ASSIST *recommends...*

Recommendations for Testing and Evaluating White LED Light Engines and Integrated LED Lamps Used in Decorative Lighting Luminaires

Volume 4, Issue 1
May 2008
Revised April 2009

A publication of the Alliance for Solid-State Illumination Systems and Technologies

Lighting Research Center

Rensselaer

Published by the Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, New York, USA. Online at http://www.lrc.rpi.edu.

This *ASSIST recommends* was prepared by the Lighting Research Center at the request of the Alliance for Solid-State Illumination Systems and Technologies (ASSIST). The recommendations set forth here are developed by consensus of ASSIST sponsors and the Lighting Research Center. ASSIST and the Lighting Research Center may update these recommendations as new research, technologies, and methods become available.

Check for new and updated *ASSIST recommends* documents at:
http://www.lrc.rpi.edu/programs/solidstate/assist/recommends.asp

ASSIST Sponsors

Acuity Brands Lighting
Bridgelux
China Solid State Lighting Alliance
Cree
Everlight Electronics Co., Ltd.
Federal Aviation Administration
GE Lumination
ITRI, Industrial Technology Research Institute
The Lighting Association (UK)
Lighting Science Group
Lite-On
NeoPac Lighting
New York State Energy Research and Development Authority
OSRAM SYLVANIA/OSRAM Opto Semiconductors
Permlight
Philips Color Kinetics
Seoul Semiconductor
United States Environmental Protection Agency
USG
WAC Lighting

Lighting Research Center Technical Staff *(in alphabetical order)*

Jean Paul Freyssinier, Lalith Jayasinghe, Nadarajah Narendran, and Jennifer Taylor

Contents

Document Revision History

Summarized below are the major changes made to this *ASSIST recommends* document during each revision. The most recent revision supersedes all previous versions.

April 2009 revision

This revision deletes previously recommended testing for the "worst-case scenario" application use. It also updates the definition of *LED lamp, integrated* to match the definition listed in the Illuminating Engineering Society's most recent (May 2008) addendum of RP-16-05, *Nomenclature and Definitions for Illuminating Engineering*.

Introduction

This document outlines a recommendation for testing and evaluating the performance of white light *LED light engines* and *integrated LED lamps* used in decorative lighting luminaires.

> **Note:** This is not a test method for evaluating complete lighting luminaires or for LED light engines or integrated LED lamps used in directional or functional lighting luminaires.[1] For example, LED light engines or integrated lamps that take the form of common reflector lamp formats (i.e., R, PAR, and MR types) should be tested using the methodology for directional lighting luminaires.

The performance (e.g., luminous flux, life) of LEDs depends heavily on the temperature at the LED junction, and this temperature can vary depending on how the LED is integrated into the luminaire and the installation environment. Given that LED light engines and integrated LED lamps can be used in many different types of decorative lighting luminaires, and because it is not feasible to test the performance of the complete decorative luminaire for every case, a method is proposed here to estimate the performance of LED light engines and integrated LED lamps when used in decorative luminaires.

The intent of this document is to encourage common, consistent methods of testing and data presentation for ease of interpretation and comparison, which will assist luminaire manufacturers in selecting suitable LED light engines and integrated LED lamps for their family of products. The target audience for this document is LED light engine and integrated LED lamp manufacturers and the users of LED light engines and integrated LED lamps, primarily manufacturers of decorative luminaires.

This recommendation was developed by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute in collaboration with members of the Alliance for Solid-State Illumination Systems and Technologies (ASSIST).

Definitions

LED light engine and LED lamp, integrated

Addendum a of Illuminating Engineering Society publication RP-16-05, *Nomenclature and Definitions for Illuminating Engineering* (IESNA 2008), provides definitions for different solid-state lighting devices and components. The definition of *LED lamp, integrated* is one presently used by IES, while the definition of *LED light engine* is one proposed by IES in the March 2008 draft version of this publication, though not presently in use:

> *6.8.5.5. LED lamp, integrated* – A lamp with LEDs, an integrated LED driver, and an ANSI standardized base that is designed to connect to the branch circuit via an ANSI standardized lampholder/socket.

---

[1] Test methods have been developed specifically for functional and directional lighting luminaires. See references below for more information.

Alliance for Solid-State Illumination Systems and Technologies (ASSIST). 2005. *ASSIST recommends: LED Life for General Lighting*. Available: http://www.lrc.rpi.edu/programs/solidstate/assist/ledlife.asp.

---. 2007. *ASSIST recommends: Recommendations for Testing and Evaluating Luminaires Used in Directional Lighting*. Available: http://www.lrc.rpi.edu/programs/solidstate/assist/directional.asp.

---. 2007. *ASSIST recommends: Recommendations for Testing and Evaluating Under-cabinet Luminaires.* Available: http://www.lrc.rpi.edu/programs/solidstate/assist/undercabinet.asp.

