From: Steven Weintraub, Art Preservation Services, Inc.
To: The Green Task Force, American Institute for Conservation
Submitted: April 28, 2010
Subject: Comments regarding LEDs and the risk to light sensitive materials

At the request of the AIC Green Task Force, I was asked to provide information on damage assessment and color rendering properties of illumination sources in order to address concerns and questions raised in a letter and posting submitted to the Green Task Force by Dale Kronkright entitled *Extreme caution urged when considering LED's for illumination of light-sensitive materials*.

Light Sources: Same Brightness, Different Results

In a supplementary note to the *Extreme Caution* posting, the author notes "*that 50 lux, 65 lux or any light level from an LED source is NOT the same as 50 lux, 65 lux, etc. from an incandescent source. The spectral power distributions are different.*" This is correct. Differences in relative radiant intensity or power of wavelengths within the visible, UV and IR regions give rise to different properties of illuminants, including:

- Damage potential
- Color temperature
- Color rendering index
- Color rendering properties

The two concerns raised in the posting deal with the relative damage potential of LEDs and tungsten halogen lamps measured at constant illuminance and the relative quality of their color rendering properties. Although research and new knowledge about risk is always welcome, there is already a great deal that we know that can be applied to the question of LEDs versus tungsten halogen lamps. The purpose of this communication is to describe current knowledge and how it applies to the question of damage (Part 1). There is a brief section on color rendering (Part 2) which will be dealt with more comprehensively in a future communication.

SUMMARY OF KEY CONCLUSIONS

- Damage calculations predict that a warm white phosphor-based LED has a lower damage potential and is therefore less damaging than a UV-filtered tungsten halogen lamp.
- Low to intermediate color temperature white phosphor LEDs (2700°K-4000°K) and tungsten halogen lamps are safe if used at an appropriate light level for museum applications.
- The quality of some of the better white LEDs, particularly those with a high color rendering index (CRI), are appropriate for museum applications.
- An illuminant with a high CRI does not mean that it is a good color rendering source. For example, a tungsten halogen lamp has a very high CRI of 99 but it has poor color rendering characteristics for colors on the blue or cool end of the palette.

PART 1: DAMAGE

Relative Damage Factor

In the early 1950s, with the rapid growth of fluorescent lamps as a general light source, a great deal of concern was raised about the potential damage to light sensitive museum collections from fluorescent lamps compared to incandescent lamps or UV filtered daylight, not unlike today's concern about LEDs. In 1953, the Metropolitan Museum of Art hired a lighting engineer, Lawrence Harrison, to study this issue. Harrison analyzed the potential hazard of different types of light sources, building on data and the method of analysis developed several years earlier by the National Bureau of Standards (NBS), now known as the National Institute of Standards and Technology.

Scientists understood that for equal amounts of radiant power, the shorter wavelengths of light (UV-blue region) should have more potential to cause damage than longer wavelengths (red-IR region) since longer wavelengths of light have less energy. The NBS team exposed low-grade paper to a full range of wavelengths in the UV and visible region and measured damage to determine the relative damage potential of each wavelength.

In order to assess and compare the damage potential of different types of light sources, the NBS and Harrison calculated an illuminant's "relative damage factor" as follows:

- Multiply the amount of power per wavelength for a light source by the NBS derived damage potential for that wavelength. This value describes the relative contribution to damage for each wavelength for a specific light source.
- Multiply this result by the relative sensitivity within the visible spectrum for each wavelength, defined as the photopic luminosity function $V(\lambda)$. This value describes the relative contribution to overall brightness of each wavelength in proportion to its power and damage potential.
- Total up the values calculated in the previous step. This sum is the total damage potential for the source.
- Finally, by knowing the illuminance (lux or foot candles) of the source, divide the sum by its luminous intensity to determine the relative damage per lux or foot candle for the source.

Harrison's results were fascinating. It turned out that a high color temperature source like daylight, filtered to remove all UV and IR radiation, had three to four times the damage potential of an incandescent lamp.

