Cree® XLamp® XB-D LED 75-watt Equivalent A19 Lamp Reference Design

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INTRODUCTION

This application note details the design of a 75-watt equivalent A19 replacement lamp using Cree's XLamp XB-D LED. The XLamp XB-D LED is designed specifically for high lumens/dollar applications, such as the price-sensitive replacement lamp market. This XB-D A19 lamp is intended to be a replacement for incandescent A19 lamps in omnidirectional indoor lighting applications.

Many replacement lamps currently on the market use a snow cone design and do not replicate the light pattern of an incandescent lamp. This reference design betters the snow cone design to produce a lamp that matches the light pattern of an incandescent, enabling its use in omnidirectional applications and also enabling it to meet ENERGY STAR® intensity distribution requirements.

The high flux output and efficacy offered by the XB-D LED make it a particularly strong candidate for use in an A19 lamp. The performance of the XB-D LED means that a small number of LEDs can be used to create an A19 lamp that meets the ENERGY STAR light distribution requirements for a 75-watt equivalent replacement lamp.

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DESIGN APPROACH/OBJECTIVES

In the "LED Luminaire Design Guide"[1] 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 the design is an XLamp XB-D LED-based 75-watt equivalent A19 lamp that can replace incandescent lamps in omnidirectional applications. As a replacement lamp, this design uses the A19 form factor that is familiar to consumers.

1. DEFINE LIGHTING REQUIREMENTS

Table 2 shows a ranked list of desirable characteristics to address in an high-bay luminaire design.

Importance	Characteristics	Units
Critical	Illuminance distribution	footcandles (fc)/lux (lx)
	Electrical power	watts (W)
	Luminous flux	lumens (lm)
	Luminous efficacy	lm/W
	Lifetime	hours
Important	Operating temperatures	°C
	Operating humidity	% relative humidity
	Correlated color temperature (CCT)	K
	Color rendering index (CRI)	100-point scale

Table 2: Ranked design criteria for a high-bay luminaire

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

Table 3 below summarizes the ENERGY STAR requirements for all integral LED lamps.[2]

<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 (Ra) of 80. R9 value must be greater than 0.</td></tr>
<tr><td>Dimming</td><td>Lamps may be dimmable or non-dimmable. Product packaging must clearly indicate whether the lamp is dimmable or not dimmable. Manufacturers qualifying dimmable products must maintain a web page providing dimmer compatibility information.</td></tr>
<tr><td>Warranty</td><td>3-year warranty</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 PF
Lamp power > 5 W: PF > 0.70</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 integral LED lamps

2 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 summaries ENERGY STAR requirements for omnidirectional replacement lamps.[3]

<table>
<tr><th>Criteria Item</th><th colspan="2">Requirements</th></tr>
<tr><td>Minimum luminous efficacy</td><td colspan="2">• LED lamp power < 10 W: 50 lm/W
• LED lamp power ≥ 10 W: 55 lm/W</td></tr>
<tr><td rowspan="3">Minimum light output</td><td colspan="2">Lamp shall have minimum light output (initial total luminous flux) at least corresponding to the target wattage of the lamp to be replaced, as shown below. Target wattages between the given levels may be interpolated.</td></tr>
<tr><td>Nominal wattage of lamp to be replaced (watts)</td><td>Minimum initial light output of LED lamp (lumens)</td></tr>
<tr><td>75</td><td>1100</td></tr>
<tr><td>Luminous intensity distribution</td><td colspan="2">Products shall have an even distribution of luminous intensity (candelas) within the 0° to 135° zone (vertically axially symmetrical).
Luminous intensity at any angle within this zone shall not differ from the mean luminous intensity for the entire 0° to 135° zone by more than 20%.
At least 5% of total flux (lumens) must be emitted in the 135° to 180° zone.
Distribution shall be vertically symmetrical as measured in 3 vertical planes at 0°, 45° and 90°.</td></tr>
<tr><td>Maximum lamp diameter</td><td colspan="2">Not to exceed target lamp diameter</td></tr>
<tr><td>Maximum overall length (MOL)</td><td colspan="2">Not to exceed MOL for target lamp</td></tr>
<tr><td>Lumen maintenance</td><td colspan="2">≥ 70% lumen maintenance (L_{70}) at 25,000 hours of operation</td></tr>
<tr><td>Rapid-cycle stress test</td><td colspan="2">Cycle times must be 2 minutes on, 2 minutes off. Lamp will be cycled once for every 2 hours of L_{70} life.</td></tr>
</table>

Table 4: ENERGY STAR requirements for replacement omnidirectional lamps

2. DEFINE DESIGN GOALS

Table 5 shows the design goals for this project.

