

Cree® XLamp® XM-L High-Bay Reference Design



Figure 1: XM-L high-bay prototypes (left: no optic design, right: Carclo Bubble optic)

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INTRODUCTION

There is a large market opportunity for LED-based high-bay luminaires. World-wide market estimates of low-bay and high-bay luminaires, both as replacements for existing fixtures and as initial installations in new construction, are in the hundreds of millions of units. High-bay luminaires incorporating the Cree XLamp XM-L LED offer numerous benefits compared to traditional high bay fixtures including energy efficiency, better illumination and the ability to integrate with building control systems.

Until the release of Cree’s XLamp XM-L LED, several hundred LEDs were needed to match the luminous output of traditional high-bay lighting. The highly efficient XM-L LED makes using this LED in a high-bay luminaire a viable alternative to a metal-halide lamp.

This application note demonstrates how to incorporate the Cree XLamp XM-L LED into a high-bay luminaire.

An XM-L high-bay luminaire has multiple advantages over traditional metal-halide lamps.

- No warm-up time
- No cool down needed before restart
- No humming or flickering
- No mercury
- Longer lifetime
- No re-lamping cost, which can be a significant expense in high-bay applications
- No risk of lamp breaking, sending glass fragments over a large area
- Dimmable, enabling the use of occupancy sensors for power savings

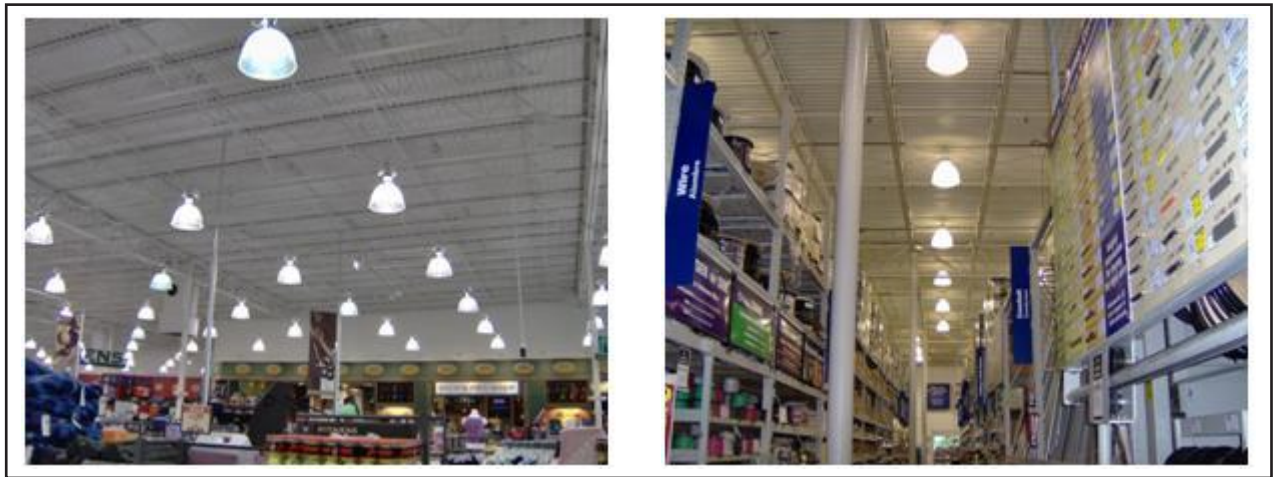


Figure 2: Typical high bay installations

Cree created these XM-L high-bay prototypes with help from several driver and optical partners to show several different approaches to an XM-L based high-bay luminaire design. These are only a few of the many possible implementations of the XM-L LED into a high-bay design.

DESIGN APPROACH/OBJECTIVES

In the “LED Luminaire Design Guide”¹ Cree advocates a six step framework for creating LED luminaires and lamps. We used this framework, with the design guide’s summary table reproduced below.

| Step | Explanation |
|---------------------------------|---|
| 1. Define lighting requirements | <ul style="list-style-type: none"> • The design goals can be based either on an existing fixture or on the application’s lighting requirements. |
| 2. Define design goals | <ul style="list-style-type: none"> • 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. |

1 LED Luminaire Design Guide, Application Note AP15, www.cree.com/products/pdf/LED_Luminaire_Design_Guide.pdf

| Step | Explanation |
|---|--|
| 3. Estimate efficiencies of the optical, thermal & electrical systems | <ul style="list-style-type: none"> 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 | <ul style="list-style-type: none"> 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 | <ul style="list-style-type: none"> 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 | <ul style="list-style-type: none"> 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 major goal for this project was to create an easy-to-implement, high-efficiency XM-L LED-based luminaire capable of replacing the traditional metal-halide high-bay fixtures on the market. Cree framed the project as a fixture replacement, so implementers can take full advantage of the XM-L LED’s superior performance.

1. DEFINE LIGHTING REQUIREMENTS

Table 2 shows a ranked list of desirable characteristics for a high-bay luminaire.

| Importance | Characteristics | Units |
|------------|------------------------------------|----------------------|
| Critical | Illuminance distribution | Footcandles (fc)/lux |
| | Electrical power | Watts (W) |
| | Lifetime | Hours |
| | Payback | Months |
| | Luminous flux | Lumens (lm) |
| | Manufacturability | |
| Important | Operating temperatures | °C |
| | Operating humidity | % RH |
| | Correlated Color Temperature (CCT) | K |
| | Color Rendering Index (CRI) | 100 point scale |
| | Ease of installation | |

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

Figure 3 below shows measured intensity data for metal-halide luminaires purchased from an industrial store, normalized to show the light distribution for two types of luminaires.

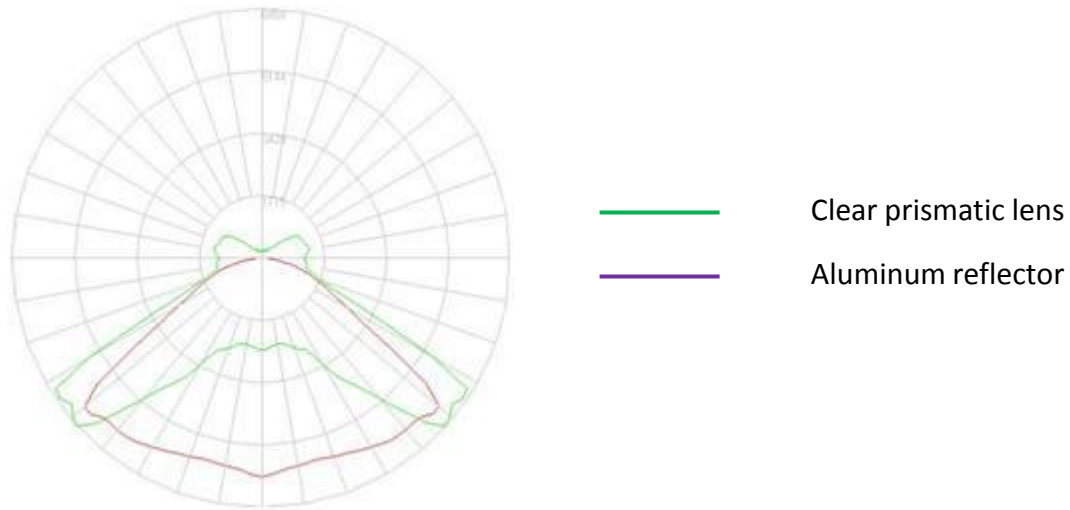


Figure 3: Goniometric intensity polar plot of metal-halide luminaires

Photometric testing and examination of existing high-intensity discharge (HID) metal-halide lamps provides comparison data, shown in Table 3.

