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LED ROADWAY LIGHTING VOLUME 1: BACKGROUND INFORMATION

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16. Abstract

Roadway lighting is a fundamental public service that leads to a safer environment for both pedestrians and drivers. It is estimated that lighting alone accounts for around 3% of the total U.S. electricity consumption. Currently, street lighting applications mostly involve high-intensity discharge (HID) sources such as metal halide lamps and high-pressure sodium (HPS) lamps. As the energy crisis spreads across the world, energy conservation is becoming an urgent priority. Light-emitting diodes (LEDs) are fourth-generation light sources that have recently appeared as an energy-efficient solution to street lighting. (LEDs are currently used and are gaining credibility in street lighting applications but are only beginning to become viable for roadway lighting applications.) This report presents a comprehensive literature review that covers the current state of technology in LED roadway lighting, detailed comparison of LED roadway luminaires with HID roadway luminaires, test procedures for photometric measurements of roadway lighting installations, and IDOT roadway lighting requirements. LED luminaires provide the advantages of energy efficiency, longer lifetime, good color characteristics, improved mesopic vision conditions, lack of warm-up time, compact size, directional light, reduced light pollution, environment-friendly characteristics, dimming capabilities, breakage and vibration resistance, and more uniform light distribution. The Department of Energy (DOE) GATEWAY demonstration projects provide good information on the potential benefits of the replacement of HPS streetlights with LED streetlights. However, LEDs are currently not frequently utilized in street lighting applications due to their lower luminous efficacy, higher heat conversion rate, higher installation cost, and issues in obtaining white light. Trade-offs between color correlated temperature and lumen output, and between color shift of LED light sources over time, lumen maintenance (LED life expectancy), and thermal management are the critical issues of LEDs that should be properly addressed in street lighting applications. Because of the significant differences in HID and LED technology, there has been a gap in industry test standards and test procedures for product comparisons and ratings. Thus, ENERGY STAR® criteria, along with other important new standards and test procedures, have been released and continue to be developed. Some institutions also published their own specifications for LED roadway lighting. There is a significant push by the industry to research and develop LED luminaires for street lighting, and this is evidenced in the number and improved characteristics of new products being released by practically every major player in the street lighting sector. Given the clear trend toward the use of LED luminaires in the industry, it is expected that efficient LED luminaires for highway applications will be available in the near future for higher mounting heights and lumen output requirements.

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EXECUTIVE SUMMARY

Roadway lighting is a fundamental public service that leads to a safer environment for both pedestrians and drivers. It is estimated that lighting roadways alone accounts for around 3% of the total U.S. electricity consumption. As the energy crisis spreads across the world due to decreasing oil and gas reserves and increasing demand, energy conservation is becoming an urgent priority. To alleviate the energy crisis, the use of energy-efficient technology is indispensable in roadway lighting. At present, street lighting applications mostly involve high-intensity discharge (HID) sources such as metal halide lamps and high-pressure sodium (HPS) lamps. Although high-intensity discharge (HID) sources such as high-pressure sodium (HPS) and metal halide are energy-efficient light sources with high lumen efficacy, they also have some performance drawbacks such as low color rendering abilities, low lumen maintenance compared to LEDs, and longer time required to re-strike after a power interruption.

Light-emitting diodes (LEDs) are fourth generation light sources that have recently appeared as an energy-efficient solution to street lighting. LEDs have been used since the 1960s as indicator lamps in consumer products, and recent rapid advancements in LED lighting technologies are making LEDs a more feasible and efficacious alternative for street lighting. As a result, the market share of LEDs is also continuously increasing. It is expected that high-power LEDs will gradually replace around 25–30% of incandescent lighting applications by 2025.

This report presents a comprehensive literature review that covers the current state of technology in LED roadway lighting, a detailed comparison of LED roadway luminaires with HID roadway luminaires, test procedures for photometric measurements of roadway lighting installations, and roadway lighting requirements from the Illinois Department of Transportation (IDOT). It is noted that a second report, Volume 2 of this study, presents the results of a field evaluation of three LED luminaires for roadway lighting applications.

According to the available information in the literature, LED luminaires can be a promising choice for street lighting systems since they provide the advantages of energy efficiency, longer life, good color characteristics, the potential to improve mesopic vision, lack of warm-up time, compact size, directional light, reduced light pollution, environment-friendly characteristics, dimming capabilities, breakage and vibration resistance, and more uniform light distribution. The Department of Energy (DOE) GATEWAY demonstration projects provide good information on the potential benefits of the replacement of HPS streetlights with LED streetlights. Despite their advantages, LEDs are currently not frequently used in street lighting applications due to their lower luminous efficacy, higher heat conversion rate, uncertain life expectancy of the LEDs (lumen maintenance) and the driver (electrical components), higher installation cost, and issues in obtaining white light. Nonetheless, a continuous rise in the efficacy of LEDs is expected over the coming years, and uncertainty over the expected life of the luminaire is being addressed through emerging industry standards.

Some of the critical issues in LEDs are the trade-off between correlated color temperature (CCT) and lumen output, and between color shift of LED light sources over time and thermal management of LEDs. For instance, LEDs convert around 75–85% of their electrical power into heat, as opposed to 37% of electrical power into heat in metal halide lamps. All those issues must be properly addressed in street lighting applications.

Because of the significant differences in HID and LED technology, there has been a gap in industry test standards and test procedures for product comparisons and ratings. Thus, ENERGY STAR® criteria along, with other important new standards and test procedures, have been released. Among the important test procedures are IESNA RP-8-00 (American National Standard Practice for Roadway Lighting), IESNA LM-79-08 (IESNA

Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products), IESNA LM-80-08 (IESNA Approved Method for Measuring Lumen Maintenance of LED Lighting Sources), and IESNA TM-21-11 (Projecting Long Term Lumen Maintenance of LED Light Sources). Some institutions, such as the Bureau of Street Lighting in the City of Los Angeles and the Minnesota Department of Transportation, published their own specifications for LED roadway lighting. Such specifications can include requirements for luminaire, housing, LED module, roadway application, power supply/ driver, heat management, and color shift.

There is a significant push by the industry to research and develop LED luminaires for street lighting. This is evidenced by improved characteristics and the number of new products being released by practically every major manufacturer in the street lighting sector. Given the clear trend toward the use of LED luminaires in the industry, also supported by public agencies and the U.S. government, it is expected that efficient LED luminaires for highway applications will be available in the near future for a wider range of roadway lighting applications, including those with more lanes of traffic, higher mounting heights, and higher lumen output requirements.

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CHAPTER 1 INTRODUCTION

Roadway lighting is a fundamental public service that leads to a safer environment for pedestrians and drivers alike. The benefits of roadway lighting include the following (Kodisingle 2008):

- Facilitation of traffic flow at night
- Reduction in nighttime traffic accidents
- Promotion of the use of public facilities during nighttime
- Aid to police protection
- Enhanced sense of personal security and traffic safety

As of 2007, approximately 131 million installed street and area lights existed in the U.S. The 131 million installed bases consist of 34.7 million street lighting fixtures, 3.1 million parking lot/garage lighting fixtures, 47.8 million area lighting fixtures, and 45.8 million floodlighting fixtures. Table 1 gives the light source distribution for those installed lights. According to the light source distribution in Table 1, high-pressure sodium (HPS) are the most predominantly used light sources for street and area lights in the U.S., whereas incandescent light sources are the least common. The total annual electricity consumption of the street and area lights listed in Table 1 was 178.3 billion kilowatt-hours (kWh) in 2007 (Navigant Consulting, Inc. 2008). In addition, it is estimated that road lighting alone accounts for an annual energy usage of 14 billion kWh, which corresponds to 3% of the total U.S. electricity consumption (Li et al. 2009a). As the energy crisis spreads across the world due to decreasing oil and gas reserves and increasing demand, energy conservation is becoming an urgent priority. To alleviate the energy crisis, the use of energy-efficient technology is indispensable in road lighting.

Table 1. Street and Area Light Installed Base in the U.S. as of 2007 (Navigant Consulting, Inc. 2008)

Light Source	Percentage	Number of Street and Area Lights
Incandescent	2.4	3,159,000
Halogen Quartz	7.5	9,917,000
Fluorescent	5.7	7,530,000
Mercury Vapor	13.5	17,675,000
Metal Halide	29.2	38,330,000
High-Pressure Sodium	41.7	54,745,000
Total	100	131,356,000

Reducing energy consumption is also a big issue in China, where the public lighting system represents 6% of the annual electricity demand, most of which comprises road lighting (Li et al. 2009a). In South Africa, 24% of the energy consumed by municipalities is attributed to street lighting. Recently, programs have been initiated to improve the efficiency of street lighting, such as the replacement of mercury vapor lights with high-pressure sodium lights, which use around 50% of the power of mercury vapor lights and last up to 6,000 hours longer (Urban SEED 2008). Moreover, about 50% of the electricity consumed by communities in Germany is from street lighting. Because around one-third of the street lamps in Germany are older than 30 years, energy conservation through the renovation of streetlights has been a topic of intense public discussion (Timinger and Ries 2008). Although one of the most commonly used light sources for street lighting is a mercury arc lamp, European Union (EU) regulations are moving in the direction of banning mercury lamps from trade in Europe in order to bring about further energy savings and adhere to the Kyoto Protocol (Timinger and Ries 2008).

At present, street lighting applications mostly involve high-intensity discharge (HID) sources such as the metal halide lamps and high-pressure sodium (HPS) lamps as listed in Table 1. Although HID sources can display high efficacy, they also have some performance drawbacks. For instance, while HPS lamps generally have low color rendering abilities, metal halide lamps may bring about visible color shifting over time and poor lumen maintenance. Besides, both types of HID sources usually bear the disadvantage of long re-strike times (i.e., the time required for a lamp to re-strike after a power interruption) (U.S. Department of Energy 2008b).

LEDs, which are fourth-generation light sources, have recently appeared as an energy-efficient solution to street lighting. They are semiconductors that emit light when electrical current runs through them. While LEDs have been used since the 1960s as indicator lamps in consumer products, recent advancements have made them practical not only for backlighting for cell phones, LCD displays, automotive lighting, and signals but also for street lighting (Luo et al. 2009a). The quality of LEDs has improved ten times in the past decade, whereas the production cost of LEDs has been reduced by around 90% (Xiaoyun, Xiaojian, and Yan 2009).

Currently, rapid advancements in LED lighting technologies are progressively making LEDs a more feasible and efficacious alternative for street lighting. LED technology is advancing so rapidly that new generations of LED devices are released approximately every 4 to 6 months (U.S. Department of Energy 2009a). In the near future, conventional incandescence and fluorescent light sources may be displaced by LEDs similar to how vacuum tubes for electrical switches were displaced by inorganic semiconductor transistors (You, He, and Shi 2007).

The market share of LEDs is also continuously increasing. For instance, the Chinese LED market scale reached 4.85 billion yuan (around US$710 million, according to the exchange rate in May 2010), which displayed a 43.5% increase compared to the market scale in 2006 (Xiaoyun, Xiaojian, and Yan 2009). It is expected that high-brightness LEDs will prevail in general lighting applications that currently account for around 15% of the total energy consumption all over the world (Luo, Xiong, and Liu 2008) and will gradually replace around 25–30% of incandescent lighting applications by 2025 (Wang et al. 2008; Luo et al. 2007; Ton et al. 2003).

CHAPTER 2 LED ILLUMINATION SYSTEMS

The following components make up the general construction of an LED street lamp (Neary and Quijano 2009):

- LED chip (package)
- LED module
- Heat sink for thermal management
- Optics
- Control circuit
- Power supply or driver

2.1 LED CHIP (PACKAGE)

Figure 1 illustrates the typical structure of a high-power LED package. The LED chip (i.e., LED die) consists of thin layers of semiconductors that emit light when a voltage is applied across them. In order for the LED chip to form a functional light source, it must be encased in epoxy with a heat sink slug, metallic leads, and a light reflector, which are collectively referred to as the “LED package” (Ton et al. 2003). The operating current ranges from 350 milliamperes to 1 ampere while the luminous flux ranges from 20 lumens to 150 lumens (Neary and Quijano 2009). Details about the typical heat sink slug of an LED package can be found in Section 8.2.

2.2 LED MODULE

Multiple LED packages are incorporated into lighting systems. The building block of the larger system consists of the LED module that contains a circuit board with multiple LED packages. Sometimes, the LED module may include additional electronic components that may be used as a driver circuit or a current-regulating circuit. Additionally, the LED module may also include secondary optics in order to better focus, intensify, or direct the optical energy for the desired application (Ton et al. 2003; Neary and Quijano 2009).

2.3 HEAT SINK FOR THERMAL MANAGEMENT

The heat sink provides heat removal from an LED to the immediate surroundings. The size of the heat sink depends on the thermal properties of the material that the heat sink is made of and the amount of heat that has to be dissipated (U.S. Department of Energy 2007). The heat sink can dissipate heat via three different mechanisms (Arık et al. 2007):

- Conduction, which is defined as heat transfer from one solid to another
- Convection, which is defined as heat transfer from a solid to a moving fluid
- Radiation, in which heat transfer from two bodies of different surface temperatures occurs via electromagnetic waves

Approximately 90% of the heat removal occurs through conduction in LEDs.

2.4 CONTROL CIRCUIT

The control circuit is the unit that regulates the current flow.

2.5 OPTICS

The optical components of an LED street lamp are used to shape its radiation pattern. Generally, lenses and/or reflectors are used as optical components in LED streetlights. Optical components have a significant influence in the success of a light fixture. For small LED light sources that consist of one to four dies, the use of a lens is recommended. Since a lens has at least three surfaces, the light beam can be better controlled. On the other hand, if the light source consists of an array of dies under a common phosphor layer, the use of a big lens may induce high cost. In that case, a reflector or a reflector system can be used as the optical component. Moreover, mixing of different lenses can be required for achieving a specific light pattern, such as in street lighting (Kuntze 2009).

2.6 POWER SUPPLY OR DRIVER

If high-power LEDs are subjected to reverse voltage, they will fail. Likewise, high peak currents may shorten the lifetime of LEDs. Therefore, LEDs should be protected from reverse voltage and should be surged for the regulation of output current (Nuttall, Shuttleworth, and Routledge 2008). For this reason, LEDs require a power supply or driver to convert the line (i.e., alternating current) power to the appropriate direct current voltage and current. The converted direct current generally ranges from 2–4 volts and 200–1,000 milliamperes for high-brightness LEDs (U.S. Department of Energy 2009b). Although LEDs are best operated with a constant current driver or power supply, constant voltage supplies can also be used with additional circuitry on the LED module in order to regulate the current. Operating characteristics of LEDs for a specified operating current can be found in manufacturers' data sheets (Neary and Quijano 2009).

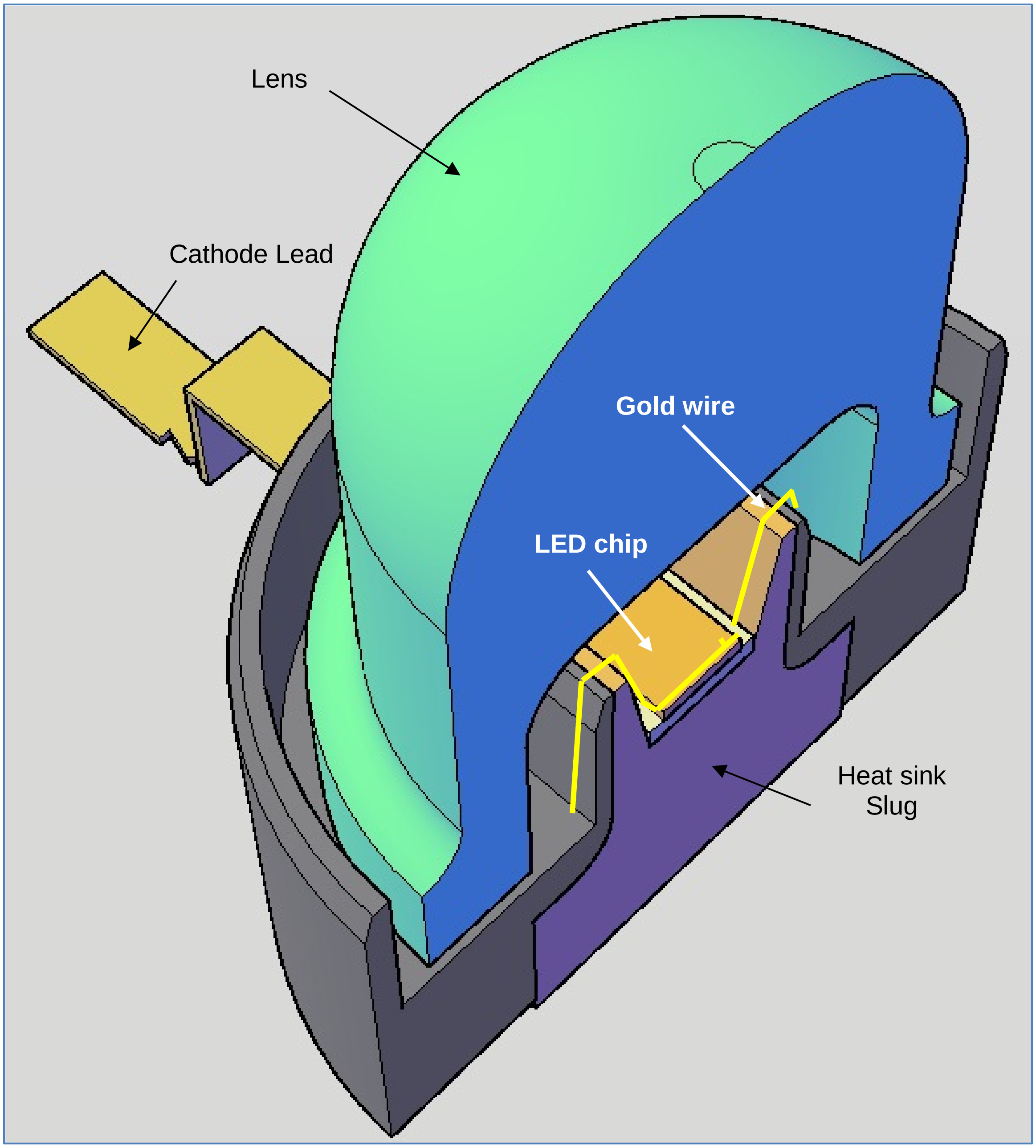


Figure 1. Typical LED package (redrawn not to scale from Neary and Quijano [2009]).

CHAPTER 3 ADVANTAGES OF LEDS

Because they are emerging as a viable substitute for HID sources, LED luminaires can be a promising choice for street lighting systems. The major advantages of LEDs are their low energy consumption, longer life span, good color characteristics, improved performance in mesopic vision conditions, instant on (no warm-up or re-strike time), compact size, directional light, reduced light pollution, environment-friendly characteristics, dimming capabilities, breakage and vibration resistance, and improved performance in cold temperatures (U.S. Department of Energy 2009a). The following subsections provide detailed explanation of the advantages of LED streetlights.

3.1 ENERGY EFFICIENCY

Low energy consumption is one of the most apparent advantages of LED streetlights. Compared to conventional lighting, LEDs can lead to reduction in energy consumption by as much as around 80%, as shown in Table 2. It is estimated that the use of LEDs in traffic signals brings about an approximately 90% reduction in energy and cost (Tetra Tech EM Inc. 2003). Table 2 gives the LED replacement wattages as of 2007, which were computed based on the same lumens delivered by the conventional light source, which in the past has been predominantly incandescent. The LED replacement wattages given in Table 2 also take into account the 30–50% depreciation of the light output from fluorescent and HID light sources over their respective lifetimes.

As shown in Table 2, since LEDs require less wattage than conventional light sources, the conversion of current streetlights to LED can lead to considerable savings in energy costs. For instance, there are around 160,000 streetlights in Toronto, and it is roughly estimated that converting all those streetlights to LEDs could lead to an annual saving of $6 million in energy costs (Whitaker 2007). Moreover, the integration of energy-saving units such as solar energy batteries can further contribute to LEDs being a promising source for environment-friendly illumination in the near future (Cheng 2007).

Table 2. LED Replacement Wattages for Conventional Light Sources (Navigant Consulting, Inc. 2008)

Light Source	Conventional System Wattage	LED Replacement Wattage as of 2007
Incandescent	150	26
Halogen Quartz	150	31
Fluorescent	159	151
Mercury Vapor	254	108
Metal Halide	458	327
High-Pressure Sodium	283	276

Curran and Keeney (2006) undertook a feasibility study on replacing the existing fluorescent lighting system on a four-lane, 2,148-ft bridge where lighting fixtures were mounted on the concrete walls of the bridge. They found that it would be feasible to replace the fluorescent roadway lighting system with LEDs even though the efficacy of the LEDs available in the market at that time was lower than that of those available today. Likewise, Wu et al. (2009) investigated the feasibility of solar-powered LED streetlights. They compared the energy costs of using mercury lamps, grid-powered LEDs, and solar-powered LEDs on a 6.2-mile (10-km) two-lane highway segment where the streetlights were installed 98 ft. (30 m) apart in two staggered rows on both sides of the street. They found that use of grid-powered LEDs can lead to annual energy savings of around $250,000 and use of solar-powered LEDs can result in annual energy savings of around $350,000 compared to that of mercury lamps.

Luminaire efficacy of a roadway luminaire is found by dividing the luminous flux of the luminaire by the total power input to the luminaire (expressed in lumens per watt). It is estimated that if LEDs with an average luminaire efficacy of 57.5 lumens per watt accomplished 100% market penetration in the U.S., an annual energy savings of 44.7 billion kWh could be achieved, which amounts to 25% of the annual electricity consumption of street and area lights in 2007 in the U.S. The potential energy savings of 44.7 billion kWh also amounts to 482.0 trillion British thermal units (TBtu) per year, which is equivalent to the annual electricity consumption of 3.7 million residential households or seven large (100 MW) electric power plants (Navigant Consulting, Inc. 2008). Also, it is estimated by Chinese authorities that savings of up to one-third of the power consumption in China could be achieved if LEDs dominated the Chinese lighting market in 2010 (Luo et al. 2007; Luo et al. 2009a).

3.2 LONGER LAMP LIFE

Lamp life is typically defined as the period in which a particular percentage of the tested lamps fail. That percentage is 40% for metal halide, and 50% for mercury and HPS lamps. Similar to mercury lamps, LEDs do not fail catastrophically, so the lifetime of an LED light source is defined as the point at which the light output reduces below a certain threshold, usually 70% of the lumen output at installation (Neary and Quijano 2009). A major advantage of LED streetlights is that they last longer than metal halide and high-pressure sodium lamps since the average life of LED street lamps is around 50,000 hours (Timinger and Ries 2008). Several LED manufactures claim that LEDs may last up to 100,000 hours with less than 40% lumen depreciation (Tetra Tech EM Inc. 2003). On the other hand, the expected life of mercury, metal halide, and HPS street lamps is around 10,000, 22,000 and 24,000 hours, respectively, all of which are significantly lower than that of LED street lamps (Timinger and Ries 2008; Harder 2007). Unlike HID streetlights, on/off cycling does not affect LED lifetime (Tetra Tech EM Inc. 2003).

Although LEDs have an expected life of 10 years or longer, they are currently not easily replaced and, due to the high cost of labor, it may be more cost effective to install a whole new LED luminaire instead of attempting to replace the failed LEDs. By contrast, the HID luminaire is designed to last 30 years or more, and when the lamp fails, it is easily replaced. However, the lifetime of LED light sources is adversely affected by junction temperature (i.e., LED internal temperature). Driving the LED at a current greater than the rated current also reduces the LED useful life, although it increases the relative light output in the short-term. Thus, proper electrical design and efficient thermal design are essential to ensure long life of LED light sources (U.S. Department of Energy 2006). Further details on LED thermal management can be found in Section 8.5.

On average, street lamps operate 4,000 hours per year in Europe (Nuttall, Shuttleworth, and Routledge 2008), so LED streetlights may last up to 10 years or more. Hence, the longer lifetime of LEDs makes them a practical choice for lighting applications for bridges, tunnels, and other locations where it is difficult or costly to replace the lights (U.S. Department of Energy 2006). The longer lifetime of LEDs is also more compatible with the lifetime of most solar panels (longer than 25 years). Thereby, autonomous LED street lighting systems based on solar energy as a primary source can be an alternative for remote localities (Costa et al. 2009). Similarly, LED systems can be considered relatively maintenance free, which makes them suitable for use in high mountainous regions and on isolated islands (Aoyama and Yachi 2008).

3.3 COLOR QUALITY

Color appearance and color rendering of light sources are among the most important aspects of lighting quality. The relative color appearance of a light source is described by correlated color temperature (CCT), which indicates whether a light source appears more yellowish or more bluish. Theoretically, CCT denotes the appearance of a black body heated to high temperatures such that as the black body is heated more, it turns red, orange, yellow, white, and blue, respectively. CCT is given in degrees Kelvin, and the CCT of a light source gives the temperature in degrees Kelvin at which the color of the heated black body matches the color of the light source in question. Figure 2 illustrates the CCT for five different temperatures.

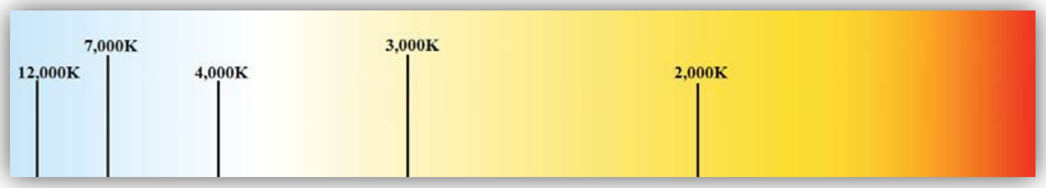


Figure 2. Correlated color temperature (U.S. Department of Energy 2008a).

On the other hand, the color rendering index (CRI) shows how well object colors are rendered by a light source. CRI is defined on a scale of 0 to 100 in comparison to a reference light source of similar color index value. The higher the CRI, the better the light source renders object colors (U.S. Department of Energy 2008a).

Desirable color rendering characteristics is another major advantage of LED streetlights. While most LED light sources used to have CCTs often above 5,000K and cool bluish-white appearance, neutral and warm white LEDs have recently been available (U.S. Department of Energy 2009a). LED products for street and parking lot applications are usually designed to have a range of 85–90 on the color rendering index (CRI). On the other hand, the CRI range of mercury vapor, metal halide, and HPS lamps is 20 to 60, 60 to 80, and 20 to 80, respectively. While the yellowish color of HPS light sources makes it difficult to distinguish color differences in objects, the white light produced by LEDs can lead to accurate rendering of an object’s actual color. Hence, LEDs can successfully help color differences in objects be discerned (Tetra Tech EM Inc. 2003). The higher color rendering index of LED light sources may even help improve traffic safety by making it easier for drivers and pedestrians to see street signs and other objects illuminated by the fixture and thereby reduce driver reaction times (Hamburger 2008; Nuttall, Shuttleworth, and Routledge 2008).

3.4 MESOPIC VISION CONDITIONS

There are two types of photoreceptors in the human retina, rods and cones, both of which are responsible for sending visual signals to the brain. Cones are the principal photoreceptors at high light levels, i.e. in photopic vision conditions, whereas rods are the major photoreceptors at low light levels, i.e., in scotopic vision conditions (Costa et al. 2009). The light levels at which both the rods and cones contribute to human vision are called mesopic vision. Generally, photopic vision conditions prevail above 3 cd/m^2 and scotopic vision conditions prevail below 0.001 cd/m^2. Hence, the mesopic vision range falls generally between 0.001 and 3 cd/m^2. Figure 3 illustrates the approximate ranges for rod and cone operation.