Characteristic	Unit	Minimum Goal	Target Goal
Light output	lm	1100	> 1100
Power	W	20	< 20
Luminaire efficacy	lm/W	55	> 55
Intensity distribution			ENERGY STAR requirement
Lifetime	hours	25,000	50,000
CCT	K	3000	3000
CRI	100-point scale		> 80
Power factor		0.9	> 0.9

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.[4] For the 1100-lm target, we estimated 87% optical efficiency and 90% driver efficiency. We also estimated a solder point temperature of 90 °C.

The PCT output highlighted in Figure 1 shows that, at 750 mA, eight XB-D LEDs provide sufficient light output to meet the design goals.

3 Ibid., Table 7A

4 PCT is available at pct.cree.com

System:	Target Lumens :	1,100	Optical Efficiency:	87%	Electrical Efficiency:	90%

	LED 1				LED 2				LED 3		
	Model	Cree XLamp XB-D {AWT}			Model	(none)			Model	(none)	
	Flux	Q4 [100]	Tsp (ºC)	90	Flux	Tj (ºC)	25		Flux	Tj (ºC)	25
	Price	$ -			Price	$ -			Price	$ -	

Current (A)	SYS # LED	SYS lm tot	SYS W	SYS lm/W
0.150	27	1103.2	12.292	89.8
0.200	21	1105.9	12.929	85.5
0.250	18	1149.6	14.032	81.9
0.300	15	1117.8	14.2	78.7
0.350	13	1100.5	14.515	75.8
0.400	12	1131.5	15.466	73.2
0.450	11	1137.9	16.097	70.7
0.500	10	1121.8	16.4	68.4
0.550	10	1204.9	18.183	66.3
0.600	9	1155.7	17.986	64.3
0.650	9	1224.2	19.623	62.4
0.700	8	1146.2	18.91	60.6
0.750	8	1201.6	20.389	58.9
0.800	8	1255.1	21.883	57.4
0.850	7	1143.4	20.469	55.9
0.900	7	1186.8	21.802	54.4
0.950	7	1229.2	23.152	53.1
1.000	7	1270.2	24.518	51.8

Figure 1: PCT view of the number of LEDs used and drive current

Optical Requirements

Perhaps the major challenge for an LED-based A19 lamp intending to meet ENERGY STAR light output requirements is the intensity distribution beyond 90°, i.e., light emitted back toward the lamp base. Figure 2 is a graphic representation of the ENERGY STAR luminous intensity distribution requirement.[5] Most LED lamps on the market have a snow cone design in which light is directed mainly forward and therefore are not able to meet this requirement.

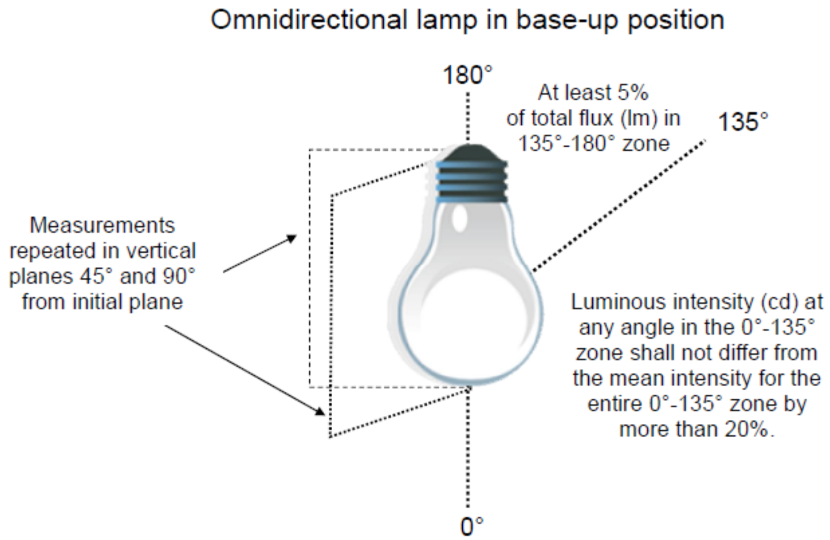

Figure 2: ENERGY STAR luminous intensity distribution requirement

5 *Op. cit.*, Appendix B

The heart of this reference design is a unique polycarbonate Total Internal Reflection (TIR) optic, shown in Figures 3 and 4, custom designed for the XB-D LED.[6] The lens is designed to direct the light from the LED in an omnidirectional pattern.