| Source | Luminaire Power (W) | Lamp Luminous Flux (lm) | Fixture Total Lumens | Fixture Efficiency | Usable Lumens* | Efficacy (lm/W) |
|---|---------------------|-------------------------|----------------------|--------------------|----------------|-----------------|
| HID aluminum reflector BT37 metal-halide lamp | 436 | 29,013 | 20,924 | 54% | 15,771 | 36.2 |
| HID clear prismatic lens BT37 metal-halide lamp | 436 | 29,013 | 26,790 | 61% | 17,597 | 40.4 |

Table 3: Metal halide comparison data

* Usable lumens define the light in the 0-60° zonal lumens distribution. The rest of the light is considered to be wasted. The fixture efficiency, as defined in Cree’s “LED Luminaire Design Guide,”² reflects the percentage of light that is useful.

² Ibid., 6

Figure 4, Figure 5 and Figure 6 show the advantages of directional XLamp XM-L LEDs in this application. Omnidirectional metal-halide lamps do not transmit all their light toward the target to be illuminated, resulting in losses within the fixture. The directional XM-L LED transmits all its light toward the target, with minimal to no losses within the fixture. As a result of this difference, a lumens-for-lumens match between an XM-L LED and a metal-halide lamp is only partially relevant.

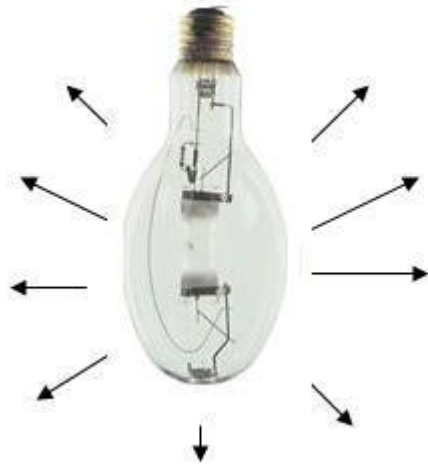


Figure 4: Typical metal-halide lamp light distribution

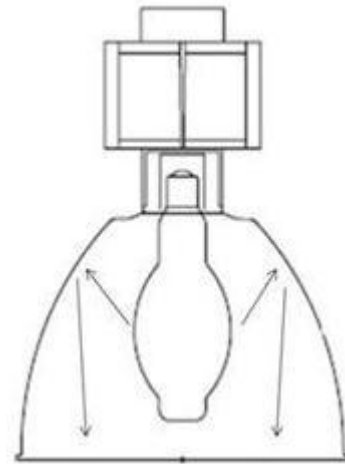


Figure 5: Typical high-bay luminaire light distribution

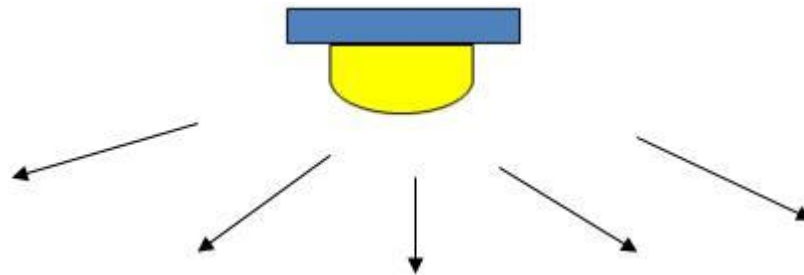


Figure 6: Typical high power LED light distribution

The Illuminating Engineering Society of North America (IESNA) gives performance requirements³ for various situations.

| Category | Fc | Lux | Description | Example |
|----------|-----|--------|---|-------------------------------|
| A | 3 | 32.3 | Public space | Wine cellar |
| B | 5 | 53.8 | Simple orientation | Toilets & washroom |
| C | 10 | 107.6 | Working space simple tasks | Auditorium, locker room |
| D | 30 | 322.9 | Visual tasks of high contrast and large size | Library, museum |
| E | 50 | 538.2 | Visual task of high contrast and small or low contrast and large size | Commercial kitchen, classroom |
| F | 100 | 1076.4 | Visual task of low contrast and small size | Basketball court |
| G | 300 | 3229.2 | Visual task near threshold | Autopsy table, surgical task |

Table 4: IESNA requirements

The ENERGY STAR program provides general performance requirements.⁴ There are currently no specific ENERGY STAR requirements for high-bay fixtures, however the following requirements apply to directional, commercial and indoor luminaires.

| Characteristic | Requirement |
|--------------------------|--|
| CCT | The luminaire must have one of the following nominal CCTs and fall within the corresponding 7-step chromaticity quadrangles as defined in ANSI/NEMA/ANSI C78.377-2008. 2700 K 3000 K 3500 K 4000 K 5000 K |
| Color angular uniformity | The variation of chromaticity shall be within 0.004 from the weighted average point on the CIE 1976 (u', v') diagram. |
| Color Maintenance | The change of chromaticity over the first 6,000 hours of luminaire operation shall be within 0.007 on the CIE 1976 (u', v') diagram. |
| CRI | Luminaire shall meet or exceed $R_a \geq 80$. |
| Off-state power | Luminaires shall not draw power in the off state. |
| Dimming | The luminaire and its components shall provide continuous dimming from 100% to 35% of total light output. Step dimming, if employed, shall provide at least two discrete light output levels $\geq 35\%$ of total light output and not including 100% output. |
| Source start time | Light source shall remain continuously illuminated within one second of application of electrical power. |

³ IESNA Lighting Handbook, 9th Edition

⁴ ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) - Eligibility Criteria - Version 1.0
http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/luminaires/ES_Luminaires_V1_Final_Specification.pdf

| Characteristic | Requirement |
|-------------------------------|---|
| Source run-up time | Light source shall reach 90% of stabilized lumen output within one minute of application of electrical power. |
| Power Factor (PF) | Total luminaire input power ≤ 5 W: PF ≥ 0.5 Total luminaire input power > 5 W: PF ≥ 0.7 for residential PF ≥ 0.9 for commercial |
| Warranty | 3-year warranty for luminaires with replaceable drivers. 5-year warranty for luminaires with non-replaceable drivers. |
| Driver case temperature | Measured temperature for the hottest location on the driver case shall not exceed the driver manufacturer's maximum recommended temperature during in situ operation. |
| Minimum operating temperature | -18°C or below |
| 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. |
| Luminaire efficacy | 42 lm/W |
| Minimum light output | ≤ 4.5 in. aperture: 345 lumens > 4.5 in. aperture: 575 lumens |
| Zonal lumen density | Minimum of 75% of total initial lumens within 0-60° zone (axially symmetric about the nadir) |
| Lumen maintenance requirement | $L_{70} \geq 35,000$ hours for commercial luminaires |

