



Guidelines for Selecting Solid-State Lighting for Museums

James R. Druzik and Stefan W. Michalski

September 2011

Canadian Conservation Institute
The Getty Conservation Institute

A Users Guide for Selecting Solid-State Lighting for Museum Use

Table of Contents

Acknowledgments	3
Introduction.....	4
SECTION 1: What's an LED and how does it differ from traditional lighting?	5
How LEDs fit into sustainability goals for museums	8
Comparison of LEDs to traditional lighting.....	9
Luminous efficacy	9
Lifespan and Lumen Maintenance	10
Correspondent properties.....	11
Color Rendering Index (CRI)	12
Color consistency and appearance over time	12
Form Factor (retrofit versus dedicated LED design).....	15
Cost and ROI Payback.....	15
Mature versus evolving technologies.....	16
Final remarks on Glare	17
LED Decision-Making In a Nutshell	17
SECTION 2: Making the Decision: Which LEDs Products to Buy	19
REVIEW	19
READ	19
Product Testing (CALiPER).....	20
IES LM-79.....	20
IES LM-80.....	20
GATEWAY Demonstration	21
Lighting Facts Labels	21
LOOK.....	22
AGREE	24
Recap: Getting the Most Out of Your LED Products	26
Sources for Solid-State Lighting Products Described in this Document.....	27
U.S. Department of Energy Internet Resources.....	27
Formulating an Institutional Lighting Policy.....	29
Bibliography	30

Acknowledgments

Much of the information in this guideline is taken from programs created by and for the United States Department of Energy, Lighting Research and Development Building Technologies Program. The authors are particularly in debt to Naomi Miller, Senior Lighting Engineer, Pacific Northwest National Laboratory whose insights and suggestions were invaluable to virtually all sections of this document. Ken Kane, Lighting Services, Inc. and Ron Steen of Xicato have provided difficult to find information into the strength and limitation of warranties when purchasing LED lighting from the manufacturer's point of view. Further manufacturing insights came from Mark Sieber, Tom Healy, and Valerie Khiaban from ERCO Lighting, Inc. For advice on lighting design we appreciate our many conversations with Scott Rosenfeld, lighting designer at the Smithsonian American Art Museum and the National Portrait Gallery. Christopher Cuttle, Lighting Consultant, New Zealand, has provided many useful comments and observations and has been a close associate for a number of years. We also appreciate the help of Harold Murray, P. Eng., LC LEED AP, Ameresco Canada, Toronto, Ontario, Canada, who has offered his observations on dimming. As far as we know, Richard Kerschner, Director of Preservation and Conservation at the Shelburne Museum, has the distinction of being one of the first, if not the first, adopter of LED lighting in an American museum. The fruits of his experience can also be found in this document. We also thank Salvador Muñoz Viñas for also reading the manuscript from the conservator's point of view.

This document was originally prepared for a lighting workshop conducted at the Canadian Conservation Institute in the summer of 2011. We likewise appreciate the advice and questions of those workshop participants.

Lastly, we'd like to thank our colleagues at the Getty Conservation Institute and the Canadian Conservation Institute for making projects like this possible.

A Users Guide for Selecting Solid-State Lighting for Museum Use

In 2012 the United States will consume 10 quads of electrical power on general illumination. From 2010 to 2030 it is estimated that a national SSL program could save 16 quads in energy. 1 quad is the equivalent of one quadrillion BTUs or roughly 36 million tons of coal or one trillion cubic feet of natural gas.

Introduction

The process of selecting solid-state lighting (SSL) products for museums can be an intimidating experience. But by following four reasonable steps that process can be simplified into an organized search of discovery that will be enriching and hopefully enjoyable.

In Section 1, this document begins by giving a simplified outline of how SSL, and light-emitting diodes (LEDs) in particular, work, their performance parameters, and what can go wrong with them. If all you want is a quick answer to the question, “Are LEDs safe and effective in museums, and how do I evaluate them?” jump to the end of Section 1 and read *LED Decision-Making In a Nutshell*.

If you are called upon to assist in a central role selecting, evaluating and purchasing SSL products, Section 2 will then lead you through the process of learning how to REVIEW the uses in museums where SSL may be applied, realizing that the requirements for general illumination may not be the same as those for gallery installations. We’ll then summarize the many written reports and programs that have been created to provide the consumer with high quality information on SSL performance criteria. Selectively READ those documents that align most closely with your interest. Most museum staff will be able to appreciate the GATEWAY demonstration project reports, but facilities managers and in-house lighting specialist might be better suited to consult on fact sheets, standards and specifications and particularly CALiPER reports which provide independent laboratory testing of each product. We’ll explain what those reports cover.

Color in SSL products is a significant factor in making a final aesthetic decision on what to buy and for what to illuminate. While color in SSL is not any greater than more traditional types of museum lighting, it certainly may appear that way. In the final analysis you may decide on several types of lamps, from different manufacturers, in at least two or more color temperatures. They will likely all look slightly different. Always LOOK at all the options and we’ll describe several methods to maximize that evaluation.

Finally, SSL is currently more expensive than other forms of common illumination. Therefore you will not want to consider simple replacement at your own expense if a lamp does not meet your expectations, if it fails catastrophically, or if it changes color in an unacceptable manner during use. A manufacturer who produces a top tier LED product intended for museums or other high-end users should be expected to stand behind their product’s performance. That is why it is important to AGREE on those conditions well in advance of any purchase. Many manufacturers will give a three or even five-year written warranty.

We shall end with a review of techniques for getting the best results using LEDs. You will also see that LEDs fit into any lighting risk management or preventive conservation program seamlessly.

SECTION 1: What's an LED and how does it differ from traditional lighting?

At the onset we should establish that LEDs can produce white light in two basically different ways. First, white light can be created by combining the colored contribution three or more “primaries” as television sets have for decades. The simplest design combines narrow band emissions in the regions of the visible spectrum that we sense as red, green, and blue (RGB), aligning somewhat closely with the three types of cone photoreceptors on our retina. To improve color rendering, amber is sometimes added (RAGB). The second way to create white light is to use a broadband white fluorescent compound, or mixture of several, that is excited by a short wavelength (blue) LED. The light emitted by the phosphor is always of lower energy than the photons of light that causes its excitation and this is called the Stokes shift of the phosphor material. Some of the short wavelength energy passes out of the LED and, combining with the broadband fluorescence, jointly produce the color appearance we perceive. Figure 1 shows one design for a white LED with a highly prominent peak near 460 nm, the wavelength that stimulates our blue visual receptor. It sits on the edge of the broadband fluorescence curve. The spectrum in Figure 1 is from an MR16 light source that's rather cooler in appearance than many types of gallery lighting. Some LED designs however, employ a second LED chip that lowers the color temperature closer to that of a tungsten source. Figure 2 is one such design, a Cree LRP-38. The peak near 630 nm serves the function of warming the overall appearance but even though the peak is large, some of it lies in a region of the spectrum that our visual system is less sensitive towards.

But just because the fluorescence excitation is caused by a short wavelength LED it doesn't mean that a blue peak is inevitable or needs to be large. Some manufacturers of high quality LEDs perfectly suitable for museums have small or almost no peak in this region. These types of lamps not only have no ultraviolet light (like most LEDs) but the quantity of short wavelengths they produce is generally no greater than an incandescent light source. Figure 3 is an example that comes very close to replicating a true incandescent source in the visible.

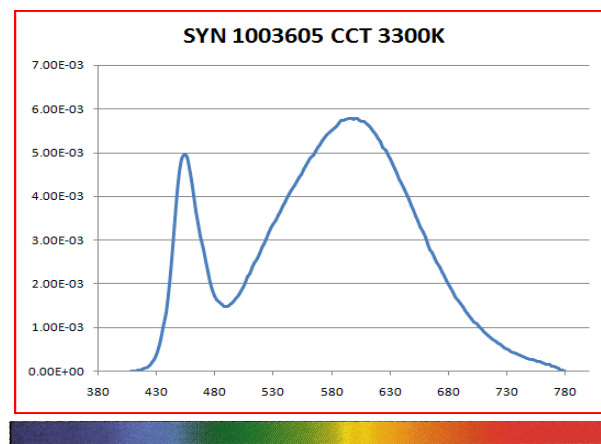


Figure 1

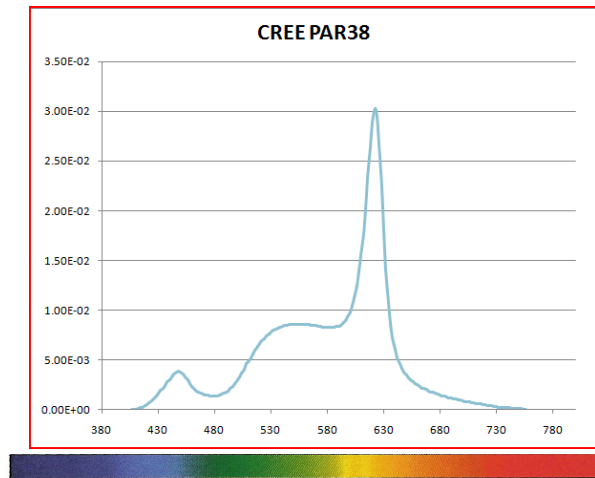


Figure 2

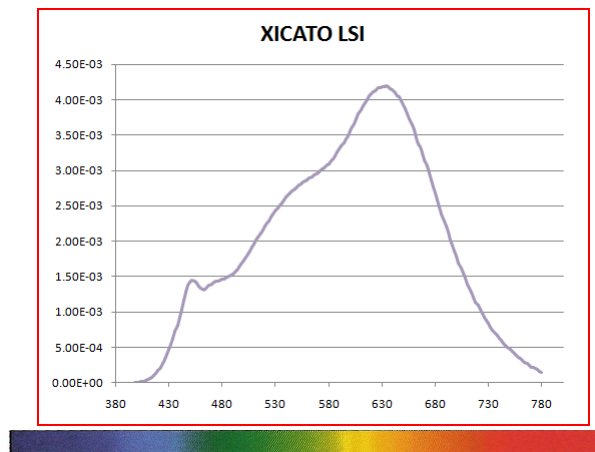


Figure 3

We will show one last example that affords a valuable lesson in looking at a spectrum. Figure 4 is another MR16, this time produced by CRS Electronics with a small blue peak upon which a spectrum for a tungsten halogen MR16 has been overlaid. What little blue peak remains is partially compensated for by the fact that the LED cuts off at about 420 nm (blue arrow) when the halogen lamp continues to about 385 nm (yellow arrow).