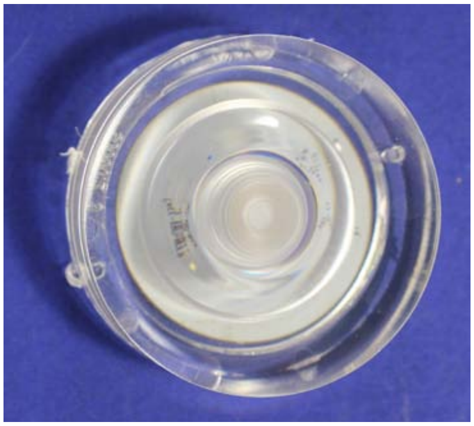

Figure 3: XB-D A19 optic (top view)

Figure 4: XB-D A19 optic and clear cover

Electrical Requirements

Another challenge for an LED-based A19 lamp design is the driver lifetime. A lamp design will not be successful if the driver has a much shorter lifetime than the LEDs.

Driver

A major component of most driver designs is a capacitor to minimize ripple current from the AC input cycle. Normal electrolytic capacitors fail at high temperatures, increasing ripple, which may result in noticeable flickering. Further, to meet ENERGY STAR requirements, a lamp operating at more than 10 W must be tested in a 45 °C environment between measurements, further challenging a driver's ability to maintain performance under high temperature. The A19 form factor provides limited space for components such as the heat sink and driver, leading to a high solder point temperature (T_{SP}) and driver operating temperature. This reference design needs a driver efficiency of 90% to meet the efficacy requirement. We selected a driver, shown in Figure 5, able to operate at high temperatures and be 90% efficient.[7]

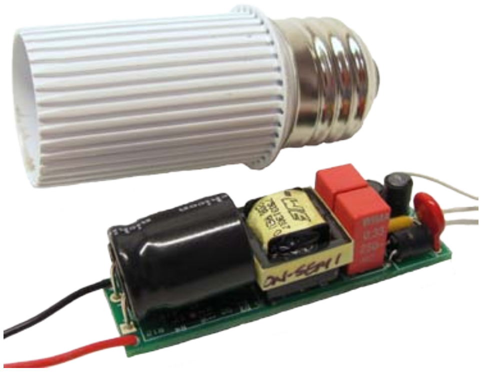

Figure 5: Driver and driver housing

6 Model STAR0080, Aether Systems Inc., www.aether-systems.com

7 Model NCL30002LED1GEVB, ON Semiconductor, www.onsemi.com/PowerSolutions/product.do?id=NCL30002

Thermal Requirements

Heat is always a major concern in an LED-based lamp or luminaire design. We estimate that 70% of the 21 W of input power, or about 15 W, will be converted to heat that must be dissipated.

The thermal solution is a key factor in the success of this reference design. To make this design feasible, we worked with two partners to design and fabricate a custom metal core printed circuit board (MCPCB) and heat sink.

MCPCB

As shown in Figure 6, this A19 lamp design has eight XLamp XB-D LEDs arranged in a circular pattern with a precise diameter matching the TIR optic.

Although not addressed in this reference design, using a different number of LEDs to achieve other lumen output levels is possible with this optic as long as the LED layout diameter is maintained.

Figure 6: MCPCB

To aid heat dissipation we used a special copper MCPCB from Rayben.[8] As shown in Figure 7, where a typical MCPCB has a copper trace layer and a dielectric layer to transfer heat to the aluminum base layer and on to the surrounding environment, the Rayben MCPCB in this design has a "micro heat exchanger" (MHE) layer to transfer heat to the copper base layer and offers greater heat transfer capability. The electrically neutral thermal path of the XB-D LED makes this possible.

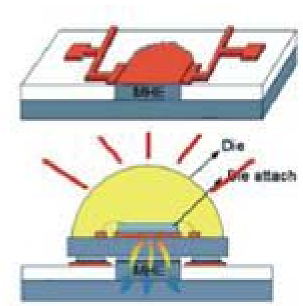

Figure 7: MHE thermal substrate

Heat Sink

This reference design uses a custom heat sink and driver housing designed by Cree and fabricated by TaiSun Precision Parts, shown in Figure 8.[9] The lightweight heat sink has slender fins that allow light to be directed back toward the lamp base. The driver is contained in the driver housing that fits into the heat sink and serves as the lamp base.