6.8.5.6. LED light engine (proposed) – A subsystem of an LED luminaire that includes one or more LED packages, or an LED array, or an LED module; and LED driver; electrical and mechanical interfaces; and an integral heat sink to provide thermal dissipation. An LED light engine may be designed to accept additional components that provide aesthetic, optical, and environmental control (other than thermal dissipation). An LED light engine is designed to connect to the branch circuit. An LED light engine with standardized base is an LED lamp – integrated.

To summarize, LED light engines and integrated LED lamps are intended to be used in their entirety in luminaires. This document outlines testing procedures for LED light engines and integrated LED lamps that are intended only for *decorative* luminaires. A representative example of an LED light engine, including a heat sink and a driver, is shown in Figure 1. An LED light engine can also include optics such as lenses or reflectors, which could even be part of the heat sink.

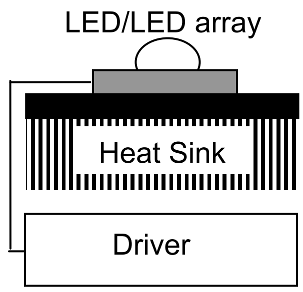
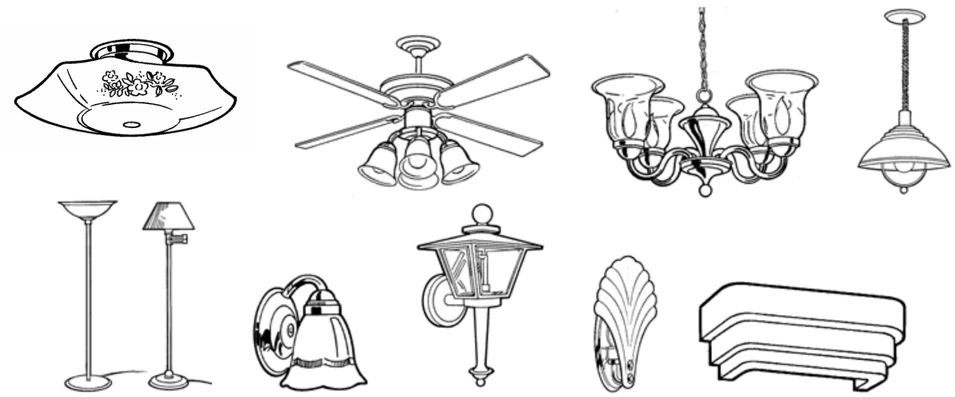


Figure 1. Example of an LED light engine.

Decorative lighting luminaire

Luminaires used in general lighting applications can be classified as functional lighting luminaires or as decorative lighting luminaires. Both types of luminaire can be intended for similar mounting locations but their purposes are different. Functional luminaires are designed to illuminate the space to a sufficient light level that allows the occupants to perform their visual tasks well. Their design is based primarily on achieving the best performance. Decorative luminaires, on the other hand, do not always add significant ambient illumination. They are designed to provide an attractive appearance to the lighted space while providing some amount of ambient lighting. Whereas functional lighting luminaires typically are efficient and control light precisely, decorative lighting luminaires are designed to complement the space; thus, their appearance often takes precedent over technical merit and cost. Decorative lighting is an important part of the visual environment that reinforces the message and the theme of the space and provides architectural integration. Decorative lighting can add visual interest, sparkle, and a bit of festive character. For these reasons, decorative lighting luminaires are almost always surface mounted (wall or ceiling), suspended, or portable, and can be installed either indoors or outdoors.

Decorative luminaires are frequently designed with materials less common in functional luminaires, such as colored and textured glass, metals, and plastics. Many types of light sources can be used in decorative luminaires, including incandescent, halogen, compact fluorescent, and LED. Figure 2 illustrates some examples of residential decorative lighting luminaires.



Bruce Kaiser – Kaiser Illustration

Figure 2. Examples of residential decorative lighting luminaires.

Background

Lighting manufacturers often design families of decorative luminaires that have a similar look and complement each other. For example, a family of sconces, pendants, table and floor lamps can provide a coordinated look and character to different areas throughout a space while serving different functions. To this end, there could be a large number of design variations in a family of decorative luminaires that use a common light source, such as an incandescent or compact fluorescent lamp, or an LED light engine or lamp.

The current practice among decorative luminaire manufacturers is to select a single lamp or lamp and ballast (or driver) combination and integrate this light source combination into several different luminaires within a given product family. With LEDs, manufacturers are taking a similar approach where an LED light engine or lamp is incorporated into several different luminaires within a given product family. This standardization helps reduce luminaire complexity, can reduce testing costs, and limits the number of component suppliers that a luminaire manufacturer needs to work with.