LEDs have little or no infrared radiation. This explains their high efficiency at producing only visible light. But few people realize until they see an LED spectrum just how far this extends down towards the visible. The red arrow in Figure 4 illustrates how much very near infrared is missing. Typically we think of IR as causing thermally driven physical effects like the loss of environmental moisture, but the energy of photons in the area pointed out by the red arrow is capable of instigating photochemical reactions. This is probably why some light-sensitive blue dyes have been shown to fade less rapidly under white LEDs than tungsten or tungsten halogen lighting (Ishii et al. 2008; Druzik, 2011).

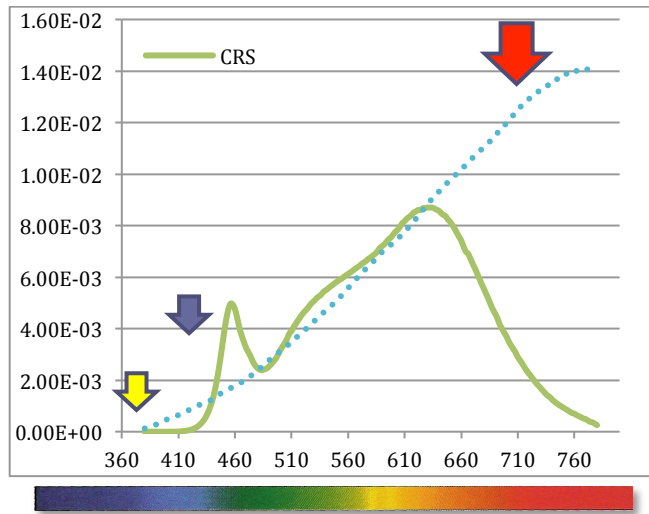


Figure 4

Depending upon the correlated color temperature the manufacturer desires, the blue peak can show up in the spectrum as almost undetectable or be very large.

Another distinction is that LED's generally refer in this document to *inorganic* light-emitting diodes. The future will no doubt see solid-state lighting also incorporate organic light-emitting diodes (OLEDs), subdivided into polymer light-emitting diodes (PLEDs), light-emitting polymer (LEPs), and small molecule devices (SMOLEDs).

However, at the present time, only inorganic LED lamps that incorporate broadband phosphors meet all the requirements for museum gallery lighting.

In some ways LEDs are radically different than light sources commonly found in museums and archives and in other ways have similarities. Rather than using heat to produce light as do incandescent light sources, LEDs use a process called electroluminescence that operates at a much lower temperature. While the chip itself is usually kept below 85° C the outer surface of the lamp is often still cool enough to hold with bare fingers.

An LED is a semiconductor unique in the quantity of light it can product. To understand how they work, we need to know the difference between a metal, an insulator, and a semiconductor, and how electron mobility resides at the root of their electrical properties.

Metals conduct electricity because the electrons that bind atoms together (valance electrons), their outermost electrons, are highly mobile and can be thought of as existing in a free-flowing cloud. Every metal differs slightly in how strongly they hold onto their electrons (electronegativity). Of course, there is nothing like a "cloud" at the atomic level but this serves our purpose for visualization. Non-metals bind together with strong covalent bonds that constrain the mobility of valance electrons. Non-metals do have electron orbitals that permit conduction like metals but they are unfilled and have such a large energy gap between the valance band and the conduction band they are non-conducting or insulators. Now if enough energy is supplied that band gap can be overcome, restrained valance electrons can be "pushed" up into the conduction band and some weak current induced. But it is impractical.

Between these two extremes are "semimetals" with small energy (band) gaps between valence and conduction orbitals. Silicon is one such element. But silicon by itself will not work very well. Similarly sized elements are added in a controlled method to the silicon matrix. This is called doping and gives the electrons even greater mobility. Aluminum for example is the right size and has fewer electrons in

the valence band than silicon. This produces a vacancy and makes room for an electron to move into. It's called a p-type semiconductor (positive-type) because it's deficient in electrons, carriers of negative charge. Phosphorus on the other hand when inserted into a silicon matrix allows for an excess of electrons and is known as an n-type semiconductor.

A *diode* is a structure that has a p-type semiconductor in contact with an n-type semiconductor and the contact area is called a junction. The p-type semiconductor has extra space in its valence band and no electrons in its conduction band. While the n-type semiconductor is just the opposite – having no extra spaces in its valence band and extra electrons in its conduction band. It only takes a small electrical current applied to the n-type side to fill the conduction band. As more electrons pile into the conduction band they are pushed across the junction to the higher energy conduction bands on the p-type side. If there are “holes” available at lower energy levels of the valence bands, electrons will occupy these locations. Electricity supplies the initial energy requirements to overcome the gaps but the cascade back down to lower energy levels will release that energy. Some of that energy will be heat but most will be released as photons of light.

The exact size of the energy gap is narrow so the emitted photons that are created occupy a narrow range of wavelengths. This is why LEDs tend to produce pure bright colors. A white phosphor LED can be made from a blue indium-gallium-nitride (InGaN) light-emitting diode coupled to a cerium-doped yttrium aluminum garnet phosphor.

The production of LED chips from large round wafers is a remarkably precise coating and assembly process. Even with all the research and development efforts underway and the billions of dollars spent by the industry to minimize variation, it is simply not possible to produce highly consistent LEDs at high yield. So to maximize product yield and knowing that there are many diverse LED requirements in the market, manufacturers routinely sort production into bins according to lumen, color, and occasionally voltage. This process, called “binning”, means that applications like LED strip lighting, often used inside display cases with very little heat gain, can incorporate individual sources with the same brightness and color. LED strip lighting is often superior to fiber optic illumination.

How LEDs fit into sustainability goals for museums

The conservation field has always been known for its willing response to social, cultural and historical responsibility - for that is within the nature of, and what it means to be, a conservator. In 1987, the Brundtland Commission of the United Nations joined those ideas with development in a formal definition for *sustainability*: “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (United Nations 1987). Substitute the words “education” and “preservation” for “development” and this statement applies equally to conservation.

During the 37th Annual Meeting of the American Institute for Conservation in Los Angeles, 2009, the Green Task Force presented the results of a survey it conducted of its members regarding green practices in museums. After recycling, the second most dominant theme called for a reduction in energy consumption. The survey report noted that 55% of conservator's workplaces still used incandescent lighting with compact fluorescent (CFL) and T8 tube fluorescents on the rise in use. LED's in exhibit situations trailed.

The Federal Clean Air Act of 2007, in the United States, has mandated the elimination of old style incandescent lamps by 2014. California has stricter rules with their elimination by 2013, and in Canada by 2012. In other parts of the world the move away from inefficient lighting is even faster. In Europe, EU Directive 2005/32/EC by the Ecodesign Regulatory Committee (IP/08/12/2008) plans that the European production of tungsten light bulbs will be phased out between 2009 and 2012.

Similar action is going on in Australia. The Energy Efficiency Regulations are published on the Natural Resources Canada website.

The largest replacement lamp in numbers now is the CFL containing 5 milligrams of mercury. What is not often realized is that even tungsten lamps contribute mercury to the environment in the form of pollution from coal-fired electricity power plants. The Environmental Protection Agency estimates that even though CFLs contain some mercury, they use less power and reduce total environmental mercury by about 40%. Still, there is no federal law mandating household recycling of fluorescent lamps. Only 2% of households and only one third of businesses recycle them according to the Association of Lighting and Mercury Recyclers. Thus it is estimated that approximately 4 tons of mercury is added to the atmosphere and storm water runoff annually (Bohan, 2011).

LEDs contain no mercury and, by the end of 2010, commonly reduce energy requirements in general illumination by 60%. The efficiency of LEDs will most decidedly increase in the near future. As a current example, the Brooker Gallery at the Field Museum in Chicago (See a fuller description under “Cash Payback” later in this guidelines) converted from halogen display lighting, already 25% more efficient than conventional tungsten lighting, to LEDs. This reduced the gallery’s lighting power from 894 watts to 335 watts for an expected payback of 3.25 years.

Knowing that the Brooker Gallery operates 2912 hours per year allows calculating kWh savings and converting that to annual carbon footprint reduction from published tables of summary data (EPA 2011). Using the State of Illinois adjusted value of 1.113 lbs of CO₂ per kWh, this represents a net decrease in the annual carbon footprint of 1812 lbs of CO₂ (824 kg). The same conversion in California would gain a much lower, but still significant, annual reduction of 925 lbs. of CO₂ (420 kg).

Another complaint by conservators to the AIC Green Task Force was the impression that energy consumption from environmental controls, HVAC in particular, was excessive. It is important to note in this regard that LEDs have a major beneficial influence on building cooling costs. The general rule is that for every three watts of power saved in operational costs with LEDs one watt is saved from HVAC operational costs. The Brooker Gallery lighting payback incorporating this slight reduction in heat load was calculated to be 2.4 years.