8 Model R13648AA-1F1-06K, Rayben, www.rayben.com/English/contact/contact.asp
9 Model A19-HS-XBD-W1, TaiSun Precision Parts, www.hztaisun.com

Figure 8: XB-D A19 heat sink and driver housing

We performed thermal simulation to verify this thermal design is sufficient. Figure 9 shows a cross section view of the thermal simulation. The simulated solder point temperature (T_{SP}) was 107 °C.

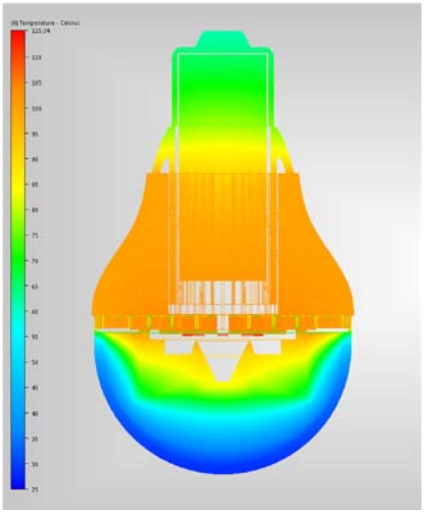

Figure 9: Thermal simulation of XB-D A19 lamp

4. CALCULATE THE NUMBER OF LEDS

Using Cree's PCT, we determined that 8 XLamp XB-D LEDs produce sufficient light to meet the 1100-lm design goal.

The XB-D LED offers a wide range of color temperatures. We selected a warm white LED for this A19 lamp design, shown highlighted in Table 6.

Color	CCT Range		Base Order Codes Min. Luminous Flux @ 350 mA (lm)		Calculated Minimum Luminous Flux (lm)*		Order Code
	Min.	Max.	Group	Flux (lm)	700 mA	1000 mA	
Cool White	5,000 K	8,300 K	R2	114	199	252	XBDAWT-00-0000-000000E51
			R3	122	213	270	XBDAWT-00-0000-000000F51
			R4	130	227	287	XBDAWT-00-0000-000000G51
70 CRI Minimum Cool White	5,000 K	8,300 K	R2	114	199	252	XBDAWT-00-0000-00000BE51
			R3	122	213	270	XBDAWT-00-0000-00000BF51
			R4	130	227	287	XBDAWT-00-0000-00000BG51
Neutral White	3,700 K	5,000 K	Q4	100	172	222	XBDAWT-00-0000-00000LCE4
			Q5	107	187	236	XBDAWT-00-0000-00000LDE4
			R2	114	199	252	XBDAWT-00-0000-00000LEE4
80 CRI Minimum White	2,600 K	4,300 K	Q2	87.4	153	193	XBDAWT-00-0000-00000HAE7
			Q3	93.9	164	207	XBDAWT-00-0000-00000HBE7
			Q4	100	172	222	XBDAWT-00-0000-00000HCE7
Warm White	2,600 K	3,700 K	Q2	87.4	153	193	XBDAWT-00-0000-00000LAE7
			Q3	93.9	164	207	XBDAWT-00-0000-00000LBE7
			Q4	100	172	222	XBDAWT-00-0000-00000LCE7

Table 6: XB-D order codes

5. CONSIDER ALL DESIGN POSSIBILITIES

There are many ways to design an LED-based A19 lamp. This reference design aims to show that the XB-D LED enables an A19 lamp offering superior performance.

Figure 10 shows the how the challenges of this design have been met.

- Custom optics direct the light output of the XB-D LEDs into an omnidirectional pattern.
- A custom heat sink not only dissipates heat, but its thin fins also enable light to be directed toward the lamp base.
- The driver must operate at high temperatures and fit within a housing that is contained within the heat sink.