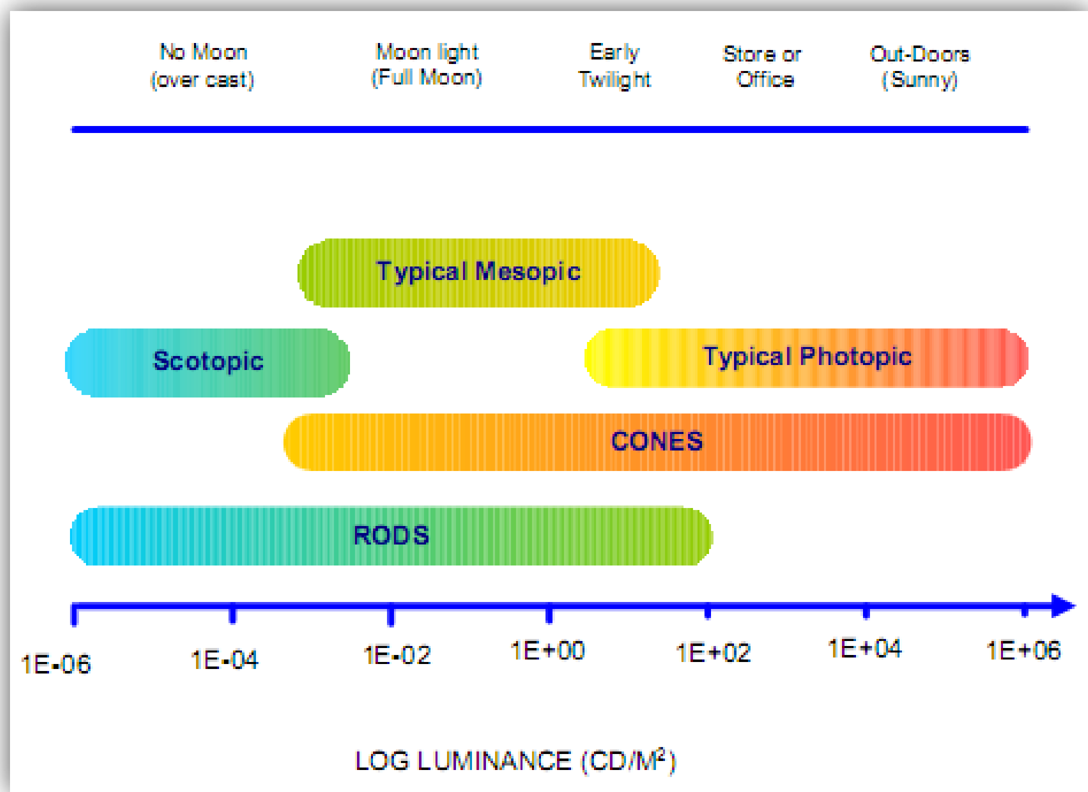


Figure 3. Approximate ranges of rod and cone operation (Szary et al. 2005).

Researchers are currently investigating the combined effect of color rendering, color temperature, and mesopic light sensitivities on the human perception of brightness. Evidence suggests the “white” light emitted by LEDs can be perceived as more intense and brighter than conventional light sources at the same lumen output. Since most white LEDs consist of a blue-emitting chip and a yellow-emitting phosphor material, the spectrum of LED light has considerable blue content. Displaying higher sensitivity to the blue end of the spectrum under mesopic vision conditions, the human eye can detect more light if the light spectrum has significant blue content (Whitaker 2007). Therefore, the higher blue content of the LED light spectrum can render LEDs brighter than conventional light sources at the same lumen output.

Eloholma and Halonen (2006) showed that the performance of light sources at low mesopic levels is misestimated by the current photometry based on photopic functions. They also observed significant differences between photopic and mesopic dimensioning for light sources with high output in the short wavelength region, and the differences were observed to increase with decreasing light level. Thus, the perceived lighting level of LEDs may not be fully represented by the conventional lumen and surface-level footcandle measurements (Tetra Tech EM Inc. 2003). More detailed information on how the human eye perceives lighting levels may be found in Berman (2000).

3.5 LACK OF WARM-UP TIME

Conventional streetlights such as HPS lamps require re-strike time, which means they need a startup time of several minutes in order to reach full brightness. The longer response time of conventional streetlights does not enable their integration with instant sensors. In contrast, LEDs can instantly turn on and off to full brightness without re-strike time. Owing to the high responding speed of LEDs, it is possible to design LED streetlights that have intelligent control coupled with instant sensors. With the use of luminance and moving sensors, LEDs can instantly be turned on/off and their working condition can immediately be adjusted according to environmental changes, which can lead to further energy savings (Wang and Liu 2007). For instance, Taguchi et al. (2001) designed an LED street lamp that could increase its brightness from an energy-saving level of 80 lx to 660 lx whenever the sensor detected a person within 2 m of the lamp. The energy consumption rate of the LED street lamp was only one-eighth of a white incandescent lamp (Taguchi et al. 2001).

The instant response speed of LEDs also enables their lighting intensity to be changed through the adjustment of relative pulse duration and interpulse time difference without causing appreciable damage (Xingming and Zhou 2008). Having made use of this advantage, Xingming and Zhou (2008) designed and tested an intelligent driver for LED streetlights that provided the proper voltage and current for LEDs and adjusted their working conditions with regard to ambient lighting and thermo-factors. Using the pulse width modulation method, the intelligent driver enabled the LEDs to operate at four different stages: (1) soft start, which takes 60 seconds to reach from zero brightness to pre-determined brightness,(2i) full on, (3) half on, and (4) off. The intelligent driver was set to the full-on stage only when the ambient lighting sensor detected that it was dark enough to operate at the full-on stage. The driver was set to half on during low traffic conditions and set to off when street lighting was not required. The results of a 3-month testing program showed that the intelligent driver reduced LED startup stress at soft start, improved LED lifetime by controlling the working temperature, and achieved 72% energy savings compared with conventional streetlight sources (the authors did not specify the exact type of the conventional streetlight) by operating at the four different stages. It should be noted that the savings in that study were achieved with the use of an intelligent driver.

Moreover, LED roadway luminaires can be integrated with some intelligent transportation systems owing to their high response speed. Kitano (2004) showed that LED roadway luminaires could replace the costly infrared beacons used in vehicle information and communication systems in Japan because of the very quick response of LED light sources.

3.6 COMPACT SIZE

Another specific advantage of LEDs is their small size compared to conventional streetlight sources. Due to their compact size, LEDs allow flexibility in their form and design. Instead of relying on the standard geometry of pre-determined lamps such as bulb or tubular geometry, customized light arrays or patterns can be created by luminaire manufacturers. LEDs thereby enable development of unique fixtures with new light patterns (Neary and Quijano 2009). The compact size of LEDs also enables mixing of different colors in small areas to fulfill special optical needs. Another benefit of LEDs that stems from their small size is that they offer more optical control (Tetra Tech EM Inc. 2003). The optical conversion efficiency of a single-chip LED light source can be as high as 70–90%, which is significantly higher than the optical conversion efficiency of a bulb-type light source, which ranges from 40–70% (Wang et al. 2008). One downside to the small size of LEDs is the large number required in a roadway luminaire to produce adequate lumen output.

3.7 DIRECTIONAL LIGHT

Redirection of the light emitted by the light source into a target area on the ground is the optical task of a street lamp. According to street lighting regulations, either certain average levels of illuminance should be maintained within the target area or an observer should obtain certain luminance levels (Timinger and Ries 2008). Since LEDs enable more optical control, they can be designed to emit light in a specific direction, which reduces the need for reflectors and diffusers. Standard bulb-shaped lamps emit light in all directions, which causes much of the light to be lost within the fixture, be reabsorbed by the lamp, or escape from the light fixture in a direction that is not intended for application. Around 30–50% of the total light output from conventional light sources may be lost inside the fixture (U.S. Department of Energy 2009b).

3.8 REDUCED LIGHT POLLUTION

Light pollution occurs in the form of light trespass, over-illumination, sky glow, glare, and clutter. Light trespass results from unwanted light entering one's property, such as light shining over a neighbor's fence or entering one's house from outside through the window, which may lead to sleep deprivation. Over-illumination is the excess use of light, which accounts for approximately two million barrels of oil per day wasted in terms of energy in the U.S. (Lay-Ekuakille et al. 2007). Glare, on the other hand, stems from excessive contrast between bright and dark areas in the field of view. Glare is a serious concern in road safety because it can make it difficult for drivers and pedestrians to adjust to the differences in brightness at nighttime. Clutter is the excessive grouping of lights, such as badly designed streetlights or brightly lit advertising boards surrounding roadways. Clutter may bring about confusion for drivers and pedestrians and distract from obstacles, which may in turn reduce traffic safety. Sky glow is the effect seen over populated areas that is caused by reflected and badly directed light in that area. It interferes with astronomical observatories and obscures stars to city dwellers (Lay-Ekuakille et al. 2007).

Streetlight systems should be designed so as not to exceed a certain contrast level within their target areas. They should also confine glare in direct view to the lamp. Stray light, which is the light falling outside of the target area, can lead to light pollution, light trespass, and glare. In addition, the illuminance level can usually exceed the minimum required level in the hot spot, generally right below the lamp, whereas the far ends of the target area have darker regions (Timinger and Ries 2008). Conventional streetlights such as HPS lamps emit light in all directions and can cause over-illumination, sky glare, and light pollution. In contrast, because LEDs enable more optical control, they can be designed to focus light on the preferred location, such as a roadway surface (Tetra Tech EM Inc. 2003). Consequently, they provide more control over lighting, which may result in less light pollution and light trespass to adjacent areas not intended to be lit (City of Ann Arbor 2008). Moreover, they can reduce over-illumination and glare, which can in turn improve traffic safety for drivers and pedestrians alike.

It should be noted that poorly designed street lighting using LEDs can have all the same shortcomings as conventional HID systems. Therefore, good design practices are essential to good lighting, no matter what the lighting source.

3.9 ENVIRONMENTAL BENEFITS

Because of the concern over environmental waste and disposal, new laws have been enacted to restrict disposal of mercury-based lamps (Neary and Quijano 2009). Unlike conventional light sources, LEDs are free of toxic materials such as mercury. Mercury-free LEDs are not only safe for landfills but also compliant with mercury bans, such as the Restriction of Hazardous Substances (RoHS) directive of the European

Union (Hamburger 2008). In many cases, the manufacturing and assembly process of LEDs is also free of heavy metals such as lead (Neary and Quijano 2009). Additionally, LEDs do not produce ultraviolet and infrared light, which makes them more environment friendly than conventional streetlights (City of Ann Arbor 2008).

Another factor that makes LEDs more environmentally friendly is that they may bring about considerable reductions in greenhouse gas emissions. For instance, it is estimated that greenhouse gas emissions in Toronto can be reduced by 18,000 tons annually, equivalent to the removal of 3,600 cars from the streets, provided that all 160,000 streetlights in Toronto are converted to LEDs (Whitaker 2007). Similarly, annual CO_2 emissions can be reduced by approximately 6 to 9 million tons in Japan if LED streetlight systems are adopted (Aoyama and Yachi 2008).

However, estimates of potential energy savings can be overstated. Also, it may not be possible to replace conventional streetlights with LED luminaires on a one-for-one basis due to reduced lumen output.

3.10 DIMMING CAPABILITIES

Dimming and intelligent control is a method employed to conserve energy. As the traffic volume decreases in the late night and early morning hours, energy consumption can be decreased by reducing the illumination level. Energy savings of up to 30% can be achieved by dimming and intelligent control. Mercury vapor and metal halide lamps have poor diming capabilities (Timinger and Ries 2008). Dimming HPS lamps can be achieved by changing the illuminance in steps with the use of multilevel ballasts (Li et al. 2009a). On the other hand, the light intensity of LEDs can be modified by adjusting the relative pulse duration and the time between pulses, which is called pulse width modulation (Long, Liao, and Zhoui 2009). By reducing the drive current, LEDs can be dimmed to as low as 10% of maximum output. With the use of pulse width modulation, LEDs can be dimmed to as low as 0.05% of maximum output. While dim HPS lamps lead to reduced luminous efficacy and color shifting, dim LEDs can bring about slightly increased luminous efficacy unless the dimming range is very low. Therefore, LEDs provide more advantages in dimming over mercury vapor, metal halide, and HPS lamps (Li et al. 2009a; Timinger and Ries 2008).

It should be noted that dim light sources reduce the visibility of motorists, which in turn decreases the safety of other drivers and of pedestrians; current lighting standards do not allow dimming for this reason. Studies on dimming showed that visibility is not significantly affected by dimming unless the amount of dimming exceeds 50% (Li et al. 2009a).

3.11 BREAKAGE AND VIBRATION RESISTANCE

In contrast to conventional light sources, LEDs do not have a filament, arc tube, or fragile glass components. Hence, LEDs offer a more robust light source and are more resistant to breakage and vibration. Therefore, it would be more suitable to use an LED light source in areas exposed to high vibrations, such as on bridges or in mining operations (Neary and Quijano 2009). For instance, Curran and Keeney (2006) found that LEDs could feasibly replace the existing fluorescent lighting system on a four-lane 2,148-ft bridge where vibrations due to traffic caused intermittence and failure of electrical connections to the fluorescent bulbs. The use of LEDs may not only prevent failures due to vibration, but it could also eliminate frequent replacement of lamps on the bridge. Reduced maintenance of the bridge lighting system minimizes the duration of lane closures on the bridge, the resultant traffic delays, risk of potential accidents, and injury to maintenance personnel.

CHAPTER 4 DISADVANTAGES OF LEDS

Despite their many advantages, LEDs are not frequently used in street lighting applications. The luminous efficacy of LEDs is less than or equal to that of HID light sources. The high installation cost of LED street lighting systems is another factor that reduces LED usage in street lighting applications. In addition, thermal management of LEDs is a challenging task that may reduce expected life. There are also issues in obtaining consistent white light and a desirable CCT. Together these issues create a disadvantage of uncertainty regarding life expectancy, color shift, and long-term performance of LED street lighting, which may be a deterrent to its use. The following subsections provide a more detailed explanation of the disadvantages of LED streetlights.

4.1 LUMINOUS EFFICACY

The luminous efficacy of a light source is calculated by dividing the total luminous flux of the light source by the lamp wattage, expressed in lumens per watt. Luminaire efficacy is computed by dividing the luminous flux of the luminaire by the total power input to the luminaire, also expressed in lumens per watt. The term "efficacy" is used for these two parameters because they both have different input (watt) and output (lumen) units. The term "efficiency" is used when the input and output units are equal, so the term "efficiency" is dimensionless (U.S. Department of Energy 2009b). In simple terms, luminous efficacy is how much light a light source produces from a given amount of energy.

Luminous efficacy of LED streetlights is not yet superior to conventional street lamps, which is the main challenge for LED outdoor lighting technology. The conventionally measured lumen output of LEDs is currently lower than that of HID light sources. The conventionally measured lumen outputs of mercury vapor, metal halide, and HPS light sources are in the range of 30 to 60, 60 to 110, and 40 to 120 lumens per watt, respectively (Timinger and Ries 2008; Tetra Tech EM Inc. 2003), whereas the luminous efficacy of commercially available LEDs has recently increased to around 100 lumens per watt (Li et al. 2009a).

The necessity of using LED drivers also reduces the luminous efficacy of LED luminaires. While HID light sources require a ballast to provide a starting voltage and to limit electrical current to the lamp, LEDs require a driver to convert the line (i.e., alternating current) power to the appropriate direct current voltage (generally 2–4 volts for high-brightness LEDs) and current (typically 200–1,000 milliamperes). Supplementary electronics are included in LED drivers for dimming and/or color-correction control.

Currently, LED drivers have a typical efficiency of around 85%, so LED luminaire efficacy should be reduced by 15% to account for driver efficiency (U.S. Department of Energy 2009b). Good LED system and luminaire design can contribute significantly to the luminous efficacy of an LED streetlight system. For instance, a luminaire efficacy of 107 lumens per watt was achieved by designing a new LED recessed downlight that consisted of multicolored high-efficiency LEDs, successful thermal management, and sophisticated optical design. However, the luminous efficacy of an LED streetlight system may be very low, even with the use of the best LEDs, on account of poor luminaire design (U.S. Department of Energy 2009a).

Although LEDs are still relatively inefficacious compared to HPS lamps, the luminous efficacy of LED street lamps has rapidly increased in the last decade. This rapid increase indicates the potential of commercial LEDs to exceed the luminous efficacy of metal halide and HPS lamps in the future. For instance, it is reported that GaN-based high-power white LEDs with luminous efficacy higher than 130 lumens per watt have been recently achieved in the lab (Long, Liao, and Zhou 2009; Luo et al. 2008b).

4.2 HEAT CONVERSION RATE

Low heating and favorable operating characteristics are among the benefits of LED streetlights. LEDs produce cold light, usually below 60°C (140°F), whereas HPS lamps operate on the basis of molten metal in an arc tube at above 572°F (300°C). However, LEDs have a higher rate of power-to-heat conversion compared to conventional streetlights. High-power LED chips generally transform around 80% of the input power into heat, so only around 20% of the input power is converted into light. Contrary to conventional streetlights whose heat removal mechanism relies primarily on infrared radiation, the heat removal mechanism of LED systems relies mostly on conduction, which induces further challenges in the thermal management of LEDs. Table 3 compares the heat removal mechanisms of different types of light sources. Table 3 shows that more than 90% of heat removal from LED systems occurs through conduction, as opposed to incandescent and high-intensity discharge light sources, from which more than 90% of heat removal occurs through radiation.

Table 3. Comparison of Heat Removal Mechanisms of Different Light Sources (Arık et al. 2007)

Light Source	Heat Lost by Radiation (%)	Heat Lost by Convection (%)	Heat Lost by Conduction (%)
Incandescent	>90	<5	<5
Fluorescent	40	40	20
High-Intensity Discharge	>90	<5	<5
LED	<5	<5	>90

LEDs also have a low internal quantum efficiency of 40–50%, light extraction efficiency of 70–85%, and packaging efficiency of 70–85% (Cheng et al. 2009). Thus, LED chips generate lots of heat when they run brighter, which leads to an increase in the LED junction temperature. Higher LED junction temperatures may lead to reduced light output, shorter life, shifts in emission wavelength, and even catastrophic failures. For instance, LED useful life can be reduced from 42,000 hours to 18,000 hours if the LED junction temperature increases from 40°C to 50°C (Christensen, Ha, and Graham 2007). Therefore, unlike with incandescent and florescent lighting solutions, thermal management is a design challenge for LED lighting solutions, so the thermal issues of high-power LEDs need to be carefully addressed (Cheung, Noska, and Heide 2009). Temperature gradients in the LED structure may also induce significant stresses in materials along the interfaces if the material coefficients of thermal expansion and Young's modules mismatch (Cheng et al. 2009). Additional information on the thermal sensitivity of LED light sources is found in Section 8.1.

4.3 INSTALLATION COST

The high installation cost of LED streetlights is another reason for a conservative attitude toward LED street lighting. The price of most current commercially available LED light fixtures for roadway lighting ranges from approximately $500 to $1,000 per fixture. On the other hand, the cost of 100W and 250W HPS lamp fixtures is around $100 and $250, respectively, which is significantly below the price of an LED streetlight fixture (Tetra Tech EM Inc. 2003). Not only is the initial cost of LEDs higher than that of HID streetlights, but the lamp replacement cost of LEDs is considerably higher because the printed circuit boards must also be replaced.

Excluding labor, it costs around $400 to replace circuit boards with a full set of LEDs, but it costs only $15 to $40 to replace the lamp in conventional HID fixtures. Nevertheless, replacement of the circuit board containing the LEDs is generally not required for at least 10 years (Tetra Tech EM Inc. 2003).

Huang et al. (2007) compared installation costs of mercury lamps and grid-powered and solar-powered LEDs on a 10-km two-lane highway segment where the streetlights were installed 30 m apart in two staggered rows on both sides of the street. They estimated installation costs at $1.88 million, $2.25 million, and $3.09 million for the mercury lamps, grid-powered LEDs, and solar-powered LEDs, respectively. Although the installation cost of LED streetlights was significantly higher than that of mercury lamps, Huang et al. (2007) also found that the payback time for the excess investment cost was 1.2 years and 3.3 years for the grid-powered LEDs and solar-powered LEDs, respectively, since they could lead to significant energy savings compared to the mercury lamps. Thus, in addition to the installation cost, the total electricity and maintenance costs over the expected lifetime should also be considered when comparing multiple alternatives for a street lighting system.

Furthermore, although LED streetlights currently require significantly higher investment costs compared to conventional streetlights, rapid decline in the cost of LED streetlights is being observed. For instance, Long, Liao, and Zhoui (2009) designed a nine-LED module and adaptive driver for street lighting applications with a price less than $1 per watt and luminous flux higher than 110 lumens, which was lower in price than a typical high-power LED fixture with similar parameters. It is also estimated that the prices for integral LED lamps will be reduced from approximately $200 per thousand lumens in 2007 to around $2 per thousand lumens by 2025 (U.S. Department of Energy 2009a).

Another very important factor affecting the total installed cost is the ability of the LED fixture to provide the same light on the roadway as the HID luminaire it is replacing. Where more LED fixtures are needed to properly light the same section of roadway, the installed cost of the LED system is greatly increased over the cost of HID due the addition of costly support poles, structures, and wiring.

4.4 ISSUES IN OBTAINING WHITE LIGHT

Unlike the incandescent lamp, an LED is not inherently white. The light emitted by a single LED light source falls within a very narrow band of wavelengths in the visible spectrum, so LEDs emit virtually monochromatic light. While the emission of virtually monochromatic light makes LEDs very efficient for colored light applications such as traffic lights, white light has to be obtained from LEDs in street lighting applications. There are three main methods that enable the extraction of white light from LED light sources (U.S. Department of Energy 2008a; IESNA Light Sources Committee 2005):

- *RGB (Red, Green, Blue) Systems:* White light is obtained by mixing multiple monochromatic (red, green, and blue) LEDs. An amber chip can also be added to “fill in” the yellow region of the spectrum.
- *Binary Complementary Wavelength Conversion:* Cool white LEDs are obtained by coating a blue or near-ultraviolet LED chip with yellow phosphor(s), usually cerium-doped yttrium aluminum garnet (YAG). The typical CCT is 5,500K for LEDs produced in this manner. Warm white LEDs with a typical CCT of 3,200K can be produced by adding a secondary red phosphor. However, the downside to obtaining a warmer color is a corresponding reduction in lumen output.
- *Ultraviolet Wavelength Conversion:* A tri-color phosphor is excited with the use of a single ultraviolet LED, thereby creating white light.

Currently, most white LED chips are obtained through the phosphor conversion approach. Nonetheless, the phosphor conversion technology may lead to too high of a correlated color temperature, which in turn may lead to a cool and bluish appearance and to color variability in the beam (U.S. Department of Energy 2008a). Additionally, the efficiency of the phosphor used in phosphor conversion affects the brightness of the LED chip. Generally, phosphors with quantum efficiencies lower than 90% may lead to adverse effects on LED luminous efficiency (Mesli 2007). Although neutral and warm white LEDs can also be obtained through phosphor conversion, those LEDs may have lower efficiencies than cool white LEDs because the latter require less phosphor and generate a light wavelength closer to the peak sensitivity of the human scotopic vision (U.S. Department of Energy 2009a; Costa et al. 2009).

RGB LED chips are generally used in architectural settings. RGB systems may bring about the problem of individual colored LEDs responding differently to drive current, operating time and temperature, and dimming. Thus, additional expense may be required due to the controls needed for color consistency. In addition, RGB systems generally have lower luminous efficacy and a lower color rendering index score (Nuttall, Shuttleworth, and Routledge 2008; U.S. Department of Energy 2008a). Nonetheless, CRI may not provide an accurate evaluation of color rendering for RGB LED systems. A new metric to evaluate the color rendering of such systems is being developed for that reason (U.S. Department of Energy 2009a).

Moreover, ultraviolet wavelength conversion offers the advantages of good color uniformity and a simpler driver. These LEDs also have the potential for limited “tint” variation. However, white LEDs manufactured with this method are generally characterized by their lower luminous efficacy and shorter lifetime compared to the white LEDs produced with the other two methods. Clouding of the epoxy is another issue for white LEDs produced via the ultraviolet wavelength conversion method. Such LEDs may also encounter UV packaging problems. New phosphors need to be developed to overcome the problem with the LEDs produced by this method (IESNA Light Sources Committee 2005).

4.5 USE OF LED MODULE ARRAYS

Compared to conventional streetlight sources such as metal halide and HPS lamps, the illumination generated by a single LED chip (package) is significantly weaker. The power of a single LED chip used in lighting ranges from 1W to 10W (Sá et al. 2007), while an HPS lamp is commonly sized at 100W, 250W, 400W, and higher. Hence, LEDs can be used for road illumination only if numerous LED chips are incorporated into an LED module and several LED modules into an LED module array. As mentioned in Section 2.2, an LED module is the building block of a lighting system. It contains a circuit board with multiple LED chips (packages) and sometimes a driver circuit or a current-regulating circuit and secondary optics (i.e., reflector, lens, etc.).

Although the use of LED module arrays provides redundancy in lighting that enables the fixture to stay illuminated if one or more chips fail (Neary and Quijano 2009), it also brings about some disadvantages. One problem regarding the use of LED module arrays is that the chance of a component failure increases with an increasing number of LED chips used. A possible breakdown may cause a significant amount of time and energy to repair the LED module array. For a given number of LED chips, the reliability of an LED module array generally increases with a decreasing number of series connections and increasing number of parallel connections (Aoyama and Yachi 2008).

Another disadvantage that stems from the use of LED module arrays is that it may lead to distinct multiple shadows, making pedestrians and/or drivers uncomfortable.

The multiple shadows become more distinguishable as the spacing between LED modules is increased or as the light distribution of each LED module is narrowed. Hence, LED modules should be located in a concentrated pattern, which results in multiple shadows situated so close to each other that they become indistinguishable (Wang et al. 2008). However, the closer together the LED chips are located, the more challenging the thermal management of the LED street lamps becomes (Luo et al. 2009b).

Wang et al. (2008) recommends the use of arrayed bare LED chips as light sources instead of LED modules since arrayed bare LED chips are more compact than an LED module that consists of LED chips, reflector, and lens. With the use of arrayed bare LED chips instead of LED modules, both the required LED lamp volume and total lamp cost can be reduced (Wang et al. 2008).

Another disadvantage of LED module arrays is the overdriving of individual LEDs in the array as LEDs begin to fail. The LEDs in an array require a better driver. Otherwise, each LED that fails results in the remaining LEDs being driven harder, which in turn further increases temperature and reduces the life of the system.

CHAPTER 5 COMPARISON OF LED AND METAL HALIDE STREET LAMPS

Metal halide lamps were developed in the 1960s following the development of HPS lamps. Metal halide lamps brought about significant advancements over mercury vapor lamps, such as an increase in efficacy to 60–110 lumens per watt (Timinger and Ries 2008). A metal halide lamp has an arc tube that contains various metal halides, including mercury and argon. At full operating temperature, all metal halides in the arc tube are vaporized. The halide vapors are disassociated into halogen and metal atoms as their temperature increases toward the central core, with metal atoms radiating their light spectrum. The halogen and metal atoms recombine as they move near the cooler arc tube wall through diffusion and convection, which completes one cycle (Szary et al. 2005).

Because European Union (EU) regulations may ban the use of mercury arc lamps in the near future, one of the up-to-date light sources for street lighting is metal halide lamps. Timinger and Ries (2008) performed photometric comparison of LEDs and metal halide lamps both at the light source level and lamp level. They also compared an LED system with tailored optics to an up-to-date metal halide street lamp. Optics design was inferred to play a fundamental role in the overall efficiency of LED street lamps and their economic performance.

5.1 LIGHT SOURCE COMPARISON OF METAL HALIDE LAMPS AND LEDS

By using the current catalogs, Timinger and Ries (2008) made a comparison of mercury, metal halide, and LED light sources, as shown in Table 4. It should be noted that the comparisons made in this section are for original metal halides, and the relatively new technologies such as pulse start metal halide and ceramic metal halide are not considered. Comparison of the efficacies for the three light sources shows that mercury light sources yield the poorest lumen output per unit electric power. Although metal halide light sources have significantly superior luminous efficacy than LEDs, a continuous rise in the efficacy of LEDs is expected over the upcoming years. Table 4 shows that the wide power range of a single mercury or metal halide lamp can provide the luminous flux required for one street lamp. On the other hand, the power of a single LED is so low that only modular systems of at least 20–50 LEDs can provide the luminous flux for one street lamp (Timinger and Ries 2008).

Next, comparison of the typical lamp prices shows that LEDs are significantly more costly than mercury and metal halide light sources, especially when the manufacturing cost of a modular LED system is considered. Nonetheless, if the annual duty time of a street lamp is assumed to be around 4,000 hours, the estimated average lifetime of LEDs is over 10 years, whereas metal halide lamps and mercury lamps promise an average service-free period of around 5.5 and 2.5 years, respectively. Also, while a wide range of color temperatures can be obtained from LEDs by means of different luminescent converters or color mixing with additional amber or red LEDs, the cold white color of metal halide lamps is regarded as a disadvantage for street lighting (Timinger and Ries 2008).