Comparison of LEDs to traditional lighting

Luminous efficacy

Luminous efficacy characterizes the ratio of visible light produced per watt of electrical power consumed for a given light source in lumens. A *lumen* being the basic photometric unit of light linked to human visual perception. Table 1 presents a few common light sources. Incandescent light sources produce low levels of visible light per watt because heat produces radiant energy over a very wide range of wavelengths that bracket our visual range.

Description	Lamp Lumen Efficacy (lm/W)
Candle	0.3
60 W tungsten incandescent	5-14
Tungsten halogen	15-26
Compact fluorescent (9-26W)	35-70
White LED	30-150
T8 fluorescent, electronic ballast	80-100

Table 1. Luminous efficacy of several light sources

This is a fundamental penalty paid by all blackbody radiators that create photons through heat alone. An ideal blackbody radiator at 4000K has an upper limit of 48 lumens per watt. Contrast this with the

theoretical upper limit of white light if it could be created by a perfectly efficient mechanism that renders all radiant power in the visible range - about 500 lumens per watt. For a 3000-4000K light source, the difference is largely waste *heat*. At present, most white LEDs operate at the lower end of their efficacy range but the expectation is that it will go much higher in the future and their high performance over incandescent sources means they consume less energy for their light output and meet much stricter government energy standards.

Lifespan and Lumen Maintenance

Lifespan and lumen maintenance of LED products is a second dramatic feature. Table 2 illustrates this fact.

Lamp Type	Average Lifetime (h x 10 ³)	CCT (K)	Lumens/watt
Tungsten bulb	0.75-1.5	2800	5-14
Tungsten halogen	2-2.5	3000	15-26
CFL bulb	6-12	2800	35-70
White LED	50*	2700,3000	30-150

Table 2. Comparison of typical light sources.

LEDs seldom burn out – they simply lose light output over time and the current measurement protocol for LED chips (not fixtures of lamps) is to define “end of life” as the point when light output drops below 70%. Many manufacturers can probably meet this standard at 50,000 hours but some cannot as shown in Figure 5

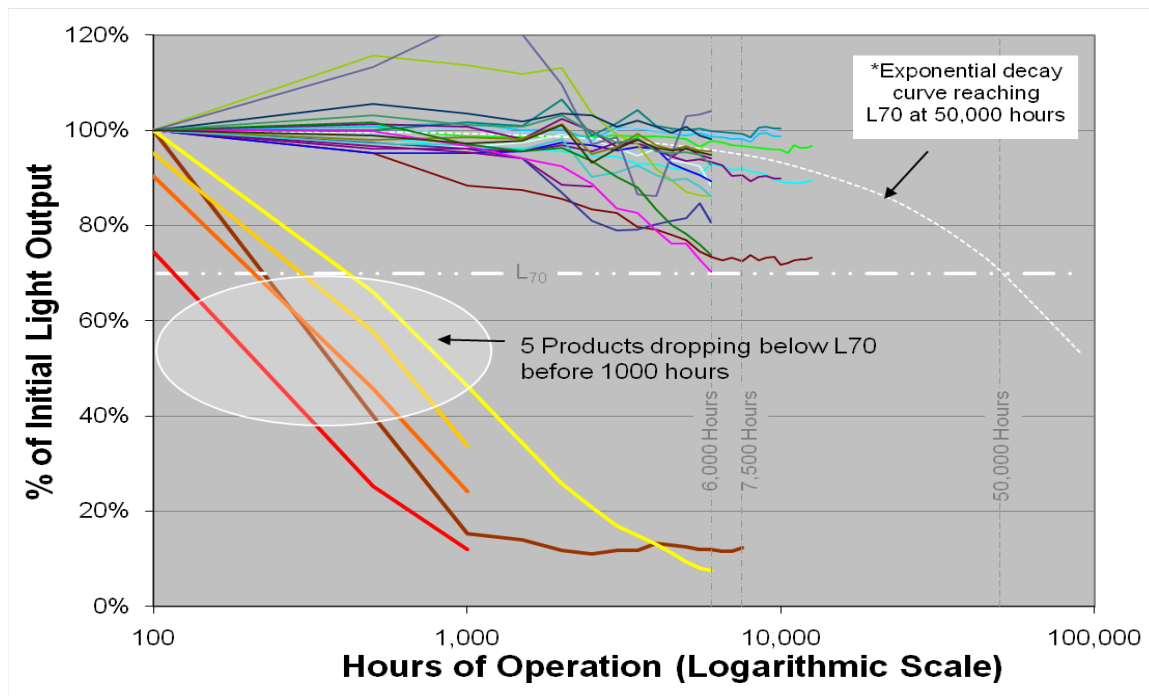


Figure 5. Cumulated operating time (hours) – Logarithmic Scale (Source: DOE Caliper Program, <http://www1.eere.energy.gov/buildings/ssl/caliper.html>)

LM-80 Reports document long-term performance of LED chips but most products have not been in existence long enough to guarantee 50,000 hour lifespans. For this reason, lifespan and lumen

maintenance are important considerations in any agreement with a vendor as a cause for free replacement if the product selected does not meet manufacturing expectations.

A closely related concept is that of luminous output. Initially, white LEDs had a very low lumen rating, often as low as 50 lumens. For a LED MR16 to match a low wattage halogen MR16 in a gallery with a 12-foot ceiling, an output of 300 is more reasonable. PAR38s need to be much higher, closer to 500-1000 lumens. For ceilings up to 40 feet or higher – 2000 lumens would be minimally needed. It is important to keep the geometry of the gallery in mind, as well as the likely display contents, when considering LED replacements. A gallery intended only for Old Master drawings will find itself severely under-illuminated if the curator decides to show paintings or dark bronzes in the same space at some point in the future. Fortunately, a range of luminous outputs are often available in the same LED lamp types.

Correspondent properties

Existing incandescent lamps often encountered in museums range from high intensity low voltage pin spots (4 degrees) to wide flood lamps (50 degrees) and from 20W MR16 to 250 W PAR38 lamps. LED replacement lamps can be found for most halogen lamp types in lower wattages. However, 100W to 250W lamps cannot yet be replaced with LEDs, but can sometimes be replaced with metal halide lamps (Rosenfeld, 2011). Replacement lamp with beam angles at the extremes used at the Smithsonian American Art Museum and the Renwick Gallery (4 and 54 degrees) were initially difficult to find but have since been made available (Brodrick 2011). The main caveat is that, speaking generally, not all of the available lamps have been tested to fully meet the aesthetic, conservation, and durability requirements of an art museum.

Some properties that a lighting engineer may want to know when establishing corresponding capabilities between a lamp currently used and a possible replacement LED are center beam candle power, beam angle, intensity distribution and illuminance plots, and other electrical characteristics. These will not be described in this section but can be found in IES LM-79 reports described later in these Guidelines. URLs to find and download many of these reports are shown in the section on Internet resources. Others are available directly from the manufacturer.

LEDs often deliver more glare than the lamps they replace. Two options are to use lamps with integrated “filament” shields like the Cree LRP38 or Optiled Radar series, or specify the inclusion of an external cutoff “snoot”. These lamps are retrofits so most of the time they can be used along with a flexible set of accessories such as asymmetric lenses, spread lenses, diffusion filters, baffles, and window screens (to cut intensity when needed). These tools will come in handy because some LEDs project a more even light pattern but a few do not (Rosenfeld, 2011).

Two differences between incandescent lamps and LEDs are (1) while incandescent lamps drop in color temperature as they are dimmed, LEDs generally do not change color, and (2) LEDs unlike almost every other light source is “instant on”. The comment that LEDs do not change color when dimmed is *always true* for the type of dimming called Pulse Width Modulation (PWM). If the forward current through the chip is kept constant and only the duty cycle, or period the current is actually turned on, is varied, color remains constant for all types of chips. If the on-off cycle exceeds 120 Hz (above 300 Hz is often recommended), the human visual system is unable to detect any flicker, yet the eye still integrates intensity over time. This effectively dims apparent brightness. The percent of time the chips are “on” is linearly related to brightness. The second major method for dimming is to lower the current and LEDs do not change color when this is done *except* for the most important chip design in use with white phosphor LEDs – Indium Gallium Arsenide LEDs – InGaN. In one way this is a benefit since the bright blue InGaN chips can also be made to produce two new high intensity colors, verde and true green (Ott, Plotz et al. 2003). It has been reported that some white LEDs may appear bluer when dimmed (DOE 2011). The J. Paul Getty Museum tends to avoid all these issues by employing screens to hit their target illumination levels.

Color Rendering Index (CRI)

The Color Rendering Index, widely used within the lighting industry since 1965, is a metric that is sometimes misunderstood to represent “color rendering quality” in some absolute way. In fact, CRI has little to do with color quality, and at high or low values of correlated color temperature a CRI of 100 will be calculated when actual color fidelity or naturalness in appearance is questionable. It is also based on an outdated uniform color space. The red region is particularly non-uniform (Davis and Ohno 2005). For this and other reasons at least two other color metrics have been proposed recently to replace it (Ohno and Davis; Rea and Freyssinier-Nova, 2008). The CRI rather is a color matching metric that uses a set of 8 Munsell color swatches to estimate how closely a test light source will be to a reference source in color matching. For a test light source with color characteristics that place it on the blackbody locus (See “Color consistency” below and Figures 6 & 7) at 3000K, the CRI is computed against a theoretical blackbody at 3000K regardless of how good or how bad that reference source actually renders a specific color in the eyes of the beholder. The CRI has been adjusted to render a value of 100 if the color match of the Munsell reference color swatches is perfect between test and reference light sources. It is generally agreed that a CRI about 85 is suitable for display purposes. Many early LED products failed to achieve this target and often rendered some high chroma (i.e. highly saturated) colors dismally. Today the best quality white LEDs routinely measure above 90 and often above 95 when evaluated against a 3000K incandescent reference source.