Generally, LED performance—in terms of luminous flux, luminous efficacy, color, and life—is affected by the heat at the LED junction. During operation, the LED junction temperature can reach up to 150°C. At such temperatures, the heat transferred to the ambient via radiation is very small. Therefore, conductive and convective heat transfer techniques are employed to keep the LED junction temperature as low as possible. This is why an LED light engine or lamp should always include a heat sink.

When an LED light engine or lamp is used in a luminaire, the thermal environment near the LED is altered depending on the luminaire's design and installation environment. As an example, an LED light engine or lamp could be incorporated into three different styles of decorative luminaires: a wall sconce, a table lamp, and a pendant (Figure 3). In the case of the table lamp, the heat sink and the driver may be placed inside the ceramic base of the luminaire where the ventilation is restricted and the volume of air is limited. In the case of the pendant luminaire, the heat sink may be hanging in open air with much more ventilation, and the driver may be remotely placed in the base of the pendant. In this example, even though the same LED light engine or lamp is used in the luminaires, the junction temperature of the LED will be higher in the table lamp than in the pendant. Thus, the performance of the LED light engine or lamp in terms of light output, luminous efficacy, and life will be poorer when the light engine or lamp is inside the table lamp than when it is inside the pendant luminaire.

Furthermore, any optics, transmissive or reflective, placed around the LED could further affect the light output and the color of the light. As an example, if we take the pendant luminaire and use two different cover glasses, one red and the other diffused white, the overall luminous flux into the space will be lower for the red glass compared to the white glass, even though the junction temperature of the LED remains the same.

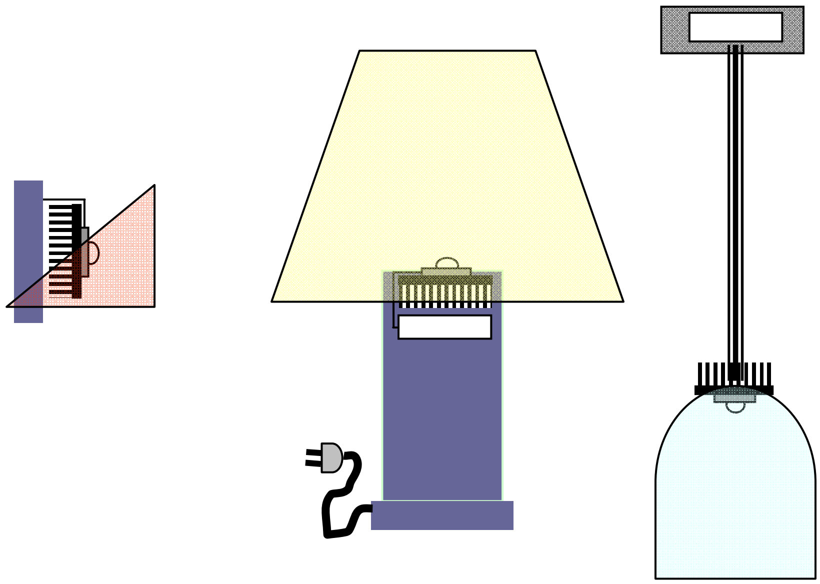


Figure 3. Examples of three different styles of luminaires incorporating the same LED light engine/lamp.

Because functional luminaires should meet particular performance criteria based on application standards and recommendations set forth by lighting organizations and societies, functional luminaires should be tested as a system. However, because decorative luminaires are not meant to provide illumination for critical applications, traditionally luminaire manufacturers have not provided photometric data for their products; they generally specify only the type of lamp and maximum allowable wattage. This approach has been successful because with incandescent lamps, end users already have certain expectations about the light output for a given lamp wattage and a sense of the lamp’s longevity. Likewise, some residential end users and most commercial end users have expectations for compact fluorescent lamps. Further, for most decorative luminaires, end users typically rank aesthetics over technical criteria, such as light output and efficacy. As a result, manufacturers of decorative luminaires base their products’ designs first on the appearances of the luminaire and the light produced by it. The next logical step then would be to design luminaires to be used with the most efficient light source able to produce the desired effects.

For these reasons, testing decorative LED luminaires as a system is not feasible and also does not provide much useful information. Therefore, the question is how can the performance of a decorative luminaire using an LED light engine or lamp be tested and evaluated?

Proposed Method

The proposed method in this document calls for characterizing the LED light engine or lamp performance as a function of LED board temperature. Board temperature is used because the junction temperature of an LED cannot be measured directly. The board temperature of an LED is directly related to the junction temperature and can be measured accurately using a thermocouple. Once the performance is known as a function of board temperature, the performance of the LED light engine or lamp when incorporated into a decorative luminaire can be estimated by measuring the board temperature while it is operating inside the luminaire.

