Cree® XLamp® XB-D LED MR16 Reference Design

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INTRODUCTION

The compact MR16 form factor, with limited space for drive electronics and thermal dissipation, presents a difficult design challenge. The small footprint and industry-leading light output of the XB-D LED make it particularly well-suited for use as the light source in an MR16 lamp.

Building on Cree's reference designs of MR16 replacement lamps using XLamp MT-G, XM-L EasyWhite and XP-E LEDs, this design demonstrates the possibility of employing the XLamp XB-D LED as the light source of a 20-watt equivalent MR16 replacement lamp for use as an indoor spotlight.[1]

1 Cree XLamp MT-G MR16 Reference Design, Application Note AP62, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Reference%20Designs/XLampMTG_MR16_Ref.pdf
Cree XLamp XM-L EZW MR16 Reference Design, Application Note AP71, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Reference%20Designs/XLampXML_MR16_Ref.pdf
Cree XLamp XP-E MR16 Reference Design, Application Note AP76, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Reference%20Designs/XLampXPE_MR16_Ref.pdf

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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 20-watt equivalent retrofit MR16 lamp that shows the performance available from the XLamp XB-D LED.

1. DEFINE LIGHTING REQUIREMENTS

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

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	

2 LED Luminaire Design Guide, Application Note AP15, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Application%20Notes/LED_Luminaire_Design_Guide.pdf

Importance	Characteristics	Units
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]

<table>
<tr><th>Characteristic</th><th>Requirements</th></tr>
<tr><td>CCT and Duv</td><td>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.
<table>
<tr><th>Nominal CCT</th><th>Target CCT (K) and Tolerance</th><th>Target Duv and Tolerance</th></tr>
<tr><td>2700 K
3000 K
3500 K
4000 K</td><td>2725 ± 145
3045 ± 175
3465 ± 245
3985 ± 275</td><td>0.000 ± 0.006
0.000 ± 0.006
0.000 ± 0.006
0.001 ± 0.006</td></tr>
</table></td></tr>
<tr><td>Color maintenance</td><td>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.</td></tr>
<tr><td>CRI</td><td>Minimum CRI (R_a) of 80. R_9 value must be greater than 0.</td></tr>
<tr><td>Allowable lamp bases</td><td>Must be a lamp base listed by ANSI.</td></tr>
<tr><td>Power factor</td><td>Lamp power < 5 W and low voltage lamps: no minimum power factor is required
Lamp power > 5 W: power factor must be ≥ 0.70
Note: Power factor must be measured at rated voltage.</td></tr>
<tr><td>Minimum operating temperature</td><td>-20 °C or below</td></tr>
<tr><td>LED operating frequency</td><td>≥ 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.</td></tr>
<tr><td>Electromagnetic and radio frequency interference</td><td>Must meet appropriate FCC requirements for consumer use (FCC 47 CFR Part 15)</td></tr>
<tr><td>Audible noise</td><td>Class A sound rating</td></tr>
<tr><td>Transient protection</td><td>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.</td></tr>
<tr><td>Operating voltage</td><td>Lamp shall operate at rated nominal voltage of 120, 240 or 277 VAC, or at 12 or 24 VAC or VDC.</td></tr>
</table>

Table 3: ENERGY STAR requirements for all lamps

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 ∏ 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

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

4 Ibid., Table 7C

Criteria Item	ENERGY STAR Requirements
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 20-W equivalent MR16 lamp with a 25° beam angle needs to provide CBCP of 876 cd.

ENERGY STAR® Integral LED Lamp Center Beam Intensity Benchmark Tool

MR-16 Lamps

Target Halogen Lamp Parameters

Enter Nominal Lamp Wattage: **20** watts
Enter Nominal Beam Angle*: **25** degrees

Minimum Center Beam Intensity: 876 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		20	25		7.271	6.775		1438	876
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 20-W equivalent MR16 lamp with 25° beam angle

2. DEFINE DESIGN GOALS

The aim of this project is a 20-W equivalent MR16 indoor spotlight with a 25° beam angle using the XLamp XB-D LED. Table 5 shows the design goals for this project.

Characteristic	Unit	Minimum Goal	Target Goal
CBCP - 25° beam angle	cd	876	880
Light output	lm	280	> 280
Power	W	5	< 5
Efficacy	lm/W	70	75
Lifetime	hours	50,000	50,000
CCT	K	3,000	3,000
CRI	100-point scale		> 80

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 280-lumen target, we estimated 90% optical efficiency and 85% driver efficiency. We also estimated a solder point temperature of 65 °C.