Table 4 also shows that LEDs can lead to significant advantages over mercury and metal halide lamps in dimming, which is a method that further conserves energy and still maintains basic illumination levels required for safety and convenience (Timinger and Ries 2008). Another advantage of the LED light source over metal halide light sources is that LED light sources can be instantly turned on/off, but it takes a long time (several minutes) for metal halide lamps to reach an ideal operating temperature (Nuttall, Shuttleworth, and Routledge 2008).

Table 4. Comparison of Mercury, Metal Halide, and LED Light Sources (Timinger and Ries 2008)

	Mercury	Metal Halide*	LED
Efficacy (lm/W)	50	110	80
Power (W)	50–1,000	20–250	2–15
Price/k lumen (€)	<1.00	~7.00	10.00–20.00
Lifetime (h)	10,000	22,000	50,000
Color	White	Cold white	White
Efficient dimming	Poor	Poor	Excellent

**Relatively new technologies such as pulse-start metal halide and ceramic metal halide are not considered.*

A comparison of the power conversion of metal halide lamps and LEDs is shown in Table 5. Unlike metal halide lamps, LEDs do not emit a significant amount of infrared and ultraviolet light. However, while metal halide lamps convert 37% of electrical power into heat, LEDs convert around 75–85% of their electrical power into heat. Therefore, thermal management is a basic concern for LED light sources, although they operate at lower temperatures compared to metal halide and HPS lamps (U.S. Department of Energy 2007).

Table 5. Power Conversion of Metal Halide Lamps and LEDs (U.S. Department of Energy 2007)

	Metal Halide Lamps	LEDs
Visible light	27%	15–25%
Infrared	17%	~0%
Ultraviolet	19%	0%
Heat	37%	75–85%

In summary, metal halide light sources can be significantly more cost effective than LEDs in large-scale installations, particularly because LEDs have to be manufactured as modular systems to provide the luminous flux for one street lamp. On the other hand, LEDs can have a longer life span, offer more color choices, and offer additional conservation of energy with dimming. It should be noted that dimming is not allowed and generally not yet practiced in roadway lighting due to safety. Although the modular design of LED street lamps necessitates significantly higher manufacturing cost, LEDs offer more options to stylists for designing products with an innovative look (Timinger and Ries 2008).

5.2 OPTICAL COMPARISON OF METAL HALIDE AND LED STREET LAMPS

In order to achieve the highest efficiency from a particular light source, two objectives have to be fulfilled (Timinger and Ries 2008):

- The system should guide the highest possible fraction of the light into the target area
- Good uniformity should be provided within the target area

Unlike metal halide lamps that emit light in all directions, modern high-power LEDs consist of small, flat light sources that emit light only into one hemisphere. Both the luminance and color is non-uniformly distributed in the phase space of metal halide lamps, which brings about challenges in optical design. In contrast, LEDs provide uniform distribution of luminance and color in the phase space, which can eliminate hot spots (Timinger and Ries 2008; Hamburger 2008).

Both systems require a reflector to redirect the light into the target area. In metal halide street lamps, an opening is left between the light source and the reflector for the emerging light, but a significant portion of the light does not fall into the target area because it travels from the lamp through this opening without being redirected by the reflector. It is, however, possible in principle to redirect this direct light to the target area by designing a larger system that separates the reflected light and direct light, but this system significantly increases the cost of the system (Timinger and Ries 2008). On the other hand, LEDs are lambertian point sources such that maximum intensity is at its center and it drops away from the axis (Nguyen, Terao, and Laski 2005). Compared to metal halide lamps, it is easier to redirect the light of LEDs to the target area with the use of a single optical system for each LED so that the light emitted by each LED chip fills a different part of the target area. LEDs can thereby lead to superior optical efficiency compared to metal halide lamps (Timinger and Ries 2008). However, it should be noted that LEDs must be grouped together in arrays in order to effectively light roadway; in so doing, it is no longer a point source, and optical challenges arise.

5.3 USING TAILORED OPTICS TO COMPARE METAL HALIDE AND LED STREET LAMPS

Although some other light sources for street lighting may bear performance characteristics similar to those of LEDs, analysis of a streetlight as a complete system shows that LED streetlights can be significantly more advantageous, provided that highly efficient optics are employed (Timinger and Ries 2008). Timinger and Ries (2008) used 3-D tailoring algorithms to develop optics that could exactly redistribute the light from a source to the target area at the desired illuminance level. They computed the required optics for a 20-ft post that had a target range of 66 by 33 ft. The following criteria should be met within the target area:

- An average illuminance above 10 lux
- A minimum illuminance of 5 lux

Then Timinger and Ries (2008) simulated the system by using LightTools® and a physical model of a high-power, single-chip LED. According to the results, using 2,400 lumens of light flux at 80% efficiency could meet the required criteria. Thirty LEDs, each emitting 60 lumens, could provide the required flux of 2,400 lumens, which corresponds to around 40W of electric power. On the other hand, they found that 70W of electric power was required to meet the same criteria if a metal halide lamp was used with around 40% efficiency from the lamp to the target area. In addition, they computed how much luminous flux inside the target area was provided by the street lamp by multiplying the optical efficiency of the system by the lamp efficacy. This value was found to be over 60% for an LED street lamp and 44% for a metal halide street lamp, which demonstrated that LED street lamps could surpass the overall efficiency of metal halide street lamps with the use of tailored optics.

CHAPTER 6 COMPARISON OF LED AND HPS STREET LAMPS

Since 1968, commercial high pressure sodium (HPS) lamps have been available for street lighting (Li et al. 2009a). They have a long and slender arc tube made of ceramic material that contains electrodes, sodium, mercury amalgam, and a small amount of xenon (Szary et al. 2005). HPS lamps produce light when the materials enclosed in the arc tube are vaporized and are excited into fluorescence (Lay-Ekuakille et al. 2007). Currently, HPS lamps are the most commonly used light source for roadway lighting in the U.S. Low color rendering and high luminous efficacy (up to 120 lumens per watt) are the most well-known characteristics of HPS lamps. On the other hand, LEDs are becoming a promising alternative for road lighting thanks to noteworthy improvements in their luminous efficacy. With the recent advancements in LED technology, the efficiency of commercial LEDs has been increased to around 100 lumens per watt, and even more efficient LEDs have been developed in the lab. Nevertheless, HPS lamps still outperform LEDs in efficiency and LEDs usually involve higher initial cost, which is probably why a conservative approach toward LED street lighting is still observed (Li et al. 2009a).

Li et al. (2009a) compared the energy efficiency of LED systems with HPS systems for roadway lighting. They also analyzed some of the factors that can affect system efficiency, such as mesopic vision, color of illumination, and dimming. Although the luminous efficacy of LEDs is not superior to that of HPS lamps, some recent dramatic improvements in luminous efficacy demonstrated a promising prospect in the near future for LEDs.

6.1 LIGHT SOURCE COMPARISON OF HPS LAMPS AND LEDS

Although luminous efficacy of the light source is one of the key factors that determines the performance of a lighting system, it is more appropriate to evaluate the performance of a lighting system by using luminaire efficacy. Typical photometric data for HPS lamps and LEDs are compared in Table 6. The data given in Table 6 show that the typical luminous efficacy of HPS lamps is slightly higher than that of commercial LEDs. However, there is still a continuous increase in the luminous efficacy of LEDs, but it is very difficult to further improve the efficacy of HPS lamps. Some white LEDs with a luminous efficacy of 150 lumens per watt have been recently developed in the lab, which demonstrates that LEDs may potentially provide more efficient roadway lighting in the near future (Li et al. 2009a).

Table 6. Comparison of Typical Photometric Quantities of HPS Lamps and LEDs (Li et al. 2009a)

	HPS	LED (Commercial)	LED (Lab)
Luminous Efficacy (lumens per watt)	110	100	150
Thermal Efficiency (%)	100	90	90
Electrical Efficiency (%)	85	90	90
Luminaire Efficiency (%)	75	90	90
Luminaire Efficacy (lumens per watt)	70.1	72.9	109.4

Moreover, LED streetlights can lead to more uniform luminance along the road because of their smaller and multiple point-source and directional characteristics. Conversely, the use of reflectors and the optical design of most HPS lamps provide uneven luminance along the road. HPS lights emit light in all directions and can give rise to light pollution by directing light beyond the public right of way, over-illumination and glare by excessive contrast between bright and dark areas, and sky glow by releasing light into the night sky. While this can be reduced or eliminated with full-cutoff optics, LED streetlights are designed to focus light and do not emit light in all directions. Consequently, LEDs can significantly reduce light pollution, over-illumination, and glare. Also, contrary to HPS light sources, LEDs do not contain mercury and do not produce heat, ultraviolet, and infrared light (Li et al. 2009a).

6.2 MESOPIC VISION COMPARISON OF HPS LAMPS AND LEDS

Most luminance levels that are generated by streetlights fall within the mesopic vision range, which is generally between 0.001 and 3cd/m^2 (Bullough and Rea 2004; Costa et al. 2009). However, the photometric quantities that are used to estimate the visual performance of light sources are weighted by photopic functions, and most of the street lighting standards are based on photopic vision instead of mesopic vision. Since streetlights generate luminance levels mostly in the mesopic range, photometric quantities weighted by photopic function may not provide an accurate estimation of the visual performance of light sources (Li et al. 2009a; Eloholma and Halonen 2006; Bullough and Rea 2004). Because HPS lamps have high output around the peak wavelength of the photopic function, HPS lamps are generally favored in current road lighting practices (Eloholma and Halonen 2006). However, an LED evaluation project in Toronto showed that even though LEDs produced around half the footcandle output of HPS lamps, observers who were asked to compare the LED and HPS fixtures expressed that the LEDs appeared brighter and made people and objects much clearer. This was attributable to the considerably higher blue content in the spectrum of LED light. Since the human eye is more sensitive to the blue end of the spectrum in the mesopic range, LED light with high blue content can be detected more by the human eye (Whitaker 2007).

It is believed that roadway lighting conditions should be assessed with mesopic functions. Even though researchers have not set up a standard system of mesopic photometry, some characteristics of the mesopic model are lucid. In order to precisely assess the potential visibility of light sources, the National Electrical Manufacturers Association (NEMA) and the Illuminating Engineering Society (IES) are presently active in defining mesopic standards (Li et al. 2009a). A different classification of light sources in terms of their luminous output can stem from the adoption of mesopic photometry, which in turn can improve visual effectiveness and energy efficiency of roadway lighting (Eloholma and Halonen 2006).

6.3 COLOR OF ILLUMINATION COMPARISON OF HPS LAMPS AND LEDS

LED light sources have a higher correlated color temperature and color rendering index than HPS lamps. Thus, LED light sources provide superior color rendition compared with HPS lamps. The color rendering index (CRI) of LEDs is typically around 60 to 90, whereas the CRI of HPS lamps is around 20. The CRI of an HPS lamp can be as high as 80 if a color-corrected version of the HPS lamp is used, but this lamp is less efficacious. Contrary to HPS lamps, whose yellowish color makes it difficult to distinguish color differences in objects, the white light of LEDs helps discern color differences in objects (Tetra Tech EM Inc. 2003). Figure 4a and Figure 4b show night shots of an HPS street lamp and LED street lamp, respectively, used on the same street (Willamette Bluff in Portland, OR). Both photos were taken on the same evening and with the same camera settings. The HPS fixture shown in Figure 4a includes a 115W HPS lamp with a correlated color temperature of 2,097. Figure 4a clearly indicates that the yellowish color of HPS provides poor color rendition of the street. In contrast, the night shot shown in

Figure 4b depicts the superior color rendition of the LED street lamp owing to the white light it generated. The LED fixture shown in Figure 4b includes a 110W LED light source with a correlated color temperature of 6,667, which is drastically higher than that of the HPS lamp shown in Figure 4a.

(a)

(b)

Figure 4. Use of (a) HPS street lamp and (b) LED street lamp in Willamette Bluff in Portland, Oregon (Tuenge 2010).

Color temperature and color rendering index (CRI) of light sources can affect perception and well-being. Figure 5 shows the chart developed by the Dutch researcher A. A. Kruithof that presents the relationship between illumination level, color temperature, and their "preferred" combination. In Figure 5, the preferred combination of color temperature and illumination level is illustrated as a white area. It is claimed that the lower shaded area produces drab and cold environments, whereas the upper shaded area produces overly colorful and unnatural environments (Kruithof 1941). The white area in Figure 5 shows that the higher the color temperature, the higher the illumination level required to accomplish a “preferred” lighting environment. According to the Kruithof curve, more LED luminaires are needed compared to HPS luminaires to obtain “preferred” lighting conditions because LEDs have a higher color temperature than HPS lamps. Therefore, LED street lighting may not gain a high rate of acceptance among motorists and pedestrians (Li et al. 2009a).

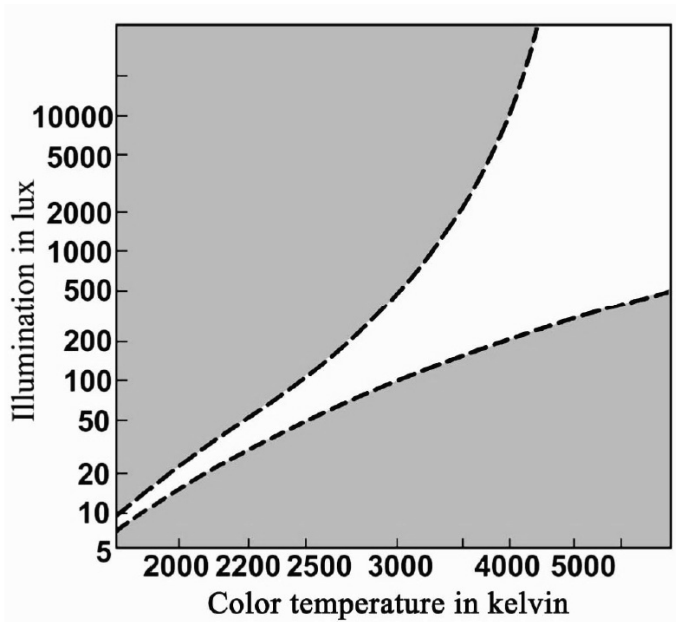


Figure 5. The Kruithof effect (Kruithof 1941; Li et al. 2009a).

6.4 RESULTS FROM SOME PAST STUDIES

The following subsections summarize the results from some past LED studies, mostly from the GATEWAY demonstration projects. It should be noted that while some of the projects involved parking lots and city street applications, the main focus of the current project is highway lighting and DOT applications.

6.4.1 Street Lighting Test in Raleigh

Henderson (2009) reported the results of a before/after study that involved replacement of HPS street lamps with LED streetlights in October 2008 in the 100 block of East Davie Street in downtown Raleigh, North Carolina. Progress Energy Carolinas removed seven 250W and two 200W HPS streetlight fixtures and installed nine 167-W LEDway™ fixtures from Beta Lighting. Each LED fixture consisted of 60 LED chips; the driving current was 700 milliamperes. While the HPS fixture cost was $70 each, the LED fixture costs $485. Progress Energy Carolinas used the existing pole locations and mounting height for the new LED streetlights and installed them on a one-for-one replacement basis. The fixtures were then observed for proper operation. Light level (footcandle, ft-c) readings taken for the LED fixtures were compared with those taken for the HPS fixtures. After the footcandle calculations were completed for both fixtures, the following technical findings were drawn:

- The LED lighting led to a footcandle reduction of 51% and 8% at the selected points on the street and on the sidewalks, respectively

- The overall footcandle reduction for the entire street induced by the LED lighting was found to be 43%
- Despite the 43% overall footcandle reduction, LED fixtures improved the overall visibility on Davie Street, owing to color improvements with a blue-white light and superior uniformity
- The LED lighting reduced the wattage by 42%
- The LED lighting gave rise to improvements in uniformity

Following the installation of the LED fixtures, visibility improvements to the eye were observed on Davie Street. Figure 6 shows the before and after photos on Davie Street. Based on the observations of Progress Energy Carolinas, Henderson (2009) also reported that the LED fixtures did not involve any operational problems and the installation of the LED fixtures was easy thanks to the fixtures being lighter and more balanced. Hence, Progress Energy Carolinas concluded that the Beta LEDway™ fixture was a viable substitute for the HPS fixtures. It was also anticipated that the LED light source could require fewer maintenance trips over its life, although a long-term maintenance experience such as that does not yet exist in the industry (Henderson 2009). It should be noted that the 51% reduction in footcandle performance of the replacement LED luminaires causes the roadway to no longer comply with lighting guidelines (IESNA RP-8) in most cases.

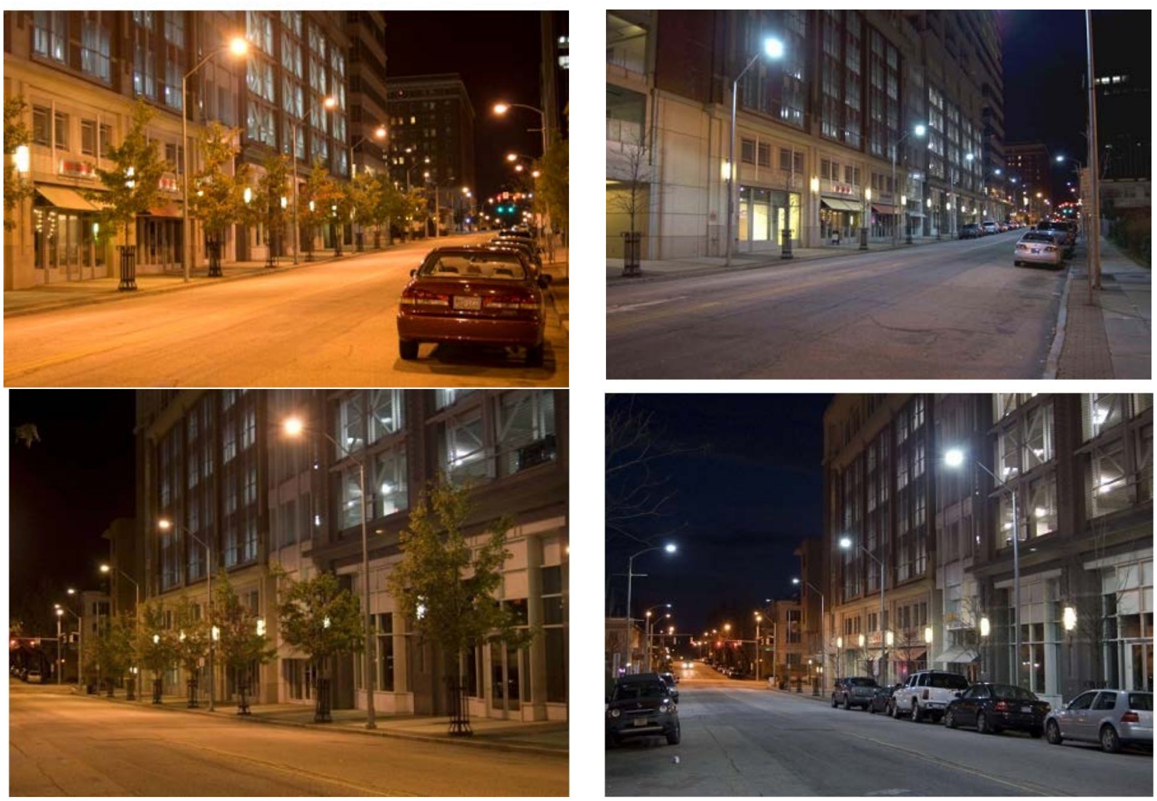


Figure 6. Use of HPS (left, top and bottom) and LED (right, top and bottom) street lamps on East Davie Street in downtown Raleigh (Henderson 2009).

6.4.2 LED Road Lighting Evaluation in a Re-Construction Project

Liu et al. (2009) investigated the potential benefits of replacing the current 250W HPS luminaires with LED streetlights in a re-construction project. In the re-construction area, there were 10-m-high HPS fixtures arranged in a zigzag pattern with a pitch of 14 m. Each HPS street lamp is proposed to be replaced with an 81W six-module LED street lamp to provide the similar illuminance value and uniformity. By using Dialux, Liu et al. (2009) found that the 81W six-module LED streetlights could not only provide better illumination than the 250-W HPS streetlights in use but also lead to 67% energy savings in the same roadway conditions. The road illumination simulation results for the existing HPS and proposed LED street lamps are summarized in Table 7. However, they no longer meet the required lighting guidelines (RP-8-12) for LED fixtures.

Table 7. Summary of Road Illumination Simulation Results for Proposed 81W Six-Module LED Streetlights and Existing 250W HPS Street Lamps (Liu et al. 2009)

	81W 6-module LED streetlight		250W HPS lamp	
	Average lux	Uniformity	Average lux	Uniformity
Footpath Width: 3 m	33.5	0.8	33.1	0.8
Main Road Width: 7 m	45	0.945	39	0.939
Footpath Width: 3 m	33.5	0.8	33.1	0.8

6.4.3 LED Street Lighting Test Near Oakland International Airport

A joint project conducted by the U.S. Department of Energy, Pacific Gas & Electric, and the City of Oakland compared the performance of HPS and LED streetlights (U.S. Department of Energy 2008b). In order to compare LED and HPS luminaires in a variety of ways, three test roadways were selected. The first test road was Sextus Road, where the western half was illuminated with LED luminaires and the eastern half was illuminated with re-lamped HPS luminaires. The second test road, Tunis Road, was an adjacent and parallel road that was exclusively illuminated with LED luminaires. Cairo Road was the third roadway; it was also adjacent and parallel to the first road, and it was illuminated with only re-lamped HPS luminaires. On these three test roadways, a total of fifteen 121W HPS luminaires (100 nominal watts) were replaced with fifteen 78W LED luminaires. The mounting height was 28.5 ft. for all luminaires, and spacing values of 110, 120, and 165 ft. were used between the poles. The photometric results on the test roadways are summarized in Table 8 (Cook et al. 2008a, 2008b).

Table 8. Summary of Photometric Measurements for HPS and LED Luminaires (Cook et al. 2008a, 2008b)

	Average Illuminance (footcandle)		Minimum Illuminance (footcandle)		Average-to-Minimum Uniformity Ratio		Maximum-to-Minimum Uniformity Ratio	
Pole Spacing (ft)	100W HPS	78W LED	100W HPS	78W LED	100W HPS	78W LED	100W HPS	78W LED
110	1.00	0.58	0.19	0.19	5.4:1	3.1:1	19.0:1	6.5:1
120	0.80	0.53	0.09	0.09	8.7:1	5.7:1	40.0:1	16.0:1
165	0.47	0.35	0	0	>10.2:1	>7.5:1	>60.0:1	>26.0:1

The results in Table 8 show that HPS luminaires had inferior uniformity compared to LED luminaires. Being large point sources, HPS lamps produce considerably higher illuminance levels right below the luminaire, but the illuminance level reduces significantly going farther away from the source. Therefore, the area below an HPS lamp is usually over-lighted. Since the future lumen depreciation of HPS light sources must also be made up with a higher-than-required initial illuminance level, this over-lighting effect is even more noticeable during the initial stages of installation. The over-lighting effect is also the reason that the HPS luminaires displayed higher average-to-minimum uniformity ratios than LED luminaires. The results shown in Table 8 indicate that the LED luminaires have superior uniformity, which means that fewer but more effectively used lumens were required to provide the minimum required illuminance levels in the test area. Another factor that further reduces the over-lighting effect in the case of HPS luminaires is the flatter lumen depreciation curve of LEDs over their lifetime compared to HPS luminaires (U.S. Department of Energy 2008b). It should be noted that the flatter curve is based on predictive models only and has not been verified like HPS lumen depreciation curves. Many variables can change the outcome of the LED curves.

Next, Cook et al. (2008a, 2008b) reported the results of a resident survey that was conducted to seek qualitative satisfaction regarding LED luminaires. The results of the survey demonstrated a strong and consistent preference for LED luminaires. Of the 20 responses received, 12 respondents stated that they strongly preferred the LED luminaires and two stated that they somewhat preferred the LED luminaires (Cook et al. 2008a, 2008b). The results of the survey were attributed to the enhanced visibility for drivers and pedestrians as well as the positive effects of the LED luminaires on the overall appearance of the neighborhood and nighttime safety. **Error! Reference source not found.** shows the photographs from the test sites with HPS and LED luminaires in use. It is seen in **Error! Reference source not found.** that the LED luminaires had superior color rendering capability, thanks to their significantly higher correlated color temperature compared to the HPS luminaires. In this study, the average correlated color temperature was 1,991K and 6,255K for the HPS and LED luminaires, respectively, which is why the photographs showing the HPS luminaires in **Error! Reference source not found.** appear yellowish compared with the white appearance of the LED luminaires (Cook et al. 2008a, 2008b).

Furthermore, economic cost estimation was performed for both types of luminaires.

Table 9 shows the power and energy consumption estimates for the HPS and LED luminaires at the test site. Comparing the estimated annual energy consumption of an LED luminaire with that of an HPS luminaire shows that LED luminaires can reduce the annual energy consumption by around 36% per luminaire. Considering these energy savings and assuming zero regular maintenance for LED luminaires over their lifetime, it was estimated that each LED luminaire could bring about an annual combined energy and maintenance savings of $42 and $33 compared to HPS luminaires under a spot replacement and group replacement scheme, respectively. Depending on the selected replacement scheme, the simple payback period for LED luminaires was estimated to be 12–15 years in a new construction setting where LED luminaires are installed instead of HPS luminaires, and 20–25 years in a retrofit setting where the LED luminaires replace existing HPS luminaires (Cook et al. 2008a, 2008b). Nonetheless, no empirical data are yet available to support the projected values, so the projected values were based on the best available information from manufacturer and U.S. Department of Energy reports. Although the estimated payback periods are rather long, they may be acceptable as long as the visibility and cost-saving benefits of LED luminaires are considered (U.S. Department of Energy 2008b). It should be noted that zero maintenance costs for LEDs is a poor assumption. LED luminaires are likely to last 12–15 years, while HPS luminaires are known to last 30 years or more. Dirt depreciation without regular cleaning may become a problem for LED fixtures.

Table 9 reveals the potential energy savings that could be achieved with use of 58W LED luminaires.

Table 9. Power and Energy Consumption for Roadway Luminaires at Test Site (Cook et al. 2008a, 2008b)

Luminaire Type	Power (watt)	Luminaire Efficacy (lumens/watt)	Annual Operating Hours	Estimated Annual Consumption (kWh)
100W HPS	121.0	60.0	4,100	496
78W LED	77.7	57.5	4,100	319

Following installation of fifteen 78W LED luminaires on Sextus Road and Tunis Road, the project progressed to a subsequent phase, which involved replacement of four 78W LED luminaires with 58W next-generation LED luminaires from the same manufacturer. Following installation of four 58W LED luminaires, the same suite of electrical power measurements, lighting performance tests, and economic analyses were performed for the 58W LED luminaires. The power and energy consumption measurements for the 58W LED luminaires are given in Table 10 (Cook et al. 2008a, 2008b). Comparing the power consumption of the 58W LED luminaires shown in Table 10 with those of the 100W HPS and 78W LED in

Table 10. Power and Energy Consumption for 58W LED Roadway Luminaires at Test Site (Cook et al. 2008a, 2008b)

Luminaire Type	Power (watt)	Annual Operating Hours	Estimated Annual Consumption (kWh)
58W LED	58.3	4,100	239

Each 58W LED luminaire annually consumes 257 kWh (52%) less energy than a 100W HPS luminaire and 80 kWh (25%) less energy than a 78W LED luminaire. Considering the energy savings of the 58W LED luminaires and assuming zero regular maintenance for those luminaires over their lifetime, it was estimated that each LED luminaire could bring about an annual combined energy and maintenance savings of $52 and $43 compared to the HPS luminaires under a spot replacement and group replacement scheme, respectively. Depending on the selected replacement scheme, the simple payback period for the 58W LED luminaires was 5–6 years and 12–15 years in a new construction scenario and a retrofit scenario, respectively.

In addition, Table 11 summarizes the measured illuminance levels for the 58W LED luminaires. Comparing the photometric results given in Table 11 with those given in Table 8 shows that the 58W next-generation LED luminaires maintained the lighting performance of the 78W LED luminaires while reducing energy consumption. A visual comparison of the 100W HPS luminaires and 58W luminaires in operation is illustrated in Figure 7. It is apparent from the photos shown in Figure 7 that the 58W LED luminaires had color rendering characteristics superior to the 100W HPS luminaires. The average correlated color temperature of the 58W LED luminaires was 6,746K, which was slightly higher than that of the 78W LED luminaires (6,255K).