Similarly, the life of some components typically used in drivers (e.g., electrolytic capacitors) is likely to be affected by the operating temperature inside the luminaire. This is particularly true in cases where the heat generated by the LEDs may contribute directly to the driver's temperature. Some manufacturers of fluorescent ballasts and LED drivers specify a maximum operating temperature and identify a location on the case of the ballast or driver to monitor the operating temperature. When an LED light engine or integrated lamp includes a driver, it is important to monitor the case temperature during the characterization to ensure it is within limits and that the driver will function properly during the life of the system.

For the purpose of this document, LED board temperature is denoted as T_s, LED junction temperature is denoted as T_J, and driver case temperature is denoted as T_c.

Characterizing LED light engine/lamp performance as a function of operating temperature

LED light engine and integrated lamp manufacturers should identify and diagram thermocouple attachment points T_s for the light source and T_c for the driver's case. Temperatures at these respective points have a direct relationship to the performances of the LED light source and driver. Some examples of thermocouple attachment points are:

- For an LED or an LED array, a point on the LED or on the circuit board that has a direct correlation to the junction temperature, which dictates the LED performance. If an array of LEDs is used, several thermocouples may be needed. The thermocouples should be attached to the T_s point of the LEDs whose junction temperatures are higher than the rest, such as the center LEDs in the array. The highest T_s should be used for data analysis.
- For a fully enclosed replacement-type integrated LED lamp, if an external point cannot be identified as having a direct relationship to the LED junction temperature, the manufacturer should pre-attach a thermocouple for testing purposes. The tip of the thermocouple should be attached to the cathode LED lead wire (or pin, or connection pad) or to the circuit board.
- For a driver, a point on the case closest to the electrolytic capacitor or another component whose performance is affected the most by heat.

Setting the LED light engine/lamp operating temperature

Step 1: Attach thermocouples to the LED and the driver at the manufacturer-specified locations.

Step 2: Place the LED light engine or lamp inside a thermal test chamber as described in Appendix B (e.g., a cubical box constructed of wood similar to that used in UL test boxes [UL 2004] and surrounded by insulation) such that the heat sink and the driver are inside the box but the LED (or the LED array) is outside the box, as shown in Figure 4. A heater placed inside the chamber uniformly raises the ambient temperature within the chamber and heats the heat sink, LED, and the driver. The test chamber is painted white on the outside. The white paint should have a diffuse (matte) finish, a high reflectance, and be as spectrally neutral as possible. The goal is to minimize self-absorption and spectral shifts when the test chamber is used within an integrating sphere for photometric measurements. If any dimension of the thermal chamber is larger than 10% of the diameter of the integrating sphere, the thermal chamber should be painted with photometric sphere paint (IESNA 1994).

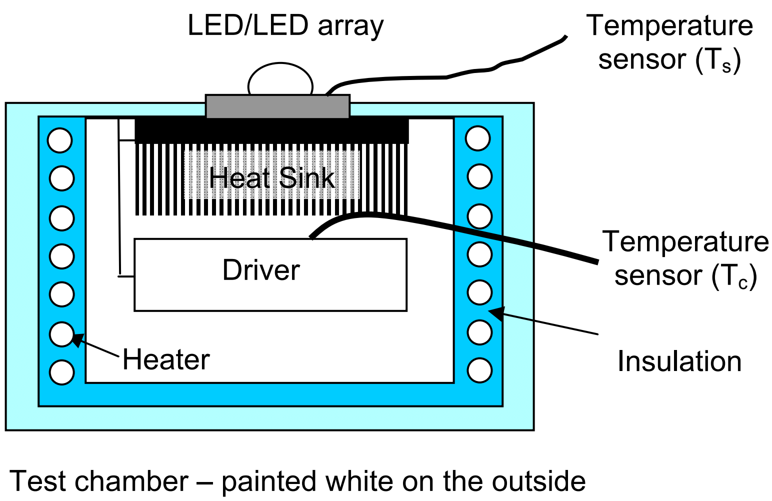


Figure 4. Schematic of the LED light engine placed inside the thermal test chamber.

Step 3: Turn the LED light engine/lamp on for 100 hours for seasoning the LED light source (or as recommended by the LED package manufacturer).

Step 4: If the LED light engine/lamp was turned off after seasoning, turn on the LED light engine/lamp and the heater. Change the amount of heat supplied by the heater until T_s reaches 40% of the maximum allowed junction temperature (T_{Jmax}) specified by the LED package manufacturer. For example, if the rated T_{Jmax} is 150°C, the target temperature will be 60°C. Once stable, T_s should remain ± 1°C of the target value (i.e., 40% of T_{Jmax}).

Step 5: Measure the luminous flux once temperature T_s stabilizes at the target value. Temperature T_s is considered stabilized when the differences in sequential readings are no greater than 0.5% with a minimum of three readings taken 15 minutes apart; see Appendix A "Testing conditions: LED stabilization – preburning." Monitor T_c to verify that it is within the manufacturer's specifications.