Current (A)	LED 1			
	Model	Cree XLamp XB-D {AWT}		
	Flux	Q3 [93.9]	Tsp (ºC)	65
	Price	$ -		
	SYS # LED	SYS lm tot	SYS W	SYS lm/W
0.100	10	292.6	3.24	90.4
0.150	7	294.2	3.45	85.2
0.200	6	325	4	81.3
0.250	5	328.5	4.22	77.9
0.300	4	306.7	4.1	74.9
0.350	4	348.5	4.83	72.1
0.400	3	291.1	4.18	69.6
0.450	3	319.5	4.75	67.3
0.500	3	346.5	5.32	65.1
0.550	3	372.2	5.9	63.1
0.600	3	396.8	6.48	61.2
0.650	2	280.2	4.71	59.5
0.700	2	295.2	5.11	57.8
0.750	2	309.6	5.51	56.2
0.800	2	323.4	5.91	54.7
0.850	2	336.8	6.32	53.3
0.900	2	349.6	6.73	52
0.950	2	362.2	7.14	50.7
1.000	2	374.3	7.56	49.5

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

To keep the MR16 lamp's cost low, we wanted to minimize the number of LEDs used. The PCT shows that, at 400 mA, 3 XB-D LEDs provide light output that exceeds the design goal. With some basic calculation, we estimate that 3 XB-D LEDs at 380 mA will provide sufficient light output.

5 PCT is available at pct.cree.com

Thermal Requirements

With the XB-D LEDs operating at about 4 W of input power, the thermal requirements for this reference design are not so difficult. About 75% of the input power will be converted to heat, which the heat sink must be able to dissipate. We selected a commercially available heat sink that also serves as the lamp housing. The heat sink is part of a kit, shown in Figure 3, that includes a metal optic-locking ring and plastic driver-housing cap.[6]

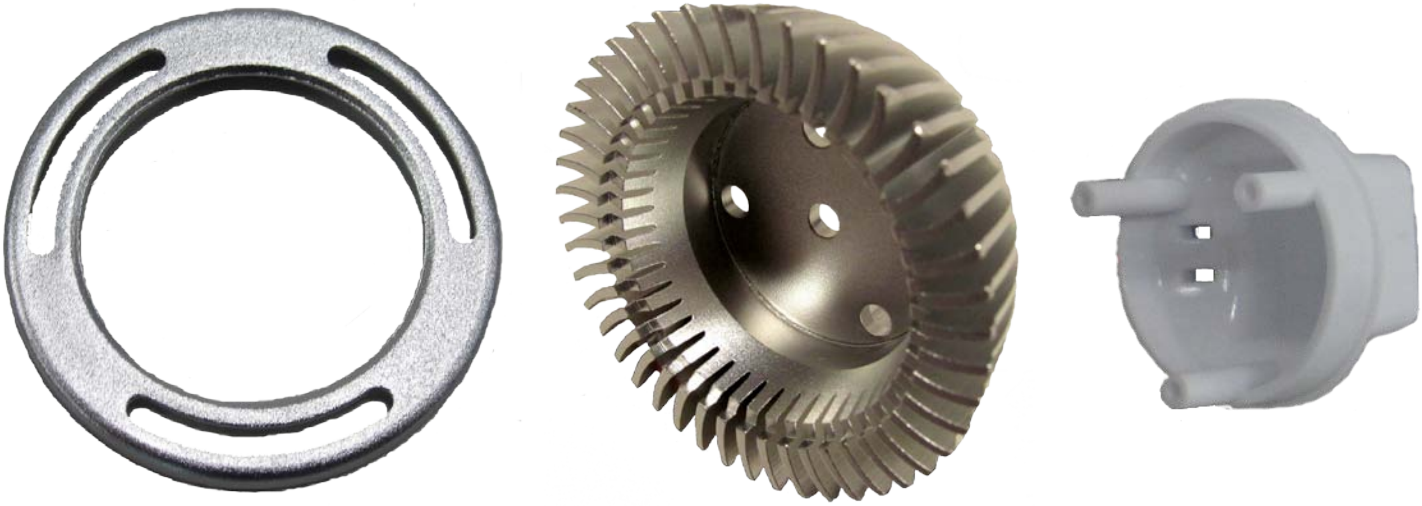


Figure 3: Heat sink/housing kit components

The thermal demands of this reference design are not an issue and we did not perform thermal simulation. We did use a thermocouple to perform thermal testing to verify the performance of the heat sink.