Table 11. Summary of Photometric Measurements for 58W Next-Generation LED Luminaires (U.S. Department of Energy 2008b)

Pole Spacing (ft)	Average Illuminance (footcandle)	Minimum Illuminance (footcandle)	Average-to-Minimum Uniformity Ratio	Maximum-to-Minimum Uniformity Ratio
110	0.50	0.19	2.7:1	6.5:1
120	0.48	0.09	5.2:1	14.0:1
165	0.32	0	>6.8:1	>24.0:1

In short, the switch from 78W LED luminaires to 58W luminaires brought about a 26% increase in energy savings (from 78W to 58W per luminaire) and a 34% reduction in cost per luminaire (from $610 to $400), while lighting performance was maintained. The 58W LED luminaires were found to pay back in 5–6 years and 12–15 years in a new construction and retrofit scenario, respectively, compared to 78W LED luminaires that were found to pay back in 12–15 years and 20–25 years in a new construction and retrofit scenario, respectively. The shorter payback period of 58W LED luminaires was attributed to its reduced energy consumption as well as its reduced luminaire cost. It is expected that ongoing rapid advancements in LED product efficacy can bring about further improvements in their economic payback (Cook et al. 2008a, 2008b).

Figure 7. Use of 100W HPS (left) and 58W LED (right) street lamps at test sites (Cook et al. 2008a, 2008b).

6.4.4 Cost-Benefit Assessment of Retrofitting Street and Parking Lot Lights with LED Streetlights

Aberdeen Proving Ground (APG 2009) assessed the long-term economic benefits of replacing HPS street and parking lights with LED streetlights. Of a total of 2,200 street and parking lot lights, the assessment identified 1,500 HPS street and parking lot lights sources that could be replaced with LED street and parking lights. These included the HPS light sources and fixtures that could be replaced with LEDs without requiring alterations to the pole, receptacle, wiring, and power supply. The assessment found that replacement of 150W HPS streetlights with 28W LED streetlights can lead to significant economic benefits. In terms of economic evaluation, APG (2009) estimated that replacement of HPS streetlights with LED streetlights could lead to reductions in the costs of energy, handling, storage, maintenance, labor, and operations as well as disposal and hazardous items that contain mercury.

APG (2009) carried out a detailed cost analysis to estimate the savings that could result from replacing 1,500 HPS street and parking lot lights with LED street and parking lights. The results of the cost analysis are summarized in Table 12. The estimated cost savings in Table 12 indicate that despite their higher initial cost, LEDs can bring about considerable savings in energy consumption, maintenance, and labor if they replace HPS street and parking lot lights.

Table 12. Summary of Potential Cost Savings from Replacing 1,500 HPS Street and Parking Lot Lights with LEDs (APG 2009)

	Annual Savings ($)			
	Energy Consumption & Operation	Material Purchase	Maintenance & Labor	Total Annual Savings
1st year after implementation	1,111,200	–474,750	55,000	691,450
2nd year after implementation & beyond	1,111,200	40,388	59,000	1,210,588

6.4.5 LED Street Lighting Test in Toronto’s Exhibition Place

Another project that involved comparison of HPS street lamps with LED street lamps was conducted in Toronto. Twelve LED streetlights on bow-style streetlight poles were installed along the perimeter of the Automotive Building in Toronto’s Exhibition Place, and four additional LED streetlights were installed in the parking lot south of the Direct Energy Center. All LED luminaires were designed as direct replacements for conventional cobra-head fittings. The LED fixtures used in this project were manufactured by Leotek Electronics, and each contained 117 1W LEDs from Nichia. The imminent reduction in electricity, maintenance, and replacement costs was expected to recoup the relatively high initial cost of approximately $1,200 per LED luminaire (Whitaker 2007).

In order to accurately measure the power draw of the streetlight fixtures, three street-lighting poles were fitted with electrical meters. It was found that the power drawn by each LED fixture was 146W, whereas each HPS fixture drew 314W. While the HPS lamps were rated at 250W and displayed relatively low power efficiency, the LED fixtures displayed a significantly higher power efficiency of 90% or higher (Whitaker 2007).

Owing to the directional light characteristics of LED light sources, the upward flux distribution of the LED fixtures was zero. On the other hand, the cobra-head fittings with other types of light sources were found to waste up to 30% on account of their upward direction of light. It was further estimated that conversion of almost all 160,000 streetlights in Toronto to LEDs could lead to an annual reduction of $6 million in energy costs and 18,000 tons in greenhouse gas emissions, which was equivalent to the removal of more than 3,600 cars from the streets (Whitaker 2007).

What’s more, footcandle measurements at the test site showed that the footcandles produced by the LED fixtures was slightly less than half of the footcandles produced by the HPS lamps. Hence, the measured light output produced by the LEDs was about half of that produced by the HPS lamps. However, when the launch ceremony was held on February 28, 2007, observers were asked to compare the lighting from conventional HPS fixtures on one side of the street and LED fixtures on the other side of the street. All observers confirmed that the LED lighting appeared brighter, enabling much clearer viewing of objects and people. People's preference for LED lighting was attributed to the high blue content of the LED light spectrum (Whitaker 2007).

6.4.6 LED Street Lighting Test at I-35W Bridge, Minneapolis

Kinzey and Myer (2009a) reported the results of a lighting demonstration project carried out on the I-35W bridge that consists of two 1,215-ft-long spans, each with five 12-ft lanes, one 13-ft right shoulder, and one 14-ft left shoulder.

The Minnesota Department of Transportation requires that the average level of illumination across the main span be between 0.8 and 1.0 footcandles, with an average-to-minimum ratio between 3:1 and 4:1. The pole height and pole spacing for the roadway luminaire was set at 40 and 150 ft, respectively. The use of 20 250W HPS street lamps, each with a luminaire efficacy of 71 lumens per watt, would satisfy the desired level of illumination according to Minnesota Department of Transportation guidelines.

As an alternative to the 20 250W HPS roadway luminaires, the use of four Type III distribution 12-LED arrays and 17 Type V distribution 10-LED arrays was proposed. Installation of the LED luminaires was completed in September 2008. As opposed to the $8,800 total installation cost of the 20 250W HPS luminaires, total installation cost of the LED luminaires was $46,000. The initial luminaire efficacies of the LED luminaires were 65 and 67 lumens per watt for the 12-LED and 10-LED arrays, respectively. It is estimated that only 12% loss of initial lumen output will occur by the end of year 20.

Detailed power and energy consumption data for each type of roadway luminaire are presented in

Table 13 (Kinzey and Myer 2009a). The power and energy data in

Table 13 show that the total annual energy consumption of the 20 LED luminaires adds up to 22,163 kWh, which is 13% less than the total annual energy consumption of the 20 HPS luminaires, which was 25,465 kWh. Assuming zero maintenance for the LED products over their lifetime and a five-year lamp replacement schedule for the HPS lamps, it was found that the payback of the LED system was around 55 years.

Table 13. Power and Energy Consumption for Roadway Luminaire at I-35W Bridge (Kinzey and Myer 2009a)

Light Source	Quantity	Luminaire Power (watt)	Luminaire Efficacy (lumens/ watt)	Total Power (watt)	Annual Operating Hours	Annual Energy Consumption (kWh)
250W HPS	20	291	71	5,814	4,380	25,465
12-LED Array	4	289	65	1,156	4,380	5,063
10-LED Array	16	244	67	3,904	4,380	17,100

To further evaluate the effectiveness of the new LED lighting system, a survey was sent to 3,384 recipients in November 2008. Out of the total mailing, 489 recipients responded that they had crossed the bridge when the new lighting system was implemented. Out of those 489 respondents, 351 of them stated that the new lighting system either enhanced or greatly enhanced their ability to see the roadway and the objects on it. Likewise, 345 of them stated that they would either recommend or definitely recommend the use of that type of lighting elsewhere. Hence, the results of the public survey demonstrated that the new LED luminaires were preferred over the HPS luminaires (Kinzey and Myer 2009a).

6.4.7 LED Street Lighting Test in Lija Loop, Portland

The results of a lighting demonstration project conducted in a residential neighborhood in Lija Loop, northeastern Portland, were reported by Kinzey and Myer (2009b). The loop included eight streetlights mounted at 30 ft with a 125- to 150-ft spacing between the luminaires. The City of Portland typically uses 100W cobra-head HPS luminaires that have a power draw of 120W including their ballasts. The demonstration project involved installation of eight LED streetlights in Lija Loop, but before the LED streetlights were installed, the existing eight cobra heads in Lija Loop were cleaned, re-lamped, and operated for 2 weeks to provide baseline illumination and power measurements for comparison. Afterward, the HPS streetlights were replaced with LED luminaires. Table 14 gives detailed power and energy consumption data for both the HPS and LED luminaires.

Table 14. Power Measurements and Energy Calculation for Two Lighting Systems in Lija Loop (Kinzey and Myer 2009b)

Light Source	Quantity	Luminaire Power (watt)	Luminaire Efficacy (lumens/ watt)	Total Power (watt)	Annual Operating Hours	Annual Energy Consumption (kWh)
HPS	8	120	56	960	4,380	4,205
LED	8	53	71	426	4,380	1,866

According to the data in Table 14, the new LED system can provide 55% annual energy savings compared to the former HPS system. Considering the maintenance and energy savings that stem from the switch to LED, the payback time for the retrofit scenario, which involved replacement of conventional 100W HPS fixtures in good operating condition with LEDs, was 20 years. However, the payback time was estimated to be only 7.6 years in the case of a new construction scenario for an LED street lighting system such as this.

Next, Table 15 shows the illuminance values for Lija Loop. The illumination measurements for the HPS and LED systems show that both systems satisfied an average maintained illuminance of 0.2 footcandles or greater on the pavement surface, which is required by City of Portland lighting standards. According to the illuminance values in Table 15, the LED system significantly improved the illuminance uniformity in the test site by reducing the illuminance standard deviation, maximum-to-minimum illuminance ratio, and average-to-minimum illuminance ratio. Figure 8 is a visual comparison of the LED and HPS luminaires at the entrance to Lija Loop.

Table 15. Lija Loop Illuminance Values (Kinzey and Myer 2009b)

	HPS	LED
Maximum (footcandle)	2.2	0.5
Minimum (footcandle)	0.2	0.1
Average (footcandle)	0.8	0.3
Max/Min	9.8	5.4
Avg/Min	3.4	2.8

Figure 8. Visual comparison between LED and HPS luminaires at entrance to Lija Loop (Kinzey and Myer 2009b).

Additionally, a mail-in resident survey was carried out to seek the opinion of residents on the new LED street lighting system. Eleven of the surveys were returned, which yielded a 36% response rate. According to the results of the survey, nine of the residents stated that the quality of the LED street lighting system either enhanced or greatly enhanced their ability to see the street and the objects on it. Likewise, eight of the residents stated that they would either recommend or definitely recommend use of that type of lighting elsewhere. Hence, overall positive responses to the new LED street lighting system were received from the residents (Kinzey and Myer 2009b).

6.4.8 LED Street Lighting Test in Sunset District of San Francisco

Cook et al. (2008c) reported the results of an LED street lighting study that involved installation of LED streetlights on public roadways in San Francisco. The test roadways were 38th, 41st, 42nd, and 44th Avenues in the Sunset District. Five streetlights were installed on each avenue from the beginning to the end of a block. The test area included three centrally located roadway luminaires on each avenue; two streetlights on either side of the test area served as buffers. In order to make a comparison between the HPS and LED roadway luminaires, all five existing streetlights on each avenue were first replaced with new 100W HPS Type II cutoff luminaires. The luminaire spacing was 200 and 150 ft on alternating sides of each avenue, whereas the spacing between the test luminaires and the buffer luminaires ranged from 60 to 200 ft. The luminaire mounting heights were changed from 24 to 34 ft. After energy consumption, power, and illuminance level measurements were carried out, the three centrally located streetlights on each avenue were replaced with LED luminaires from four different manufacturers, designated A, B, C, and D. Each avenue included three LED luminaires from a single manufacturer.

Table 16 summarizes the results of power and energy consumption measurements for each type of tested luminaire. According to the measurements summarized in Table 16, energy savings ranging from 49.9–70.2% could be achieved per luminaire by switching from HPS to LED luminaires. Taking into account the energy and maintenance savings induced by LED luminaires, the simple payback period for each LED option was estimated for a new construction scenario and retrofit scenario. In the new construction scenario, only the difference in material costs between the LED and HPS luminaires constituted the incremental cost of installation for the LED luminaires. On the other hand, the incremental cost for the LED luminaires consisted of the full estimated cost of the LED luminaires plus the estimated installation cost. The simple payback period for the new construction scenario was estimated to be 6.3, 13.3, 3.7, and 15.3 years for the LED options of A, B, C, and D, respectively. Likewise, the simple payback period for the retrofit scenario was estimated to be 10.8, 18.1, 7.4, and 20.4 years for the LED options of A, B, C, and D, respectively (Cook et al. 2008c).

Table 16. Luminaire Power and Estimated Annual Energy Savings by LEDs (Cook et al. 2008c)

Light Source	Luminaire Power (watt)	Luminaire Efficacy (lumens/ watt)	Annual Operating Hours	Estimated Annual Energy Consumption (kWh)	Estimated Annual Energy Savings (kWh)
HPS	138.2	45.0	4,100	567	—
LED A	58.7	54.7	4,100	246	321 (56.6%)
LED B	62.2	18.7	4,100	255	342 (60.3%)
LED C	41.3	71.2	4,100	169	398 (70.2%)
LED D	69.2	46.9	4,100	284	283 (49.9%)

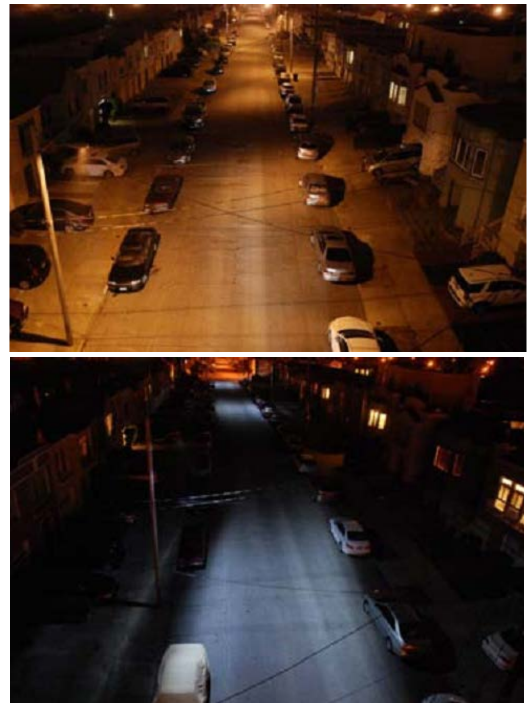
In addition,

Table 17 summarizes the photometric measurements at each site. According to the measurements given in

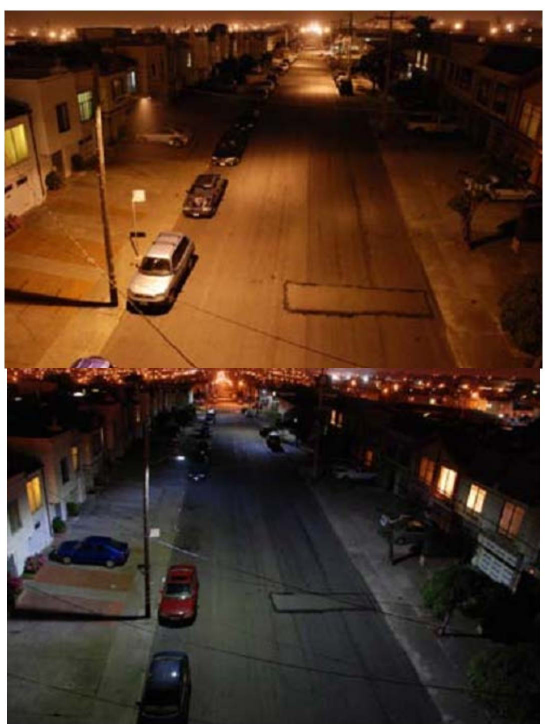
Table 17, LED options B and D turned out to have limited applicability for the test sites, although they may perform well in other types of applications. LED options A and C displayed lighting performance equivalent to or better than the HPS luminaires by most metrics, and they both improved the uniformity in the test sites. On the contrary, the HPS luminaires led to over-lighting of the area directly beneath the luminaires. Hence, LED options A and C can be promising in similar applications. Figure 9 illustrates photographic comparison of the HPS and LED luminaires at each test site. In all four cases, the LED luminaires gave rise to superior color rendering characteristics compared to the HPS luminaires. The average correlated color temperature was measured as 2,077K, 6,573K, 12,710K, 4,582K, and 5,781K for the HPS, LED A, LED B, LED C, and LED D luminaires, respectively. The cool bluish appearance seen in Figure 10b, lower image, is caused by the relatively high correlated color temperature (12,710K) of LED B (Cook et al. 2008c).

A customer opinion survey was also managed by the Pacific Northwest National Laboratory to seek public opinion on the new LED luminaires. A public opinion research firm contacted 46 residents of the neighborhood, 31 of which claimed to have had discerned the new streetlights. However, the number of respondents per each avenue ranged from only 9 to 15, which could introduce a high sampling error. No statistically significant preference for or against the new LED luminaires was observed.

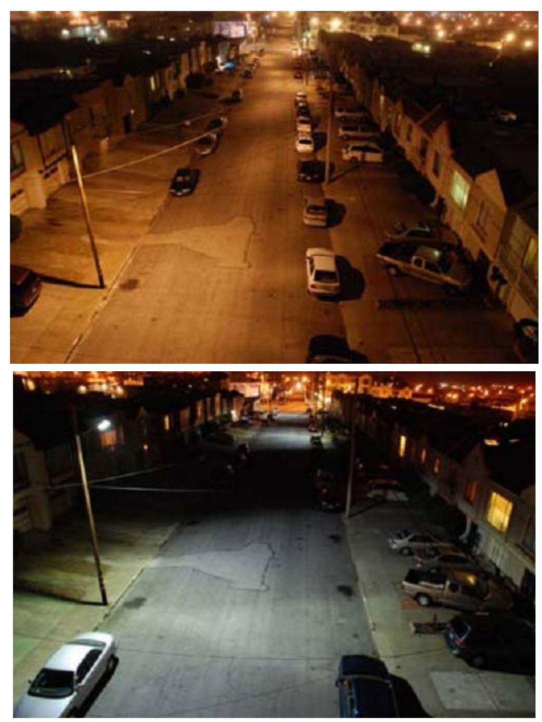
(a) HPS (top) vs. LED A (bottom)



(b) HPS (top) vs. LED B (bottom)



(c) HPS (top) vs. LED C (bottom)



(d) HPS (top) vs. LED D (bottom)

Figure 9. Photographic comparison of HPS and LED luminaires at test sites (Cook et al. 2008c)

Table 17. Comparison of Measured Photopic Performances for Entire Test Area (Cook et al. 2008c)

Test Site	Luminaire	Grid Points Illuminated	Average Illuminance (footcandles)	Coefficient of Variation	Average-to-Minimum Uniformity
A	HPS	85%	0.5	0.98	5.3:1
	LED A	95%	0.3	0.82	3.4:1
B	HPS	86%	0.5	0.84	5.5:1
	LED B	56%	0.2	1.42	3.7:1
C	HPS	79%	0.6	1.08	7.5:1
	LED C	83%	0.2	0.90	2.5:1
D	HPS	99%	0.5	0.96	5.0:1
	LED D	66%	0.3	1.34	5.2:1

CHAPTER 7 COLOR SHIFT OF LED LIGHT SOURCES

7.1 TRADE-OFF BETWEEN COLOR RENDERING INDEX AND LUMEN OUTPUT

In conventional white light sources, there is a trade-off between color rendering index (CRI) and luminous efficacy. Please refer to Sections 3.3 and 4.1 for the detailed definitions of CRI and luminous efficacy, respectively. If, for instance, the color rendering ability of a particular light source is increased, its luminous efficacy consequently generally decreases (Mirhosseini et al. 2009a). For high CRI, a broad spectral distribution of emission band throughout the visible region is required. A good example would be the sun and blackbody radiation, both of which have a CRI of 100. On the other hand, monochromatic light sources that radiate at 555 nm have the highest luminous efficacy (Mirhosseini et al. 2009b). Take the case of a typical low-pressure sodium lamp, for example. It has a luminous efficacy of around 200 lumens per watt, which is high compared to other types of discharge lamps. Despite its high luminous efficacy, it has a light orange color, which provides a very low CRI. In such a case, colors would not be that distinguishable—for example, a red car would appear to be gray. On the contrary, a xenon arc lamp typically displays high CRI because its spectrum is very similar to that of daylight. In spite of its excellent color rendering, the xenon arc lamp has a luminous efficacy of around only 30 lumens per watt (OIDA 2002). The number of wavelengths is one of the factors that affect the maximum CRI a light source can achieve. For instance, the maximum achievable CRI for a three-color light source can be around 85, whereas it can increase up to 95 for a four-color light source. Nevertheless, the greater number of colors brings about more complexity in the lamp structure (OIDA 2002).

White light LEDs also suffer from the trade-off between luminous efficacy and CRI (Spring, Fellers, and Davidson 2010) compared the luminous efficacy and CRI of the four different types of LED, all of which had identical coordinates of (0.31,0.32) on the chromaticity diagram. Comparison of the luminous efficacy and CRI of those LEDs is presented in Table 18. As shown in Table 18, the luminous efficacy of the LEDs typically decreases as the CRI increases. In addition, the CRI of the LEDs listed in Table 18 demonstrates that illuminants that have identical chromaticity coordinates may still have considerably different color rendering properties. The reason is the variations in details of the output spectrum of each light source.

The recent study by Pengzhi et al. (2011) is also a good example demonstrating the trade-off between luminous efficacy and CRI for LEDs. Pengzhi et al. (2011) packaged a series of high-power white LEDs. They covered blue LED chips with red phosphor, yellow phosphor, and two phosphors mixed by appropriate mass ratio. They found that the LEDs covered with red phosphor had the lowest luminous efficacy compared to the others since the blue LED chips could not efficiently excite red phosphor. Conversely, the CRI of the LEDs with a higher proportion of red phosphor provided better CRI by supplementing the blue LED chips.

Table 18. Luminous Efficacy and CRI of Four Different Types of LEDs (Spring, Fellers, and Davidson 2010)

Type of LED	Luminous Efficacy (lumens/watt)	General CRI
Dichromatic LED	336	10
Broadened output dichromatic LED	306	26
Trichromatic LED	283	60
Phosphor-based LED	280	57

The required CRI and luminous efficacy depends on the application for which LEDs are used. For instance, the CRI may not be of primary significance for LED light sources that are used in signage applications. For such applications, monochromatic LED arrays that have high luminous efficacy are required (Spring, Fellers, and Davidson 2010). On the other hand, both luminous efficacy and color rendering index are two of the key factors in general lighting. Therefore, the trade-off between CRI and luminous efficacy should be optimized for general lighting applications (Mirhosseini et al. 2009a). The luminous efficacy and CRI of a light source both depend on the spectrum of the source. Hence, the design of the spectra of white LEDs should target both good color rendering and high luminous efficacy (Pengzhi et al. 2011). For example, Mirhosseini et al. (2009b) demonstrated through simulation that the use of phosphor-converted white LEDs with dual-blue emitting active regions could significantly increase CRI and enhance luminous output compared to those with single-blue emitting active regions. Erdem et al. (2010) demonstrated through a simulation study that ultra-efficient white-light LEDs with a CRI greater than 90 and luminous efficacy greater than 380 lumens per watt could be achieved with the use of nanocrystal luminophores.

7.2 LED BINNING TO ACHIEVE COLOR

Compared to traditional light sources such as HIDs and incandescent lamps, LEDs are unique in many ways. One of the unique features of LEDs is binning. LEDs are created in a large sheet of substrate. Many LEDs are cut from a single sheet, and the quality of the LEDs across the sheet varies. LED binning is a systematic process that tests and sorts LEDs into smaller subgroups. The LEDs in the same subgroup may have similar color, brightness, or voltage characteristics (Philips 2011). Factors such as the needs of the solid-state lighting industry, application requirements, and industry standards drive the binning, and the performance requirements for LED lighting applications are becoming more rigorous. Take the case of the “ENERGY STAR® Program Requirements for Integral LED Lamps,” for instance. This document proposes stringent requirements in CRI, correlated color temperature (CCT), lumen, and color maintenance for an Energy Star–approved LED product. For this reason, there is a need to produce repeatable and well-defined results in the LED manufacturing process (CREE 2010). Although tighter binning of LEDs increases the cost and lead time for manufacturers, it reduces the variation in LED luminaire performance. Consequently, tighter binning of LEDs ensures high quality and consistency with respect to critical performance characteristics such as color and light output. In turn, this minimizes the probability of negative impact to end users (Lithonia Lighting 2010).

In the manufacturing process of LEDs, a single round wafer is coated with appropriate materials (epitaxial growth) to create a semiconductor. That semiconductor is then sliced into dies, which are extremely small rectangles. After electrical connections are inserted, phosphor is added as either a suspension or coating within the enclosure. A finished white LED package is obtained by encapsulating the assembly. However, significant inherent variations are introduced during the coating process. Such variations affect the lumen output, CCT, and voltage of the LEDs. It is hard to tightly control the LED production process and eliminate such variations in the end product. Thus, LED products are sorted into color, lumen, and voltage bins so that manufacturers can maximize yields (Lithonia Lighting 2010). Color binning of LEDs is accomplished based on their CCTs (Philips 2011). The (x,y) coordinates on the CIE 1931 chromaticity diagram are used to define the CCT bins. For a specified CCT, the CCT bins are grouped as quadrants around the standard chromaticity lines as shown in Figure 10. Smaller bin sizes allow for less variation in CCT within a particular bin, whereas bigger bin sizes lead to more variation in CCT within each bin. The bin standard, ANSI C78

377A, was established by the American National Standards Institute and the National Electrical Manufacturers Association in 2008 and specifies a bin size that is approximately correlated with the degree of color variation that exists in commercial CFL sources. The ANSI C78 377A bin standard is also a requirement for ENERGY STAR® certification (Lithonia Lighting 2010).

Broader CCT binning used to be applied to early white LEDs. Owing to the recent advancements in blue LED chips, phosphor, and phosphor deposition technologies, CCT binning became tighter, which in turn led to more consistent color from LED to LED. Consequently, LED manufacturers can provide LED luminaires with more consistent white light and can also manufacture LEDs with CCTs similar to traditional light sources (Philips 2011). More specifically, Philips claims that using their proprietary Lumiramic phosphor technology, which in turn uses a ceramic phosphor plate and Philips Lumileds Thin Film Flip Chip (TFFC), a specific CCT can be targeted. This is accomplished by matching Lumiramic plates of the appropriate thickness with the correct wavelength of TFFC die in advance of final manufacturing. These improvements are intended to reduce variations in LED production to a minimum, changing the binning process and the need for binning as it was required before (Philips 2008).