Because LEDs, like fluorescent lamps, are not blackbodies that generate light with heat it is not strictly accurate to classify them by a blackbody color temperature. For this purpose Correlated Color Temperature is used to make this distinction. High CRI white LEDs often fall closer to the blackbody locus for a given CCT than some dichroic halogen lamps.

There are many reasons one might wish to have high CRI LED replacement illumination in galleries. But not all locations and lighting requirements in museums and archives necessarily demand it. Facilities managers can easily get by in food services areas, elevators, office spaces, machine shops, exterior walkways, general down lighting, cove accent lighting, and HVAC service areas using LEDs that meet less rigorous standards in CRI, luminous efficiency, or luminous output. A particular type of lamp may only be available in one format and for these less critical areas they would serve perfectly well. Furthermore, since CRI is not necessarily a reliable metric for color preference, the curator’s eye may find lower CRI LED products to be superior for their use in different circumstances. The Shelburne Museum completed an LED retrofit assessment employing MR16, PAR20 and PAR30 lamps manufactured by Sylvania and Philips, predicated their selection solely on aesthetics. The CRI metric was a secondary consideration. They settled on lamps with a CRI in the mid-80s.

Color consistency and appearance over time

Product consistency is a very important quality for a lamp that is expected to function for the majority of the next two decades. There is little point in demanding a high set of performance criteria if those criteria are not stable. Most light sources undergo a color shift as they age. Some fluorescent lamps are notorious for doing this and everyone has seen tungsten lamps brown out as they age. Figure 6 illustrated the blackbody locus, also known as the spectrum or Planckian locus. All blackbodies fall upon this line as a function of color temperature (and approximately real temperature). Figure 7 expands upon Figure 6 to show an area between 3000K and 7000K.

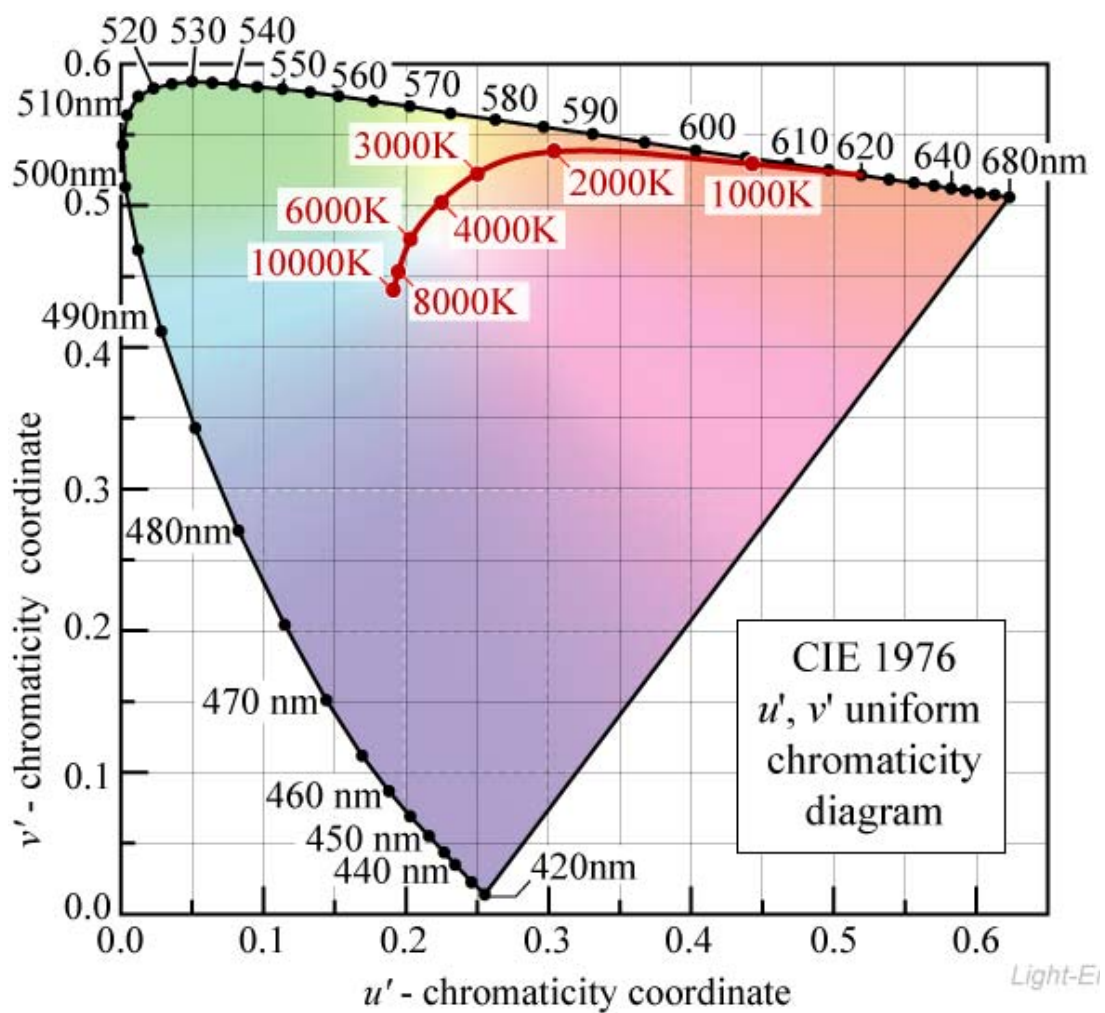


Figure 6. CIE 1976 u' - v' chromaticity diagram

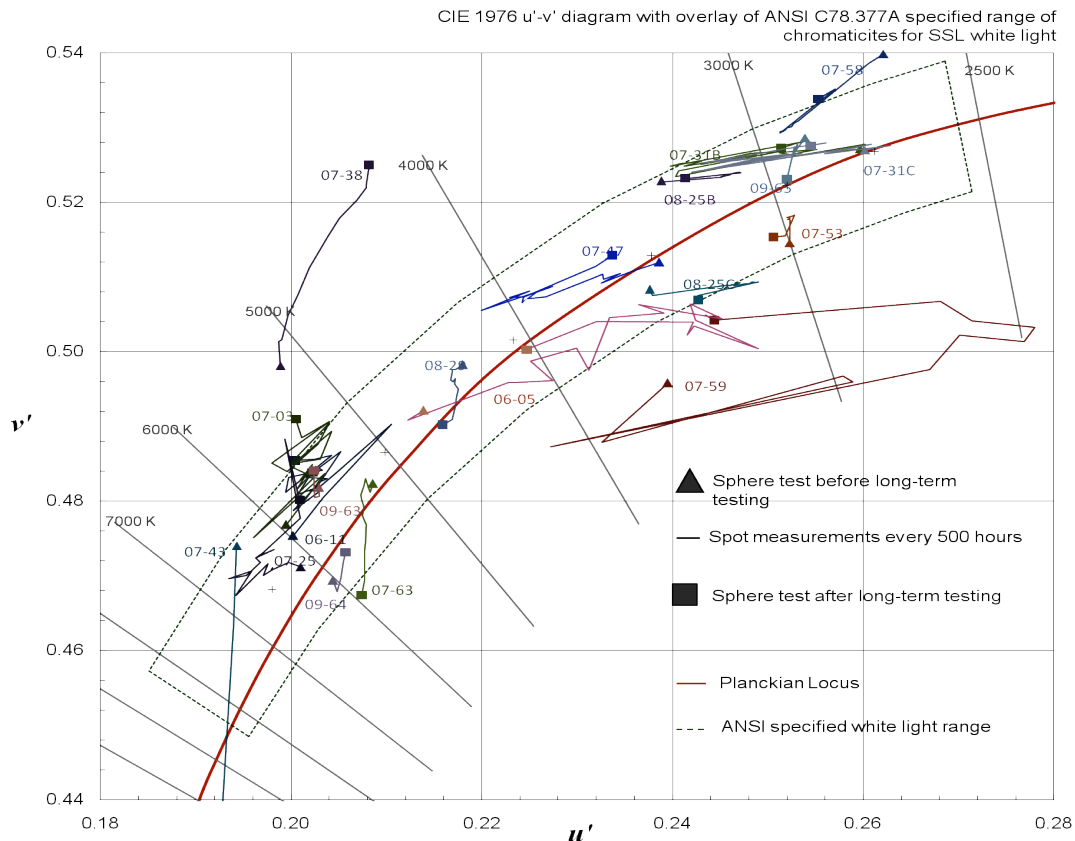


Figure 7. Enlargement of the $u'v'$ chromaticity diagram with several tested LED chips. (Source: DOE Caliper Program, <http://www1.eere.energy.gov/buildings/ssl/caliper.html>)

Figure 7 shows the repeated color measurements of about a dozen LED chips as they were measured every 500 hours. The curved quadrilateral flanking the blackbody (Planckian locus) represents an ANSI standard for acceptable variability. You will notice the presence of lines perpendicular to the locus. A light source positioned on one of those lines may be classified as that CCT no matter how far off the locus it actually falls. The distance off the locus on a given CCT line is called the Duv (Delta uv) and may be positive value (greener) or negative in value (pinker). This is why different products all look differently and why it is important that a specific product maintain its color appearance from lamp to lamp and over time. Figure 7 shows that some manufacturer's products can stay within ANSI specifications but some cannot.