Table 5: ENERGY STAR requirements

The DesignLights Consortium provides requirements for a high-bay luminaire.⁵

| Characteristic | Application | |
|----------------------------|---|-------------------------|
| | High-Bay and Low-Bay Fixtures for Commercial and Industrial Buildings | High-Bay-Aisle Lighting |
| Minimum light output | $> 10,000$ lm | $> 10,000$ lm |
| Zonal lumen density | $\geq 30\%$ 20-50° | $\geq 50\%$, 20-50° |
| Nominal requirement, zone | | $\geq 30\%$, 0-20° |
| Minimum luminaire efficacy | 60 lm/W | 60 lm/W |

5 Technical Requirements Table v1.5 <http://www.designlights.org/solidstate.manufacturer.requirements.php>

| Characteristic | Application | |
|---|---|-------------------------|
| | High-Bay and Low-Bay Fixtures for Commercial and Industrial Buildings | High-Bay-Aisle Lighting |
| Allowable CCTs | 2700 K | 2700 K |
| | 3000 K | 3000 K |
| | 3500 K | 3500 K |
| | 4000 K | 4000 K |
| | 4500 K | 4500 K |
| | 5000 K | 5000 K |
| | 5700 K | 5700 K |
| | 6000 K | 6000 K |
| Minimum CRI | 70 | 70 |
| Minimum lumen maintenance requirement at 6000 hrs | 94.1% | 94.1% |
| Minimum luminaire warranty | 3 years | 3 years |

Table 6: DesignLights Consortium high-bay luminaire requirements

2. DEFINE DESIGN GOALS

The design goals for this project:

| Characteristic | Unit | Minimum Goal | Target Goal |
|------------------------------|-------|---------------------------------|---------------------------------|
| Illuminance profile | Fc | same as 400 W metal halide lamp | same as 400 W metal halide lamp |
| Power | W | < 250 | 200 |
| Luminaire efficacy | lm/W | > 70 | 80 |
| Lifetime | hours | 25,000 | 50,000 |
| CCT | K | 7000 | 7000 |
| CRI | | identical | better |
| Maximum ambient temperature | °C | 30 | 40 |
| Bill of materials (BOM) cost | \$ | 400 | 400 |
| Lumens (round output) | lm | 17,000 | 17,000 |
| Lumens (oval output) | lm | 10,000 | 10,000 |

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

Optical Efficiency

The two main optical losses in an LED system are light loss within the fixture and secondary optic loss. To eliminate light loss within the fixture we designed the fixture so there is no light loss within it. This was done by spacing the LEDs far

enough from the edge of the fixture and close enough to the output so no light hits the sides and has to be reflected out. Secondary optics can have light loss as high as 20% and as low as 7%.

To achieve as little secondary optic loss as possible, Carclo⁶ and Ledil⁷ optics were chosen having efficiencies as high as 93%.



Figure 7: Carclo Bubble optic

The Carclo optic produces a round distribution of light wider than that of a high-bay luminaire without an optic. Such a distribution is useful in illuminating a space such as a large retail store.



Figure 8: Ledil Strada optic

The Ledil optic produces an oval distribution of light that is useful in illuminating spaces such as aisles in a warehouse.

Thermal Requirements

The XLamp XM-L LED operates at up to 10 watts of electrical power, depending on the drive current, and requires a heat sink to dissipate this thermal load. About 40% of that energy is converted to radiant flux and the rest to heat. Because we want the fixture to operate at less than 200 W, the heat sink will have to support a thermal load of 120 W.

The heat sink has two functions in this high-bay design: primarily to dissipate the thermal load of the LED, but also to provide a frame for the fixture. This allows for as much surface area as possible to be exposed to ambient conditions and takes full advantage of designing the luminaire around the XM-L LED. Cree chose to work with machined aluminum to provide a series of large cooling fins. Machining of this prototype was done with the help of a local machine shop.

A STEP file for the heat sink and assembly mounting arm is available on the Cree website.⁸

⁶ Carclo Technical Plastics Ltd. website: <http://www.carclo-optics.co.uk/>

⁷ Ledil Oy website: <http://www.ledil.com>

⁸ http://www.cree.com/XLampModels/XLamp_ML_Highbay.zip

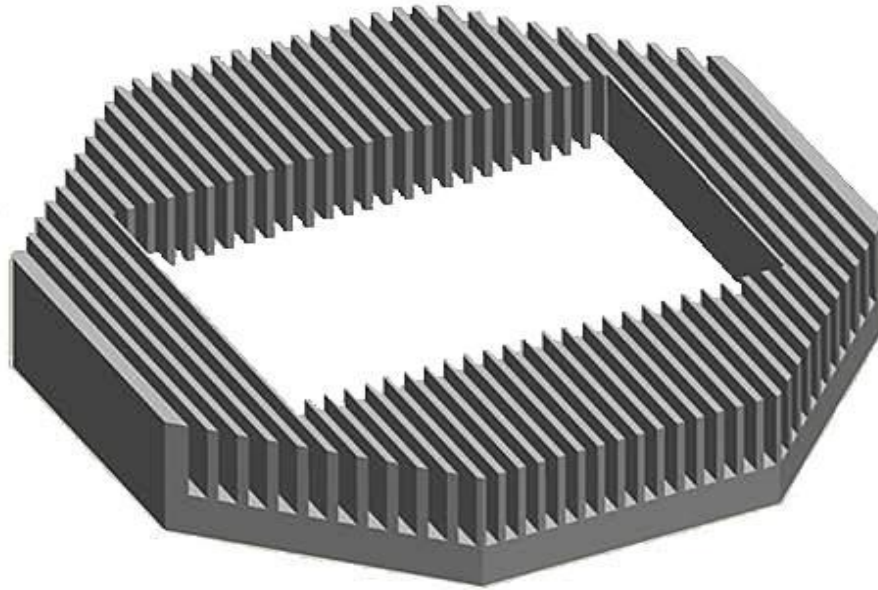


Figure 8: Machined aluminum heat sink

To verify the utility of this design, Cree performed thermal simulations using Ansys simulation software.⁹ Shown below in Figure 9 is a simulation showing a cross section of the heat-sink housing with a 150-W thermal load at steady state in a 25°C-ambient operating environment. The highest temperature in the simulation is at the solder point; the LED/heat-sink boundary never goes above 76°C, or 51°C above ambient. The thermal resistance of the XM-L LED is 2.5°C/W, so the junction temperature will be ~89°C. With heat-sink thermal dissipation like this, the design will have no trouble achieving a 50,000-hour L_{70} lifetime.¹⁰

⁹ Cree used Ansys Design Space, <http://www.ansys.com/products/structural-mechanics/products.asp>

¹⁰ That is, after 50,000 hours of operation, in a well-designed system, the LED will still deliver at least 70% of its initial luminous flux.