Step 6: Measure the photometric and electric quantities: luminous flux, spectral power distribution, voltage, current, active and apparent power, power factor, total harmonic distortion, etc.; see "Measuring luminous flux, luminous efficacy, CCT, CRI, and chromaticity" below for more information on photometric measurements.

Step 7: Next, adjust the heater until T_s reaches 60% of T_{Jmax}. Following the same example as in Step 4, for a rated T_{Jmax} of 150 °C, the target temperature will now be 90°C. Once stable, T_s should remain ± 1°C of the target value (i.e., 60% of T_{Jmax}).

Step 8: Repeat steps 5 and 6.

Step 9: Adjust the heater until T_s reaches 80% of T_{Jmax}. Following the same example as in Steps 4 and 7, for a rated T_{Jmax} of 150 °C, the target temperature will be now 120°C. Once stable, T_s should remain ± 1°C of the target value (i.e., 80% of T_{Jmax}).

Step 10: Repeat Steps 5 and 6.

Step 11: Conduct life tests as recommended in *ASSIST recommends: LED Life for General Lighting* (ASSIST 2005), except in setting the three life-test temperatures (ASSIST 2005), use the same T_s values determined in the present test (i.e., T_{s1} = 40%(T_{Jmax}), T_{s2} = 60%(T_{Jmax}), T_{s3} = 80%(T_{Jmax})).

Step 12: With the data collected, develop the following graphs:

a) Luminous flux (lm) vs. Board temperature (T_s)
b) Luminous efficacy (lm/W) vs. Board temperature (T_s)
c) Chromaticity (CIE x,y) vs. Board temperature (T_s)
d) Correlated color temperature (K) vs. Board temperature (T_s)
e) General color rendering index (R_a) vs. Board temperature (T_s)
f) Life (L_{70}) vs. Board temperature (T_s)

Estimating LED light engine/lamp performance in actual conditions

The data collected in the previous section is intended to provide a baseline for luminaire manufacturers interested in using a given LED light engine or lamp in their products. With the baseline information, luminaire manufacturers can determine by interpolation the main photometric and life performance parameters of the LED light engine/lamp when used in a particular luminaire design. To do so, luminaire manufacturers need to determine the actual LED board temperature when used in the intended luminaire. The following procedure details how to measure the board temperature in actual conditions.

LED light engine/lamp operating temperature measurement when used in its intended luminaire

The actual operating temperature condition is simply the board temperature (T_s) measured when the LED light engine/lamp is being operated in the intended luminaire and tested using the corresponding thermal test apparatus as outlined in publication UL 1598 *Underwriters Laboratories Inc. Standard for Safety: Luminaires* (UL 2004). Publication UL 1598 describes the characteristics of the thermal test apparatuses for a number of possible luminaire designs. The most relevant types include surface mount luminaires (wall and ceiling) and pendant luminaires. By following the UL 1598 test procedures, luminaire manufacturers can ensure that the LED board temperature will be representative of realistic conditions; thus, the performance of the LED light engine/lamp will not be overestimated.

Once the T_s value has been determined for each luminaire type, luminous flux, luminous efficacy, CIE x,y, CCT, and CRI can be estimated from the graphs developed in Step 12 of the previous section, “Setting the LED light engine/lamp operating temperature.”

Measuring luminous flux, luminous efficacy, CCT, CRI, and chromaticity

Sphere photometry can be used (see “Integrating sphere measurement” section below) for measuring luminous flux and the spectral power distribution of the beam, from which luminous efficacy, CCT, CRI, and chromaticity (CIE x,y coordinates) can be calculated.

Luminous flux can also be measured by using standard goniophotometry. Alternative equipment, such as the Flux-O-Meter, has the capability to measure both the luminous flux and the spectral power distribution of the luminaire (Bierman 2007). The Flux-O-Meter measures the illuminance and spectral power distribution at many points around a virtual sphere surrounding the luminaire being tested. The luminous flux of the LED light source can be calculated by integrating the illuminance over the virtual sphere’s area, and color properties can be determined at each measurement point or averaged across all measurements. As an additional advantage, the Flux-O-Meter does not require a minimum distance between the sensors and the luminaire, and it is relatively insensitive to positioning, size, color, and shape of the luminaire being tested.

Integrating sphere measurement

The basic photometric characteristics of the LED light engine or lamp can be determined by measuring the radiant energy at each wavelength in the visible spectrum (i.e., the spectral power distribution). With the spectral power distribution, metrics such as luminous flux, luminous efficacy, chromaticity, correlated color temperature, and general color rendering index can be derived following existing standards (CIE 1984, 1989, 2007; Rea 2000).

Test data presentation

Appendix C outlines the testing information that manufacturers of LED light engines and lamps should provide as part of their specification sheets.

Appendix A: Photometric Measurements

The procedures described below are taken from existing standards published by the Illuminating Engineering Society of North America (IESNA) and the Commission Internationale de l'Éclairage (CIE) and are to be used as further guidance to setting up and conducting the tests described in this document.