Again we shall return to this point when it comes to selecting products and requesting color stability as a precondition to purchase. Early LED strip lighting often had slight variations in color along the strip that could be disconcerting. This problem has been solved for the most part by carefully matching individual LEDs (binning) as described above. It is still good advice to visually examine strip lighting for color consistency closely before purchasing the product.



Figure 8. Comparison of lamp designs

Form Factor (retrofit versus dedicated LED design)

Figure 8 illustrates three lamps, two filling the MR16 niche and the third is a PAR38. The smaller lamp on the right is a MR16 retrofit that will work in many halogen MR16 fixtures requiring the two-pin connection. (Be aware that the shape and size of LED MR16 replacement lamps can vary from manufacturer to manufacturer, and may or may not fit into a specific luminaire. Also, clips used to hold screens and lenses for halogen lamps may not fit all luminaires lamped with LED retrofits.) On the left is a lamp with a dedicated design (i.e. not designed as a retrofit) that requires an adapter for a pre-existing track or a custom track. In theory, an LED lamp can be more effectively designed to maximize performance if it is not given the added requirement of fitting into existing fixtures. The values that a dedicated design light source offers should be measured against the reduction in flexibility that comes along with it.

Another consideration when comparing retrofit vs. dedicated LEDs is heat management. LEDs retrofit products and their integral drivers are electronics, and heat is their Achilles heel. Existing tightly-enclosed track heads or luminaires, especially if there is glass blocking airflow, may cause the LED retrofit lamp to overheat and fail prematurely. Dedicated products should be designed with the proper thermal characteristics that will maintain the expected life of the electronics.

Cost and ROI Payback

Statistics on museum cost savings is sketchy due to the fact that at the time this guideline was written, comprehensive data on only one museum installation existed to draw upon. Nevertheless, the example of the Brooker Gallery at the Field Museum in Chicago, Illinois is still illustrative.

Display case illumination ranged from approximately 40 lux (4 footcandles) to a high of 370 lux (37 fc). This gallery was originally illuminated using 32 halogen track luminaires drawing 894W. They were replaced by 26 LED track luminaires supplied by Lighting Services, Inc. drawing a total of 335W. The annual operating schedule of the gallery was 2912 hours, making the two systems' annual energy use 2603 kilowatt-hours (kWh) and 975 kWh, respectively. The overall energy reduction was 63%. Table 3 shows the simple payback comparing a halogen system to the LED system.

As stated elsewhere in these guidelines, reduced heating loads from the cooler-operating LED lamps saved one watt off cooling costs for every 3 watts of savings from lighting. This is shown by the 2.38 years payback when lighting is combined with HVAC savings. However, the above scenario is representative for instances of new construction or renovation. More frequently a luminaire-for-luminaire replacement will have a payback ranging from 5 to 11 years. These scenarios also do not factor in scenarios involving lamp replacement using retrofits. The LSI LED system employed dedicated LED luminaire designs. Retrofits are designed to work within existing fixtures. Factoring in maintenance costs over time and the inevitable drop in LED costs in the near future – both of which are poorly modeled by simple payback analysis – retrofit payback will probably end up on the shorter side of those ranges. One area where *return on investment* (ROI) occasionally plays a role is in evaluating product warranties. Ideally, one would like to see warranty coverage exceed payback periods and if a museum conversion is large enough that could theoretically be reflected in the purchase agreement between the museum and the vendor.

The lamps used at the Field Museum were not retrofit designs but dedicated LED products in which fewer replacement lamps were needed. An LED retrofit lamp matched to the incandescent lamp it is designed to replace is a different situation and they are never a perfect one-to-one replacement. In replacing halogen lamps with LED MR16, PAR20, and PAR30 lamps, the Shelburne Museum estimated that it only needed one additional fixture for every ten to achieve the same balanced lighting. With the proper spread lenses the lumen distribution over the walls from the LED lamp was actually far superior.

	Halogen System	LED System
Total Initial Cost	\$ 7645.00	\$ 8216.00
Annual Hours of Operation	2912	2912
Operating Power of System	836	312
Electricity Operating Cost	\$292.13	\$116.99
Payback: Lighting alone (years)		3.26
Payback: Lighting + HVAC (years)		2.38

Table 3. Source: U.S. Department of Energy (2010), "Demonstration assessment of light-emitting diode (LED) accent lighting", Prepared by Pacific Northwest National Laboratory under Contract DE-AC05-76RL01830.

One factor that was experienced during the Field Museum installation, reported to be common with systems involving LEDs, is that as the LEDs were dimmed by the control system, the illuminance decreased but the measured current did not. This means that although the LED save significant energy, any further savings from dimming may be small.

Mature versus evolving technologies

One often hears that the reason for not adopting some technology, especially if it is expensive or contains a high resource barrier to exploit, is that the technology may be so new that if one waits, a better variant will surely appear on the horizon very soon. This excuse for inaction ignores the reality that what we call "a technology" is rather a large set of product development cycles that began at different times, will mature at different rates, and demonstrate different degrees of product durability in the market. White phosphor LEDs are a rapidly maturing subset of products that have among their

members, excellent products that when well-matched to their application should not need replacement. In 2010, U.S. DOE testing (CALiPER Round 10) saw an increase in larger, higher wattage products that might function better in higher ceiling applications. LED products are expanding rapidly into product areas considered impractical just a few years ago.

Final remarks on Glare

One remark that has occasionally been raised is that LEDs seem to introduce more potential for problems with glare. All lighting produces the potential for glare. But with solid-state lighting part of the solution comes from selecting lamps that minimize glare and part is in thoughtful lighting design.

Direct Glare is caused by high contrast between the lighting source and the background. When the source is especially small, like an LED, the glare potential is increased. The best method to decrease glare is to install a "cutoff" that shields the viewer from the light source. A 45-degree cutoff is ideal. The cutoff can take any number of shapes from a shallow hex-cell louver, to a simple snoot (tube). For most museum applications the cutoff should be painted matte black. It is inherently difficult to produce a wide beam light that is low glare; a common solution in museums is to use narrower beam lamps (25-35 degrees) and install them at regular intervals (every 3-6 feet depending on the ceiling height). Another method to reduce glare is to increase the surface area of the illuminant. This is a guiding principle in office design but some lighting designers feel that for museums it may be a flawed strategy. In museums you might find that spotlights are often more prone to glare because the surface area of "the bright spot" is smaller as compared to floodlights - this might be counterintuitive because the spotlights produce a more collimated light

Approaching the problem from a design standpoint, the lighting designer needs to know where the viewer is most likely to be standing and at what points they are looking. Keep in mind the viewer may be standing at a large number of points in the gallery. You now know a series of viewing directions. Next you know where the artwork is and where the light fixture can potentially be located. The trick of the lighting designer is to locate that light fixture and aim it toward the art so that it illuminates the art in an appropriate way, but at the same time the bright part of the light source is not visible to the viewer or multiple viewers. The designer also worries about reflected glare from any shiny surfaces, including reflections from shiny oil paint or protective glass on the art, or glass case surfaces. As mentioned above, it is easier to control glare if you are lighting the object with more narrow beams of light, because you can anticipate the reflective angles more precisely, and hence the glare locations. That is the reason why the Cree LRP38 is easy to use for display lighting: The beam is pretty accurately contained within the 20 degree beam because there is no exposed filament or LED that sends uncontrolled light into any angles outside that 20 degree beam. That is the beauty of the halogen AR111 lamp, as well. The filament shield blocks the stray light so that all you get out of the lamp is the luminous intensity that is forced to bounce off the reflector into the intended beam angle.

Glare may be in the eye of the beholder but the solution is clearly in the mind of the lighting specialist.

LED Decision-Making In a Nutshell

- ❖ LED lighting contains no ultraviolet and little infrared. They are warm to the touch in spite of some industry claims that they produce no heat so consider carefully how they might be used inside enclosures.
- ❖ To save the most energy (and reduce cost of operation), insist on high *luminous efficacy*. 40 lumens/watt is a good starting point. Lower than this, cost savings will be marginal.

- ❖ To illuminate areas with a more utilitarian such as machinery, many science exhibits, food services, hallways, educational activities, etc. settle on a color rendering index (CRI) above 80. When color matching may be more an attentive activity such as viewing art, ethnography, some natural history collections exhibits, etc. select LEDs with a CRI above 90. However, because CRI is an imperfect metric, CRI should be considered a target, not a firm criteria.
- ❖ If you wish to replace tungsten, tungsten halogen, or an equivalent fluorescent lighting and you prefer your lighting a little warmer, select a color temperature between 2700K and 2800K; for preferences a little cooler or “whiter,” pick 3000K. Generally avoid higher color temperatures for light sensitive materials as these LEDs may have an unacceptably large peak in the “blue region” of the spectrum.
- ❖ Be cautious of color temperature and CRI claims because lamp-to-lamp consistency may not be adequate. Agree with vendor on your right to have replacements lamps supplied when consistency is inadequate out-of-the-box or a lamp changes color during operation.
- ❖ Ask your facilities manager to acquire and review LM-79 reports from lamp manufacturers. Have him/her look for a positive D_{uv} specification greater than 0.006. These lamps may introduce a greenish appearance and should perhaps best be avoided.
- ❖ Look for any GATEWAY project reports from the U.S. Department of Energy (DOE) that describes a solid-state re-lamping project in an art museum. Contact that institution and ask for their recommendations. Visit them if possible.
- ❖ Once you have made preliminary decisions on several candidate lamps look at all of them yourself.
 - Check color rendering on your own skin
 - Try dimming it with recommended dimmer and specified transformer
 - Check for flicker in undimmed and dimmed state.
 - LED strip lighting should be dimmable to provide a high level of control in compact space. Dimming may extend lamp life but flicker could be a problem. Check this carefully.
- ❖ Most large, brand-named lighting companies supply high quality products but they also supply poor ones. Make no assumptions of quality based on brand alone. Many smaller companies are motivated to provide good support.
- ❖ Don't compromise too easily if a given manufacturer does not have the right lamp for you (beam angle, lumens, type of lamp). There are many good products in the marketplace that cover a range of uses and another manufacturer's products may fit your need better. You can expect to find many MR16, PAR30, PAR38 and A-lamps offered.
- ❖ Retrofit lamps are easiest to install in existing tracks and fixtures. But don't discount lamps with a dedicated or unique design and shape. Some of these only require an adapter to fit an older track or one from another manufacturer.
- ❖ If you are going to be dimming your LEDs confirm that the method of dimming is compatible with the LED chip and driver used. No LED will change color upon dimming when the technique used is pulse width modulation (PWM), but some PWM techniques can introduce flicker. White phosphor LEDs may change color if dimming is accomplished in the same manner as with incandescent lighting – reducing the line voltage.