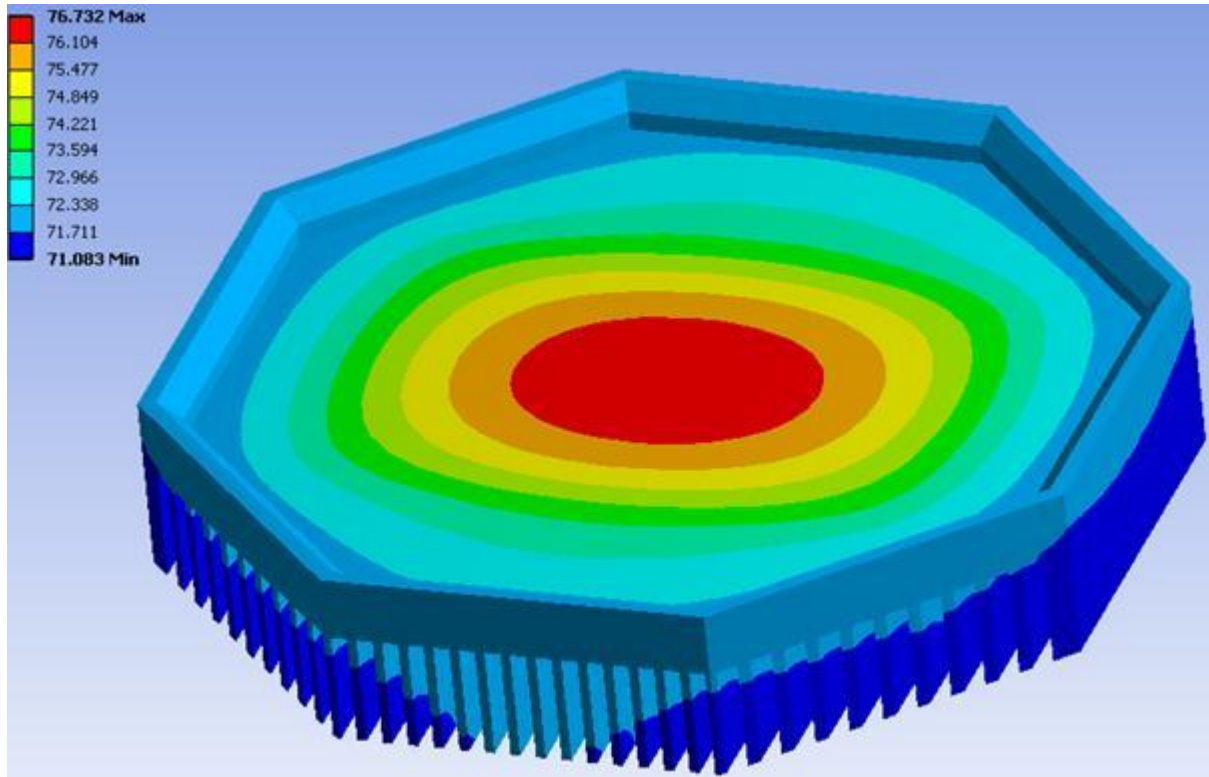


Figure 9: Ansys thermal simulation

Examining either the Cree Product Characterization Tool (PCT) or the relative flux vs. junction temperature graph in the XM-L data sheet,¹¹ an XM-L LED operating at a 89°C junction temperature will have a brightness of just less than 90% of the 85°C binning flux. Our measurements confirm this.

11 <http://www.cree.com/products/pdf/XLampXM-L.pdf>

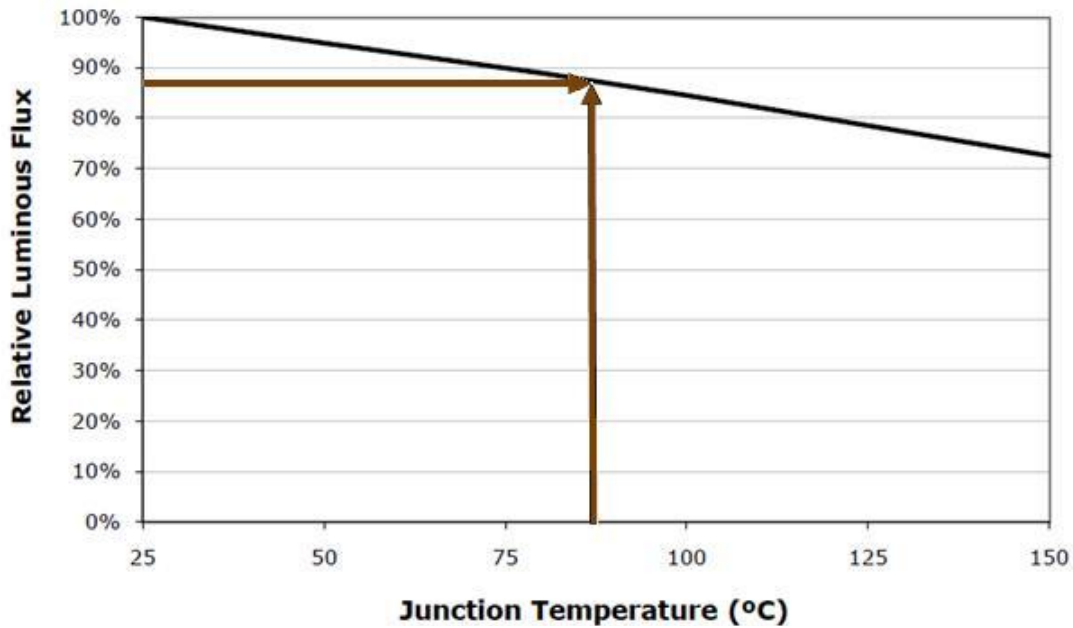


Figure 10: XLamp XM-L data sheet: Relative luminous flux vs. junction temperature

Drive Electronics

While there are many excellent suppliers of LED control electronics and many ways to deliver controlled DC power to the XLamp XM-L LED, Cree chose a readily available, full-range, off-the-shelf power supply from Thomas Research¹² and Mean Well¹³ and a custom driver from NXP Semiconductors.¹⁴ We chose the Thomas Research driver because it is already CE/UL certified, available from multiple distributors, has efficiencies as high as 91% and a power factor greater than 0.9. The NXP custom driver provides efficiency of ~95%, has four-channel output, a power factor above 0.9 and can be configured to have occupancy sensing dimming.