Driver

The driver for this MR16 lamp must be located inside the lamp housing. We decided to use a market-ready constant-current driver that fits within the MR16 form factor and matches the design's current and voltage range.[7]

Figure 4: Driver

6 Model: S3.7-MR16, Super Heat Pipe, www.zklhcd.cn
7 Model TXM26-0000-XX, TXM Power Co., www.ledpower.com.cn

Secondary Optics

Although many different lens optics are available for an MR16 spotlight, this design targets the 20-W equivalent 25° market. We selected a 3-in-1 lens optic from LedLink, shown in Figure 5.[8]

Figure 5: XB-D MR16 optic

4. CALCULATE THE NUMBER OF LEDS

Using Cree's PCT, we determined that 3 XLamp XB-D LEDs produce sufficient light to meet the 280-lm design goal.

5. CONSIDER ALL DESIGN POSSIBILITIES

There are many ways to design an LED-based MR16 lamp. This reference design aims to show that the XB-D LED enables an MR16 lamp offering superior performance.

The XB-D 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 low-level flux bin, we ensured that this design meets its goals using an LED that is readily available.

Color	CCT Range		Base Order Codes Min. Luminous Flux @ 350 mA (lm)		Order Code
	Min.	Max.	Group	Flux (lm)	
Warm White	2,600 K	3,700 K	Q2	87.4	XBDAWT-00-0000-00000LAE7
			Q3	93.9	XBDAWT-00-0000-00000LBE7
			Q4	100	XBDAWT-00-0000-00000LCE7

Table 6: XB-D order codes

6. COMPLETE THE FINAL STEPS: IMPLEMENTATION AND ANALYSIS

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

8 Model LL03LU-DO25, LedLink Optics, Inc., www.ledlink-optics.com/productsmodule.aspx

Prototyping Details

1. We verified the component dimensions to ensure a correct fit.

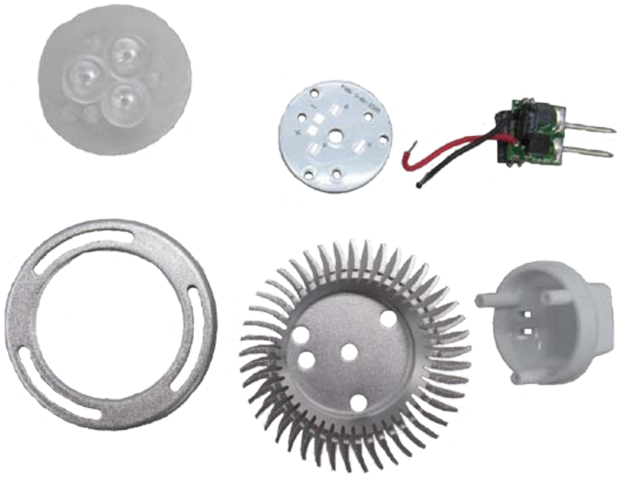


Figure 6: XB-D MR16 lamp components

2. Following the recommendations in Cree's Soldering and Handling Application Note for the XB-D 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 soldered the driver input wires to the MCPCB.
4. We tested the connection by applying power to the LEDs and verified the LEDs lit up.
5. We applied a thin layer of thermal conductive compound to the back of MCPCB and attached it to the heat sink/housing with screws.
6. We fit the LED driver into the heat sink/housing, covered it with the plastic housing cap and secured the cap to the heat sink/housing with screws.
7. We placed the optic on the LED MCPCB, aligning the positioning tabs, and secured it to the outer rim of the heat sink/housing with the metal locking ring.
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 65 °C, the junction temperature (T_J) can be calculated as follows.

$T_J = T_{SP}$ + (LED power * LED thermal resistance)
T_J = 65 °C + (1.3 W * 6.5 °C/W)
T_J = 73 °C

9 Cree XLamp XB-D LED Soldering and Handling, Application Note AP90, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Application%20Notes/XLampXBD_SH.pdf

Estimated LED lifetime

Based on thousands of hours of long-term testing of the XB-D LED at higher temperatures than the measured 65 °C T_{SP}, Cree expects an L_{70} lifetime significantly longer than the 50,000-hour goal for this design.