- ❖ Know what your product warranty covers. A one-year warranty is common but for longer periods of time coverage may be limited to a catastrophic failure of the LED chip. Failure of ballasts and drivers may not be covered at all. Consider the return on investment payback (ROI) period. You may be satisfied if ROI payback is less than the warranty period. Warranties exist that cover major failure, significant loss of luminosity and any visible change in color temperature for up to 25,000 hours.

SECTION 2: Making the Decision: Which LEDs Products to Buy

REVIEW

Ever increasingly, museum, library and archives are being asked to consider steps that will reduce their energy needs. Sometimes the motivation is simply budgetary but often it is linked to larger pressures to reduce the overall institutional carbon footprint. Nowhere is this more visible than institutions operated by universities, government agencies, or in regions where new laws have been passed mandating such changes by a specified date. One area of focus is in lighting. Conservators, registrars, and curators are being asked to consider whether or not lighting can be switched to LEDs.

White phosphor LEDs can be used in cultural institutions for virtually any purpose but the requirements will vary between areas with different functions. Sources used for display lighting in art galleries will tend to have color rendering index values higher than 90 and CCTs between 2700K and 3000K. This makes the transition as inconspicuous as possible as LEDs replace incandescent lighting. Given the costs of a solid-state lighting switchover, galleries may be phased in on a schedule and one may wish to reduce the differences in appearance of adjacent spaces.

Since one application might be to augment general gallery illumination from existing skylights when the daylight contribution is low, the color targets may be relaxed to employ lamps with higher correlated color (such as 4000K to 6000K), closer to some form of daylight.

Keep in mind that color metrics do not always match human perception and should be considered guidelines rather than rigid criteria. Sometimes the displayed objects look better under a lower-CRI lamp. And museum staff interviews suggest that a lower CRI is difficult to quantify particularly in the absence of highly chromatic (strong hues) colors. The Brooker Gallery at the Field Museum in Chicago (See *Cost Payback*) converted to 80 CRI LEDs rather than use LEDs with CRIs near 95. The museum staff were split on the question of how accurate the subject colors were rendered, with 11 responding that “some” colors were accurate and 14 responding that “most” or “all” were accurate. This type of statistical distribution is very common and may indicate nothing more than a random scatter of preferences that could have occurred even with a higher CRI light source. The Shelburne Museum also settled on LEDs with a CRI in the mid-80s based solely on the curatorial judgment of how well the objects looked in a historical house setting.

READ

After you have reviewed your own requirements for establishing a solid-state lighting effort in your institution, whatever the proximal motivation, you’ll wish to review some of the powerful resources available from various government agencies on the Internet.

One of the most extensive sets of resources in North America is the U.S. Department of Energy (DOE) solid-state lighting program. This program is broad in scope:

- ❖ Development of product standards and specification
- ❖ Product testing (CALiPER)
- ❖ Development of fact sheets, product labeling, and educational materials
- ❖ Product design competitions
- ❖ GATEWAY demonstrations

We will not describe these resources in detail. Many of them are more appropriately used to assist designers and other consultants in making thoughtful decisions for clients. We will briefly list their values.

Product Testing (CALiPER)

Solid-state lighting (SSL) technologies today are changing and improving rapidly, and products arriving on the market exhibit a wide range of performance. There is a need for reliable, unbiased product performance information to foster the developing market for high-performance SSL products. The DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) program supports testing of a wide array of SSL products available for general illumination. DOE allows its test results to be distributed in the public interest for non-commercial, educational purposes only. Detailed test reports are provided to users who provide their name, affiliation, and confirmation of agreement to abide by DOE's NO COMMERCIAL USE POLICY.

IES LM-79

These reports comply with standards of measurement in conformance with the Illuminating Engineering Society of North America (IESNA) and are directed toward LED-based products incorporating control electronics and heat sinks. Most lamps, since they are integrated sources, are covered under these procedures. These are independent laboratory measurements of total flux, electrical power, efficacy and chromaticity. Figure 8 illustrates this data in an MR16 retrofit lamp. The LM-79 report does not cover lamp performance over time. An approved method for documenting lumen depreciation of solid-state sources, arrays, and modules is contained in a separate report called an LM-80.

IES LM-80

This report measures the luminous flux of LED products under continuous operation. Three temperatures are employed 55C, 85C and a third temperature selected by the manufacturer. Since LED products used in general illumination have not been in existence for as long as their functional lifetime is expected to be, a minimum period of testing was set for 6,000 hours with 10,000 hours preferred and repeated every 1,000 hours. Since the LM-80 only documents lumen maintenance for the period of time it is conducted a separate estimate method for lifetime (TM-21) is in development. Both these types of reports should be available on the manufacturers website or by request. Many are also available on the U.S Department of Energy website.

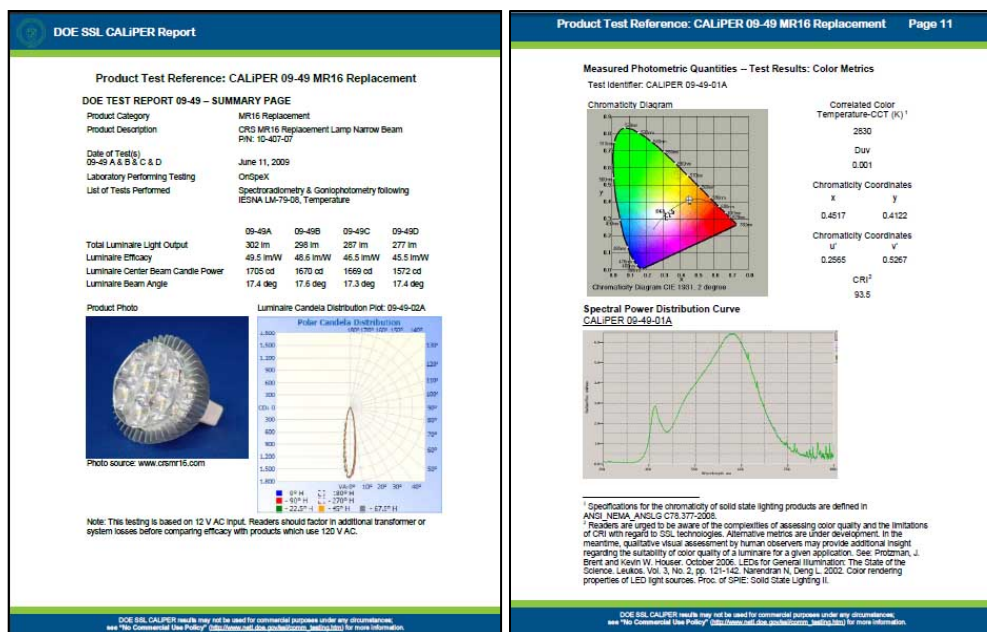


Figure 9. Sampling of the type of information available from an LM-79 report

GATEWAY Demonstration

This program supports demonstration projects of high-performance solid-state lighting (SSL) products. The purpose is to capture empirical data and experience with in-the-field applications that save energy, are cost effective, and maintain or improve light levels in the tested lighting application. An important outcome focuses on providing a source of independent, third-party data for use in decision-making by a diverse group of users and lighting designers with similar requirements and lighting challenges. The GATEWAY program staff realizes that this data should be considered in combination with other information relevant to the particular site and application under examination. This is understood fully when it comes to museums and other cultural institutions. (U.S. DOE, 2010)

The GATEWAY program has documented one small museum-based application to date at the Field Museum, Chicago Illinois, November 2010. Other museums are being considered including several art museums. Since all reports can be downloaded off the Internet this is a good place to begin examining the issues you're likely to also run into. The evaluation questionnaire and the analysis of simple payback from the Field Museum has been adapted and included in the present guidelines.

Lighting Facts Labels

This label is sponsored by the U.S. Department of Energy (DOE) to assure and improve quality in LED products. For the average consumer it de-mystifies technical performance reports like the LM-79 and can be found on the boxes of lamps made by companies that partner with DOE. Figure 9 is an example. It shows light output, watts, luminous efficacy, the color rendering index, the correlated color temperature and importantly, it shows that these results were obtained by a third part approved test method (IESNA LM-79-2008). Not shown in this figure would be three additional lines of text that indicate the registration number, model number, and type of lamp for which these test results apply. At the start of 2011 there were 231 partner manufacturers covering 2594 products.