In the 1970s-1980s, a group led by Krochmann reassessed the NBS work. They used a large range of light sensitive materials. Their results reconfirmed the NBS work for low-grade paper. For materials that were more photochemicaly stable, including, rag paper, oil on canvas, textiles and watercolors on rag paper, damage per radiant unit of light exposure increased with a decrease in wavelength, but at a slower rate compared to low-grade paper. Follow-up work by Saunders and Kirby in the 1990s showed similar results. They also observed that damage is reduced in the wavelengths where the object has the highest reflectance value, since less radiant energy is absorbed in this region.

All of these studies were assimilated and published by Cuttle in 1996 and were embodied within the Commission Internationale de l´Eclairage (CIE) Museum Report entitled *Control of Damage to Museum Objects by Optical Radiation* (CIE 157:2004) .

In sum, the damage curves described in the CIE report provide the best (and so far, the only) basis for assessing damage based on the unique spectral distribution of any light source. It is essential to note that each light sensitive museum artifact has its own unique risk characteristics. However, it is not possible to characterize the unique photochemical risk of each and every object in a museum. The CIE report, building on the previous studies cited above, provides a useful basis for characterizing general risk for a broad range of materials based on wavelength distribution. It is important to continue this line of research and refine the approach. However, even in the absence of more current research, the Krochmann-based damage values described in the CIE report provide a valid basis for risk assessment. Their calculations take into account the higher damage potential of shorter wavelengths, an essential factor that must be considered when comparing the potential hazard of different light sources.

Comparison of Relative Damage Potential from Light Sources

The CIE Report includes a table of relative potential damage for full spectrum sources ranging from 2500°K to 7500°K in 500°K increments. It did not include any discontinuous spectral sources such as fluorescent, metal halide, or LED lamps, since the emphasis was on the overall impact of color temperature on damage, rather than the unique damage potential of specific light sources. The report utilized the method of calculation described previously. To simplify comparison, all values were normalized based on an assignment of a value of 1.0 for Source A (2856°K) and all wavelengths below 400nm were excluded. A summary of some of the values are listed as:

Color Temperature of Source	Relative Damage Potential	Example of Lamp Type
3000°K	1.04	Tungsten halogen
4000°K	1.37	Cool white fluorescent
5000°K	1.71	Sun + Daylight
6000°K	2.01	Daylight fluorescent
7000°K	2.28	

According to this data, a museum collection illuminated with daylight at 6000°K will cause twice the damage of a tungsten halogen source at the same level of luminous intensity.

For purposes of this communication, Art Preservation Services analyzed six different lamp/filter combinations to assess the relative potential damage of LEDs compared to tungsten halogen sources. All damage values were normalized based on the assignment of a value of 1.0 for an unfiltered tungsten halogen MR-16 lamp.

All measurements were done with an Ocean Optics 2000 USB spectrometer. All color temperature readings are based on manufacturer data. All calculations utilized the CIE published damage values.

Lamp and Filter*	Source	Color Temperature or CCT	Relative Damage Potential
MR-16, No Filter	T-H	3000°K	1.00
MR-16, UV filter	T-H	-	0.96
Ledtronics, No Filter	LED	3200°K	0.86
Cree MP-L, No Filter	LED	3500°K	0.93
Solux, No Filter	T-H	4700°K	1.37
Solux, UV Filter	T-H	-	1.14

* MR-16 Sylvania Tru-aim MR16 35/12; Ledtronics PAR 30 10w; Cree MP-L: XLamp MP-L EasyWhite at 700mA; Solux 4700°K; UV filter Optium Museum Acrylic

According to the above results, the two warm LEDs had the lowest relative damage potential and the unfiltered 4700°K Solux tungsten halogen lamp had the highest relative damage potential. These results are not surprising.

- A typical warm LED has a peak in the blue region around 445-455 nanometers (nm). It has very little power in the short wavelength region (below 440 nm), which is more damaging and provides less luminous intensity than the blue region at or above 440 nm. Therefore, a warm LED would be expected to do less or approximately the same damage as a tungsten halogen lamp of an equivalent brightness, based on the total amount of power within the blue region for each source.
- The Solux 4700°K tungsten halogen lamp has a relatively high proportion of short to long wavelengths compared with a normal tungsten halogen lamp, which is why it has a high color temperature. The higher proportional amount of blue to red explains why this type of lamp has a higher damage potential than a warm LED or a conventional 3000°K tungsten halogen lamp. The higher proportion of blue also results in a higher proportion of UV, which is why a UV filter has a bigger benefit for this lamp than for a 3000°K tungsten halogen lamp.