Selection of LED light engine or integrated lamp

The LED light engine or integrated lamp selected for test should be in good working condition and representative of the manufacturer's regular product. The driver used for the test should be the same model used in the final luminaire assembly.

Photometric measurements

Testing conditions

Air movement. The LED light engine/lamp shall be tested in relatively still air. A maximum airflow of 0.08 meter/second (15 feet/minute) is suggested (IESNA 2004).

Lamp seasoning. The test LED light engine/lamp should be seasoned for a certain number of hours such that their characteristics remain constant during the test to be conducted. Presently, there are no standards for LED light engine or lamp seasoning. In the interim, it is recommended that the test product be seasoned for 100 hours.

LED stabilization – preburning. The LED light engine/lamp requires a certain number of hours from start to allow the LED or LED array and driver to reach normal operating temperatures before starting the performance testing. Restarting of the LED light engine/lamp during the test should be avoided. However, if restarting is necessary, the test should be continued only when complete stabilization is achieved again. The light source is considered stabilized when monitoring light output over a period of 30 minutes produces differences of sequential readings no greater than 0.5% with a minimum of three readings taken approximately 15 minutes apart (IESNA 1998).

Test voltage. The LED light engine/lamp shall be operated at its driver rated input voltage. If the driver's rated input voltage is a range (e.g., 108 V to 132 V), the center value shall be used as a test condition (IESNA 2001).

Instrumentation. Instruments shall be selected and used with care to ensure accurate measurements. Instruments should be calibrated a minimum of once per year. Instrument indications should have good reproducibility. The effect, if any, of instruments on measured quantities shall be addressed. See IESNA LM-28-89, *IES Guide for the Selection, Care and Use of Electrical Instruments in the Photometric Laboratory* (1989) for detailed information.

Photodetectors. Use photodetectors with a spectral response that follows the CIE photopic ($V\lambda$) spectral luminous efficiency function (IESNA 1998; CIE 1989).

Measurement of total luminous flux

Total luminous flux for the LED light engine/lamp may be obtained with the integrating sphere method. Inside the integrating sphere, air movement is minimized and temperature is not subject to the fluctuations usually present in a temperature-controlled room. Appropriate corrections shall be made unless substitution standards agree in spectral power distribution, physical size, and shape with the LED light engine/lamp under test. When the test product and the calibrating lamp are not of the same physical size and shape, compensation for differences in self-absorption shall be made (CIE 1989). If the self-absorption is higher than 25%, a larger size integrating sphere should be used (Bierman 2007).

Measurement of color

The light output color of an LED light engine or lamp is typically specified by its chromaticity coordinates (i.e., CIE x,y), which are derived from the spectral power distribution of the light source (CIE 1984). The measurement can be carried out by placing the LED light engine/lamp inside an integrating sphere.

The characteristics of the spectroradiometer used for the testing will impact the accuracy of the measurements. For best results, the CIE recommends that:

> "For practical LED measurements, a bandwidth of 5 nm or less is acceptable and recommended. Bandwidths of larger than 5 nm are generally not recommended for LED measurements, but might be used with appropriate bandpass correction..." (CIE 2007).

For further guidance on spectroradiometric measurement procedures and possible sources of error, see also CIE's publication CIE 063-1984, *The Spectroradiometric Measurement of Light Sources*.

Appendix B: Test Enclosure for Sphere Measurements

The objective is to create a test enclosure for sphere photometry that can keep the LED light engine's or lamp's light source and driver at operating temperatures similar to what they would be in real-life applications. Figure B1 shows the schematic of the proposed test enclosure. The proposed enclosure has heaters to raise the temperature within the enclosure in order to maintain the LED and driver temperatures (T_s and T_c, respectively) at values predetermined for testing. The outside of this test enclosure and the necessary mounting hardware are all painted white. The white paint should have a diffuse (matte) finish, a high reflectance, and be as spectrally neutral as possible. The goal is to minimize self-absorption and spectral shifts when the test chamber is used within an integrating sphere for photometric measurements. If any dimension of the thermal chamber is larger than 10% of the diameter of the integrating sphere, the thermal chamber should be painted with photometric sphere paint (IESNA 1994).