Figure 11: Power supplies (left: Thomas Research, right: NXP)

12 Thomas Research model TRC-129S175ST http://www.thomasresearchproducts.com/led_drivers.htm

13 Mean Well USA Inc. website: <http://www.meanwellusa.com>

14 NXP Semiconductors website: <http://www.nxp.com/>

Table 8 below summarizes the calculated efficiencies of the optical, thermal and electrical systems for this high-bay design.

| System | Efficiency | Type |
|------------|------------|-------|
| Optical | 93% | Light |
| Thermal | 88% | Light |
| Electrical | 92% | Power |

Table 8: Optical, thermal, electrical efficiencies

4. CALCULATE THE NUMBER OF LEDS

The design goal is to have a total of 17,000 lumens in a round beam and 10,000 lumens in an oval beam out of the prototype fixture, so the actual lumens needed out of the LEDs after all the system efficiencies are take into account is shown below.

$$\text{Actual Lumens Needed} = \text{Target Lumens} / (\text{optical efficiency} * \text{thermal efficiency})$$

| |
|---|
| Round beam |
| Actual Lumens Needed = 17,000 / (93%*88%) |
| Actual Lumens Needed = 20,772 lm |
| Oval beam |
| Actual Lumens Needed = 10,000 / (93%*88%) |
| Actual Lumens Needed = 12,219 |

The XM-L LED delivers industry-leading flux and efficacy. Based on the initial data, we chose to work with the Cool White, highlighted in yellow in Table 9 below, to give the closest possible CCT to a metal-halide lamp. These LEDs, running at 1.5 to 2 A, deliver less total flux than a 400-W metal-halide lamp, but the directionality of the XM-L LED source, with a 125° beam spread, direct more flux toward the fixture opening than the spherical illuminance profile of the metal-halide lamp.

| Group Code | Min. Luminous Flux @ 700 mA (lm) | Max. Luminous Flux @ 700 mA (lm) |
|------------|----------------------------------|----------------------------------|
| S6 | 182 | 200 |
| T2 | 200 | 220 |
| T3 | 220 | 240 |
| T4 | 240 | 260 |
| T5 | 260 | 280 |
| T6 | 280 | 300 |
| U2 | 300 | 320 |

Table 9: Order codes from XM-L binning and labeling document

Basic XM-L LED electrical data and optical output from Cree’s Product Characterization Tool (PCT)¹⁵ is listed in Figure 12.

| | | LED 1 | | | |
|-------------|-----------|--------------|----------------------|---------|----|
| | | Model | Cree XLamp XM-L {CW} | | |
| | | Flux | T6 [280] | 280.0 | |
| | | Price | \$ - | Tj (°C) | 85 |
| | | LED Multiple | | x1 | |
| Current (A) | SYS # LED | SYS lm tot | SYS lm/W | SYS W | |
| 0.700 | 76 | 17176 | 109.4 | 156.96 | |
| 0.750 | 71 | 17111 | 107.6 | 158.98 | |
| 0.800 | 67 | 17152 | 107.1 | 160.22 | |
| 0.850 | 63 | 17073 | 106.1 | 160.92 | |
| 0.900 | 60 | 17100 | 104.5 | 163.7 | |
| 0.950 | 57 | 17043 | 103.4 | 164.8 | |
| 1.000 | 55 | 17215 | 102.1 | 168.59 | |
| 1.100 | 50 | 17050 | 99.9 | 170.65 | |
| 1.200 | 47 | 17296 | 97.9 | 176.76 | |
| 1.300 | 44 | 17336 | 95.9 | 180.78 | |
| 1.400 | 41 | 17179 | 94 | 182.72 | |
| 1.500 | 39 | 17355 | 92.2 | 188.22 | |
| 1.600 | 37 | 17353 | 90.5 | 191.84 | |
| 1.700 | 35 | 17220 | 88.8 | 194.02 | |
| 1.800 | 34 | 17510 | 87.1 | 201.04 | |
| 1.900 | 32 | 17216 | 85.6 | 201.04 | |
| 2.000 | 31 | 17329 | 84 | 206.22 | |

| | | LED 1 | | | |
|-------------|-----------|--------------|----------------------|---------|----|
| | | Model | Cree XLamp XM-L {CW} | | |
| | | Flux | T6 [280] | 280.0 | |
| | | Price | \$ - | Tj (°C) | 85 |
| | | LED Multiple | | x1 | |
| Current (A) | SYS # LED | SYS lm tot | SYS lm/W | SYS W | |
| 0.700 | 73 | 17009 | 116.5 | 146 | |
| 0.750 | 69 | 17181 | 114.8 | 149.62 | |
| 0.800 | 65 | 17160 | 114 | 150.53 | |
| 0.850 | 61 | 17019 | 112.8 | 150.89 | |
| 0.900 | 58 | 17052 | 111.3 | 153.24 | |
| 0.950 | 56 | 17304 | 110.4 | 156.8 | |
| 1.000 | 53 | 17172 | 109.1 | 157.33 | |
| 1.100 | 49 | 17248 | 106.5 | 161.96 | |
| 1.200 | 45 | 17100 | 104.3 | 163.89 | |
| 1.300 | 42 | 17094 | 102.3 | 167.12 | |
| 1.400 | 40 | 17320 | 100.3 | 172.63 | |
| 1.500 | 38 | 17442 | 98.2 | 177.6 | |
| 1.600 | 36 | 17424 | 96.4 | 180.76 | |
| 1.700 | 34 | 17272 | 94.6 | 182.53 | |
| 1.800 | 32 | 17024 | 92.9 | 183.24 | |
| 1.900 | 31 | 17205 | 91.2 | 188.61 | |
| 2.000 | 30 | 17310 | 89.6 | 193.26 | |

Figure 12: Cree’s Product Characterization Tool with XLamp XM-L flux data (left: with 92% optical efficiency and 90% driver efficiency, right: with no optical loss and 93% driver efficiency)

Depending on the drive current and the specific design goals to be achieved, the number of XM-L LEDs can vary greatly. The PCT data in Figure 13 above shows this. After some experimentation and basic calculations with the use of the PCT, we chose to drive 40 XLamp XM-L LEDs at 1.4 A for the no optic version. For the version with a wide-beam secondary optic we chose to drive 32 XM-L LEDs at 1.7 A, but as few as 31 and as many as 76 LEDs can be used. Both versions will be capable of meeting our 17,000 lumen output and less than 200 W power requirements. For the version with an oval-beam secondary optic, we chose to drive 24 XM-L LEDs at 1.4 A. This version will be capable of meeting our 10,000 lumen output and less than 200 W power requirements.

The purpose of this design exercise was to show that there are various ways to use XLamp XM-L LEDs achieve the light output required of an LED based high-bay luminaire. The number of LEDs in the design depends on critical design goals such as high efficiency and cost.