General Photochemical Damage versus "Hole-Burning"

What is the basis for the statement in the *Extreme Caution* posting that a light-sensitive material "*would undergo damage at 20% to 400% faster rates than if lit at the same light levels with an unfiltered MR-16*"? It is based on the graphs in Diagram 1 where "*the power of the narrow wave peaks produced by the LEDs is 20% to 400% higher than the halogen MR-16 at the same light level.*"

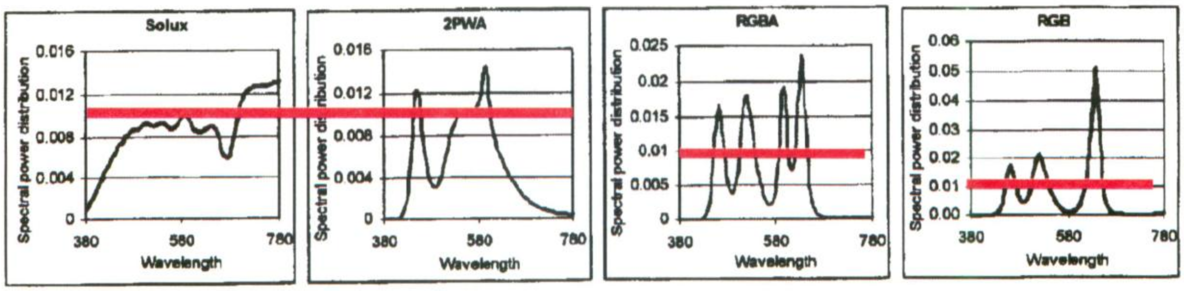

Diagram 1: Spectral power distributions (SPD) of four lamps - Solux and three types of LEDs. These are the graphs accompanying the *Extreme Caution* posting: "*Each of the SPD's has a heavy horizontal line at* $0.01 W \cdot m^{-2} \cdot nm^{-1}$, *the highest power output of a broad, continuous incandescent lamp*".

Unfortunately, these graphs start with a misleading comparison. According to the text of the *Extreme Caution* posting, the LED sources (2PWA, RGBA and RGB) were supposed to be compared to an "*un-filtered MR-16 halogen incandescent lamp*". However, in the graphs accompanying the posting, the reference source is a Solux 4700°K lamp. A Solux 4700°K lamp is a very heavily filtered source that has a high color temperature specifically because a high proportion of the long wavelength visible light is filtered out.

What happens when an unfiltered MR-16 tungsten halogen lamp (3000°K) is compared to a warm/neutral white LED (3500°K) and a Solux 4700°K lamp, all at equal illuminance? The results in Diagram 2 (measurements provided by APS) are quite different from those in the *Extreme Caution* posting. In this comparison, the unfiltered tungsten halogen lamp would be the most damaging source.