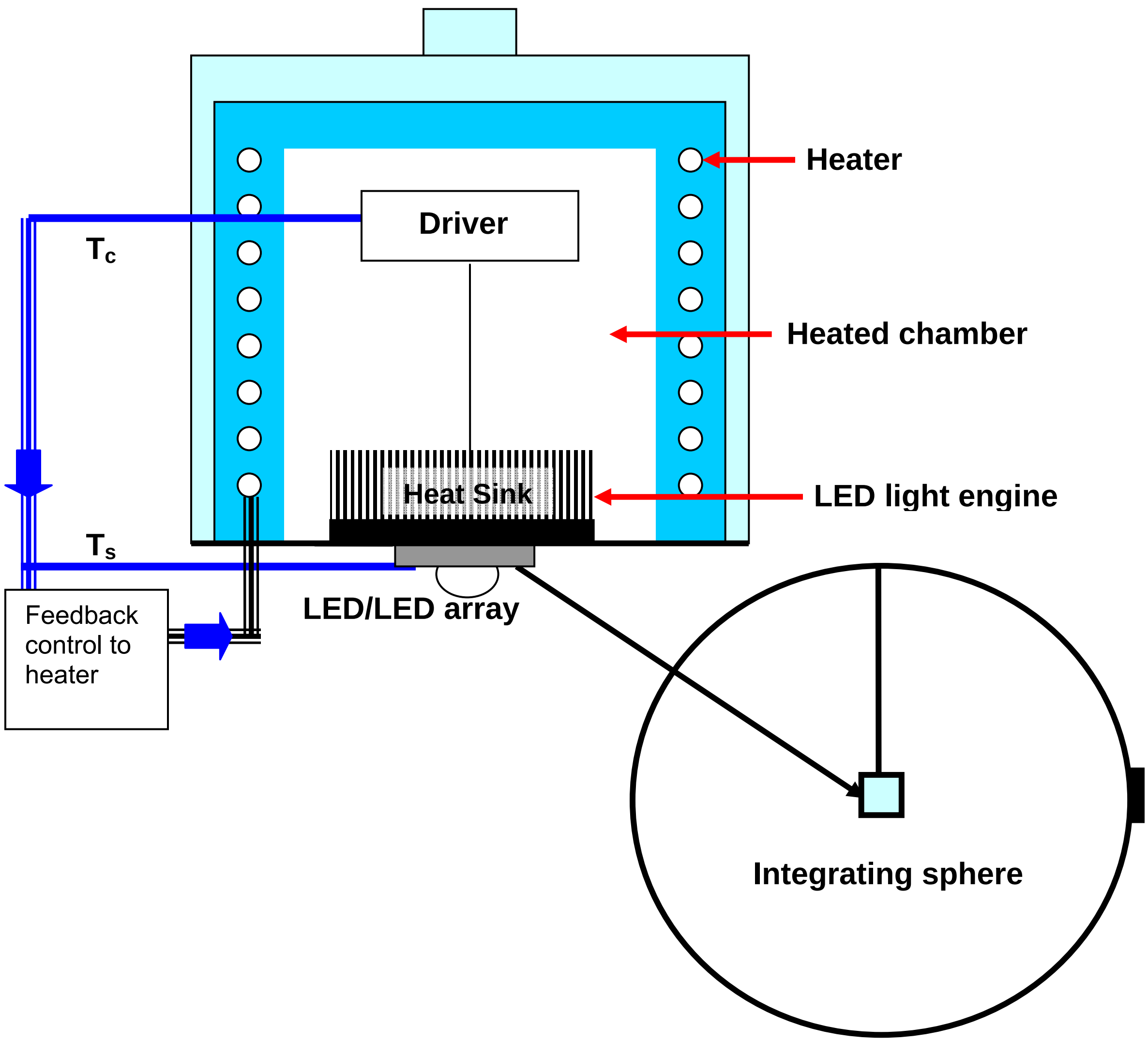


Figure B1. Schematic of the proposed test enclosure for sphere measurements.

Appendix C: Data Reporting Sheet for LED Light Engine and Integrated Lamp Manufacturers

Below is the information recommended for LED light engine and integrated lamp manufacturers to include in their data sheets.

Sketch or picture of thermocouple attachment location	*Sketch or picture of the temperature testing setup*

Table C1. Recommended information to be included in LED light engine/integrated lamp specification sheets.

Test date
LED light engine/integrated lamp description and catalog number
Light source
LED manufacturer
LED maximum junction temperature (T_{Jmax})
LED driver description (manufacturer, description, catalog number, input and output parameters)

	T_{s1} = 40% T_{Jmax}	T_{s2} = 60% T_{Jmax}	T_{s3} = 80% T_{Jmax}
Room temperature (°C)			
T_s (°C)			
T_c (°C)			
t (life; hours to L_{70}) per ASSIST (2005)			
Luminous flux (lm)			
Luminous efficacy (lm/W)			
CIE chromaticity (x,y)			
Correlated color temperature (K)			
General color rendering index (R_a)			
Active power (W)			
Voltage (V)			
Current (A)			
Apparent power (VA)			
Power factor			
Total harmonic distortion (%)			

With the data from Table C1, the following graphs can be developed:

a) Luminous flux (lm) vs. Board temperature (T_s)
b) Luminous efficacy (lm/W) vs. Board temperature (T_s)
c) Chromaticity (CIE x,y) vs. Board temperature (T_s)
d) Correlated color temperature (K) vs. Board temperature (T_s)
e) General color rendering index (R_a) vs. Board temperature (T_s)
f) Life (t) vs. Board temperature (T_s)

Reporting the data and graphs described above is important for decorative luminaire manufacturers interested in using a particular LED light engine or lamp for their products. With the information above, luminaire manufacturers can determine by interpolation the main photometric performance parameters for the actual LED light engine/lamp operating temperature. The actual operating condition is the board temperature measured when the LED light engine/lamp is being operated in the intended luminaire and tested using the corresponding thermal test apparatus as outlined in publication UL 1598 *Underwriters Laboratories Inc. Standard for Safety: Luminaires* (UL 2004). A sample graph of light output vs. board temperature is shown in Figure C1.