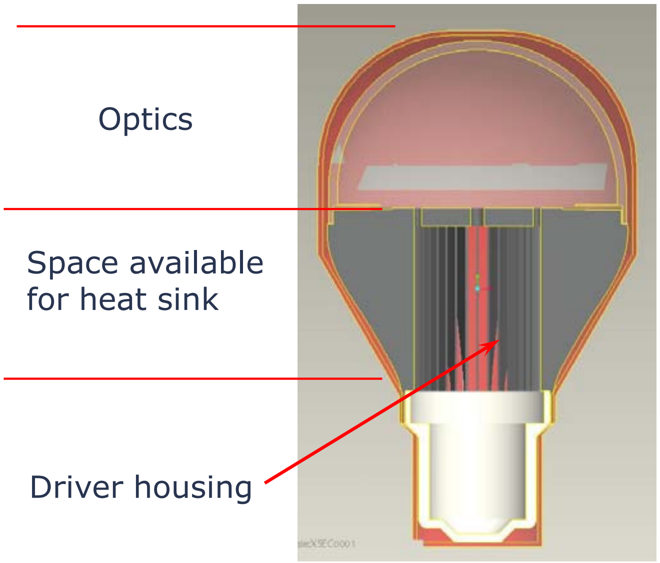

Figure 10: XB-D A19 lamp design

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 A19 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 XB-D LED, with an appropriate solder paste and reflow profile, we reflow soldered the LEDs to the MCPCB.[10] We cleaned the flux residue with isopropyl alcohol (IPA).
3. We applied a thin layer of thermal conductive compound to the back of MCPCB and secured it to the heat sink with screws.[11] Consult Cree's Chemical Compatibility Application Note for compounds safe for use with XLamp LEDs.[12]
4. We inserted the driver into the driver housing and made a solder connection to the screw base.
5. We potted the driver in the driver housing with electronics potting silicone.[13] This is an optional step, however the silicone helps to even out the heat load on the driver and ensures electrical insulation. It also provides a better thermal path to the housing than air does.
6. We applied adhesive (an epoxy or silicone-based adhesive is acceptable) to the driver housing groove and slid the housing into the heat sink, feeding the driver output wires through the heat sink to the top of the MCPCB.[14] Consult Cree's Chemical Compatibility Application Note for adhesives safe for use with XLamp LEDs.[15]
7. We waited for the adhesive to dry before proceeding. Depending on the adhesive used, heat may be applied to shorten the drying time.
8. We soldered the driver output wires to the MCPCB.
9. Aligning the TIR optic to the alignment holes in the heat sink, we secured the optic to the heat sink with adhesive.
10. We secured the clear cover to the heat sink with adhesive.
11. We performed final testing.

10 Cree XLamp XB-D LED Soldering and Handling, Application Note AP54, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Application%20Notes/XLampXM_SolderingandHandling.pdf
11 Timtronics Silver Ice 710, www.timtronics.com/electricallyconductive.htm.
12 Cree XLamp LEDs Chemical Compatibility, Application Note AP63, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Application%20Notes/XLamp_Chemical_Comp.pdf
13 Dow Corning Sylgard 160, www.dowcorning.com/applications/search/products/details.aspx?prod=02356368&type=PROD
14 Dow Corning RTV Silicone, www.dowcorning.com/content/publishedlit/80-3375.pdf.
15 *Loc. cit.*

Results

Figure 11 shows that the XB-D A19 lamp is a near match for the form factor of the familiar incandescent lamp. Additionally, Figure 12 shows the size of this lamp compared to the ANSI standard.[16] Dimensions are given in millimeters.

Figure 11: XB-D A19 lamp and incandescent lamp

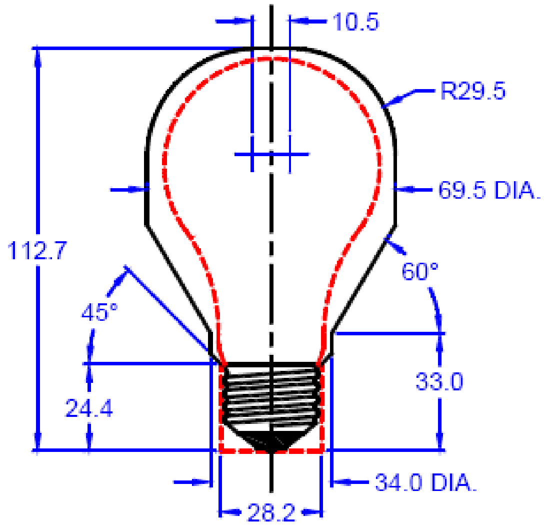

Figure 12: A19 lamp dimensions

Thermal Results

Cree verified the board temperature with a thermocouple and an infrared (IR) camera to confirm that the thermal dissipation performance of the heat sink aligns with our simulation.