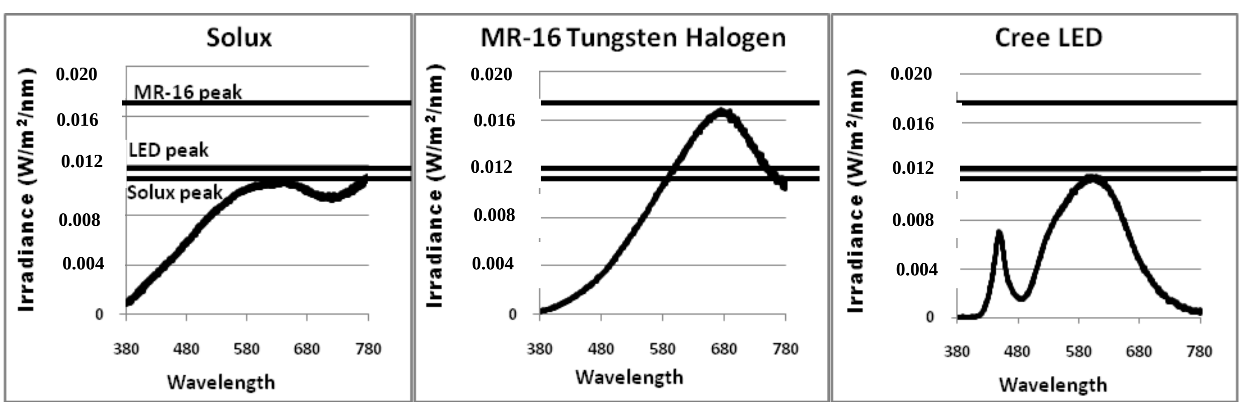

Diagram 2: Spectral power distributions of three lamps – Solux 4700°K, Tungsten Halogen, and a 3500°K LED. All lamps normalized to 660 Lux to match scale in Diagram 1. Horizontal lines placed at $0.0165 W \cdot m^{-2} \cdot nm^{-1}$ for the MR-16 peak, $0.012 W \cdot m^{-2} \cdot nm^{-1}$ for the LED peak, and $0.011 W \cdot m^{-2} \cdot nm^{-1}$ for the Solux peak.

According to the measurements illustrated in Diagram 2, the highest intensity tungsten halogen peak wavelength is 40% greater than the broad band peak and 130% greater than the narrow blue peak of the LED. Furthermore, the Solux 4700°K lamp would be the least damaging of the three light sources.

These results are the opposite of the *relative damage potential* values obtained based on Harrison/CIE calculations, where an unfiltered tungsten halogen lamp was slightly more damaging then a 3500°K white LED, and considerably less damaging then the unfiltered Solux 4700°K lamp.

What is the cause of this significant discrepancy regarding relative damage?

- <u>*Relative damage potential* deals with the entire UV through visible spectral output of a light source.</u>
- <u>Total photochemical damage cannot be calculated based on the comparison of the highest peak in the spectrum.</u>

The alarming statement in the *Extreme Caution* posting regarding LEDs causing *20% to 400% faster rates* of damage is based on the phenomenon of "Hole-Burning", and assumes that "*isolated LED output peaks*" will cause accelerated damage. The validity of this assumption must be tested based on the following information:

- The phenomenon of hole-burning occurs in the unique case where a very high energy peak from a light source closely aligns with a region of high absorption by a light-sensitive material, referred to as its action spectrum.
- Potential damage from hole-burning does not take into account the damage potential of the overall spectral output.
- More research would be useful to determine the level of risk to the overwhelming majority of museum materials from concentrated bundles of energy within narrow wavelength bands such as with fluorescent and metal halide sources. For warm and neutral white phosphor-based LEDs, the risk of hole-burning damage at an illumination level of 5 to 20 foot candles is very small.

<u>Based on current knowledge, both low to intermediate color temperature white phosphor-based LEDs (2700°K-4000°K) and tungsten halogen lamps are safe if used at an appropriate light level for museum applications.</u>

PART 2 – COLOR RENDERING PROPERTIES OF LEDS

The second concern of the *Extreme Caution* posting deals with the color rendering properties of LEDs. The posting states that LEDs "*are deficient where accurate color discrimination within the human visible spectrum is required,"* and notes that LEDs have a CRI value of 60 "*at best*". In fact, quality white phosphor LEDs are currently available with a CRI of 90+.

The Department of Energy initiated a program called CALiPER that tests a sampling of commercially available LEDs and evaluates the lamp characteristics and makes this information available to the public (http://www1.eere.energy.gov/buildings/ssl/search.html). Between 2007 and 2009, twenty MR-16 LED replacement lamps were tested of which fifteen were within the color temperature range of 2600-3500°K with the following CRI and Luminous Efficacy distribution:

CRI	# of LED Lamps	Luminous Efficacy Range
40-49	1	17
50-59	0	x
60-69	3	19-29
70-79	4	26-50
80-89	5	16-46
90-96	2	33-48
	# of Benchmark T-H Lamps	
99	6	8-18

CRI values varied between a low of 48 and a high of 96. Luminous efficacy values (ratio of how many lumens per Watt) varied widely from 16 lm/W to 50 lm/W for LEDs and 8 lm/W to 18 lm/W for tungsten halogen lamps. It is already possible to find LED lamps with good color rendering that are at least five times as efficient as a standard tungsten halogen lamp, with further improvement in power efficiency just around the corner.