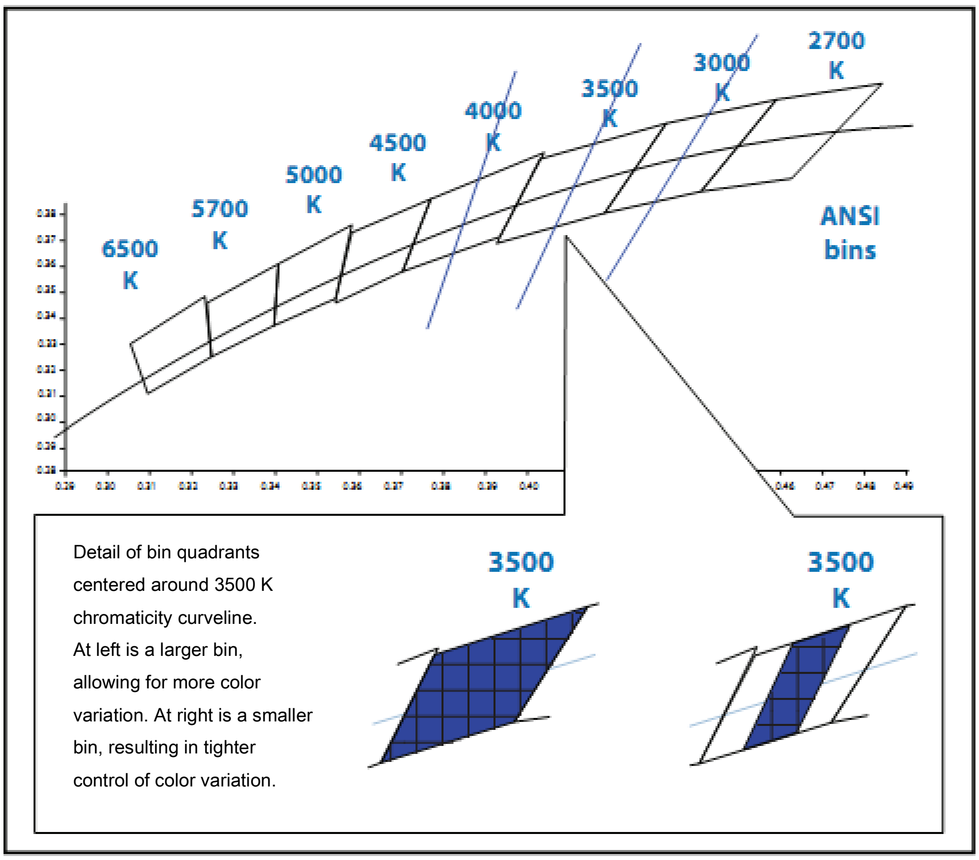


Figure 10. Color bins of LEDs based on CCT (Lithonia Lighting 2010).

7.3 COLOR SHIFT OVER TIME AND PREVENTION TECHNIQUES

LEDs may experience color shift over time. The color shift is generally toward either blue or yellow. If there is color shift toward blue, there is a reduction in the yellow part of the spectrum. In such cases, reduction in phosphor efficiency with heat and time can lead to a reduction in the yellow part of the spectrum. Conversely, when there is color shift toward yellow, yellowing of the epoxy may be the causing factor. Further research is needed to understand the causal factors for color shift over time (Narendran et al. 2007).

Hsu et al. (2008) investigated the color shift mechanism for high-power phosphor-based white LEDs in thermal aging. They used a white high-power LED that included a 3W blue LED chip, a silicone yttrium aluminum garnet (YAG) phosphor, and silicone. To measure the effects of silicone phosphor on LED performance, Hsu et al. (2008) used three different combinations of silicone YAG phosphor thickness and concentration: (1) 1.0 mm and 5.48%, (2) 2.0 mm and 3.20%, and (3) 3.0 mm and 2.40%. Then they heated the LED module in a furnace at a controlled temperature of 150°C to monitor the performance changes of the white-light LEDs. According to the results, the color shift of the LEDs over time increased significantly with an increasing concentration of the silicone YAG phosphor. Conversely, the thickness of the silicone YAG phosphor was not found to significantly affect the color shift of the LEDs over time. Hence, Hsu et al. (2008) recommended a lower concentration of the YAG phosphor for use in packaging of the phosphor-based white-light LEDs.

Chhajed et al. (2005) analyzed the effect of junction temperature on the long-term color shift of trichromatic (i.e., RGB) white-light LEDs. Specifically, they observed the change in the color rendering index (CRI) and correlated color temperature (CCT) due to an increase in junction temperature. The results showed that as the junction temperature increased from 20°C to 80°C, the CRI decreased from 84 to 72 and the CCT increased from 6,500K to 7,200K. Such a reduction in CRI may be problematic for certain applications. To overcome this, Chhajed et al. (2005) recommended an appropriate power adjustment of each individual LED in an LED array. In doing so, the original power ratio between LEDs changes, which consequently impacts the emission spectrum for the trichromatic LED white-light source. Accordingly, high CRI can still be maintained at high junction temperatures such as 80°C.

On the other hand, too much increase in CCT may have undesirable consequences. When CCT is too high (i.e., rather bluish), objects are irradiated and their color looks rather untrue. Moreover, high CCT may have health effects, such as making people feel irritable and depressed (DMX Technologias 2011).

CHAPTER 8 THERMAL PROPERTIES OF LED LIGHT SOURCES

8.1 THERMAL SENSITIVITY OF LEDS

The operating temperature of LEDs is significantly lower than that of metal halide lamps and HPS lamps (Timinger and Ries 2008; City of Ann Arbor 2008). Thus, the light-emitting surface of an LED is significantly lower compared to that of conventional streetlight sources. However, every light source achieves conversion of electric power into radiant energy and heat in different proportions. LEDs, like every other light source, produce heat while they are operating. Metal halide lamps convert 37% of the electrical power into heat, whereas around 75–85% of the electrical power driven by white LED light sources is converted into heat (U.S. Department of Energy 2007). Although the heat conversion rate may be reduced to 60–70% in green LED devices (Cheng et al. 2005), the still high percentage of electrical power converted to heat reduces the luminosity of LED chips (Luo et al. 2007). Furthermore, LEDs are generally more temperature sensitive than standard solid-state electronic components (Arık et al. 2004).

The recent increase in wattage of high-brightness LEDs draws more attention to thermal management of LEDs. A typical 1W LED has a surface area of 1 mm^2 and operates with a driving current of 350 mA. Since the approximate LED light efficiency is around 20%, the heat flux in a high-power LED can exceed 80 W/cm^2, which leads to serious thermal concentration called the hot-spot phenomenon (Yuan et al. 2007; Huang et al. 2009). Also, it is expected that the heat flux of LED chips will reach around 100 W/cm^2 by 2018 (Arık and Weaver 2005), which is why one of the most challenging tasks in LED street lighting design is to prevent the overheating of LEDs. Indeed, the selected cooling method plays a key role in the success of LED systems, and the efficiency and reliability of LEDs have strong dependence on thermal management (Weng and Abbott 2009).

8.1.1 Short-Term Effects of Inadequate LED Thermal Design

If an LED system has inadequate thermal design, the hot-spot phenomenon causes an increase in the junction temperature of LED dies. Consequently, higher junction temperature leads to adverse effects in both short-term and long-term performance of LED light sources. In the short-term, excess heat can reduce the power conversion efficiency and LED light output, lead to power loss, and shift the peak wavelength of the LED light source, which gives rise to change in light color (U.S. Department of Energy 2007; You, He, and Shi 2007; Luo and Liu 2007; Luo et al. 2009a; Rada and Triplett 2010).

LED products are tested and binned for luminous flux and color with regard to a 25-millisecond power pulse at a fixed temperature of 25°C. However, the junction temperature of LEDs is typically around 60°C or greater, provided that constant current and engineered heat mitigation mechanisms are maintained at room temperatures. Consequently, the light output of LEDs is lower at typical application temperatures than the manufacturer's rating.

Figure 11 illustrates the change in relative light output with respect to the junction temperature of LEDs with various colors. Take the case of the white LED shown in

Figure 11, for instance. Because of the temperature sensitivity of the light output of LEDs, white LEDs produce at least 10% less light output at typical application temperatures of around 60°C than the manufacturer's rating at 25°C. If the thermal design of LEDs is inadequate, the resultant application temperature will even be higher, which will consequently lead to further reductions in light output. According to the chart in

Figure 11, blue LEDs are the least sensitive to temperature changes, whereas amber and red LEDs are the most sensitive. Therefore, the effect of thermal design on light output becomes more significant as the light emitted by LED light sources changes from blue to amber in the color spectrum (U.S. Department of Energy 2007).

Thermal saturation phenomenon is another short-term problem induced by high junction temperature of LEDs. Normally, LED light sources become brighter as the driven electrical current increases. However, if the LED junction temperature rises too much, increasing the driven electrical current may not result in a concurrent proportional increase in LED brightness anymore, which indicates the state of thermal saturation (Cheng 2007). Moreover, too much increase in LED junction temperature may in the short-term lead to high thermal stress levels that may cause failure of the wire bond, delamination, detached internal solder joints, and die-bond epoxy damage (Wilcox 2008). Likewise, if the thermal management of LEDs further runs out of control, it may result in irreversible damage to the LED and a broken junction, which consequently brings about complete thermal runaway and spontaneous failure (Weng and Abbott 2009). There are some cases in which early failure of LED street lamps have been reported, which may limit public and administration acceptance of LED street lamps (Luo et al. 2009b).

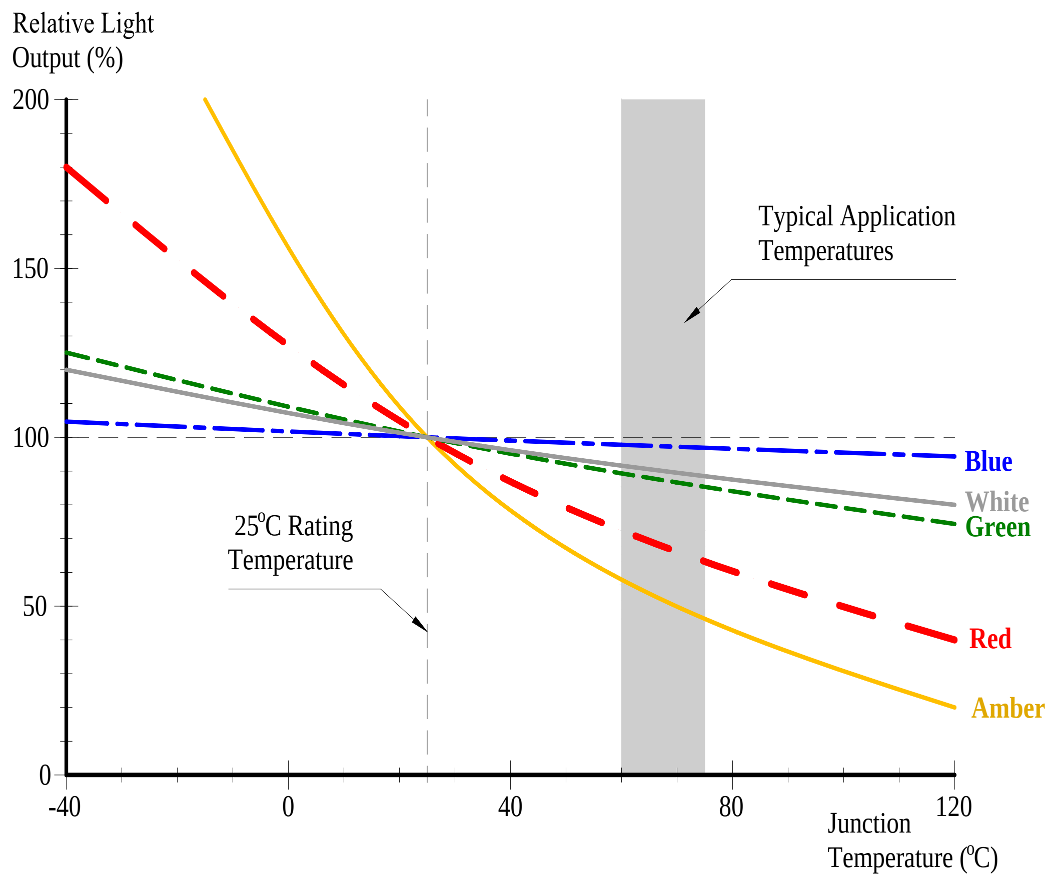


Figure 11. Relative light output of different-colored LEDs with respect to junction temperature (redrawn from Sá et al. [2007]).

8.1.2 Relationship Between LED Light Output and LED Junction Temperature and Input Current

Biber (2008) analyzed two major factors that affect LED light output in the short-term: junction temperature and the driven forward current. Setting a reference condition with two variables, $\Phi_{V,ref}$ *(reference light output)* and $T_{j,ref}$ *(reference junction temperature),* she showed that the difference [$T_j - T_{j,ref}$] had an inverse (negative) linear relationship with the relative light output, [$\Phi_V / \Phi_{V,ref}$], where T_j denotes a given junction temperature and Φ_V stands for the corresponding light output at that junction temperature. Likewise, she showed that there was a second-order (quadratic) relationship between the difference [$I_f - I_{f,0}$] and the relative light output, [$\Phi_V / \Phi_{V,ref}$], where $I_{f,0}$ denotes the reference forward current at $\Phi_{V,ref}$, and I_f stands for the forward current at Φ_V, respectively. By combining these two relations, she derived the following mathematical expression to indicate how thermal conditions and forward current influence LED light output:

$$\frac{\phi_V}{\phi_{V,ref}} = \left[c_0 + c_1\left(T_j - T_{ref}\right)\right] * \left[d_0 + d_1 \frac{I_f}{I_{f,0}} + d_2 \left(\frac{I_f}{I_{f,0}}\right)^2\right]$$

where

Φ_V: Light output in prevailing conditions
$\Phi_{V,ref}$: Light output in reference conditions
T_j: Junction temperature in prevailing conditions
$T_{j,ref}$: Junction temperature in reference conditions
I_f: Forward current in prevailing conditions
$I_{f,0}$: Forward current in reference conditions
c_0, c_1, d_0, d_1, d_2: Coefficients

8.1.3 Long-Term Effects of Inadequate LED Thermal Design

Regarding long-term effects, excessive heat increases the phosphor temperature in white LED chips that are manufactured through phosphor conversion. The increase in phosphor temperature leads to a consequent reduction in quantum efficiency. Reduced quantum efficiency can accelerate lumen depreciation, resulting in shortened lifetime of LEDs (Liu et al. 2007). Figure 12 shows the change in light output over time for two identical LED light sources that were driven at the same current but at different temperatures. The upper curve belongs to an LED light source whose junction temperature was 63°C, whereas the lower curve was obtained from an LED light source whose junction temperature was 74°C. Experimental data were available up to 10,000 hours, and the rest of both curves were extrapolated appropriately. According to the chart in Figure 12, the useful lifetime of the LED light sources, which is based on 70% of the initial lumen output, is found to be 16,000 hours and 37,000 hours at the junction temperatures of 165°F (74°C) and 145°F (63°C), respectively. Hence, a 20°F (11°C) increase in LED junction temperature was observed to reduce the useful lifetime of the LED light source by 57% (U.S. Department of Energy 2007). It is also estimated that an LED's life expectancy is reduced by half for every 31°F (17°C) increase in LED junction temperature above 194°F (90°C) (Wilcox 2008).

Narendran and Gu (2005) conducted two experiments to test long-term temperature sensitivity of several high-power white LEDs. In the first experiment, they tested ten similar high-power white LEDs from the same manufacturing batch at different ambient temperatures. The light output of each white LED was measured for a minimum duration of 6,000 hours. Because of annealing effects, LEDs generally display an initial temporary increase in their light output, and then a gradual reduction in light output starts. Therefore, the researchers omitted the first 1,000 hours of data for each white LED and used the data beyond the first 1,000 hours to estimate the useful life of each white LED. The lifetime of the LEDs were taken as the time it took for the light output to fall below 70% of the initial lumen output. Since one of the major factors that affect LED life span is junction temperature, Narendran and Gu (2005) observed the relationship between the junction temperature and the useful life of the white LEDs in question. According to the results, the lifetime of the LEDs decreased exponentially as the junction temperature increased. The exponential relationship between LED lifetime and junction temperature is illustrated in Figure 13.

Narandren and Gu (2005) also life-tested different commercial high-power white LEDs in their second experiment. They found that different commercial LEDs had different junction temperatures under the same operating conditions because of their different cooling mechanisms. Thus, different commercial LEDs may display different life cycles even under the same operating conditions. Determining the relationship between LED life span and junction temperature can enable LED manufacturers to design longer-lasting LED systems.

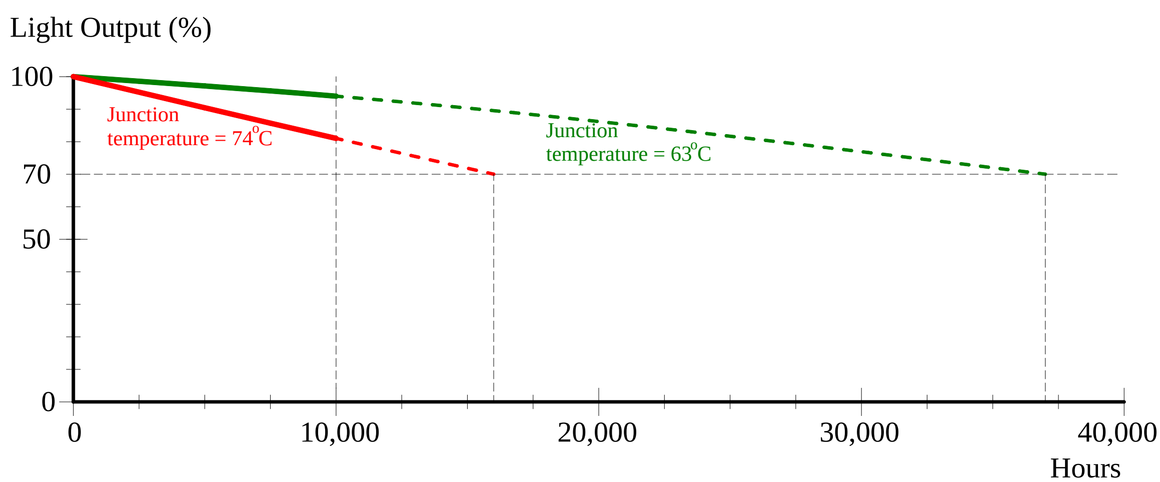


Figure 12. Light output of two identical LED light sources driven at same current but different temperatures (redrawn from U.S. Department of Energy [2007]).

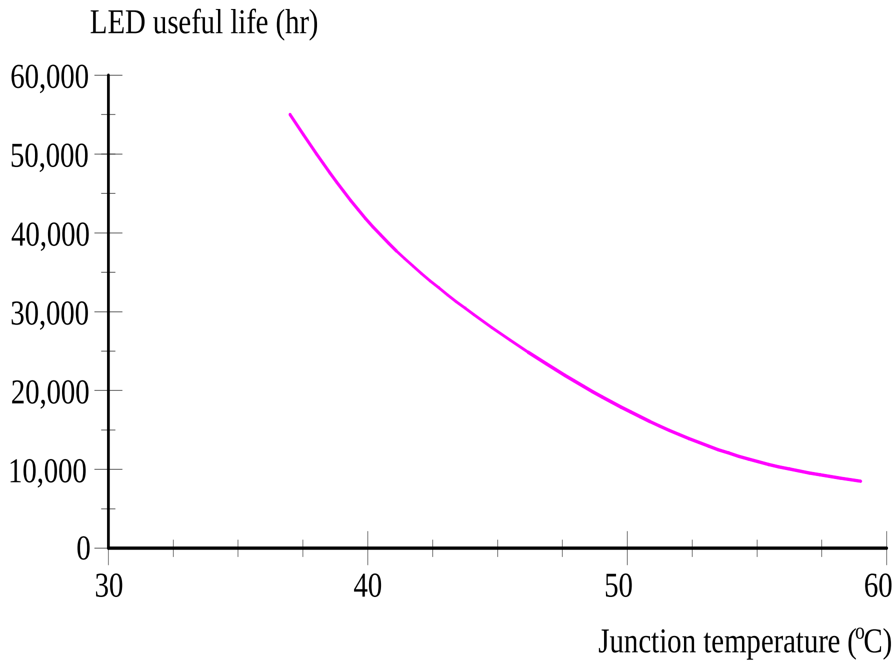


Figure 13. LED useful life as a function of junction temperature (redrawn from Narendran and Gu [2005]).

The thermal sensitivity of LEDs demonstrates the critical role of thermal management in LED street design. Nonetheless, recent advancements in the LED industry have brought about significant improvements in the durability of LEDs at higher operating temperatures. For instance, one of the products by Luxeon (K2) is claimed to have 70% lumen maintenance for 50,000 hours at drive currents up to 1,000 mA and operating temperatures 120°C or below (U.S. Department of Energy 2007). However, other manufacturers such as Philips Lumiled claim 70% lumen maintenance for 50,000 hours, provided that the maximum LED junction temperature is kept at 85°C or below (Nuttall, Shuttleworth, and Routledge 2008).

8.2 STRUCTURE OF TYPICAL HIGH-FLUX LED SYSTEMS

Figure 14 illustrates the schematic view of a typical high-flux LED system, which consists of the emitter, board, and external heat sink. Each unit of the typical high-flux LED system is briefly described as follows (U.S. Department of Energy 2007):

- *Emitter:* The optics, encapsulant, LED die (LED chip), and heat sink slug are accommodated in the emitter. The function of the heat sink slug is to draw heat away from the LED die.
- *Board:* The heat sink slug is soldered to a metal-core printed circuit board, which is composed of two layers. The upper layer is a non-conductor layer called dielectric that is bonded to the lower layer (i.e., base plate) made of metal, usually aluminum.
- *External heat sink:* The metal-core printed circuit board is mechanically attached to an external heat sink, whose size depends on the thermal properties of the material and the amount of heat that has to be dissipated. It is possible to integrate the external heat sink either into the design of the luminaire or into the chassis of the luminaire itself.

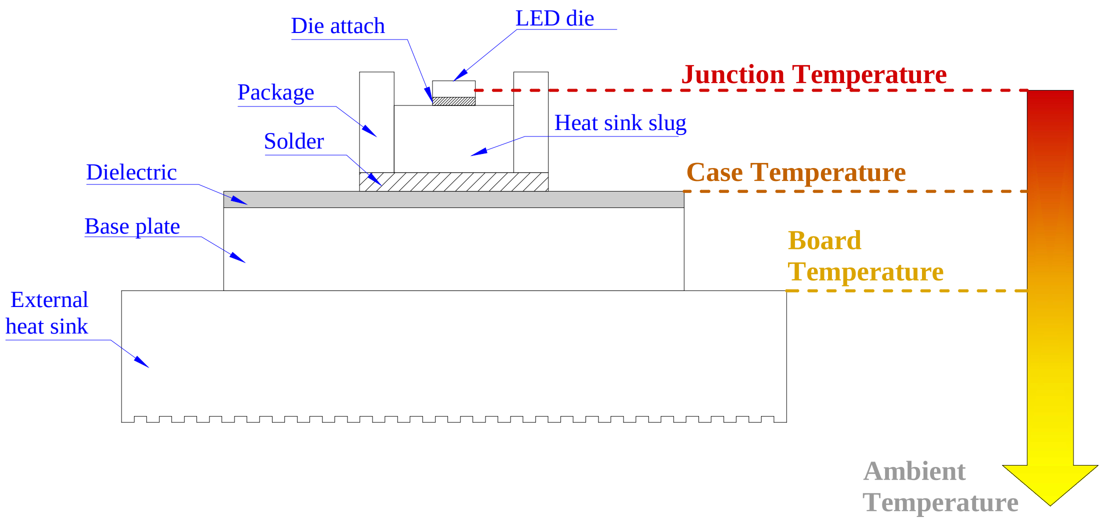


Figure 14. Schematic view of a typical high-flux LED system
(redrawn not to scale from U.S. Department of Energy [2007]).

8.3 LED JUNCTION TEMPERATURE

Because the light conversion efficiency of white LEDs is around 15–25%, most of the input power generates redundant heat, which eventually gives rise to an increase in LED junction temperature (Chi et al. 2008). While an incandescent bulk filament operates at over 1,000°C, the junction temperature of LEDs should not exceed 125°C (Liu et al. 2007; Cheng et al. 2005). Indeed, LED junction temperature not only indicates the effectiveness of thermal management, but it also directly influences lighting design because both the wavelength and relative intensity of LED light output are directly affected by LED junction temperature. Moreover, keeping the LED junction temperature low enables designers to put higher power into the system so that the light output of the LED streetlight system can be increased (Wilcox 2008).

LED junction temperature depends on three factors:

- Drive current
- Thermal path
- Ambient temperature

Higher drive currents lead to higher heat generation at the LED die. In order to meet the expected LED light output, life, and color, excessive heat must be conducted away from the LED die. Both the thermal path and the ambient temperature affect the amount of heat that can be moved away from the LED die. While incandescent and halogen light sources dissipate most of the excess heat as infrared radiation, the removal of excess heat from an LED light source occurs primarily through conduction (Nguyen, Terao, and Laski 2005). Therefore, the excess heat at the LED junction has to be spread over a larger area to reduce the LED junction temperature and to keep it within prescribed limits (Poppe and Lasance 2009).

8.3.1 Effect of High-Flux LED System Geometry on LED Junction Temperature

Some previous studies analyzed how the geometry of a high-flux LED system affects the thermal performance of the system. Weng and Abbott (2009) used a 3-D simulation method to compare the heat transfer of LED packages with different cooling conditions, heat slug, chip size, and printed circuit board. They observed that the bigger the chip size, the greater the heat transfer area and heat transfer path, which brought about reduced thermal resistance.

By developing a mathematical expression, Biber (2008) integrated thermal and optical calculations to evaluate trade-offs between thermal performance and LED light output. She showed that the higher the external heat sink volume, the greater the light output becomes, provided that the input current was constant and the junction temperature was kept below 90°C. However, the footprint area and volume of the heat sink is usually limited because of the tight boundaries of the system (Arık et al. 2004). But if there is design flexibility for the external heat sink, increasing either the heat sink assembly depth or heat sink diameter may result in enhanced light output (Biber 2008).

Moreover, Cheng (2007) showed that the cooling performance may not increase significantly when the heat sink thickness is increased beyond a particular value, depending on the material of the heat sink. Next, Chi et al. (2008) analyzed the junction temperature of a high-power LED package by using the finite element analysis software ANSYS®. They explored the effects of various factors on LED junction temperature such as the thickness of the die attach material, the thickness of the copper heat sink slug, and the area of the heat sink slug. Since die attach materials act as a thermal bottleneck on account of their low thermal conductivity, the junction temperature was observed to decrease with decreasing thickness of the die attach material. On the other hand, Chi et al. (2008) did not observe a significant effect of the thickness and area of the copper heat sink slug on junction temperature. In other words, increasing the thickness and area of the copper heat sink slug did not significantly change the LED junction temperature. The reason was the much bigger volume of the copper heat sink slug compared to the LED chip, as well as the good thermal conductivity of copper. The copper heat sink slug was already able to function as an excellent heat conductor in its original dimensions.

8.4 THERMAL RESISTANCE OF LED PACKAGES

In a typical LED luminaire, there are multiple high-brightness LED packages. Each high-brightness package is attached to a board located on the external heat sink. In order to conduct the excess heat away from the LED junction, the most efficient thermal path has to be designed by the LED manufacturer by taking into consideration the dimensional limitations, required optical performance, and economic constraints. (U.S. Department of Energy 2007; Weng and Abbott 2009). There are two thermal paths along which the excess heat at the LED die can be moved away (Weng and Abbott 2009):

- Part of the excess heat at the LED die reaches the immediate environment through convection and radiation off the exposed surface of the package.
- Part of the excess heat at the LED die is conducted into and through the board, after which it is released to the immediate environment through convection and radiation off the exposed surface of the board.

As the excess heat is dissipated from the LED junction, each part of the high-flux LED system impedes the heat dissipation to some extent, which forms the thermal resistance of the system. The thermal resistance depends on the structure, material, and size of the devices that form the system (Cheng 2007). The thermal resistance of LED modules consists of four components as follows (Luo, Xiong, and Liu 2008):

- *Packaging thermal resistance:* The thermal resistance of the high-power LED that depends on the chip packaging technology.
- *Bonding thermal resistance:* The thermal resistance between the substrate of the LED and the base with fins; it depends on the bonding material and its thickness.
- *Thermal spreading resistance:* The thermal resistance between the LED chips and the base with fins. Some geometric factors, such as the size of the chip substrate and the aluminum base as well as the material of the aluminum base, affect the thermal spreading resistance.
- *Thermal convection resistance:* The thermal resistance between the fins and the ambient. Factors such as fin area, fin structure, and the environmental wind speed influence the thermal convection resistance.

8.5 THERMAL MANAGEMENT OF LEDS

Unless effective measures for LED thermal management are taken, the reliability of an LED street lamp system may diminish, which eventually leads to reduced optical efficiency and shorter useful life. For instance, Luo et al. (2007) carried out thermal behavior analysis of an 80W LED street lamp. The LED street lamp consisted of 20 high-power LED modules that were directly bonded to an aluminum base to decrease thermal resistance. The frame of the lamp contained the aluminum base and fins, through which the excess heat was dissipated into the immediate environment. Luo et al. (2007) installed 16 thermocouples and measured the temperature at 16 different locations on the LED system when the ambient temperature was 52°F (11°C). Subsequent to several hours of lighting, the steady-state maximum temperature of the heat sink of the 80W LED street lamp was found to be 108°F (42°C) at an ambient temperature of 52°F (11°C). However, the temperature at the base exactly below the LED chip modules could not be measured, so the researchers developed a simulation model to conduct thermal analysis of the LED street lamp. By using the simulation model, they found that when the ambient temperature increased to 113°F (45°C), the maximum junction temperature of the LED chips would be 248°F (120°C), which is very close to the critical temperature of 257°F (125°C). Hence, the reliability of the LED street lamp turned out to be poor and revealed the need for more effective thermal management.