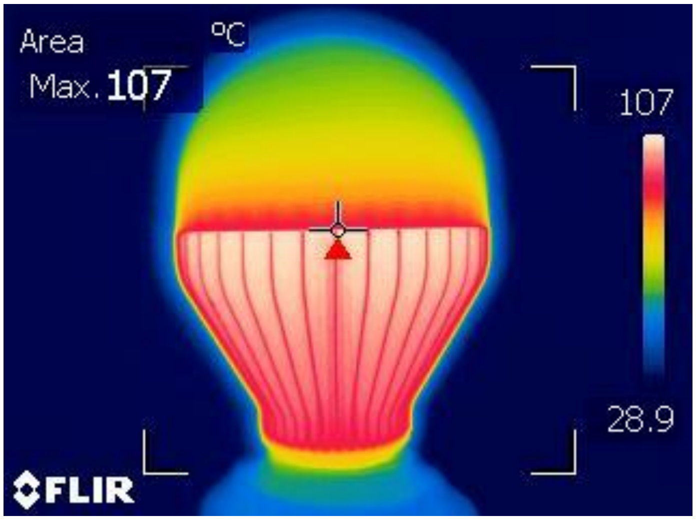

Figure 13: Thermal measurement with thermocouple

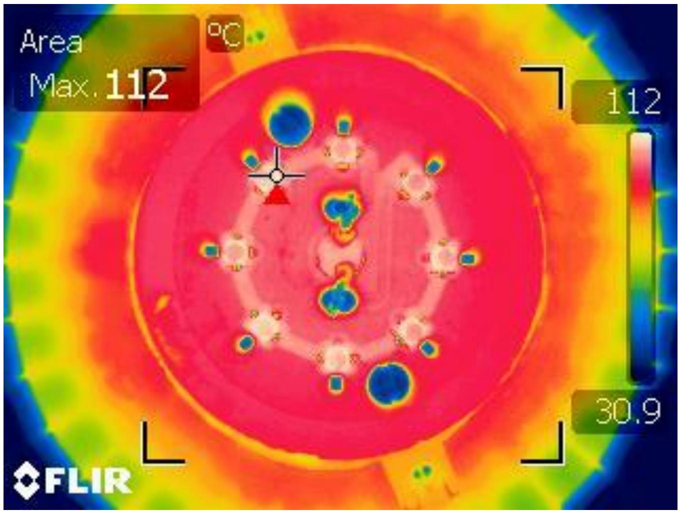

Figure 14: Thermal measurement with IR camera

16 Figure 78.20-211, ANSI C78.20-2003 - Revision of ANSI C78.20-1995

As shown in Figure 13, the solder point temperature measured with a thermocouple was 107 °C, an exact match with the simulation and which shows that the heat sink is sufficient for this design.

Based on the measured solder point temperature, the junction temperature (T_J) can be calculated as follows.

$T_J = T_{SP}$ + (LED power * LED thermal resistance)
T_J = 107 °C + ((19 W/8) * 6.5 °C/W)
T_J = 122 °C

As shown in Figure 14, we measured a T_j of 112 °C with an IR camera, reasonably close to the calculated value.

Estimated LED lifetime

Based on thousands of hours of long-term testing of the XB-D LED at operating conditions similar to those of this A19 lamp, Cree expects an L70 lifetime significantly longer than the 25,000-hour goal for this design.

Optical and Electrical Results

Photometric and performance measurements were collected using Cree's commercially available thermal, electrical, mechanical, photometric and optical (TEMPO) SPOT B Service.[17]

We determined the optical efficiency of the XB-D A19 lamp in the instant-on condition.

Optical efficiency = lumen output with optics / lumen output without optics
Optical efficiency = 1381 lm / 1519 lm
Optical efficiency = 91%

We obtained the results in Table 7 by testing the lamp in a 2-meter sphere at steady state after a 60-minute stabilizing time.[18] The values in the table meet ENERGY Star performance metrics for a 75-W equivalent lamp.

Characteristic	Unit	Result
Light output	lm	1155
Power	W	21
Lamp efficacy	lm/W	55
CCT	K	2870
CRI	100-point scale	80
Power factor		0.94

Table 7: XB-D A19 lamp steady-state results

17 www.cree.com/tempo
18 Testing was performed at Cree's Santa Barbara Technology Center.