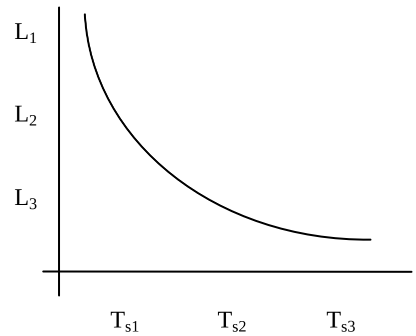


Figure C1. L_1 is the LED light engine/integrated lamp's luminous flux and T_{j1} is the LED junction temperature when T_s reaches 40% of T_{Jmax} (T_{s1}); L_2 is the luminous flux and T_{j2} is the LED junction temperature when T_s reaches 60% of T_{Jmax} (T_{s2}); L_3 is the luminous flux and T_{j3} is the LED junction temperature when T_s reaches 80% of T_{Jmax} (T_{s3}).

References

Alliance for Solid-State Illumination Systems and Technologies (ASSIST). 2005. *ASSIST recommends: LED Life for General Lighting.* Available: http://www.lrc.rpi.edu/programs/solidstate/assist/ledlife.asp.

Bierman, A. 2007. Personal communication February 14, 2007. Lighting Research Center, Rensselaer Polytechnic Institute.

Commission Internationale de l'Éclairage. 1984. *The Spectroradiometric Measurement of Light Sources,* CIE 063-1984. Vienna, Austria: CIE.

Commission Internationale de l'Éclairage. 1989. *Technical Report: The Measurement of Luminous Flux,* CIE 84. Vienna, Austria: CIE.

Commission Internationale de l'Éclairage. 2007. *Technical Report: Measurement of LEDs*, CIE 127-2007. Vienna, Austria: CIE.

Illuminating Engineering Society of North America (IESNA). 1989. *IES Guide for the Selection, Care and Use of Electrical Instruments in the Photometric Laboratory*, IESNA LM-28-89. New York: Illuminating Engineering Society of North America.

Illuminating Engineering Society of North America (IESNA). 1994. *Approved Method for Photometric Testing of Reflector-Type Lamps*, IESNA LM-20-1994. New York: Illuminating Engineering Society of North America.

Illuminating Engineering Society of North America (IESNA). 1998. *Approved Method for Photometric Testing of Indoor Fluorescent Luminaires*, IESNA LM-41-98. New York: Illuminating Engineering Society of North America.

Illuminating Engineering Society of North America (IESNA). 2001. *Approved Method for Life Testing of Incandescent Filament Lamps*, IESNA LM-49-01. New York: Illuminating Engineering Society of North America.

Illuminating Engineering Society of North America (IESNA). 2004. *Approved Method for Photometric Testing of Indoor Luminaires Using High Intensity Discharge or Incandescent Filament Lamps*, IESNA LM-46-04. New York: Illuminating Engineering Society of North America.

Illuminating Engineering Society of North America (IESNA). 2008. *Nomenclature and Definitions for Illuminating Engineering*. ANSI/IESNA RP-16-05 Addendum a. New York: Illuminating Engineering Society of North America.

Rea, M.S., ed. 2000. *IESNA Lighting Handbook: Reference and Application*, 9th ed. New York: Illuminating Engineering Society of North America.

Underwriters Laboratories Inc. 2004. *Underwriters Laboratories Inc. Standard for Safety: Luminaires,* UL 1598. Northbrook, IL: Underwriters Laboratories.

Acknowledgments

ASSIST and the Lighting Research Center would like to thank the following for their review and feedback during the initial development of this publication: Aurora International Testing Laboratory, Everfine, Federal Aviation Administration, Independent Testing Laboratories, Intertek, Lowe's Companies, OnSpex, Permlight, Philips Lighting, Underwriters' Laboratories, and United States Environmental Protection Agency.

About ASSIST

ASSIST was established in 2002 by the Lighting Research Center at Rensselaer Polytechnic Institute to advance the effective use of energy-efficient solid-state lighting and speed its market acceptance. ASSIST's goal is to identify and reduce major technical hurdles and help LED technology gain widespread use in lighting applications that can benefit from this rapidly advancing light source.