GATEWAY DEMONSTRATIONS

Demonstration Assessment of Light-Emitting Diode (LED) Retrofit Lamps

Host Site: J. Paul Getty Museum, Malibu, California

Final Report prepared in support of the U.S. DOE Solid-State Lighting Technology Demonstration GATEWAY Program

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy
The J. Paul Getty Museum and the Getty Conservation Institute

March 2012

Prepared for the U.S. Department of Energy by
Pacific Northwest National Laboratory

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Demonstration of LED Retrofit Lamps at an Exhibit of 19th Century Photography at the Getty Museum

Final Report prepared in support of the DOE Solid-State Lighting Technology Demonstration GATEWAY Program

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy
The J. Paul Getty Museum and the Getty Conservation Institute

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March 2012

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Preface

This document is a report of observations and results obtained from a lighting demonstration project conducted under the U.S. Department of Energy (DOE) GATEWAY Demonstration Program. The program supports demonstrations of high-performance solid-state lighting (SSL) products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Demonstration Program focuses on providing a source of independent, third-party data for use in decision-making by lighting users and professionals; this data should be considered in combination with other information relevant to the particular site and application under examination. Each GATEWAY Demonstration compares SSL products against the incumbent technologies used in that location. Depending on available information and circumstances, the SSL product may also be compared to alternate lighting technologies. Though products demonstrated in the GATEWAY program may have been prescreened for performance, DOE does not endorse any commercial product or in any way guarantee that users will achieve the same results through use of these products.

Acknowledgements

The J. Paul Getty Museum granted permission for this study and report, provided access to information about the exhibit and the design process, and allowed the use of exhibit photographs. We appreciate the assistance of the Preparations Department of the Getty Museum, especially Scott Hersey and the Head of Preparations, Kevin Marshall. Thomas Kren, acting Associate Director for the Collection at the J. Paul Getty Museum, granted permission to disseminate the lessons learned from the museum's LED installation.

Acronyms and Abbreviations

BCRA	British Ceramic Research Association
BLCC	Building Life-Cycle Cost
CCT	correlated color temperature
CRI	color rendering index
DOE	U.S. Department of Energy
GCI	Getty Conservation Institute
IR	infrared
JND	just noticeable differences
LED	light-emitting diode
PNNL	Pacific Northwest National Laboratory
PT	preservation target
PV	present value
SPD	spectral power distribution
SSL	solid state lighting
UV	ultraviolet

Executive Summary

In March 2011, the J. Paul Getty Museum in Malibu, California, installed an exhibit titled "In Search of Biblical Lands: From Jerusalem to Jordan in Nineteenth-Century Photography." This collection of toned albumen photographic prints presents a rare photographic narrative of the people, life, landscape, and ancient structures of the Holy Land of the Middle East. Dating from between 1840 and 1905, these large-format photographs are highly detailed albumen prints. Prints of this type were frequently hand-colored with pigments and dyes that are sensitive to light. The Getty Conservation Institute (GCI) confirmed this sensitivity with microfading testing.

The curator decided to display the photographs for 26 weeks, illuminated between 25 and 50 lux, and use light-emitting diode (LED) PAR38 lamps to replace tungsten halogen illumination, since these lamps emit no ultraviolet (UV) or infrared (IR) radiation. The GCI suggested providing additional protection by monitoring three photographs on exhibit at two-week intervals. The preliminary fading tests, although with different lamps than would be used in the exhibition but having similar correlated color temperatures, had suggested that the lamps would cause no more damage than UV/IR filtered halogen lamps, and possibly less. Regular checks of the monitored photographs showed small, but visually undetectable, changes from the installed LED lamps over the 6-month exhibition, no more than would be expected from incandescent lighting. Figure ES-1 shows a photo of the exhibit with the LED lighting installed.

Figure ES-1. Photo of the installed gallery exhibit, "In Search of Biblical Lands: From Jerusalem to Jordan in Nineteenth-Century Photography" (Not to be reproduced without written permission of the J. Paul Getty Museum.)