Figure 15 shows that the XB-D A19 lamp meets the ENERGY STAR luminous intensity distribution requirement.

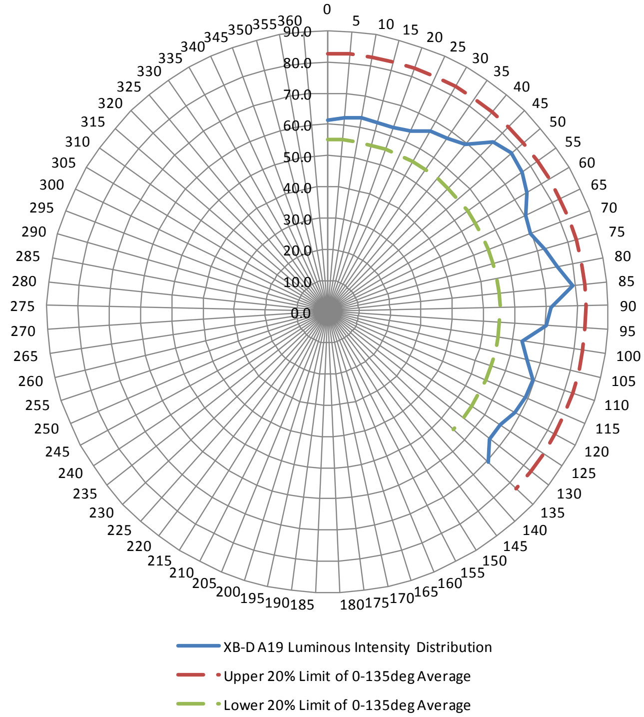

Figure 15: Luminous intensity distribution of XB-D A19 lamp

The 3-D wire diagram in Figure 16 is a graphical representation of the candela intensity values for the XB-D A19 lamp.[19]

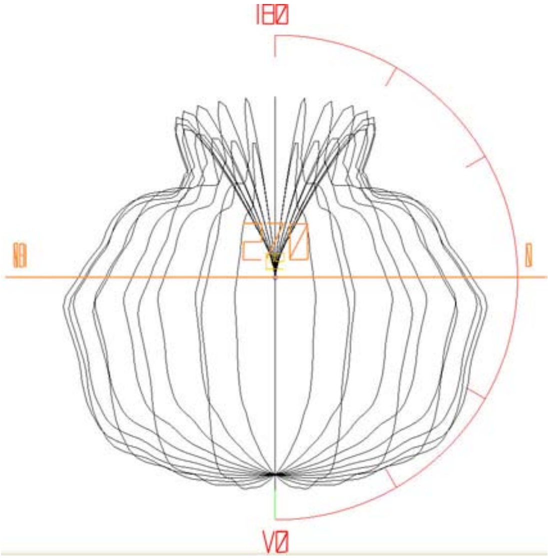

Figure 16: 3-D wire diagram of XB-D A19 candela intensity values

19 Testing was performed in a type C goniometer at Cree's Durham Technology Center. IES files for the A19 lamp are available at www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Reference%20Designs/Design%20files/xbd_a19_ies.ies.

Figure 17 compares the light output of the XB-D A19 lamp to that of a typical LED snow cone lamp. Note that the snow cone lamp directs only a small amount of light toward the lamp base compared to the omnidirectional XB-D A19 lamp.