Optical and Electrical Results

We obtained the results in Table 7 by testing the XB-D MR16 lamp in a 1.5-meter sphere after a 30-minute stabilization time.[10] As the table shows, the lamp exceeds the 880-cd CBCP and 280-lm light output targets using less than 5 W of power. The MR16 lamp also meets the ENERGY STAR efficacy, CCT and CRI requirements.

Characteristic	Unit	Result
CBCP	cd	890
Light output	lm	308
Power	W	4.6
Efficacy	lm/W	67
CCT	K	3110
CRI	100-point scale	82
Current	mA	380

Table 7: XB-D MR16 lamp steady-state results

We also tested the intensity distribution of the XB-D MR16 lamp.[11] Figure 7 shows an even intensity distribution for the 27° beam angle.

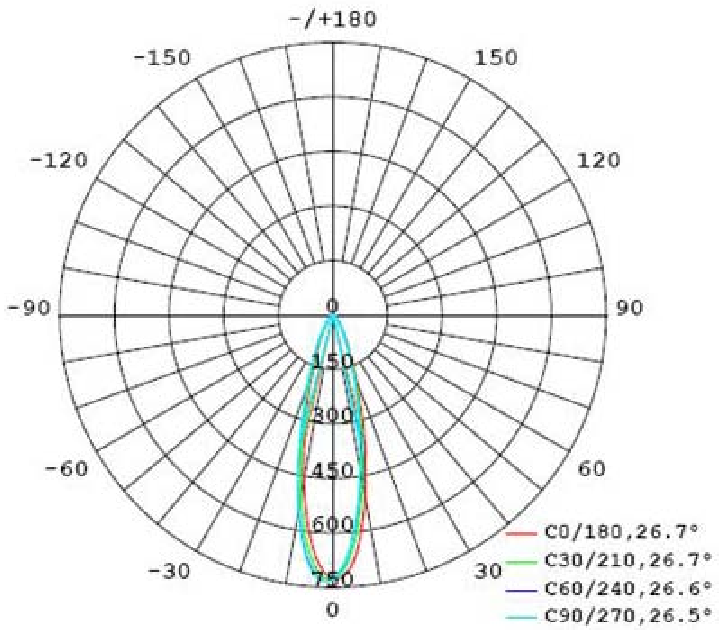


Figure 7: Angular luminous intensity distribution of XB-D MR16 lamp - 27° beam angle

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

11 Testing was performed in a type B goniometer at Cree's Shenzhen Technology Center. IES files for the MR16 lamp are available at www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Reference%20Designs/Design%20files/xbd_mr16_ies.

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

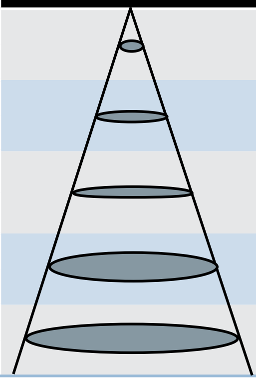
Height		Illuminance					Diameter	
		Eavg	Emax	Eavg	Emax			
1 m	3.3 ft	53.3 fc	82.3 fc	573.1 lx	886.4 lx		46.6 cm	1.5 ft
2 m	6.6 ft	13.3 fc	20.6 fc	143.3 lx	221.4 lx		93.2 cm	3.1 ft
3 m	9.8 ft	5.9 fc	9.1 fc	63.7 lx	98.4 lx		139.9 cm	4.6 ft
4.m	13.1 ft	3.3 fc	5.1 fc	35.8 lx	55.3 lx		186.5 cm	6.1 ft
5 m	16.4 ft	2.1 fc	3.3 fc	22.9 lx	35.4 lx		233.1 cm	7.7 ft

Table 8: XB-D MR16 illuminance – 27° beam angle

CONCLUSION

This reference design illustrates the superior performance of an MR16 lamp based on the Cree XLamp XB-D LED. The MR16 lamp components are all commercially available, obviating the need for the time and expense of developing custom parts during the design of an extremely capable lamp. The small footprint of the XB-D LED enables the use of lower cost, smaller size and higher efficiency LED drivers and provides more room for the LED driver and heat sink in space-constrained designs such as an MR16 lamp. The lighting-class performance of the Cree XLamp XB-D LED makes it an attractive design option for an LED-based MR16 lamp.