15 The analysis came from Cree’s Product Characterization Tool. <http://pct.cree.com/>

Figure 13 shows a comparison photometric simulation using Dialux software. IES files for the high-bay simulation are available on the Cree website.¹⁶

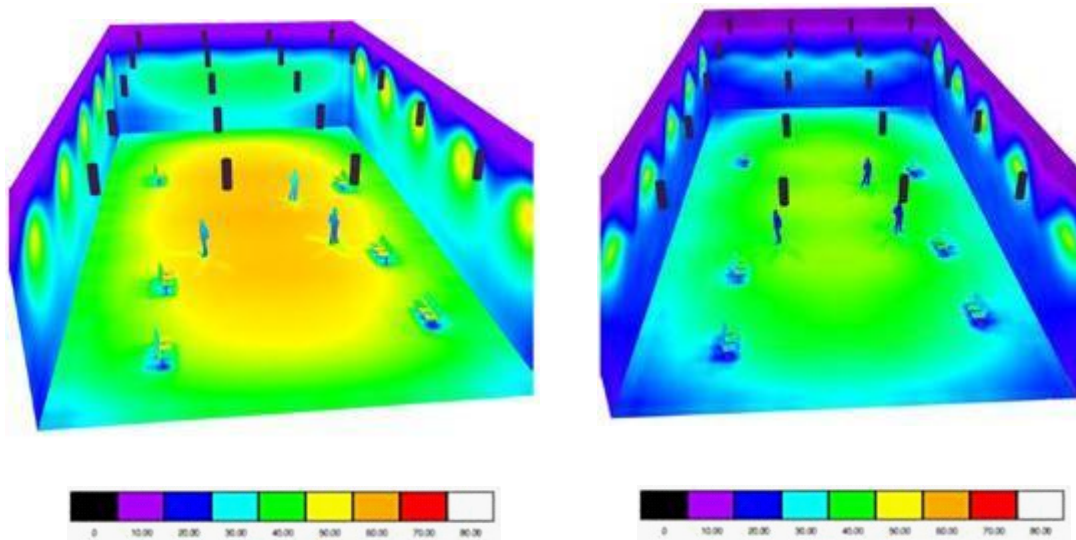


Figure 13: Photometric simulation (left 32-LED XM-L high-bay prototype, right: metal-halide)

5. CONSIDER ALL DESIGN POSSIBILITIES

The main decision for the design of an XM-L LED based high-bay luminaire is whether to design a retrofit lamp or design a fixture to replace a traditional bell-shaped fixture. Choosing to design a luminaire around the LEDs gives limitless possibilities. The luminaire can be lighter weight and smaller than a traditional fixture and can incorporate additional functions such as dimming and occupancy sensing.

For this design Cree chose to do the following.

- Maximize the coefficient of utilization.
- Use off-the-shelf optics.
- Design a heat sink that fits the design aesthetic and guarantees proper heat dissipation.
- Use an off-the-shelf driver for the simplest solution and a custom driver for a more efficient solution.
- Design a custom metal-core printed circuit board (MCPCB) that flexibly accommodates various numbers of LEDs placed on it.

6. COMPLETE THE FINAL STEPS: IMPLEMENTATION AND ANALYSIS

This section illustrates the techniques Cree used to create a prototype high-bay luminaire using the Cree XLamp XM-L LED and reviews the optical and electrical results.

¹⁶ http://www.cree.com/XLampModels/XLamp_ML_Highbay_IES.zip

Prototyping Details

The essence of this prototyping design is to assemble the XM-L LEDs onto a MCPCB, mount this PCB onto a heat sink and assemble these components with the necessary secondary optics and driver to create an LED-based luminaire comparable to existing 400-W metal-halide high-bay fixtures. The prototyping steps are detailed below.

1. MCPCB design

- a. The initial design of the PCB used an MTS rapid prototyping milling machine. This allowed the design to be adjusted before having the board made at a PCB company. Using the machine provided cost and time savings.

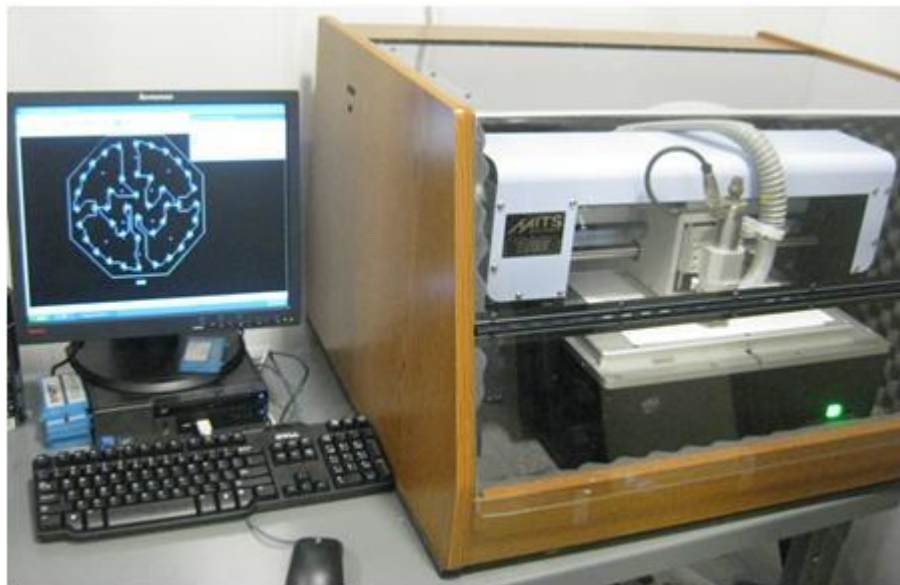


Figure 14: MTS rapid prototyping milling machine

- b. Once the PCB design was proven, it was drawn and compiled to Gerber files by Copper Wave, Inc.¹⁷ and sent to Multilayer Prototypes, Inc.¹⁸ for PCB fabrication. The result is shown in Figure 16 below. The Gerber files are available on the Cree website.¹⁹

¹⁷ Copper Wave, Inc. website: <http://www.copperwavepcb.com/company.htm>

¹⁸ Multilayer Prototypes, Inc. website: <http://www.mpi-pcb.com/>

¹⁹ http://www.cree.com/XLampModels/XLamp_ML_Highbay_MCPCB.zip



Figure 15: XM-L prototype high-bay PCB

2. Machining the heat-sink housing
 - a. To prove the design of the heat-sink housing, a prototype was machined from the drawing and files used in the thermal simulations.
 - b. The housing was machined and the mounting arm assembled by MCS Machine & Tool. The result is shown in Figure 16 below.