There are two major methods for effective thermal management of LEDs: active cooling and passive cooling. In passive cooling techniques, convection is the primary mechanism for heat removal. Passive cooling techniques involve the use of heat pipes to move heat from the LED dies to finned heat sinks outside of the LED luminaire that achieve heat convection to the ambient(Nuttall, Shuttleworth, and Routledge 2008). On the other hand, active cooling systems involve an air movement device that increases heat dissipation by forcing an increased amount of air through the heat sink, a process known as forced convection (Cheung, Noska, and Heide 2009). The air movement device used in active cooling systems can be heat pumps, force-air-cooled heat exchangers or synthetic jets (Nuttall, Shuttleworth and Routledge 2008). The advantages of active cooling systems over passive cooling systems are as follows (Cheung, Noska, and Heide 2009):

- In passive cooling techniques, the speed of fluid flow is lower than in active cooling systems because forced convection used in active cooling techniques increases the speed of air flow, which in turn leads to a higher heat transfer coefficient.
- Active cooling techniques can significantly reduce the required size of the thermal management solution, which gives luminaire designers more flexibility in design.

- Active cooling can also reduce the required weight of the heat sink by half or even more, making installation easier and lowering shipping costs.
- In contrast to passive cooling techniques in which orientation plays a significant role in heat sink design, orientation has a nominal impact on the design of active cooling systems.

Cheung, Noska, and Heide (2009) compared the required size and weight of a synthetic jet active cooling system with those of a passive cooling system for the thermal management of a 40W 2,000-lumen LED package. They found that the synthetic jet active cooling system required around 75% less weight and 57% less size compared to the passive heat sink. Although active cooling techniques offer significant advantages over passive cooling techniques, active cooling techniques may not be appropriate for street lamps. Passive cooling techniques have generally been the historic choice of the street lighting industry. The City of Los Angeles Bureau of Street Lighting (2010) does not allow the use of fans or pumps in the thermal management of LED street lamps. Although it may not be possible to cool LEDs through passive cooling to a point where enough lumens can be generated for general illumination applications (Wilcox 2008), passive cooling techniques offer a more cost-effective means of LED thermal management (Nuttall, Shuttleworth, and Routledge 2008). Several methods have been proposed in the literature to enhance the cooling performance of LED systems.

Appendices A and B present some of the proposed methods in the literature to help reduce LED junction temperature during lighting. It should be noted that while some of the methods summarized in Appendix B involve the use of fans and pumps, the Los Bureau of Street Lighting (2010) requires that the cooling system of roadway luminaires consist of a heat sink with no fan or pumps.

CHAPTER 9 GENERAL SPECIFICATIONS FOR LED ROADWAY LUMINAIRES

Roadway lighting specifications are published by the Illumination Engineering Society of North America (IESNA) in IESNA RP-8-00, “American National Standard Practice for Roadway Lighting.” The illumination levels and illumination patterns are recommended based on the roadway category, which ranges from local roadways to expressways. Figure 15 indicates different types of lighting fixtures that are classified as Type I, Type II, Type III, and Type IV. While Type IV fixtures are recommended for wide, multi-lane roads, Type I fixtures are appropriate for narrow roadways (Kodisingle 2008).

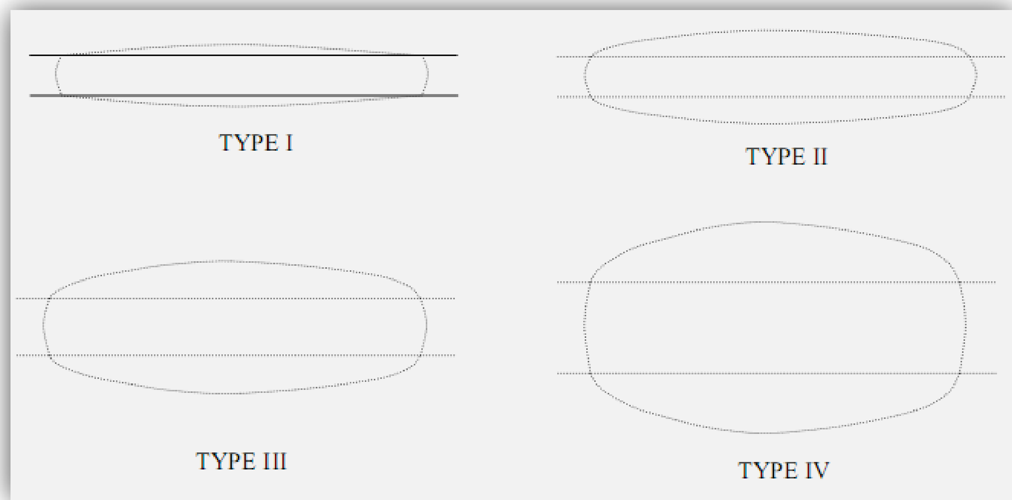


Figure 15. Lighting fixture types (Kodisingle 2008).

The Illuminating Engineering Society of North America (IESNA) published TM-15, “Luminaire Classification System for Outdoor Luminaires.” The TM-15 luminaire classification system (LCS) replaces the former IESNA cutoff classification system. In the LCS, the light distribution and optical control of roadway luminaires are defined by the number of zonal lumens expressed as a percentage of the total lamp lumens. The number of lumens in the various LCS zones is used to calculate the backlight, uplight, and glare (BUG) rating of a particular luminaire. Lighting professionals can use a luminaire’s BUG rating to evaluate its optical performance regarding sky glow, light trespass, and high-angle brightness control (AGi32 Knowledgebase, no date).

Currently, the Bureau of Street Lighting of the City of Los Angeles and the Minnesota Department of Transportation (MN/DOT) have detailed specifications for LED roadway lighting. In the MN/DOT LED roadway lighting specifications, the requirements for LED roadway luminaires are categorized under the following groups (MN/DOT 2011):

- Listing requirements
- Housing requirements
- Electrical requirements
- LED performance requirements
- Optical requirements
- Warranty requirements
- MN/DOT acceptance testing

The Bureau of Street Lighting of the City of Los Angeles has categorized the LED roadway requirements under the following groups (Bureau of Street Lighting, 2011):

- Luminaire requirements
- LED module/array requirements
- Power supply/driver requirements
- Roadway application requirements
- Measurement/performance/safety standards
- Pre-qualifications for bidding
- Delivery requirements

Appendix C summarizes some of the general specifications for LED roadway luminaires established by the Bureau of Street Lighting of the City of Los Angeles. Detailed specifications may be found in City of Los Angeles Bureau of Street Lighting (2010; 2011) and MN/DOT (2011).

CHAPTER 10 TESTING OF LED LUMINAIRES

Due to the significant differences in LED technology, there has been a gap in the industry test standards and test procedures for product comparisons and ratings. Hence, ENERGY STAR® criteria, new standards, and new test procedures have been released (U.S. Department of Energy 2009a). According to the Bureau of Street Lighting of the City of Los Angeles (2010), the following measurement/performance/safety standards shall be referenced in determining, measuring, and reporting the illuminance and luminance characteristics of LED roadway luminaires:

- ANSI C78.377.2008, "Specifications for the Chromaticity of Solid-state Lighting Products"
- IESNA LM-79-08, "IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products"
- IESNA LM-80-08 (recommended), "IESNA Approved Method for Measuring Lumen Maintenance of LED Lighting Sources"
- IESNA TM-21-11, "Projecting Long-Term Lumen Maintenance of LED Light Sources"
- UL Standards (latest approved):
    - 8750, "Light-Emitting Diode (LED) Light Sources for Use in Lighting Products"
    - 1598, "Luminaires"
    - 1012, "Power Units Other Than Class 2"
    - 1310, "Class 2 Power Units"
    - 2108, "Low Voltage Lighting Systems"

Testing of LED luminaires is generally performed for two different purposes:

- Evaluation of the photometric performance of LED luminaires (generally new installed LEDs)
- Evaluation of the lumen maintenance of LED luminaires in the long run

10.1 TESTING PHOTOMETRIC PERFORMANCE OF LEDS

Evaluation of the photometric performance of new installed LEDs is achieved in the field based on IESNA LM-50-99, "Guide for Photometric Measurement of Roadway Lighting Installations." Field measurements involve collection of illuminance and luminance data. Illuminance is defined as "the density of luminous flux incident on a surface area, and it is the quotient of the luminous flux by the area of the surface when the latter is uniformly illuminated" (IDOT 2010). The U.S. Customary System unit for illuminance is footcandle (ft-cd), which equals a light flux of 1 lumen uniformly distributed on a surface 1 ft^2 in area. Luminance is defined as "the luminous intensity of a surface in a given direction per unit of projected area of the surface as viewed from that direction" (IDOT 2010). Generally, the metric unit of candelas per square meter (cd/m^2) is used in luminance measurements. Candelas per square meter is defined as "the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square meter or the average luminance of any surface emitting of reflecting light at that rate" (IDOT 2010).

For both illuminance and luminance measurements, the roadway should be marked off in transverse and longitudinal lines in accordance with IESNA LM-50-99. At each grid point, horizontal illuminance readings are taken in order to compute system characteristics such as average illuminance, minimum/maximum illuminance, etc. Luminance measurements are made to determine the luminance level perceived by motorists. To measure luminance, an observer should move with points parallel to the roadway while keeping an appropriate detector height and a line of sight over an appropriate longitudinal distance. Further details regarding illuminance and luminance measurements are given in Appendix D.

10.2 TESTING LUMEN MAINTENANCE OF LEDS

The “lifetime” of an LED refers to end-of-life criteria such as the time span at the end of which the lumen output decreases below a particular threshold. Depending on use conditions and drive current, LEDs can exhibit a life span of 50,000 hours or more. Although gradual reduction in the light output from LEDs is observed over time, LEDs differ from traditional light sources in that they do not usually display catastrophic failure. Hence, the light output from LEDs can reduce below the level required by codes and specifications over time. Sometimes, gradual shifts in the spectra emitted from LEDs can occur over time, which may lead to color shift or undesirable appearance. The lumen maintenance can also be affected by these changes.

Since a range of factors such as ambient temperature, orientation, auxiliary equipment, and airflow influence the performance of LEDs, test procedures and conditions should be set such that comparable results can be obtained by various laboratories. The guidelines given in IESNA LM-80-08, “Guide for Photometric Measurement of Roadway Lighting Installations,” describe methods to measure lumen maintenance of sources including LED light sources (i.e., LED packages, modules, and arrays). To test the lumen maintenance of LED light sources, a sample unit is operated for a minimum required amount of time at a specified ambient temperature. Data collection is achieved at particular intervals to estimate the long-term performance and lumen maintenance of LEDs. Further details regarding the testing of lumen maintenance of LED light sources are given in Appendix E.

IESNA TM-21-11, “Projecting Long-Term Lumen Maintenance of LED Light Sources,” describes methods to extrapolate the LM-80-08 lumen maintenance data to times beyond the LM-80 test time. IESNA TM-21-11 is also referenced in EPA ENERGY STAR® guides and DesignLights Consortium qualification criteria (Municipal Solid-State Street Lighting Consortium 2011).

CHAPTER 11 INDUSTRY INTEREST IN LED LUMINAIRE SOLUTIONS

Advances in LED technology for industrial, residential, and in particular for street lighting applications have created a need to develop new specifications. A set of guidelines and standardized procedures for measuring a series of characteristics of the luminaire output are currently in use, with the objective of establishing a common ground for the industry. These documents include methods by IESNA in their LM-79-08, LM-80-08, G-2-10, and LM-50-99 standards, as described in the previous sections, and are essential to create a uniform method for users to identify product characteristics and, equally important, for luminaire manufacturers to measure their improvements and test their newest products.

Efforts to develop more efficient and cost-effective designs have resulted in LED luminaires that in some scenarios are highly competitive with respect to older technologies, more specifically with HPS. The industry's commitment to LED solutions for decorative and street lighting is currently highly emphasized and envisions a bright future for these products in both the short and long term.

The research team recognizes that while LED products for street lighting applications are still in early stages of development, especially for highway scenarios, efforts in the industry are clearly directed toward this technology, and it is expected to result in lighting products that will be highly desirable compared with older technologies.

Practically all major manufacturers of luminaires for street lighting are actively involved in the development of LED solutions, with significant research that has widened the spectrum in which these products are now applicable. LED products have surpassed ornamental and low mounting height barriers, typical of city centers and residential areas, to enter the highway domain, with mounting heights of 30 ft. or higher.

The pace at which new LED products are being developed is fast, and today LED applications for street and even highway lighting have substantial support from the U.S. Department of Energy. This support has been widely acknowledged in various ways, including the solid-state lighting GATEWAY demonstration projects. Moreover, a survey of LED manufacturers/distributors in the U.S., conducted by the research team, resulted in identification of more than 50 companies offering LED solutions for street or highway applications, confirming widespread interest in the industry toward LEDs for these applications.

Results from the demonstration projects have been mentioned in Section 6.4 of this report, as well as others that primarily address higher mounting heights or even highway scenarios. This is the main focus of this study, as the feasibility of LED products will be field-tested and aimed at applications for 30-ft. mounting heights or higher.

Current LED luminaires differ significantly in terms of internal design as well as surface area, depending on the manufacturer. For street lighting, passive cooling mechanisms are preferred over active ones, and a significant amount of research is being conducted in this regard. Some recent passive cooling techniques for LEDs are presented in Appendix A of this report. Similarly, a number of different arrangements of the LEDS in the luminaire are being investigated and show significant variation between manufacturers.

Literally every component of the luminaire, including novel driver capabilities and surge protection, is part of active research efforts to develop more efficient products. Some of the most relevant aspects of these advancements have been summarized in this report, with the objective of providing an overview of the state of the art in LED applications for street lighting and highlighting current trends in the industry.

It is expected that more advanced and efficient LED luminaires reach the market on a continual basis, further expanding the scenarios where LEDs can be competitive in terms of investment returns and in energy savings. The industry is highly committed to investing in research and development of LED luminaires, not only for low mounting heights and ornamental purposes but also for highway and highly demanding applications, thereby entering the domain of roadways maintained by state departments of transportation.

CHAPTER 12 SUMMARY

LEDs are fourth-generation light sources that have recently appeared as an energy-efficient solution to street lighting. LEDs are semiconductors that emit light when electrical current runs through them. An LED streetlight consists of LED chips, LED module, heat sink, optics, control circuit, and power supply/driver. LED luminaires can be a promising choice for street lighting systems since they provide the advantages of energy efficiency, longer life, good color characteristics, improved vision for mesopic conditions, lack of warm-up time, compact size, directional light, reduced light pollution, environment-friendly characteristics, dimming capabilities, and breakage and vibration resistance. Nonetheless, LEDs are not frequently used in street lighting applications due to their disadvantages such as shortened life expectancy, higher heat conversion rate, higher installation cost, and issues in obtaining white light.

Comparison of LED streetlights with metal halide and HPS streetlights can give more insight on the pros and cons of using LEDs in street lighting applications. LEDs have a higher installation cost than metal halide light sources and generally provide inferior luminous efficacy, but a continuous rise in the efficacy of LEDs is expected over the upcoming years. Assuming an annual usage of 4,000 hours, the estimated average lifetime of LEDs is over 10 years, whereas metal halide lamps promise an average service-free period of around 5.5. LED light sources can be instantly turned on/off, but it takes a long time for metal halide lamps to reach an ideal operating temperature. LEDs can also provide more uniform distribution of illuminance that can eliminate hot spots on the pavement encountered with use of metal halide streetlights.

Compared to HPS luminaires, LED luminaires generally have slightly lower luminous efficacy. However, unlike most HPS streetlights that do not have full-cutoff optics, LEDs are designed to focus light and do not emit light in all directions. This results in reduced light pollution and glare. Since the human eye is more sensitive to the blue end of the spectrum under dim lighting conditions, LED light with high blue content can be detected more easily by the human eye compared to HPS light. Moreover, LEDs have considerably higher CRI than HPS lamps unless a color-corrected version of the HPS lamp is used, but such a lamp would be less efficacious. U.S. Department of Energy GATEWAY demonstration projects discussed in this report offer useful information on the potential benefits of replacing HPS streetlights with LED streetlights.

Nonetheless, some of the most critical issues in LEDs are the trade-off between CCT and lumen output, color shift of LED light sources over time, and thermal management of LEDs. For instance, LEDs convert around 75–85% of their electrical power into heat as opposed to metal halide lamps, which convert only 37% of electrical power into heat. These issues should be properly addressed in street lighting applications.

Because of rapid and significant advancements in LED technology, standardization has not kept pace. Consequently, there has been a gap in industry test standards and test procedures for product development and ratings. Thus, ENERGY STAR® criteria, new standards, and new test procedures have been critical in helping to bring consistency and quality to the LED marketplace. Among the important test procedures recently released are IESNA LM-79-08 (“IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products”), IESNA LM-80-08 (“IESNA Approved Method for Measuring Lumen Maintenance of LED Lighting Sources”), and IESNA TM-21-11 (“Projecting Long-Term Lumen Maintenance of LED Light Sources”). Some institutions such as the Bureau of Street Lighting in the City of Los Angeles and Minnesota Department of Transportation published their own specifications for LED roadway lighting. Although important standards have recently been developed, there is a need to set in place additional LED standards (requirements for luminaire, housing, LED module, roadway application, power supply/driver, heat management, and color shift) so that every component and all aspects of the manufacture of LED lighting is guided by industry recognized specifications.

The industry continues to research and develop LED luminaires for street lighting, which is evidenced by the number new products being released by practically every major player in the street lighting sector. Given the clear trend toward use of LED luminaires in the industry, along with growing acceptance of LEDs by public agencies and the U.S. government, it is expected that efficient LED luminaires for highway applications will be available in the near future for higher mounting heights and lumen output requirements.

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APPENDIX A: SOME PASSIVE COOLING TECHNIQUES FOR HIGH-POWER LEDS

A.1 PROPER SELECTION OF DIE ATTACH MATERIAL

Unlike incandescent light sources that rely on radiation, the dissipation of around 90% or more of the thermal energy occurs through direct conduction from the LED die. Hence, the heat flux at the die level may be in the order of 300 W/cm^2 or greater, which necessitates excellent heat spreaders at the die level (Christensen and Graham, 2009). Thus, the thermal conductivity of die attach materials plays a key role in the dissipation of excess heat from the junction. However, in high power LEDs, chip substrate and die attach material (i.e. adhesive resin) are the bottlenecks in the heat dissipation path in the chip level and package level, respectively (Chen et al., 2008). The thermal conductivity of die attach materials is considerably lower than that of other packaging materials, so die attach materials form a bottle neck in heat flow. Consequently, the heat flow rate is highly dependent on the thermal conductivity of the selected die attach material.

Die attach materials are divided into two categories: organic metal adhesives and solder paste. Organic metal adhesives consist of metal particles suspended in a polymer carrier. The metal particles provide thermal and electrical conductivity while the polymer carrier makes a bond with the required mechanical strength. Solder pastes are the second type of die attach materials that include a high amount of solder flux. If the required amount of die attach material is large, the use of solder pastes may lead to voiding (You, He and Shi, 2007). Any void in the die attach material increases thermal resistance, which may instantly increases LED die temperature, eventually resulting in failure in operation (Kim et al., 2008). Besides, it is difficult to use silicone in combination with solder pastes due to the high sensitivity of silicone to solder flux. Since most high power LEDs involve large die and silicone encapsulants, the use of organic metal adhesives instead of solder pastes is recommended for high power LEDs (You, He and Shi, 2007).

Next, Chen et al. (2008) compared the thermal resistance of two types of high power LEDs with different die attach materials. In the first type, red, green, and blue high power LEDs were fixed on a metal heat sink by means of conventional die attach material, i.e. adhesive resin. In the second type, red, green, and blue high power LEDs were embraced in a metal heat sink using electroless and electroplating technique (EET) without adhesive resin. During lighting, the junction temperatures of the red, green, and blue LEDs with conventional adhesive resin were measured as 91^{o}C, 117^{o}C, and 82^{o}C, respectively. The reason for the significantly higher junction temperature of the green high power LED was the lower quantum efficiency of green high power LEDs compared to red and blue high power LEDs. Thermal comparison of the two types of LEDs showed that at an input current of 350 mA, the junction temperatures of the red, green, and blue high power LEDs using EET were 10^{o}C, 41^{o}C, and 5^{o}C lower than the junction temperatures of the red, green, and blue high power LEDs with adhesive resin, respectively. Likewise, compared to the use of adhesive resin, the use of EET reduced the thermal resistance of the red, green, and blue high power LEDs by 15.4%, 43.1%, and 14.0%, respectively. The reduction in thermal resistance induced by the use of EET also increased the luminous intensity of the red, green, and blue high power LEDs by up to 37.0%, 19.5%%, and 26.0%, respectively (Chen et al., 2008). The results of this study underscored the potential benefits of eliminating the use of conventional adhesive resin as die attach material in the thermal management of high power LEDs.

Furthermore, Kim et al. (2008) investigated the thermal transient characteristics of die attach material in high power LED packages. They carried out thermal transient analysis by evaluating the structure function of the heat flow path in the LED structure. By using the differential structure function of the thermal transient characteristics, they compared the thermal resistance of three types of die attach materials: Au/Sn eutectic bonding, solder paste, and Ag paste. The results of the thermal analysis demonstrated that the thermal resistances were 3.5 K/W, 4.4 – 4.6 K/W, and 115 – 14.2 K/W for the Au/Sn eutectic bonding, solder paste, and Ag paste, respectively. The low thermal resistance of Au/Sn eutectic bonding compared to the other two types of die attach materials highlighted the thermal benefits of using Au/Sn as the die attach material.

A.2. PROPER SELECTION OF LED CHIP AND ITS SUBSTRATE MATERIAL

The thermal resistance between the LED junction and the external heat sink should be as low as possible since conduction heat transfer occurs there. Two of the popular choices for LED chip substrates are SiC chips and sapphire chips that have a thermal transmittance of 400 W/m^2K and 30 W/m^2K, respectively. Arık et al. (2004) explored the effects of SiC and Sapphire chip packages on LED junction temperature. They compared SiC and Sapphire chip packages with the same metal frame and package architecture. They measured the maximum LED chip temperatures as 120.1^oC and 124.1^oC for the SiC and sapphire packages, respectively, while they were operating. The junction-to-board thermal resistance was measured as 4.4 K/W and 9.2 K/W for the SiC and sapphire packages, respectively. So the SiC chip not only led to a 4^oC-reduction in junction temperature, but also reduced the junction-to-board thermal resistance by more than half. Moreover, Arık and Weaver (2005) carried out a parametric study to reveal the effect of the thermal conductivity of the substrate material on the temperature distribution. Compared to SiC substrate, sapphire substrate was found to bring about higher temperature variation and higher maximum temperatures in the temperature distribution in a LED chip. In both studies, the improvements in the thermal performance induced by the SiC chip were mainly attributed to the superior thermal conductivity of SiC (Arık and Weaver, 2005; Arık et al., 2004). Arık and Weaver (2005) also stated that the chip bump layout has a significant effect on the temperature distribution in a LED chip.

Next, Chi et al. (2008) explored the thermal behavior of a high power LED package by using the finite element analysis software ANSYS®. The high power LED package was mounted on a heat sink that was composed of a GaN-based active layer with sapphire substrate. A copper heat sink slug was situated at the bottom of the LED package. A silicon submount was also connected by means of a die attach material between the copper heat sink slug and the LED chip to prevent electrostatic discharge. By employing ANSYS®, which was observed to provide accuracy within 4.8%, they investigated the effects of various factors on LED junction temperature, including the substrate material of the LED chip. They simulated and compared the LED junction temperature for three different LED chip substrate materials: sapphire, SiC, and copper. The results showed that when the LED input power was 1 W, the junction temperatures of the three types of LED systems did not differ significantly from each other. However, when the LED input power was increased to 5 W, the LED junction temperature was measured as approximately 112^oC, 105^oC, and 102^oC for the LED systems with sapphire, SiC, and copper substrates, respectively. Hence, changing the substrate material from sapphire to copper reduced the LED junction temperature by 10^oC at an LED input power of 5 W owing to the superior thermal conductivity of copper.

A.3 PROPER SELECTION OF THERMAL INTERFACE MATERIAL

Generally, conventional thermal interface materials used in high-brightness LED packages form a bottleneck in heat transfer from the LED junction to the cooling system since their thermal conductivity is relatively low. Their relatively lower thermal conductivity stems from the polymer matrix with thermally conductive fillers within their structure (Zhang et al., 2008). Hence, increasing the thermal conductivity of the thermal interface material can help reduce the LED junction temperature.

Zhang et al. (2008) proposed the use of a vertically aligned carbon nanotube array without polymer matrix as thermal interface material in high-brightness LEDs. The schematic side view of a high-brightness LED package that utilizes the carbon nanotube thermal interface material is shown in Figure 16. Zhang et al. (2008) conducted an experimental study to measure the thermal resistance across the carbon nanotube interface. They found that the thermal resistance of the carbon nanotube thermal interface material on substrate could be as low as 7 mm^2 K/ W, which was only around 10% of the thermal resistance of commercial silver epoxy thermal interface material that consisted of a 25-micrometer thick commercial silver epoxy pasted and cured between an aluminum alloy surface and a silicon substrate. Zhang et al. (2008) also found that the use of carbon nanotube thermal interface material enabled high-brightness LED packages to maintain a linear relationship between the light output and input current up to 900 milliamperes. Hence, the carbon nanotube array can be a promising thermal interface material for high-brightness LED packages.

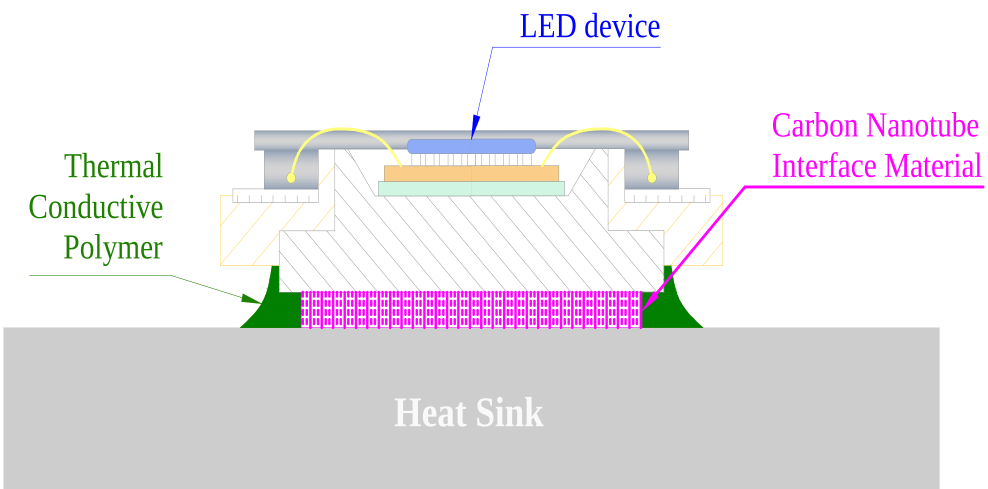

Figure 16. Schematic side view of a high-brightness LED package with carbon nanotube thermal interface material
Redrawn not to scale from Zhang et al. (2008)

A.4 OPTIMIZED DESIGN OF HEAT SINK

Luo et al. (2009) presented a new design and optimization method of horizontally located plate fin heat sink for high power LED street lamps. That the heat sink base should be located in the horizontal direction in LED street lamps makes its design more challenging since it is hard to compute the heat transfer coefficient between the fins as the direction of gravity is along the fin height. Hence, the LED street lamp industry is in need of a simple engineering solution to the design and optimization of horizontally located heat sinks. Hence, Luo et al. (2009) developed a new method to determine the optimal fin height, fin thickness and fin spacing of horizontally located plate fin heat sinks, based on simple empirical equations. Then they employed the new method to design the heat sink for a 112-W LED street lamp and found the optimum fin height, fin thickness, and fin spacing as 17 mm, 12 mm and 5 mm, respectively. Once the optimum design variables were determined, they manufactured a prototype and tested it on a 112-W LED street lamp. According to the results, several hours after the system was turned on, the maximum steady state temperature at the heat sink was measured to be 113^{o}F (45^{o}C) while the ambient temperature was 77^{o}F (25^{o}C). Thus, the system proved to be effective in cooling down the high power LED street lamp.