Programs like CALiPER provide an important tool for assessing products within an emerging marketplace that lacks industry-wide compliance standards. Although CALiPER only tests a limited number of products, it gives an excellent overview of the state of the industry and what one can or should expect from a product. It also provides an unbiased comparison between "benchmark" tungsten halogen sources and replacement LED lamps.

Another important activity regarding the characterization of color rendering properties of LEDs is the modification of the CRI metric. The National Institute for Standards and Technology (NIST) has proposed an alternative metric, the Color Quality Scale (CQS), described in the following link: http://www.nist.gov/physlab/div844/grp05/vision_color.cfm. The purpose for reconsidering the CRI metric is not because LEDs are inherently "*deficient where accurate color discrimination within the human visible spectrum is required*." Quite the opposite, it is because shortcomings of the CRI metric do not fully reflect qualitative performance of LEDs and penalize these sources, even when they provide a higher chroma value compared with a reference illuminant.

The quality of some of the better white LEDs, particularly those with a high CRI, are appropriate for museum applications. To a large extent, particularly for LEDs with a relatively high CRI (above 85), the more pertinent question regarding use of LEDs, as well as for any sources of illumination used in museums is not about a lamp's color rendering index, but about its color rendering characteristics, and most specifically, its color temperature.

For example, a tungsten halogen lamp, typically rated around 3000°K, with a CRI of 99-100, is relatively deficient in blue compared to higher color temperature sources, as can be seen with the spectra in Diagram 2. Therefore, it is not surprising that a higher color temperature source with a lower CRI would render blue colors more vibrantly and with more saturation. Therefore, an illuminant with a high CRI does not mean that it is a good color rendering source for all applications.

POTENTIAL RISK AND THE RAPID EMERGANCE OF LED TECHNOLOGY

Regarding risk, it should be emphasized that the above evaluation focuses on warm white phosphor-based LEDs, which are the most appropriate LEDs for museum applications right now. As with any new technology, there are legitimate concerns that should be considered when dealing with current and future developments regarding the use of LEDs.

- There are several methods commonly used to produce a white LED. The most common is to use a blue LED that is covered with a phosphor coating which converts some of the blue radiation into a broad yellow or yellow/red spectral output. The mix of blue and yellow or yellow/red gives the appearance of white. The distribution and proportion of wavelengths in this mix determines the color rendering and color temperature properties of the LED. A warm white phosphor LED has a relatively broad blue band compared with other discontinuous sources such as fluorescent lamps and metal halide lamps.
- Some white LEDs are produced by mixing the output of red, green, blue (RGB) and sometimes amber LEDs. Again, the output of an RGB white LED is rather broad banded compared with other discontinuous sources and is probably a low risk regarding damage. Potential problems of color rendering are more of an issue with RGB LEDs than with high CRI white phosphor LEDs.
- The current generation of white LEDs does not generate UV. In the future, UV LEDs may be used to excite colored phosphors to generate white light, similar to the process used in a fluorescent lamp. At present, these are not available because of the relatively low output and efficacy of UV LEDs. If and when UV activated white LEDs become available, the UV output should be monitored to ensure that they are safe for museum applications, either in their filtered or unfiltered state.
- High color temperature LEDs give off a large amount of blue radiation in the region of 440-455 nm. As previously discussed, short wavelength blue radiation is far more harmful than an equivalent amount of long wavelength (red). Therefore, just like a full spectrum source, a high color temperature LED will cause more damage than a low color temperature LED source. Because of the high output within a narrow region of blue, a high color temperature LED may cause more damage than its full spectrum equivalent. This should be evaluated.