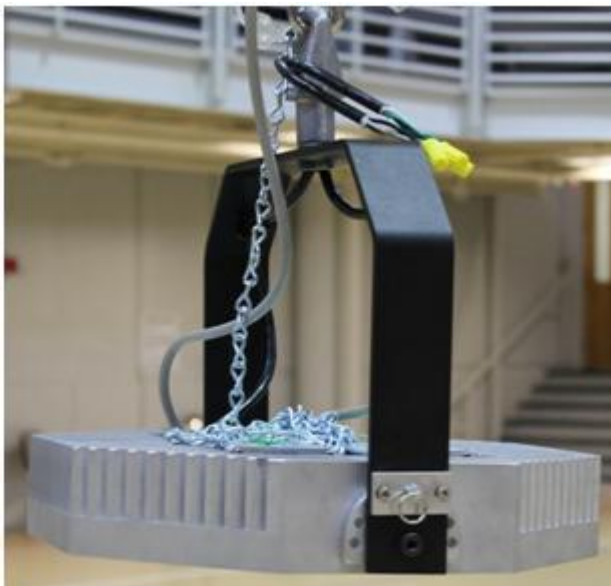


Figure 16: Machined housing

3. Assemble the drivers and PCB onto the housing
 - a. The XM-L LEDs were soldered onto the PCB following Cree’s Soldering and Handling Application Note for the XM-L LED.²⁰
 - b. The optic was attached to the PCB.
 - c. The power supply was mounted to the back of the housing.
 - d. The PCB was attached to the housing using screws with thermal grease between the back of the PCB and the housing.
 - e. The PCB was connected to the power supply.



Figure 17: Assembled XM-L prototype high-bay luminaire

Results

Thermal Results

Thermal measurements were taken according to Cree’s Soldering and Handling Application Note for the XM-L LED.²¹

As Figure 18 shows, data collected from the XM-L LEDs in the prototype high-bay luminaire driven at 1.7 A demonstrate thermal results and gradient in line with the thermal simulations.

²⁰ Cree XLamp XM-L LED Soldering and Handling, Application Note AP54
http://www.cree.com/products/pdf/XLampXM_SolderingandHandling.pdf

²¹ Ibid.

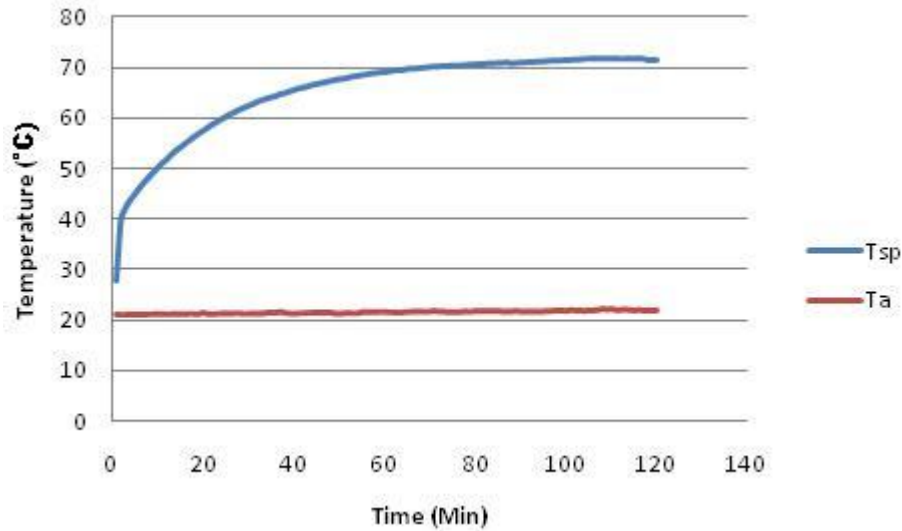


Figure 18: Thermal performance of 32-LED XLamp XM-L high-bay prototype driven at 1.7 A

Table 10 shows the solder point temperatures for the XM-L prototype high-bay luminaires.

| Criteria | No Optic Result | Bubble Optic Result | Strada Optic Result |
|----------|-----------------|---------------------|---------------------|
| Tsp (°C) | 65.8 | 71.6 | 62.5 |
| Driver | NXP | Thomas Research | Meanwell |
| Optic | none | Carclo | Ledil |
| # LEDs | 40 | 32 | 24 |

Table 10: Solder point temperature

Optical Results

Integrating sphere measurements²² show photometric and chromaticity data that exceed the design goals.

| Criteria | No Optic Result | Bubble Optic Result | Strada Optic Result |
|--------------------------|-----------------|---------------------|---------------------|
| Radiant flux (W) | 60.85 | 58.61 | 31.67 |
| Total luminous flux (lm) | 17,110 | 17,800 | 9844 |
| Power factor | .998 | .994 | .563 |
| Efficacy (lm/W) | 108 | 92.9 | 98.2 |
| Optical efficiency (%) | n/a | 92 | 92 |
| CCT (K) | 6851 | 7060 | 6898 |
| CRI (Ra) | 69.7 | 70.4 | 69.3 |
| Chromaticity (x-coord.) | 0.3076 | 0.3052 | 0.3127 |
| Chromaticity (y-coord.) | 0.3222 | 0.3173 | 0.3266 |
| Driver | NXP | Thomas Research | Meanwell |
| Optic | none | Carclo | Ledil |
| # LEDs | 40 | 32 | 24 |

Table 11: Optical results

²² Measurements taken at Luminaire Testing Laboratory, Inc., website: <http://www.luminairetesting.com/>

Electrical testing²³ shows the XM-L prototype high-bay luminaire achieves an efficacy that greatly exceeds that of the comparison metal-halide fixtures.

| Criteria | No Optic Result | Bubble Optic Result | Strada Optic Result |
|-----------------|-----------------|---------------------|---------------------|
| Power (W) | 158 | 191.6 | 100.2 |
| Power factor | .998 | .994 | .563 |
| Efficacy (lm/W) | 108 | 92.9 | 98.2 |
| Driver | NXP | Thomas Research | Meanwell |
| Optic | none | Carclo | Ledil |
| # LEDs | 40 | 32 | 24 |

Table 12: Electrical results

Goniometric measurements²⁴ show a consistent beam shape and light distribution for both XM-L prototype high-bay luminaires.