A.5 THERMOELECTRIC COOLER

Wang et al. (2009) explored the effectiveness of using a thermoelectric cooler for the thermal management of a 2x2 high-power LED array. A thermoelectric cooler (sometimes also referred to as a Peltier device/ diode) achieves heat transfer from one side to the other against the temperature gradient, i.e. from cold to hot, by consuming electrical energy. When a thermoelectric cooler is subjected to direct current, one side of it cools while the other side warms, and it conducts the heat away from the cold side at a rate depending on the amount of applied current. Compared to traditional ways of heat dissipation such as air cooling, thermoelectric cooling can provide more effective thermal management of the LED system since it is an active refrigerating technology (Wang et al., 2009).

The structure of the LED packaging with the thermoelectric cooler is shown in Figure 17; the upper side of the thermoelectric cooler is its cold side whereas the lower side of the thermoelectric cooler is its warm side. When the LED chips generate heat, the soaking block, substrate and thermal interface material conduct the heat to the cold (i.e. upper) side of the thermoelectric cooler. Subsequently, the thermoelectric cooler moves away the heat against the temperature gradient from the cold (i.e. upper) end to the warm (i.e. lower) end, cooling the substrate and the LED chips. Finally, the lamp cap and heat sink conduct the heat generated at the warm end of the thermoelectric cooler to the ambient (Wang et al., 2009).

Wang et al. (2009) developed a finite element model of LED packaging heat dissipation to evaluate the effectiveness of the thermoelectric cooler. They estimated the junction temperature of the LED array at different powers both with and without the thermoelectric cooler. They found that the thermoelectric cooler and the heat sink could keep the LED junction temperature at 114.6^{o}C when the LED power was 20 W whereas the LED junction temperature would exceed the maximum allowed value of 248^{o}F (120^{o}C) if the thermoelectric cooler was not used. Hence, the thermoelectric cooler and the heat sink could satisfy the heat dissipation needs for the LED array up to a LED power of 20 W (Wang et al., 2009).

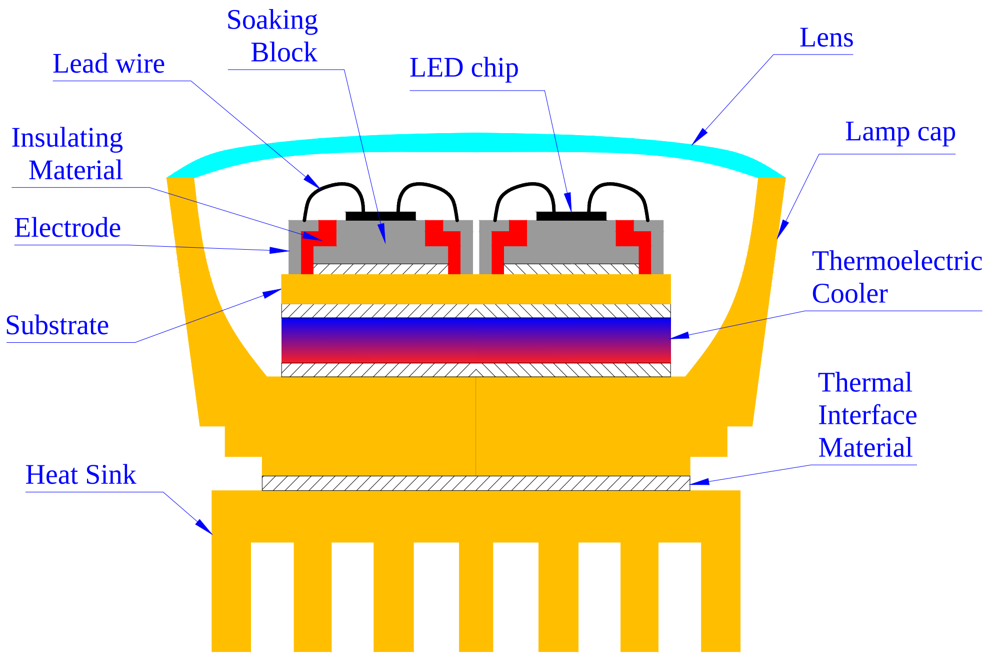

Figure 17. LED packaging with thermoelectric cooler
Redrawn not to scale from Wang et al. (2009)

A.6 SILICON-BASED THERMOELECTRIC COOLER

A thermoelectric device can be a promising solution for thermal management of LEDs (Cheng et al., 2005; Liu et al., 2007). In order to achieve steady temperature conditions in LEDs, thermoelectric devices can be integrated in LED packages owing to its small size and fast response time. A typical thermoelectric device involves two ceramic plates that conduct heat but not electrical current. The ceramic plates are usually made of Al_2O_3 (aluminum oxide). Sometimes, the ceramic plate is contacted with a heat source made of silicon such as the silicon submount of LED that prevents electrostatic discharge. Under such circumstances, the coefficient of thermal expansion of Al_2O_3 does not match with that of silicon. Therefore, it is better to use silicon substrates as the substrates of thermoelectric devices. The use of silicon substrate not only eliminates the problem of coefficient of thermal expansion mismatch, but also improves the cooling performance of the system since the thermal conductivity of silicone is three times greater than that of Al_2O_3. Hence, Liu et al. (2007) investigated a novel thermal management application of high power LED integrated with silicon-based thermoelectric cooler. The schematic diagram of the silicon-based high power LED integrated with micro thermoelectric device is illustrated in Figure 18. Liu et al. (2007) monitored the cooling performance of silicon-based thermoelectric device by means of infrared camera, measured the junction temperatures of the integrated LEDs and observed the luminous efficacy of the LEDs by integrating sphere. The cooling performance measurements showed that the silicon-based thermoelectric device could effectively reduce the LED's temperature. Since the thermoelectric device could lead to effective reductions in LED temperature, it was also observed to increase the luminous flux of the LED. It was also found out that the higher the thermoelectric device input current was, the more the luminous flux of the LED became since higher input current increased the power input of the thermoelectric device. Liu et al. (2007) also compared the luminous efficacy of two LED packages of the same type, one without the thermoelectric device and the other with the thermoelectric device. The results showed that the integration of the silicon-based thermoelectric device to the LED package brought about significant increases of up to 70% in the luminous efficacy compared to no thermoelectric device conditions. What's more, they also observed that the silicon-based thermoelectric device could effectively reduce the junction-to-case thermal resistance of the LED package to zero.

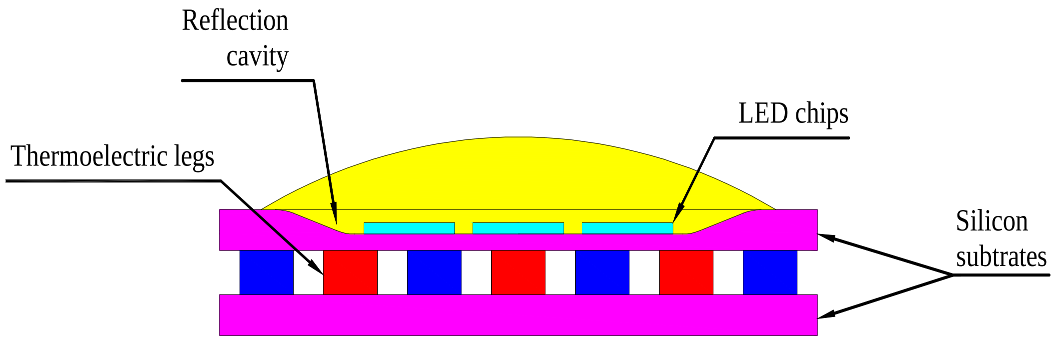

Figure 18. Silicon-based high power LED integrated with micro thermoelectric device
Redrawn not to scale from Liu et al. (2007)

A.7 LOOP HEAT PIPE

According to the requirements of Bureau of Street Lighting (2010), no fans are allowed in the cooling system of LED luminaires. Besides, the design of the heat sink should have a light weight and should not interfere with the industrial design of lighting fixture. Thus, Huang et al. (2008) designed a high-power LED lighting luminaire that had an input power ranging from 36 W to 150 W and that utilized a special heat dissipation technology, i.e. loop heat pipe.

One of the major advantages of the loop heat pipe is that it does not involve a fan. While loop heat pipe was originally developed for aerospace applications, National Taiwan University developed high-power LED lighting fixture with the loop heat pipe to achieve successful thermal management. Figure 19 illustrates the structure of the loop heat pipe used in the high-power LED lighting fixture. The system involves an evaporator attached on the backside of the LED module by means of a heat conduction block. As the heat conduction block absorbs the heat that the LED lighting module generates, the working fluid inside the low heat pipe is evaporated so that it flows through a flexible connecting pipe to the condenser. Subsequently, the vapor is condensed in the condenser and thereby, the condenser dissipates the heat to the ambient. Following this, the capillary effect of the wick inside the evaporator enables the condensed fluid to return to the evaporator through the connecting pipe. Loop heat pipes can potentially transport large amount of heat to a long distance through flexible connecting pipes because high capillary force can be induced by making the wick structure inside the evaporator at micro pores (Huang et al., 2008).

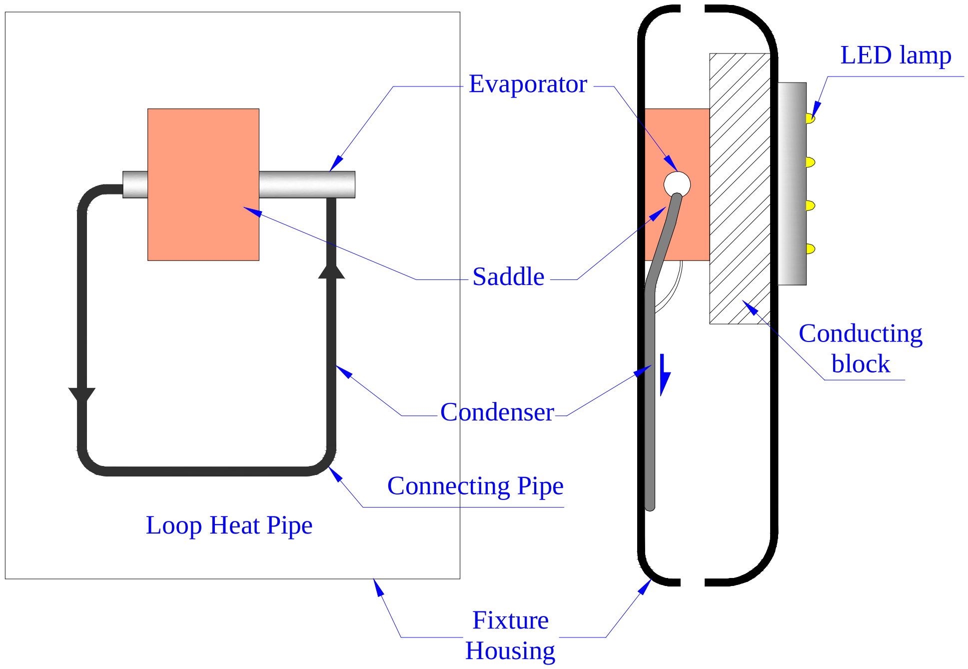

Figure 19. Design of LED lighting fixture using loop heat pipe
Redrawn not to scale from Huang et al. (2008)

For LED lighting fixtures, loop heat pipe can be designed such that the heat is transported to the housing that acts as the heat dissipation surface to the ambient. Thereby, the outlook of the fixture is not altered and light weight structure can be achieved. Although loop heat pipes had high manufacturing cost, cheap mass production of loop heat pipes can be achieved by the patented design and manufacturing process developed by National Taiwan University. The cost of the loop heat pipe is estimated around $10 for 100 W LED. Moreover, by using the loop heat pipe, LED lighting fixtures with input power of 100 W and 150 W can be accomplished with weight ranging from 0.96 kg to 1.57 kg per 1,000 lumen illuminance (Huang et al., 2008).

A.8 LAMP-TYPE VAPOR CHAMBER MODULE

Huang et al. (2009a) conducted experimental investigation of the cooling performance of a lamp-type vapor chamber module in natural convection integrated to a high power LED illumination. Figure 20 illustrates the sectional view of the lamp-type vapor chamber module. The shape of the module is designed as a lamp-holding board so that it cannot only further contribute to LED illumination but also comply with space limitation. Part of the excess heat from the LED chip junction is first conducted to the substrate and then to the lamp-type vapor chamber. Afterwards, it is transferred to the fins where it is eventually released to the immediate environment through natural convection. The rest of the heat is either transferred from the copper side of the lamp-type vapor chamber at the lighting side or directly from the LED chip surface to the surrounding. However, it was estimated that the amount of heat directly released from the LED chip surface to the immediate surrounding was negligible. Huang et al. (2009a) tested the cooling performance of the lamp-type vapor chamber on an LED illumination. Owing to the convenient shape of the lamp-type vapor chamber, Huang et al. (2009a) replaced the original lamp-holding board of the LED illumination with the lamp-type vapor chamber. The lamp-type vapor chamber was made of copper with an outside diameter, inside diameter and height of 45 mm, 30 mm and 32 mm, respectively. On the other hand, the fins were made of aluminum with thickness and pitch of 0.1 mm and 3 mm, respectively. Water vapor was utilized as the working fluid inside the system. The cooling performance of the lamp-type vapor chamber was then compared with that of copper and aluminum spreader plates of the same size. At an input power of 15 W, the temperature at seven different locations on the lighting side of each lamp-type module was measured. According to the results, the maximum temperature on the lighting side of the lamp-type modules was found to be 143.6°F (62°C), 149.5°F (65.3°C) and 152.8°F (67.1°C) for the lamp-type vapor chamber, copper spreader plate and aluminum spreader plate, respectively. Moreover, compared to the copper and aluminum spreader plate, the lamp-type vapor chamber not only led to the lowest temperature distribution, but also brought about more uniform temperature distribution in the system. Hence, it was concluded that the vapor chamber provided superior cooling performance for high power LEDs compared to solid metal spreaders.

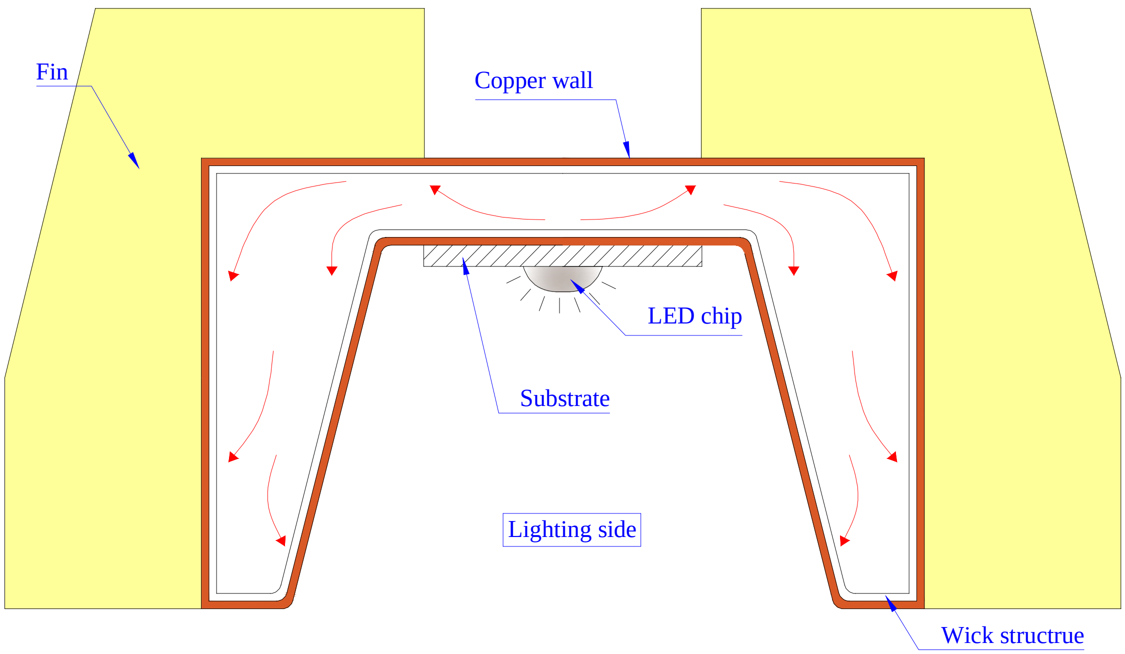

Figure 20. Sectional view of the lamp-type vapor chamber module
Redrawn not to scale from Huang et al. (2009a)

A.9 MINIATURE HEAT PIPE

Li et al. (2009b) proposed the use of a copper/ water miniature heat pipe for the thermal management of a LED packaging structure that consisted of nine 1.2-W LED chips. Figure 21 shows the structure of the miniature heat pipe that consists of evaporator and condenser. An adiabatic can optionally be situated between the evaporator and the condenser.

The miniature heat pipe, a copper block and fins makes up the whole structure of the heat transfer equipment. The LED package is situated on the copper block so that the copper block transmitted the heat flux from the LED package to the evaporator of the miniature heat pipe. As the heat flux of the LED package flows into the evaporator, the liquid (i.e. water) evaporates because of the heat. Following this, the vapor flows towards the condenser where it condenses and releases the heat to the ambient through convection. After the vapor condenses, the wick structures provide capillary pumping that enables the liquid to flow back to the evaporator, completing one cycle of circulation within the miniature heat pipe (Li et al., 2009b).

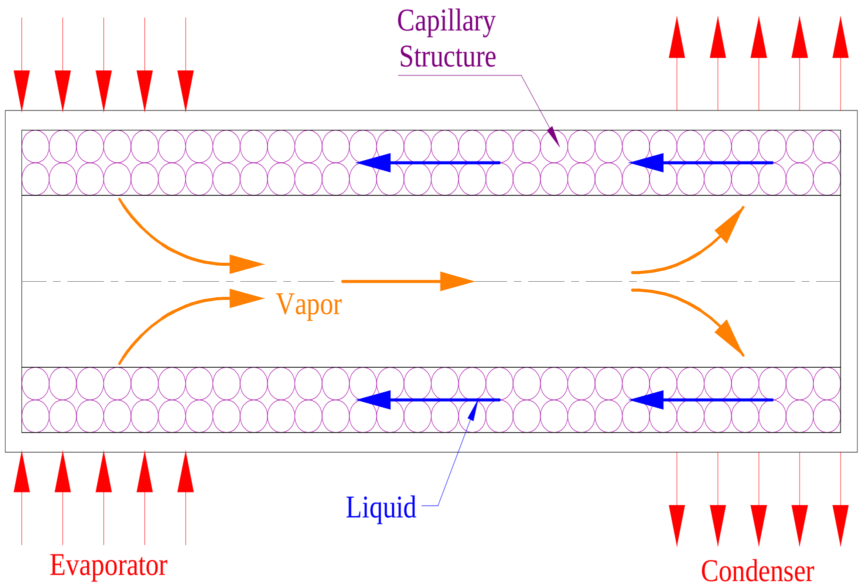

Figure 21. Miniature heat pipe
Redrawn not to scale from Li et al. (2009b)

Li et al. (2009b) employed numerical heat flow models to investigate the effectiveness of the miniature heat pipe in reducing the junction temperature of the high-power LED package. By using Icepak, the professional software to analyze the temperature field of electronics, Li et al. (2009b) found that the miniature heat pipe could keep the LED junction temperature under 70^{o}C, which is significantly lower than the maximum allowed temperature of 120^{o}C. Moreover, Li et al. (2009b) also optimized the height, thickness and the number of fins of the heat sink and estimated the maximum LED junction temperature under the optimized structure of the miniature heat pipe. By using Icepak, they found that the optimized structure of the miniature heat pipe would lead to a maximum junction temperature of 134.1^{o}F (56.7^{o}C), which indicated the potential effectiveness of the system.

APPENDIX B: SOME ACTIVE COOLING TECHNIQUES FOR HIGH-POWER LEDS

B.1 MICROJET-BASED COOLING SYSTEM

Luo and Liu (2007) proposed a microjet-based cooling system for the thermal management of high-power LEDs. The system consists of three parts as shown in Figure 22: a microjet array device, a small heat exchanger with a fan and a micropump. There is a recycling fluid in the closed system, and the micropump drives it into the microjet array device through an inlet as illustrated in Figure 22. There, the heat generated by the LED is conveyed to the recycling fluid, and then the heated fluid enters the heat exchanger to be cooled. Thereby, the heat generated by the LED is dissipated into the external environment. The micropump delivers the cooled recycling fluid again into the microjet device, which completes one operation cycle of the system. Luo and Liu (2007) designed a microjet array device for a 220-W LED lamp that had 64 high power LED chips. The microjet array device consumed 3.6 W and 2.2 W power for the fan and the micropump, respectively. By testing the cooling ability of the microjet array device on the 220-W LED lamp, Luo and Liu (2007) found that the system kept the temperature of the LED chip substrate at 156.9^{o}F (69.4^{o}C) when the room temperature was 30.8^{o}C. Likewise, Luo et al. (2008a) conducted preliminary experiments to check the feasibility of the microjet cooling system prior to its optimization. They found that while the steady-state surface temperature of a 2-by-2 LED array with an input power of 16.4 W was 234.0^{o}F (112.2^{o}C) without the cooling system, the micro-jet cooling system reduced the surface temperature of the LED array from 234.0^{o}F (112.2^{o}C) to 111.6^{o}F 44.2^{o}C after 10 minutes of operation. Luo and Liu (2007) also carried out a numerical study to explore the effects of microjet diameter, micropump flow rate and jet device material on cooling performance. They found that the cooling performance of the system as significantly affected by the microjet diameter, and an optimum microjet diameter existed, which was found to be 1.0 mm for the system they designed for the 220-W LED.

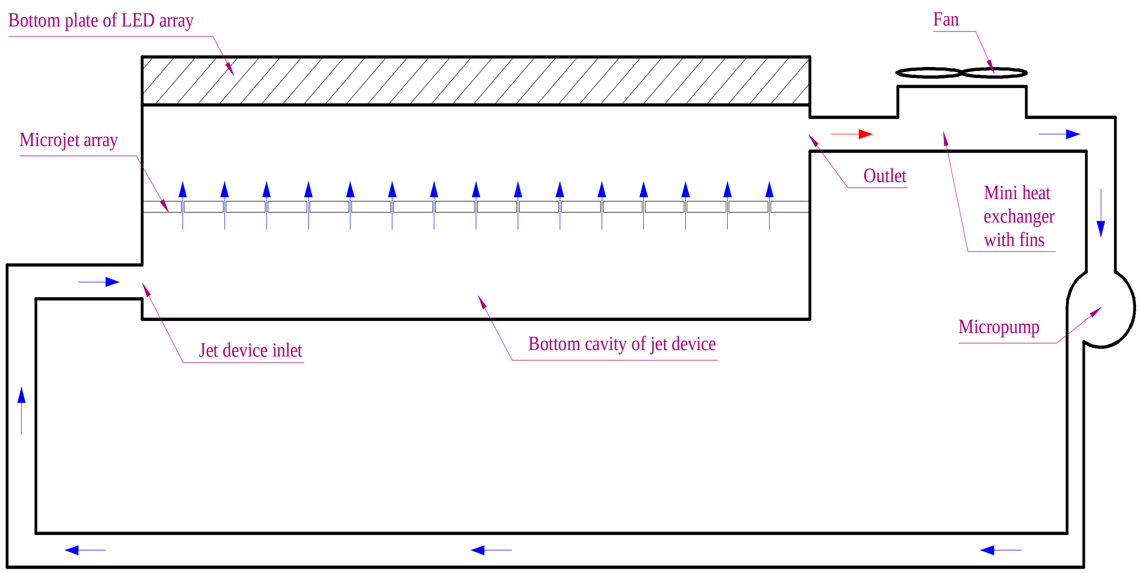

Figure 22. Closed-loop microjet array cooling system
(Redrawn not to scale from Luo and Liu (2007)

Afterward, Liu et al. (2008) conducted numerical simulations to further investigate the thermal characteristics of the 220-W LED integrated with the microjet cooling system. They compared the temperature and flow distribution in three kinds of microjet structures to find the optimum microjet structure. The first microjet structure consisted of 8x8 microjets, each with a diameter of 1.0 mm, and had single inlet and outlet, both with a diameter of 4.0 mm. On the other hand, unlike the first microjet structure which had cuboids type of impinging jet cavity and bottom cavity, the second microjet structure involved cylindrical impinging jet cavity and bottom cavity was cylindrical with a height of 5.0 mm, so it was able to house 88 microjets instead of 64. The third microjet structure had also cuboids impinging jet cavity and bottom cavity that contained of 8x8 microjects, each with a diameter of 1.0 mm. Contrary to the first microjet structure which had single inlet and outlet, the third microjet had one inlet but two outlets, all with a diameter of 4.0 mm. Comparison of the maximum LED substrate temperatures in three microjet structures showed that the optimum microjet structure was the third one which had single inlet and two outlets. The optimum microjet structure led to a maximum LED substrate temperature of 138.0^{o}F (58.9^{o}C), which was 41.4^{o}F (23^{o}C) lower than the maximum LED substrate temperature achieved by the other microjet structures. The improvements in the thermal management of the 220-W LED induced by the third microjet structure were attributed to the more uniform flow distribution in the system.

B.2 SYNTHETIC JET APPROACH

The use of synthetic jets can generate a turbulent pulsating flow of air which can provide more efficient and effective cooling of LEDs compared to conventional fans. Nuventix Inc. implemented synthetic jets in SynJet modules that use an oscillating diaphragm mounted within a cavity with precision-molded nozzles. The diaphragm is oscillated by an electromagnetic driver so that surrounding air is pulled into the housing and then expelled in a directed, unsteady, turbulent fashion. The mixing of the thermal boundary layer and the global secondary flow are enhanced by the turbulent nature of the air jets, which leads to a much higher heat transfer coefficient in comparison with typical laminar airflow. Thereby, high power LEDs can be cooled with less work (Wilcox, 2008).

Another advantage of synthetic jets is that they generate significantly less noise than conventional fans because they require less airflow to cool the same heat load. Unlike conventional fans, synthetic jets do not involve bearings, brushes, or other types of frictional parts so that they do not bring about acoustic problems due to the wearing of those parts. Moreover, the fact that synthetic jets do not have motors or bearings that can malfunction or wear out increases their reliability. Hence, cooling down LEDs can be achieved through the use of synthetic jets with near-silent acoustic levels and improved reliability (Wilcox, 2008).

B.3 MINIATURE PIEZOELECTRIC FANS

Owing to their low power consumption, nominal noise emission, and configurable dimensions, piezoelectric fans may be a practical solution for the cooling of LEDs. Although conventional heat removal methods such as rotational fans may also be thermally viable, the minimal space, power and noise requirements of piezoelectric fans make them advantageous compared to traditional rotational fans (Açıkalın et al., 2004). The fabrication of piezoelectric fans is achieved either by bonding one or more piezoelectric patches to a shim material or by using the patch material itself without a shim material. When alternating voltage is applied to the electrodes of the piezoelectric patch, alternate expansion and contraction of the piezoelectric patch occurs at the same frequency as the input signal. If the piezoelectric patch is attached to a shim material, the shim material flaps back and forth similar to a hand-held fan, though at a considerably higher frequency. Piezoelectric fans are generally driven at the frequency of resonance so that higher tip deflections of the piezoelectric patches are achieved at lower power consumption. Moreover, the design of the piezoelectric fans are accomplished such that the resonance frequency is not within the range of frequencies audible to human ear; i.e. less than 25 dB or 100 Hz (Açıkalın et al., 2004).