- White LEDs do not emit infrared radiation. However, they do generate heat. One of the biggest causes of LED failure is inadequate cooling. This is why the design of an LED heat sink is important and the context of installation and how heat is dissipated is equally important. If an LED is placed in a showcase in a very confined space without adequate means to dissipate heat, it will reduce the life and output of the lamp.
- Although an LED is a heat source, it is not a reason to avoid placing it directly in an enclosed environment such as an exhibition case. The rate of heat generation must be offset by the rate of heat dissipation to the case exterior. It is useful to think of an LED, or any light source, as if it is an electric heater. Although some of the wattage of a light source exits the case as light, most of the wattage is converted to heat. Unfortunately, no rules of thumb exist regarding how much wattage can be put into a case of a given design without adversely affecting internal temperature and relative humidity. In the absence of a guideline, empirical testing would readily confirm the extent of risk.

The greatest advantage of LEDs is their energy efficiency. Within the context of the general discussion on sustainability, this advantage will (and should) lead to more LED lighting for museums.

REVIEW OF KEY POINTS

- Differences in damage potential, color temperature and color rendering properties of light sources are due to the unique distribution of wavelengths within the UV, visible and IR spectrum.
- Shorter wavelengths (UV-blue) have more energy and therefore more damage potential than longer wavelengths (red-IR) at equal levels of irradiance (power) and illuminance (brightness).
- A protocol for comparing the damage potential of light sources was developed in the early 1950s and revised over the last few decades based on subsequent research.
- The relative damage potential of a light source can be calculated by summing up the power per wavelength of a specific lamp, multiplied by both the amount of damage and the luminosity factor - $V(\lambda)$ - per wavelength. By dividing this sum by the illuminance of the source, the relative damage potential per foot candle or lux can be determined.
- Using these calculations on illuminants that are filtered to remove both UV and IR, a high color temperature source with a full spectrum such as daylight at 6000°K has twice the damage potential of a tungsten halogen lamp.
- Damage calculations predict that a warm white phosphor-based LED has a lower damage potential and is therefore less damaging than a UV-filtered tungsten halogen lamp.
- The specific concern regarding LEDs and damage that was the basis for the *Extreme Caution* posting deals with the peak output of an LED source. It is not possible to determine the damage potential of an illuminant based solely on a single peak wavelength.
- “Hole-burning” may occur only when a large amount of energy from an illuminant at a specific wavelength aligns with a region of high absorption by a light-sensitive material.
- While “hole-burning” may be a problem for some illuminants with discontinuous spectra, the relatively broad shape and low power of the blue peak of a warm or neutral white

phosphor-based LED represents a very low level of risk, especially at the low levels of illumination recommended for museums.

- There are many reasons to be concerned when selecting an LED for museum applications, as is the case with any emerging technology that lacks tight performance standards. Currently, there are world-wide efforts to create such industry standards.
- A number of warm/neutral white phosphor LEDs has CRI values at or above 85-90 and have very good color rendering characteristics for museum applications.
- A low color temperature illuminant with a high CRI such as a 3000°K tungsten halogen lamp with a CRI of 99 may not provide as pleasing an appearance for blue tones as a higher color temperature LED in the range of 3500-4000°K.
- General color rendering characteristics regarding illumination of museum objects must take into account the color temperature of the illuminant.

CONCLUSION

There are many reasons to be wary about LEDs for museum applications. It is still a new technology in terms of main stream applications. Manufacturer claims regarding such factors as energy efficiency, lumen output, CRI, color temperature and anticipated lifetime sometimes fall short in actual performance.

LED lamp technology continues to improve at a rapid pace. As was the case in the early days of computers and digital cameras, a product that was avant-garde when first introduced may seem like ancient technology within a year or two. As with any rapidly changing technology, the decision to buy now, later or never, should be based on whether improvements over previous technologies justify the cost. While it is possible to select excellent and safe LEDs for the illumination of light-sensitive artifacts, criteria for knowing how and what to select are not well-defined. It is very much a case of Caveat Emptor (let the buyer beware)! Hopefully, through such programs as CALiPER, it will be easier to judge the merits of different lamp options.

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ACKNOWLDGEMENT

Elyse Canosa for assisting with the spectrometer readings and preparation of the graphs.