp

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