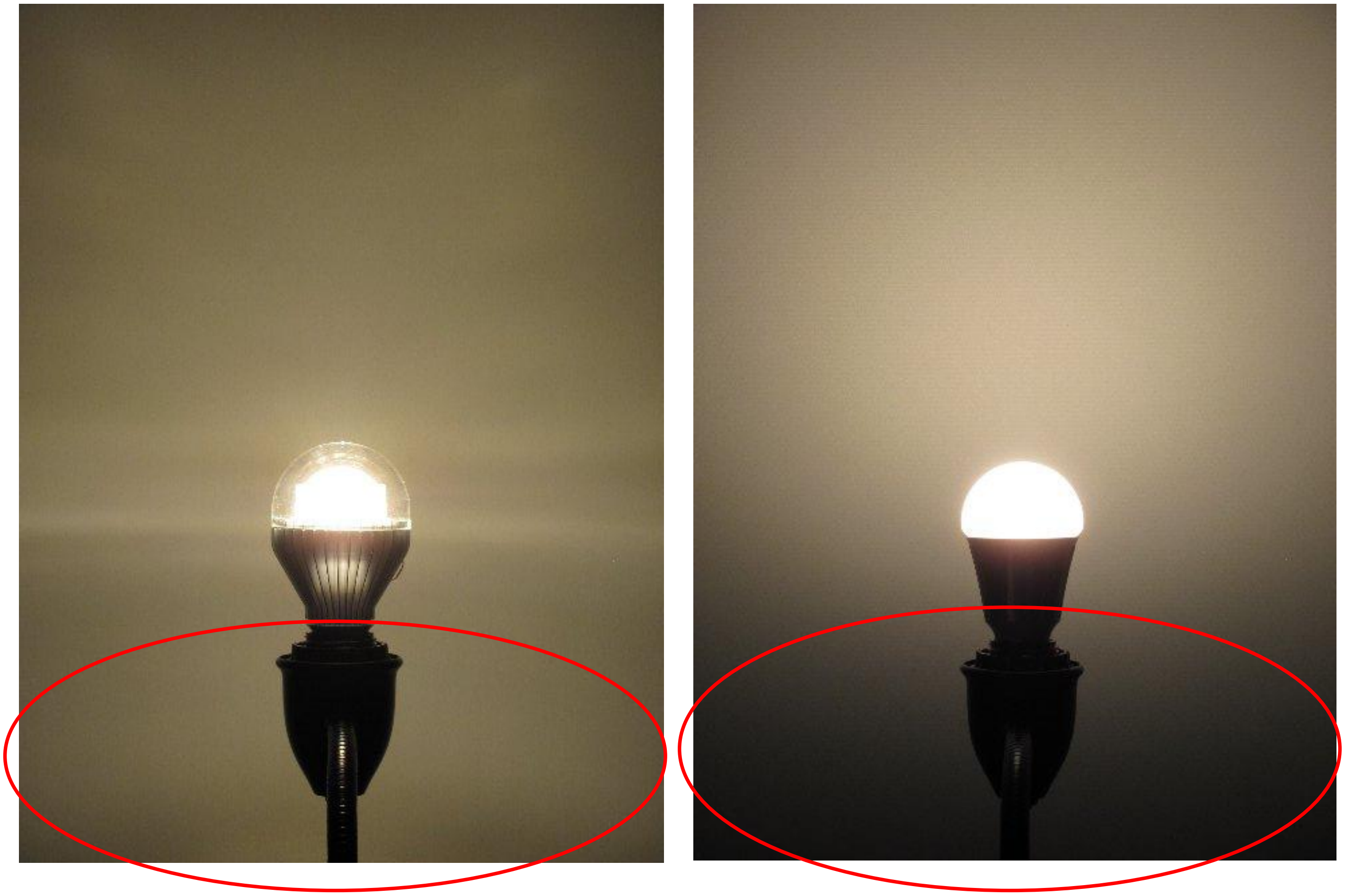

Figure 17: Light output comparison against a wall - XB-D A19 lamp (left) directs much more light toward the lamp base than the snow cone lamp (right)

CONCLUSIONS

This reference design illustrates the excellent performance of a low-cost, high-performance A19 lamp based on the Cree XLamp XB-D LED. With the assistance of several partner companies, Cree designed an A19 lamp that meets the ENERGY STAR light distribution requirements for a 75-W replacement lamp.

Those interested in meeting the full battery of 45 °C ambient temperature ENERGY STAR test requirements might elect to use a different number of LEDs, which is possible with this design. Using six XLamp XB-D LEDs would yield an omnidirectional lamp producing a lower lumen level, i.e., 800 lumens, 60-W equivalence. Additionally, using ten or twelve XLamp XB-D LEDs would result in a 75-W equivalent lamp that operates at a lower junction temperature.

The light pattern of this lamp makes it suitable for omnidirectional applications in which incandescent lamps are typically used and in applications in which the light pattern of a snow cone lamp is less than optimal. The lighting-class performance of the Cree XLamp XB-D LED makes it an attractive design option for an LED-based A19 lamp.

SPECIAL THANKS

Cree would like to acknowledge and thank the following partner companies that collaborated in the successful prototyping of this lamp.

- Aether Systems Inc. - www.aether-systems.com
- ON Semiconductor - www.onsemi.com
- Rayben - www.rayben.com
- Taisun Precision Parts - www.hztaisun.com