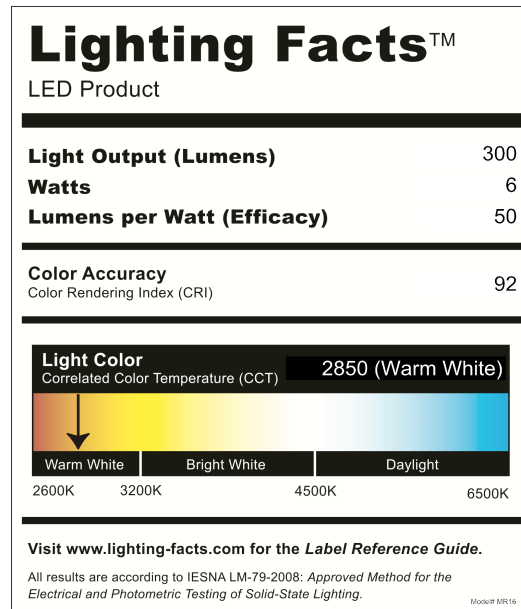


Figure 9. DOE Lighting Facts label.

LOOK

A visual assessment should be carried out using the type of objects that would be illuminated under accurate exhibition conditions including the lux levels that would be anticipated. Constant levels of illumination are important because higher illuminance can shift the perception of hue (Bezold-Brucke effect), and different spectra for two light sources with the same chromaticity can influence the perception of brightness (Helmholtz-Kolrausch effect). An example of why lighting design is important is provided by Boyce describing one of the few examples in the literature directly pertinent to museum display. Mangum carried out an assessment of a doll dressed in materials that varied in color, texture and reflective properties at 50 lux. Observers were asked to report their perceptions of the object selecting descriptors from either a word list of positive impressions or a word list of negative ones. When the lighting was diffuse, the most frequent responses included “unattractive, unpleasant, obscured, veiled, bland, boring, mundane and ordinary”. When the lighting used key-light, side-light, or back-light techniques, conditions that changed higher order perceptions, the descriptions shifted to “interesting, attractive, eye-catching, clear, pleasant, revealing, dramatic, and spectacular” (Mangum 1998). Boyce further informs us that for simple perceptions the greatest perceptual stability when making these kinds of observations occurs when there is the least opportunity for factors like past experiences and knowledge to come into play. For higher order perceptions using semantic differential rating scales can be misleading and should be interpreted understanding this risk (Boyce 2003).

Some thought should also be given to wall color. An ASTM specified neutral gray is commonly used as background for color illuminant psychophysical testing. For some people it is easier to see illuminant color knowing that the background color is neutral when two illuminants can be seen side-by-side. It is also recommended that a white card be included (Foamcore®) and a series of color swatches like the Munsell Color Checker®. The assessments could be,

- ❖ Assessment without comparison
- ❖ Assessment with single comparison
- ❖ Assessment with multiple comparisons.

Assessment without comparison, would incorporate a single type of lamp on test materials and museum staff responding verbally, or written, to a set of survey questions. Complete chromatic adaptation is assumed and judgments would be influenced by *color memory* (and color bias), *color constancy*, and *discounting the illuminant*. (See Fairchild, 2005)

Assessment with single comparison, might involve one wall illuminated with a single type of LED lamp and another wall only with the reference lamp, likely to be halogens. Chromatic adaptation is imperfect and this method allows the assessors to more fully visually estimate how close the two sources of illumination in color.

Assessment with multiple comparison, might involve up to three test illuminants and one reference condition on a small scale followed by assessment with single comparison of the LED that was found most desirable to the largest number of assessors.

These assessments can be done with as few or as many individuals as one wants to include. There is no “right” or “wrong” answer and the statistics are not intended to be used to model a larger population. Rather the function of such an assessment is to derive consensus among the many stakeholders in an institution on switching to a new form of lighting that will nevertheless closely match the lighting scheme it is replacing. The range of stakeholders should be broad in term of age and experience. A broad age demographic is often easily met by sampling both interns and docents and experience met with curators, conservators and registrars. Although those who set up the assessment conditions know the nature of all the lighting, it is preferable to get opinions from assessors with a little knowledge of the assessment as possible, although they will undoubtedly guess, in many instances correctly, which lights are LEDs and which are the halogen comparison lights. Remember, a gallery may not look the same during the day compared to the evening and it is important to recreate the overall setting as accurately as possible. One important reference on museum lighting affirms the importance of having assessors fully adapted to the test source and along with using such tools as the ColorChecker look for the “naturalness of color appearance (Cuttle 2003).

The following shows a series of test questions that have been adapted from the survey conducted at the Field Museum by staff of the Pacific Northwest National Laboratory under contract to the U.S. Department of Energy after a halogen-to-LED swap.

- (1) *The uniformity of light across the target is:*
Unacceptable/Poor/Fair/Good/Excellent/No Response
- (2) *The color temperature of the lighting in this gallery is:*
Much too High/Too High/Just Right/Good/Much too Low/No Response
- (3) *The visible variation in color temperature among the different luminaires is:*
Not Noticeable/Barely Noticeable/Slightly Noticeable/Noticeable/
Very Noticeable (Unacceptable)/No Response
- (4) *Glare from the light is:*
Disabling/Annoying/Noticeable, But Acceptable/Lower than Most/
Nonexistent/No Response
- (5) *The lighting product shows _____ of the subject colors accurately.*
None/Some/Most/All/No Response
- (6) *This product shows _____ of the subject forms clearly.*
None/Some/Most/All/No Response

- (7) *Overall, the lighting in the gallery is:*
Too Bright/Somewhat Too Bright/Just Right/Somewhat Too Dim/
Too Dim/no Response
- (8) *The artifact colors look _____ rich/saturated.*
Very/Somewhat/Slightly/Not At All/No Response
- (9) *The suitability of the lighting system for this gallery is:*
Superior/Good/Adequate/Marginal/Inadequate/No Response
- (10) *The overall impression of the gallery under this lighting is:*
Exceptional/Favorable/Adequate/Inadequate in some respects/
Unacceptable/No Response

For these questions one simplifying assumption was made in questions 2 and 3, that all visible color differences in illuminants be attributed to color temperature alone rather than color temperature and/or Duv. This distinction is not thought worthy of making for the purposes of this assessment.

One additional distinction should be made. It is assumed that light sources be judged on an equal correlated color temperature basis. Some manufacturers supply LEDs both at 2700K and 3000K for incandescent replacement. There have been some experiences conducted on limited field trails that individuals may have strong opinions viewing color temperature with this degree of separation with preferences going in both directions. Therefore this assessment should be made independently of different products with the same correlated color temperature.

These suggestions have been made to offer ideas as to how you might conduct your own evaluations in deciding which products to use or not use. The assessments may be as complicated or as simple as you want to make them and we reiterate that this activity is to help you make a decision and derive mutual agreement.

AGREE

There are two ways museum stakeholders can insure and agree on protection against failure to achieve expected performance in lighting – building commissioning and product warranties.

In the section entitled “LOOK”, the assumption was made that the users of the illuminated facility would be making the assessments of solid-state lighting themselves and passing judgment on what type of lighting is acceptable and what lighting is not, or less so. But in a major capital project involving HVAC systems, plumbing, security, life/safety requirements, and many other new construction or major renovation subsystems, the ability to accomplish those assessments for lighting is made more complex and remote. A “test mock-up” may be presented early on, then after full installation and final overall spatial perception differs from what the test promised. Also different spaces have work functions championed by unique groups of users that carry out evaluations and performance specification independently. Subsystems can be installed that do not meet original expectations. Recently, this risk has been addressed in the architectural and construction industries by introducing the idea of “building commissioning”.

Building commissioning involves the insertion of a commissioning agent as a third-party consultant who works closely with architects, engineers, users, and contractors to insure the highest quality product possible consistent with the user’s specifications. In spite of the added costs, this party can be especially useful during the practice of value engineering particularly when a competing objective is

economic sustainability during long-term operations. Realize that the in-house Building Committee or Museum Board of Trustees, the architect/engineers, and the contractors are all defending their own self-interests. The commissioning authority is best thought of as defending the interests of the project itself.

A warranty is only one of many pieces of information you will need to make an informed decision and it may not be the most important for some people. But before purchasing anything review the written warranty and know what it covers. Warranties may range from as little as 90 days to ten years. One example specifies a qualified ten-year period with only the LED chip covered between years five and ten. If a mechanical or electrical part fails before that period the company may be under no obligation to replace it. A three or five-year warranty is not uncommon.

These warranties may offer poor consolation if they do not cover color consistency (See the *Color consistency and appearance over time* in Section 1) which is arguably the most critical performance parameter for an art museum. An LED installation may deliver a beautiful 3000K illumination at the start of life and shift to a lovely shade of magenta at eight “just noticeable differences” (JND) in three years. When the client protests they may learn their warranty contained no specific qualifier in terms of performance criteria and as far as the warranty coverage is concerned – as long as the LED turned, on it is performing fine. Nevertheless, some manufacturers do take their responsibilities and reputations very seriously and if a museum has a color quality performance issue within a 3-5 year period the manufacturer reserves the right to decide if replacement is justified even if that is not specified in the warranty.

One of the biggest difficulties with performance criteria in warranties is specifying the level of performance (mean value and acceptable level of variation), specification on how to monitor the criterion, and operational limitations. Few institutions are capable of monitoring total lumen output or illuminant color and the same retrofit lamp that performs well in a well-ventilated track luminaire may fail from overheating in an enclosed down light. In addition, some transformers are electronic and some are magnetic. Some have low minimum loading requirements and operate poorly with low-wattage LED replacement lamps. Some may cause color shift or flicker or unstable output, depending on circuit design. These potential incompatibilities between transformer and retrofit lamp are often difficult to anticipate, so it is important to test out the lamp in situ for more than a week to ensure it will behave as expected.