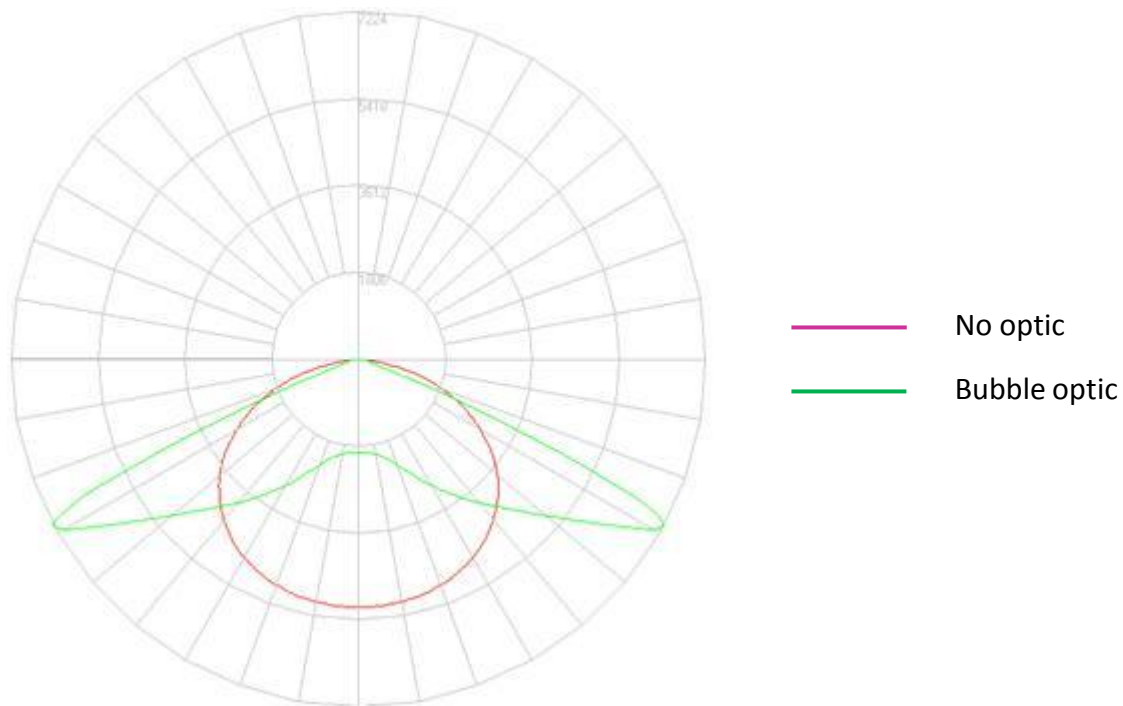


Figure 19: Goniometric intensity polar plot of XM-L prototype high-bay luminaire

The light intensity and distribution data²⁵ in Table 13 and Table 14 show the XM-L prototype high-bay luminaire effectively illuminates the area in which it is installed.

23 Ibid.
 24 Ibid.
 25 Ibid.

| Mounting Height (ft/m) | Footcandles/Lux at Nadir | | Diameter (ft/m) | |
|---------------------------|--------------------------|------------|-----------------|-----------|
| | Aluminum | Clear | Aluminum | Clear |
| | Reflector | Prismatic | Reflector | Prismatic |
| 6/1.8 | 167.1/1798.6 | 70.4/757.8 | 9.4/2.9 | 17.2/5.2 |
| 8/2.4 | 94.0/1011.8 | 39.6/426.3 | 12.5/3.81 | 22.9/7.0 |
| 10/3.0 | 60.2/648.0 | 25.4/273.4 | 15.7/4.8 | 28.7/8.7 |
| 12/3.7 | 41.8/450.0 | 17.6/189.4 | 18.8/5.7 | 34.4/11.4 |
| 14/4.3 | 30.7/330.45 | 12.9/138.9 | 21.9/6.7 | 40.1/12.2 |
| 16/4.9 | 23.5/253.0 | 9.9/106.6 | 25.17.7 | 45.8/14 |

Table 13: Metal halide light intensity and distribution

| Mounting Height (ft/m) | Footcandles/Lux at Nadir | | | Diameter (ft/m) | | |
|---------------------------|--------------------------|--------------|--------------|-----------------|--------------|--------------|
| | No Optic | Bubble Optic | Strada Optic | No Optic | Bubble Optic | Strada Optic |
| | 4/1.12 | 323/3476.7 | 122/1313.2 | 62.9/677.0 | 5.5/1.7 | 12.7/3.9 |
| 6/1.8 | 143/1539.2 | 54.3/584.5 | 28.0/301.4 | 8.25/2.5 | 19.1/5.8 | 17.8/5.4 |
| 8/2.4 | 80.7/868.6 | 30.5/328.3 | 15.7/169.0 | 11/3.4 | 25.5/7.8 | 23.7/7.2 |
| 10/3.0 | 51.6/555.4 | 19.5/209.9 | 10.0/107.6 | 13.8/4.2 | 31.8/9.7 | 29.6/9.0 |
| 12/3.7 | 35.8/385.3 | 13.6/146.4 | 6.99/75.2 | 16.5/5.0 | 38.2/11.6 | 35.6/10.9 |
| 14/4.3 | 26.3/283.7 | 9.97/107.3 | 5.14/55.3 | 19.3/5.9 | 44.5/13.69 | 41.5/12.6 |
| 16/4.9 | 20.2/217.4 | 7.63/82.1 | 3.93/42.3 | 22/6.7 | 50.9/15.5 | 47.4/14.4 |

Table 14: XM-L high bay light intensity and distribution

Cost of Ownership

The cost of the XM-L LEDs, heat sink and driver in this prototype high-bay design met the \$400 BOM target. A single HID metal-halide fixture typically retails for \$180 – \$250. Our BOM goal was not a primary factor for this design. Rather, high efficacy and effective light distribution were major considerations. This high-bay design is a prototype without any manufacturing or component optimizations. Initial fixture cost aside, the following calculations show the savings an XLamp XM-L LED high-bay luminaire can deliver.

For the cost of ownership calculations that follow:

- Assume that electricity costs \$0.10 per kWh.
- The calculations don't include the initial or replacement costs of the fixtures or the labor costs to replace a metal-halide lamp.

Table 15 compares the cost of ownership of the comparison HID metal-halide fixtures to that of the XM-L prototype high-bay luminaires over the 50,000-hour lifetime of the XM-L LEDs. The metal-halide fixtures not only use significantly more energy but also require three metal-halide lamps.

| High Bay Fixture | Lamp Wattage | Rated Lamp | Replacement-Lamp | Cost of Ownership |
|-------------------|--------------|------------|------------------|-------------------|
| | | Lifetime | Cost | |
| Metal halide | 436 | 20,000 hrs | \$11 | \$2207.50 |
| XM-L no optic | 158 | 50,000 hrs | - | \$790.00 |
| XM-L Bubble optic | 191.6 | 50,000 hrs | - | \$958.00 |
| XM-L Strada Optic | 100.2 | 50,000 hrs | - | \$501.00 |

Table 15: Cost of ownership calculations

Table 16 shows the payback expected from the XM-L prototype high-bay luminaires as opposed to the comparison HID metal halide fixtures after 3 years of use in several situations.

| Usage | Payback Total | | |
|--------------|---------------|--------------|--------------|
| | XM-L | XM-L | XM-L |
| | No Optic | Bubble Optic | Strada Optic |
| 24 hours/day | \$741.58 | \$653.28 | \$893.48 |
| 12 hours/day | \$376.29 | \$332.14 | \$452.24 |
| 8 hours/day | \$243.53 | \$214.09 | \$294.16 |

Table 16: Payback after 3 years

CONCLUSIONS

This high-bay reference design demonstrates the integration of the Cree XLamp XM-L LED into a high-bay luminaire to replace a traditional high-bay fixture with great results. The design utilized proper heat sinking, optical control where needed, and multiple driver options to efficiently and effectively hit the design targets and outperform comparison metal-halide fixtures. Cree designed the heat sink and chose a driver to achieve a minimum L70 50,000-hr designation. This design shows the level of performance that can be achieved but should not be interpreted as the only way that a good high-bay luminaire can be designed.

SPECIAL THANKS

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

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- Ledil Oy
- Mean Well USA
- Multilayer Prototypes, Inc.
- NXP Semiconductors
- Thomas Research