Açıkalın et al. (2004) investigated the applicability of piezoelectric fans in the thermal management of high power LED packages. By considering different experimental configurations of piezoelectric fans, they analyzed the effects of various design parameters of piezoelectric fans such as fan amplitude, fan length, the distance between the fan and the heat source, and the fan frequency offset from resonance. The three different types of experimental configurations that Açıkalın et al. (2004) analyzed are illustrated in Figure 23. According to the results of their analyses, they found that the fan frequency offset from resonance was the most critical parameters affecting the thermal performance. The cooling capacity of the piezoelectric fan was observed to decrease as the fan frequency deviated further from the resonance frequency because operating the piezoelectric fan further away from the resonance frequency reduced its amplitude, which in turn brought about less airflow. For instance, a 5% deviation of the operating frequency from the resonance frequency was found to decrease the cooling capacity of the fan by 18^{o}F (10^{o}C) provided that the other design parameters were at their optimal values. The cooling capacity of the piezoelectric fan was also found to decrease either when the fan was moved further away from the heat source or when the fan length was increased. Moreover, while the average heat source temperature was measured to be 159.1^{o}F (70.6^{o}C) in natural convection conditions only, the piezoelectric configuration shown in Figure 23a led to the maximum temperature reduction of 97.5^{o}F (36.4^{o}C) compared to natural convection conditions only. This maximum temperature reduction was achieved when the fan frequency was equal to the resonance frequency, fan length was 6.86 cm (2.70 in.), and the fan-to-heat source distance was 0.64 cm (0.25 in.). Hence, it was demonstrated by Açıkalın et al. (2004) that piezoelectric fans can provide a viable solution to the thermal management of high power LEDs.

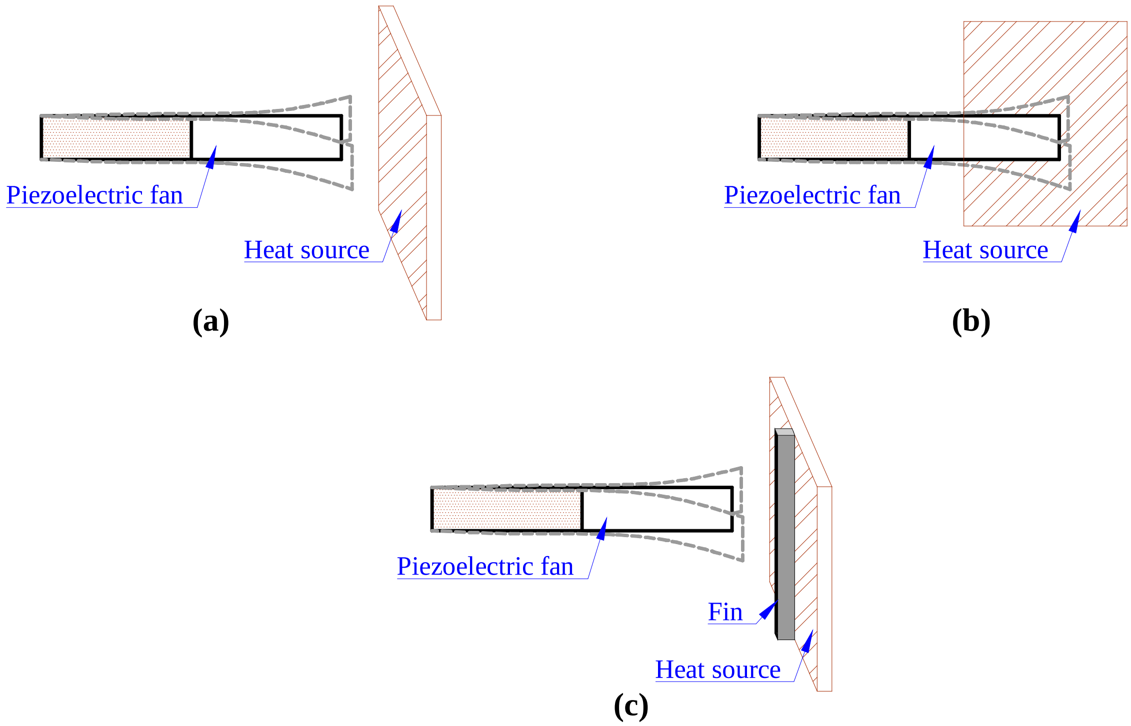

Figure 23. Different experimental orientations of the piezoelectric fan (a) Fan in front of the heat source, (b) Fan to the side of the heat source, (c) Fan in front of the heat source with fin.
Redrawn not to scale from Açıkalın et al. (2004)

B.4 MICROCHANNEL COOLER

Microchannel cooler is a relatively new cooling technology for the thermal management of high power LEDs. Yuan et al. (2007) conducted thermal analysis of a high power 5x5 5-W LED array that was integrated with a silicon microchannel cooling system as shown in

Figure 24. The high power LED chips were mounted on Pyrex glass which was bonded to the silicon microchannel. The excess heat emitted by the LED chips is transferred into a recycling fluid (water) driven by the micropump inside the micro-cooling system. The excess heat is then released to the immediate environment by means of the recycling fluid. The cross sectional view of the LED array module with the microchannel cooling system is illustrated in Figure 25.

Yuan et al. (2007) carried out thermal simulation of the 5x5 LED array integrated with the microchannel cooling system. They first simulated the system assuming the microchannel cooling system had straight fins with uniform spacing along the direction of the flow of the recycling fluid. Although the design successfully kept the maximum LED die temperature at or below 102.6^{o}F (39.2^{o}C), the design led to non-uniform temperature distribution in the LED array. The minimum LED die temperature in the LED array was 96.1^{o}F (35.6^{o}C), which differed by 6.5^{o}F (3.6^{o}C) from the maximum measured temperature of 102.6^{o}F (39.2^{o}C). In the transverse direction of the LED array relative to the flow of the recycling fluid, the centrally located LEDs had higher temperature whereas in the “stream” direction, the “upstream” LEDs in the LED array were observed to have higher temperatures. In order to make the temperature distribution more uniform, Yuan et al. (2007) designed staggered fins with decreasing hydraulic diameter of the channels towards the center. Average LED die temperature decreases with decreasing hydraulic diameter because it increases heat dissipation area. Hence, the staggered design of the fins significantly improved the uniformity of the LED die temperature distribution with the minimum and maximum LED die temperatures equal to 96.8°F (36.0°C) and 100.0°F (37.8°C), respectively. Hence, the microchannel cooling system may be a promising solution for thermal management of high power LED arrays.

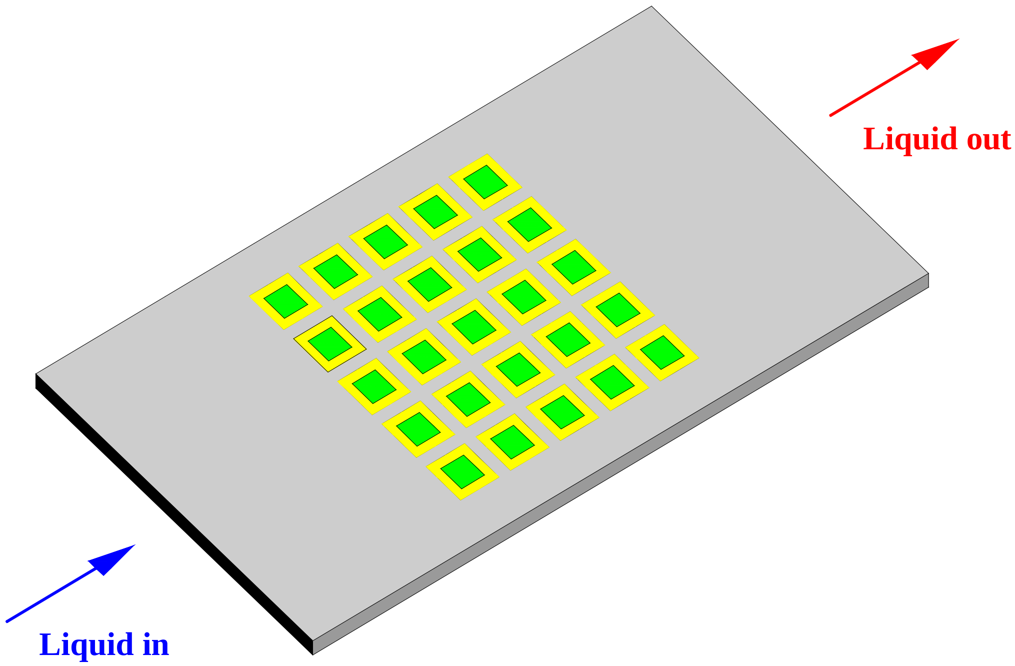

Figure 24. Integrated microchannel cooling of a 5x5 LEDs array module
Redrawn not to scale from Yuan et al. (2007)

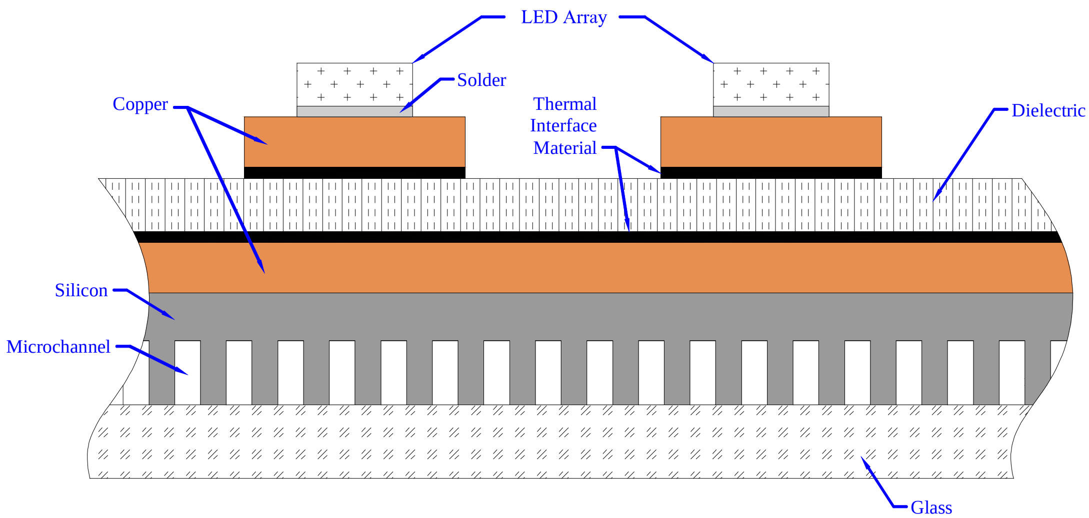

Figure 25. Cross sectional view of the LED module integrated with microchannel cooler
Redrawn not to scale from Yuan et al. (2007)

APPENDIX C: GENERAL SPECIFICATIONS FOR SOLID STATE LIGHTING LED ROADWAY LUMINAIRES

This Appendix summarizes some of the general specifications for LED roadway luminaires established by the Bureau of Street Lighting, City of Los Angeles. The reader may refer to Bureau of Street Lighting (2010; 2011) for detailed specifications.

C.1 LUMINAIRE REQUIREMENTS

According to Bureau of Street Lighting (2010; 2011), some of the requirements regarding LED luminaires are as follows:

- Excluding the optional monitoring/ control device, the power consumption of the LED luminaire shall not exceed 58 W, 85 W, and 145 W for equivalent replacement of 70 W HPS, 100 W HPS, and 200 W HPS, respectively.
- Including photoelectric (PE) or remote control devices, the off-state power draw of the LED luminaire shall not exceed 2.50 W.
- LED luminaires that have equivalent replacement for 70 W and 100 W HPS shall not weigh more than 22 pounds. LED luminaires that have equivalent replacement for 200 W HPS shall not weigh more than 24 pounds.
- Approximate dimensions for LED luminaires are (30” long) x (16” wide) x (7” tall) for equivalent replacement of 70 W and 100 W HPS; and (32” long) x (15” wide) x (7” tall) for equivalent replacement of 200 W HPS.
- LED luminaires must be provided with a warranty for the full replacement of the luminaire due to any failure for six years. For a minimum of eight years from the date of purchase, the warranty shall cover the repair or replacement of defective electrical parts (including light source and power supplies/ drivers).
- An IESNA luminaire classification of TM-15: B2 U2 G2 is used.
- The luminaires shall mount on a horizontal tenon with 2.375” outside diameter. No more than four 9/16-in. hex bolts and two-piece clamp shall be used. The two-piece clamp shall have vertical tilt adjustment range of ±5%.
- Luminaires shall contain a 3-prong twist-lock photo-control receptacle compliant with ANSI C136.10. The photoelectric (PE) socket needs to be rotatable to be able to position the PE window in the North direction.

C.2 HOUSING REQUIREMENTS

According to Bureau of Street Lighting (2010; 2011), the housing requirements for LED modules/ arrays are as follows:

- The housing shall be primarily made of metal.
- The housing finish shall be rust resistant and powder coated. It shall also be gray in color.
- A replaceable driver must be mounted internally and it must be accessible without tools.
- All screws shall be made of stainless steel.
- Any components that need maintenance after installation need captive screws on them.
- Polycarbonate shall not be used on any parts excluding those that are UV stabilized.
- The minimum rating for ingress protection shall be IP54.
- The house shield shall provide an option for house side light control.

C.3 LED MODULE/ ARRAY REQUIREMENTS

According to Bureau of Street Lighting (2010; 2011), the requirements regarding LED modules/ arrays are as follows:

- At least 70% of the initial lumens at installation shall be delivered by LED module(s)/ array(s) for a minimum of 50,000 hours.
- The assembly shall have a minimum rating of IP66.
- LED module(s)/ array(s) should have a light distribution in accordance with IESNA Type II Lighting Distribution (either designated with 2X or not) for equivalent replacement of 70 W and 100 W HPS.
- LED module(s)/ array(s) should have a light distribution in accordance with IESNA Type III Medium Lighting Distribution for equivalent replacement of 200 W HPS.

C.4 ROADWAY APPLICATION REQUIREMENTS

According to Bureau of Street Lighting (2010; 2011), the requirements regarding LED roadway applications are as follows:

- LED luminaires shall initially deliver a minimum of 3,100 lumens, 3,700 lumens, and 7,880 lumens for equivalent replacement of 70 W HPS, 100 W HPS, and 200 W HPS, respectively.
- The luminaire efficacy of LED luminaires is defined as the luminaire light output (including fixture efficiency and thermal effects) divided by the luminaire input power.
- LED luminaires shall have a minimum luminaire efficacy of 50 lumens per watt for equivalent replacement of 70 W HPS, 100 W HPS; and 57 lumens per watt for equivalent replacement of 200 W HPS.

C.5 POWER SUPPLY/ DRIVER REQUIREMENTS

According to Bureau of Street Lighting (2010; 2011), the requirements regarding LED power supplies/ drivers are as follows:

- The minimum power factor of the power supply should be 0.90.
- At an ambient temperature of 25^{o}C, maximum rating DC forward current should be 1000 mA.
- Maximum amperage at LED must not exceed 700 mA per mm2 of chip. 525 mA shall be the standard factory setting as delivered from the factory.
- Maximum amperage at LED must not exceed the driver current to meet the light output requirements.
- The design of the driver and LED arrays shall include multi-current input operation, with switchable ratings at 350 mA, 525 mA, and 700 mA.
- The operating temperature of the power supply shall be between -20^{o}C and 50^{o}C.
- In order to avoid visible flicker, the output operating frequency must be at least 120 Hz, and an input operating frequency of 60 Hz.
- There should be transient protection per IEEE C.62.41-2-2002, Class A operation. The line transient shall contain seven strikes of a 100k HZ ring wave, 10 kV level, for both common mode and differential mode. It should also meet the test procedure described in IEE C62.45.
- Power supplies shall meet consumer emission limits as described in FCC 47 CFR Part 15/18.

- To provide noise and ingress protection, the power supply shall have a Class A sound rating per ANSI Standard C63.4. The assembly of compartment shall have a minimum rating of IP54.

C.6 HEAT MANAGEMENT REQUIREMENTS

According to Bureau of Street Lighting (2010; 2011), the requirements regarding the heat management of LED luminaires are as follows:

- The cooling system of LED heat sinks shall contain a heat sink without any fans, pumps, or liquids
- The cooling system shall be resistant to debris buildup that does not cause degradation in its heat dissipation performance
- LED luminaires shall be able to operate in the temperature range of -20^{o}C to 50^{o}C

C.7 COLOR SHIFT REQUIREMENTS

According to Bureau of Street Lighting (2010; 2011), the color shift requirements of LED luminaires are as follows:

- LED luminaires shall have a nominal correlated color temperature of 4,300K ± 300K
- LED luminaires shall have a minimum color rendering index of 65

APPENDIX D: TEST PROCEDURES FOR PHOTOMETRIC MEASUREMENTS OF ROADWAY LIGHTING INSTALLATIONS

D.1 TESTING CONDITIONS

Because field photometry involves significantly higher variability than laboratory measurements, it is necessary to report the following factors which may influence the results (IESNA LM-50-99):

- Supply voltage,
- Lamp wattage,
- Lamp burning position,
- Ballast/ lamp factors,
- Mounting height,
- Overhang,
- Tilt,
- Pavement conditions,
- Weather conditions.

All luminaires should be clean and the lamps should be new and seasoned. However, if the test purpose is to check the performance of the roadway lighting installation after depreciation in service, the existing conditions of the luminaires and lamps should be recorded. Prior to taking any measurements, it is necessary to operate discharge lamps for at least one hour in order for them to reach normal operating conditions.

Since lamp luminous flux is affected by electrical circuit operating conditions, voltage, current and wattage should be measured at individual lamp sockets if possible. Thereby, whether the lamps operate in line with rated circuit conditions can be determined. Once they are recorded, it suffices to periodically measure the line voltage to the ballast for monitoring purposes.

The atmosphere should be clear and extraneous light should be at a minimum when tests are performed. Otherwise, the results of roadway lighting can be affected by extraneous light. Snow and wet pavement can also lead to reflections that can cause considerable errors, so tests should not be conducted if there is snow on the ground or if the pavement is wet. The location of nearby foliage and tree canopies should also be noted.

The starting time for the tests should be subsequent to civil twilight and earlier than moonrise. If tests are conducted after moonrise, the moon cycle and moonrise/ moonset times should be recorded.

The personnel in charge of conducting the test should avoid casting shadows on the measuring instrument detector. It is recommended that the personnel avoid wearing light colored clothing in order to not supplement the readings on the detector by reflected light (IESNA LM-50-99).

D.2 TEST EQUIPMENT

It is recommended that measuring instruments with self-luminous readouts be used since it may be difficult to read analog instruments and LCDs under low illuminance. Photometers capable of performing horizontal illuminance measurements should be used if the illuminance on the pavement is to be measured. Commercially available photometers that can be positioned without being shadowed by the user and that can be shaded from extraneous light should be preferred. Such photometers can measure illumination within ± 5 percent error.

Color-correction of the photometer should be made in accordance with the CIE Spectral Luminous Efficacy Curve. If a temperature-sensitive photometer is used, temperature-correction should be made appropriately. For local luminance measurements, the luminance meter should not have a field of view greater than two minutes of arc; otherwise, differences may not be detected to accurately determine uniformity.

It is recommended that luminaire supply voltage be monitored with the use of recording voltmeters so that if extreme fluctuations in voltage occur, photometric readings are synchronized with normal supply voltage (IESNA LM-50-99).

D.3 ILLUMINANCE MEASUREMENTS

The roadway should be marked off in transverse and longitudinal lines as shown in Figure 26. According to the mark-off pattern indicated in Figure 26 (IESNA LM-50-99):

- There should be a minimum of three luminaire cycles beyond the test area and one cycle in front of the test area,
- The transverse points should be at the two quarter-points of each lane,
- There should be a minimum of 10 longitudinal points located at equal spacing along each luminaire cycle,
- The maximum spacing between two neighboring longitudinal points should be 16.5 ft. (5.0 m).

At each grid point, horizontal illuminance readings are taken in order to compute system characteristics such as:

- Average illuminance,
- Maximum illuminance,
- Minimum illuminance,
- System ratio, etc.

The detector should not be held higher than 6.0 in. (15.0 cm) above the pavement surface. Moreover, additional measurements can be taken at special points such as on the centerline, along the curb line, immediately under luminaires where maximum illuminance is usually anticipated or halfway between luminaires where minimum illuminance is generally expected. If the principal source of light is incident at angles greater than 70 degrees, leveling the photometric detector should be done with special care (IESNA LM-50-99).

D.4 LUMINANCE MEASUREMENTS

In order to make luminance measurements, an observer should move with points parallel to the roadway while keeping a detector height of 4.6 ft. (1.4 m) and a line of sight of 1.0 degree down over a longitudinal distance of 274 ft. (83 m). Any point on the road surface should be able to be checked by an operator so that it can be compared with calculated results. Horizontal illumination measurements should be achieved if large differences between the calculated results and measured luminance values are observed (IESNA LM-50-99).

D.5 TEST REPORT CONTENT

The following items shall be included in the test report (IESNA LM-50-99):

- Location of the roadway,
- Date and time of the measurement,
- Detailed information about the lighting equipment and installation such as lamp and ballast type,
- Mounting height, luminaire spacing and arrangement and special conditions such as extraneous light sources,
- A diagram indicating test stations and dimensions,
- Electrical operating conditions,
- Condition of luminaires and other equipment,
- Weather and sky conditions,
- Temperature,
- Tabulated test data,
- Special measurements if recorded,
- Ratio of maximum and minimum-to-average illuminance and/ or luminance,
- Ratio of maximum-to-minimum illuminance and/ or luminance along longitudinal roadway lines,
- Description of measurement instruments such as manufacturer's name and model number,
- Position of instrument detector and light source,
- Names of test personnel.

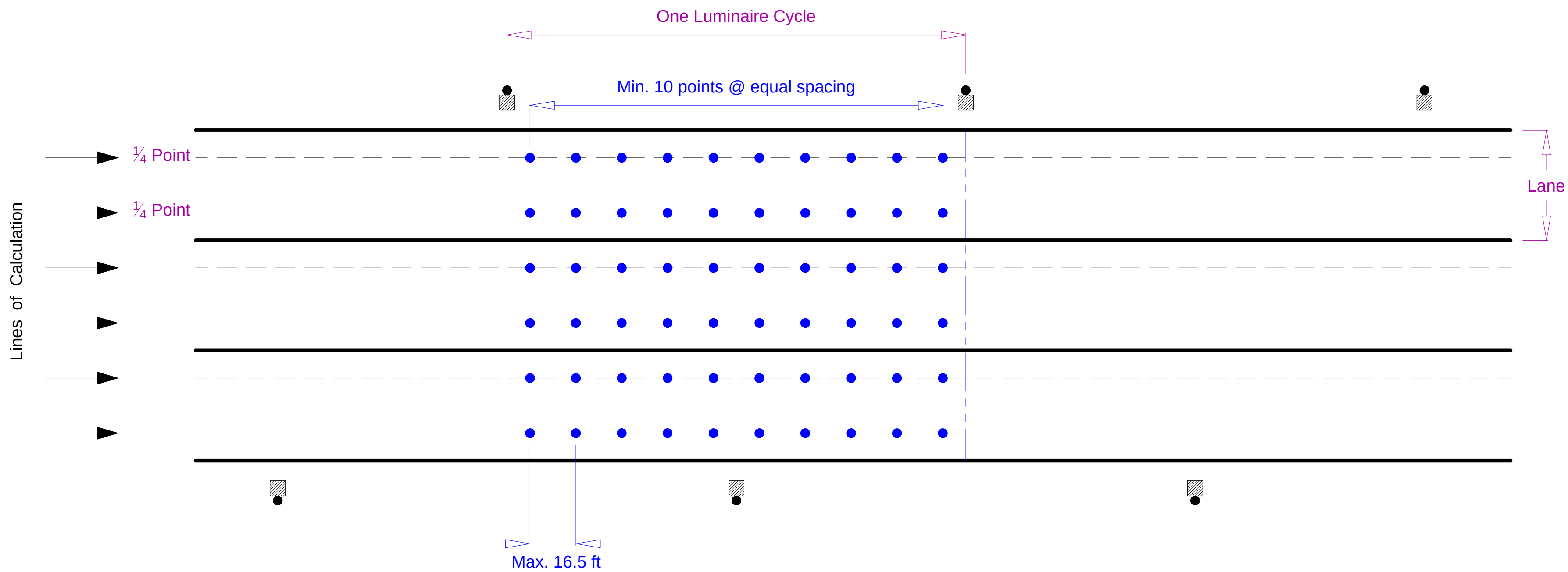

Figure 26. Test point locations for measuring illuminance and luminance on roadway
(*Redrawn from* IESNA LM-50-99)

APPENDIX E: TEST PROCEDURES FOR MEASURING LUMEN MAINTENANCE OF LED LIGHT SOURCES

E.1 AMBIENT AND PHYSICAL CONDITIONS

Prior to life testing, light sources shall be cleaned in order to eliminate handling marks. Manufacturer's instructions such as electro-static discharge shall also be observed. In order to track individual LED light sources, sample units can be marked by using appropriate marking methods such as ceramic ink marking, durable bar coding or high temperature markers. Because sampling method and sample size affect the value of the test, both of them shall be reported.

During life testing, excessive vibration of the light sources should be avoided. Between photometric measurements, LED light sources shall be operated at a minimum of three different case temperatures and at the same drive current. The first two case temperatures are 131^{o}F (55^{o}C) and 185^{o}F (85^{o}C) whereas the third case temperature as well as the drive current are selected by the manufacturer depending on the customer applications. During life testing, case temperatures shall be controlled to 28.4^{o}F (-2^{o}C) while the surrounding air temperature should be maintained to within 23.0^{o}F (-5^{o}C) of the case temperature. Within the test chamber, the surrounding air temperature should be monitored and the humidity shall be kept below 65% relative humidity. Although some air movement is required against thermal stratification, airflow should be kept at the minimum level to provide proper starting and operation of the light source. Even though solid-state light sources like LEDs are not affected by light source orientation, appropriate operating orientation should be specified by the manufacturer to minimize the effects of convention airflow caused by heat-sinks and thermal management (IESNA LM-80-08).

E.2 ELECTRICAL AND THERMAL CONDITIONS

The rated input voltage and driver frequency should be applied during life testing. When direct current is used, ripple voltage should not be greater than 2% of the direct current output voltage. It is recommended that the drive current be set at the value used to determine the manufacturer's literature rating of luminous flux. The power supply shall have a voltage wavelength with total harmonic distortion not greater than 3% of the fundamental. Since LEDs are intended to be tested at the same current as during realistic operation, monitoring and regulation of the input current shall be achieved within ±3% and ±0.5% of the rated input voltage during life testing and during photometric measurements, respectively. Monitoring of the case temperature shall also be achieved during life testing. Case temperature measurement is made on the component at the point designated by the manufacturer (IESNA LM-80-08).

E.3 TEST AND MEASUREMENT PROCEDURES

During life testing, elapsed operating time of the life source shall be accurately recorded. Current monitoring, video monitoring, elapsed time meter or other means can be used to record the elapsed operating time on condition that they provide sufficient temporal accuracy. If an elapsed time meter is used, time shall be accumulated only when the LED light sources are energized. Time shall not be accumulated in case of a power failure. The uncertainty in total elapsed operating time should be within ±0.5%.

Luminous flux measurement shall be made at the same drive current as used during life testing. Chromaticity values shall also be measured because of the importance of the color stability over life. Use of a spectroradiometer is strongly recommended for determining photometric and colorimetric values from total spectral radiant flux measurements. During lumen and chromaticity measurements, the ambient temperature shall be set to 25°C ± 2°C. Before measurement, the LED light source shall be allowed to cool to room temperature (IESNA LM-80-08).

E.4 LUMEN MAINTENANCE TESTING METHOD FOR LED LIGHT SOURCES

The sample unit shall be operated for at least 6,000 hours at the specified ambient temperature. Data collection shall be performed at a minimum of every 1,000 hours. Contrary to some other light sources whose lifetime and performance are adversely affected by power cycling, lifetime of 100%-modulated LEDs can still be slightly affected. Nevertheless, constant current shall be applied in driving the devices and modules.

Moreover, LED light sources shall be checked against failure at a minimum of every measurement interval. If failure is observed, it shall also be made certain that the failure does not stem from improper functioning of the electrical connections or auxiliary equipment and it is rather an actual LED light source failure. The chromaticity shift shall also be measured at each photometric test interval (IESNA LM-80-08).

E.5 TEST REPORT CONTENT

The following items shall be included in the test report (IESNA LM-80-08):

- Number of LED light sources tested,
  - Description of LED light sources and auxiliary equipment,
  - Operating cycle,
  - Airflow conditions, temperature and relative humidity,
  - Case (test point) temperature,
  - Drive current of the LED light source during life testing,
  - Initial luminous flux and forward voltage at photometric measurement current,
  - Lumen maintenance for each LED light source,
  - Standard deviation, median value, minimum value and maximum value of lumen maintenance for all sample units,
  - Failure conditions and time of failure if observed,
  - Monitoring interval for the LED light source,
  - Percent uncertainty in photometric measurement,
  - Chromaticity shift over the measurement time.