Some institutions have worked around warranty concerns by determining that the *return on investment* payback (ROI) is shorter than the warranty period. If L70 is 50,000 hours (70% loss of luminous intensity which is considered a standard end of life performance level) the more important value is that under a worse case scenario the lamp does not cost more than failure would cost otherwise without LEDs.

A suggested outline for a warranty review would be:

- ❖ What is the stated warranty period and is it for a specified quality and quantity of light.
- ❖ What does the warranty cover? Is it all-inclusive or do you need to read the “fine print” to discover what it does not cover.
- ❖ What are the agreements or pass-through warranties on the main components such as LED chips, LED packages, drivers or other components such as active cooling systems.
- ❖ What is the reputation or history of the company? Who do you call if something goes wrong?
- ❖ What will be replaced or repaired in the event of a warranty claim? As technology changes rapidly, will an acceptable replacement in five years or an equivalent product be available?

In conclusion, good warranties can be found. The best we have seen when framed in the context of an art museum is for LEDs warranted against manufacturers' defects for lamps operated on a daily cycle (12-14 hours/day) for five years or 25,000 hours whichever comes first. But beyond lamp failure, they are also warranted for five years or 25,000 hours if any bulb exceeds 15% lumen depreciation (becomes dimmer) or shifts in color temperature more than +/- 100 Kelvin. To avoid the difficulties described earlier on validating performance loss, this manufacturer maintains records on each lamp.

One last piece of advice on warranties applies specifically to LED strip lighting. Insure that the warranty covers the product as a whole *system*. Drivers and transformers are not bundled into a single package like a PAR38 would be. It is possible to mix components that will not perform well together.

Recap: Getting the Most Out of Your LED Products

- ❖ See it before you buy it and preferably see two or three installed.
- ❖ Require LM-79 testing for information on performance
- ❖ Evaluate lumens, lumens/W, beam spread
- ❖ Check DOE CALiPER website for impartial test data
- ❖ Use on non-dimming circuits, or test out LED, driver, transformer, dimmer, and loading of dimmer and transformer to be sure they all work together for smooth dimming
- ❖ Specify products from companies you know or whom you trust, or that have a documented support history
- ❖ Get a written warranty that includes light output and color variation performance, labor included
- ❖ Check for EPA EnergyStar® rating (Miller & Druzik, 2011)

Sources for Solid-State Lighting Products Described in this Document

CREE LED Lighting, 635 Davis Drive, Suite 100, Morrisville, NC, USA 27560
Customer Service: Phone: (919) 991-7700 Fax: (919) 991-0730
Email: info@cree.com <http://www.creeledlighting.com/>

CRS Electronics, 129 Hagar St. Unit 5, Welland, Ontario, Canada, L3B5V9 Phone: (905) 788 9039 - Toll Free: 1(888) 330.6786 - Fax: (905) 788-2739
<http://www.crselectronics.com/>

ERCO Lighting, Inc., 160 Raritan Center Parkway, Suite 10, Edison, New Jersey 08837 USA
Phone: (732) 225-8856
http://www.erco.com/homepage/homepage/start/en/en_start.php

Juno Lighting Group, (Canada): (905) 792-7335 (USA): Phone: (800) 367-5866
<http://www.junolightinggroup.com/>

Lighting Services Inc. 2 Holt Drive Stony Point, NY 10980-1996 USA
Phone: (845) 942-2800 USA & Canada: (800) 999-9574 Fax: (845) 942-2177
Email: Applications@mailLSI.com <http://www.lightingservicesinc.com/>

MSi, Solid State Lighting 1342 South Powerline Road Deerfield Beach, FL 33442 Toll Free: 888 - 778 - 9864 Local: 954 363-1085 Fax: 954 971-3725
Info@MSIssl.com <http://www.msissl.com/>

OSRAM Sylvania, Phone: (978) 750-2763 (Professional Series LED Products)
<http://www.lightsmanufacturer.com/2011/04/osram-sylvania-introduces-professional-series-led-bulbs.html>

Philips Lighting U.S., 200 Franklin Square Drive, Somerset, NJ 08873. Phone: 1 (800) 555-0050 <http://www.usa.lighting.philips.com>

Small Corp, 19 Butternut Street, I-91 Industrial Park, Greenfield, MA, USA 01301 Phone (USA): (800) 392-9500 Phone (Canada): (413) 772-0889
Fax: (413) 773-7386 Email: info@smallcorp.com ATTN: Mike Dunphy
<http://www.smallcorp.com>

Solais Lighting, Inc. 470 West Ave. Stamford, CT 06902-6359
Phone: (203) 683-6222 Fax: (888) 232-1086 Email: info@solais.com
<http://www.solaislighting.com/>

Xicato USA: Ron Steen, (847) 525-5048 ron-steen@xicato.com
<http://www.xicato.com/>

U.S. Department of Energy Internet Resources

CALiPER Program. Product performance information: Summary reports, detailed test reports, benchmark reports, and CALiPER testing laboratories.

<http://www1.eere.energy.gov/buildings/ssl/caliper.html>

CALiPER's Searchable Database

<http://www1.eere.energy.gov/buildings/ssl/search.html>

CALiPER Benchmark Reports: Testing of traditional lighting products against LEDs for a given application.

<http://www1.eere.energy.gov/buildings/ssl/benchmark.html>

The most recent Round 9 Caliper report (long term testing/Reliability)

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round-9_summary.pdf

Color Rendering Index and LEDs

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/color_rendering_index.pdf

Color Quality of White LEDs

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/color_quality_of_white_leds.pdf

LED Lifetimes

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lifetime_white_leds.pdf

LED Luminaire Reliability

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/arik_luminaire_raleigh2010.pdf

Understanding Photometric Reports for SSL Products

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/understanding_photometric_reports.pdf

Energy Star Criteria for SSL

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/portland2008_energystar_fs_0508v2.pdf

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/energystar_08fs.pdf

DOE GATEWAY Demonstration Reports

http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_results.html

Next Generation Luminaires—Design competition winners

<http://www.nglc.org/09/winners.stm>

Status of the L Prize Competition: Early 2011

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lprize_competition_2011.pdf

Materials and reports of DOE Solid-State Lighting Workshops

<http://www1.eere.energy.gov/buildings/ssl/presentations.html>

Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010 to 2030

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_10-30.pdf

Formulating an Institutional Lighting Policy

You will have noticed that these Guidelines do not involve themselves in lighting policy. The reasons for that are many, but the strongest one is that the best place to go for additional information towards building a comprehensive light policy is the website of the Canadian Conservation Institute and the link below is provided for that purpose.

<http://www.cci-icc.gc.ca/crc/articles/mcpm/chap08-eng.aspx>

Bibliography

Bohan, Suzanne, (2011), "Mercury in unrecycled CFL's takes a toll on environment" April 7, Los Angeles Times. (May need to confirm statistics given here with EPA website, etc.)

Dawson, T. (2010). "Development of efficient and durable sources of white light." Color. Technology**126**: 1-10.

Davis, W. and Y. Ohno (no date). Toward an improved color rendering metric. Fifth International Conference on Solid State Lighting. I. T. Ferguson, J. C. Carrano, T. Taguchi and I. E. Ashdown. **Proc. of SPIE Vol. 5941**.

Fairchild, M. D. (2005). *Color appearance models*. Rochester, New York, John Wiley & Sons, Inc.

Ishii, M., T. Moriyama, et al. (2008). "Color degradation of textiles with natural dyes and of blue scale standards exposed to white LED lamps: evaluation of white LED lamps for effectiveness as museum lighting." J. Light & Vis. Env.**32**(4): 8.

Miller, N. J. and J. R. Druzik (2011). "Solid-state lighting in Museums: Conserving energy, conserving art", Presented at the National Archives and Records Administration 25th Annual Preservation Conference, University of Maryland Conference Center. March

Rea, M. S. and J. P. Freyssinier-Nova (2008). "Color rendering: a tale of two metrics." COLOR: Research and Application**33**(2): 193-202.

Rosenfeld, Scott, (2011) personal communication. Lighting designer, Smithsonian American Art Museum.

United Nations General Assembly (1987) "Report to the World Commission on Environment and Development: Our Common Future". Transmitted to the General Assembly as an Annex to document A/42/427 – Development and International Co-operation: Environment.

U.S. Department of Energy (2010), "Demonstration assessment of light-emitting diode (LED) accent lighting", Prepared by Pacific Northwest National Laboratory under Contract DE-AC05-76RL01830.

<http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html>

Boyce, P. R. (2003). Human factors in lighting. London, Taylor & Francis Group.

Brodrick, J. (2011). Can museums measure up? LD+A. New York, Illuminating Engineering Society of North America. **41**: 50-55.

Cuttle, C. (2003). Lighting by design. Oxford, Architectural Press, Elsevier Science.

Davis, W. and Y. Ohno (2005). Toward an improved color rendering metric. Fifth International Conference on Solid State Lighting. I. T. Ferguson, J. C. Carrano, T. Taguchi and I. E. Ashdown. **Proc. of SPIE Vol. 5941**.

DOE, U. S. (2011). "LED Application Series: Dimming LEDs." from <http://www.netl.doe.gov/ssl>
<http://www.eere.energy.gov>.

EPA (2011). "eGrid2010 Version 1.1." from http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2010V1_1_year07_SummaryTables.pdf.

Mangum, S. R. (1998). "Effective constrained illumination of three-dimensional, light-sensitive objects." J. Illum. Eng. Soc., **27**: 115-131.

Ott, H., L. Plotz, et al. (2003) Dimming InGaN LEDs: Application Note.