The exhibit lighting designer, Scott Hersey, and Kevin Marshall, Head of Preparations, selected the Cree 12W LED PAR38 2700K lamp (brand name "LRP38") after mockups in a test gallery with similar objects and in collaboration with Jim Druzik, Senior Scientist, the Getty Conservation Institute, and Thomas Kren, acting Associate Director of Collections. The goal in the selection was to match the color quality of the Museum's standard halogen lamps as closely as possible so that there would be no apparent difference between galleries lighted with LEDs and those lighted with halogen. (Both lamp types had a CCT of 2700K–2850K, with a Duv of less than 0.002, indicating they were very close to the black body locus.) The lamps were used in place of (34) Sylvania 60W PAR38 halogen 30° flood lamps, on a one-for-one basis, in three adjacent galleries. Layers of metal screens are typically used for both lamp types to reduce illumination levels to the precise target value on each specific object.

Vertical illuminance values on the photographs were very low, ranging from 25 lux (2.5 footcandles [fc]) up to 50 lux (5 fc), and surrounding gallery illuminances were also low to allow visitors' eyes to adapt to the darkened environment. Visitors were not told about the change in lighting technology, and as far as the museum staff is aware, no visitors commented on the different light source. The museum staff considers this installation a success and has since begun using the LED replacement lamps in other exhibits.

In this gallery space with 34 display lights, the LED replacement lamp compares favorably against the incumbent 60W PAR38 halogen lamp, reducing power use by 83% and recovering the higher initial cost of the LED in year three of operation. In a 10-year life cycle cost analysis, at $0.12/kWh melded[1] electric rate, the total present value (PV) energy savings amount to $4,621, with a total PV life-cycle cost savings of $9,843 including maintenance. Spot-relamping frequency and cost (at $30 per lamp for spot-relamping) are reduced considerably because of the LED's longer expected life.

This GATEWAY report also summarizes some of the research findings on LED replacement lamps from the GCI. Compared to earlier generation LED products, current warm white (2700–3000K) LEDs deliver less of a spike in the short-wavelength (blue) region, resulting in filtered halogen and LED light sources performing similarly in fading tests. On some materials, the LEDs may have slight conservation benefits compared to filtered halogen, but it would take decades for these benefits to become evident. LED light sources are one tool that curators and designers can use to achieve the preservation targets for objects of art. This report includes further recommended reading for museum lighting issues.

[1] The melded (or blended) electric rate is the average rate charged by the utility per kilowatt-hour, including time-of-use rate variations, demand charges, taxes, and fees.

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1.0 Introduction and Background

The J. Paul Getty Museum at the Getty Villa is a museum of antiquities and fine art located in Malibu, California (Figure 1). From March through September 2011, the Villa featured a special exhibit, "In Search of Biblical Lands: From Jerusalem to Jordan in Nineteenth-Century Photography." Featuring daguerreotypes, salted-paper prints, and albumen silver prints produced between 1840 and the early 1900s, the works by leading photographers of the time show rare views into the daily life and landscape of the Holy Land, as well as landmarks of Jerusalem, Nazareth, Jaffa, and Petra.

Figure 1. The J. Paul Getty Museum at the Getty Villa in Malibu, California (The Getty Research Institute, © Richard Ross with courtesy of the J. Paul Getty Trust.)

Lighting designers and curators at the Getty Museum wanted to explore the use of light-emitting diode (LED) replacement lamps in this exhibit. Pacific Northwest National Laboratory (PNNL), supported by the Department of Energy (DOE) GATEWAY Solid State Lighting Technology Demonstration Program, collaborated with the Getty Conservation Institute (GCI) to describe the process and results of this endeavor.

The albumen prints had been toned pink overall with an unknown colorant that is highly sensitive to light. To minimize potential damage from light exposure, a range of options had been discussed, including installing draperies across each photo, which visitors would open to view the art then close before going to the next photograph.

Museum lighting designers consulted with Jim Druzik, Senior Scientist at the Getty Conservation Institute, about the sensitivity of the artifacts and the potential for fading from LEDs compared to the conventional halogen lamps the museum typically uses. Druzik's preliminary work examining fading of museum materials from light exposure suggested that LEDs would do no more harm, and possibly less, than halogen lamps with standard ultraviolet (UV) filtering. He suggested that the exhibit be designed with LED replacement lamps, and that he and his conservation colleagues collect in situ color measurements every two weeks from three of the exhibited photographs. The most sensitive images would be rotated at the halfway point of the exhibition, but one image was so important it would be on display for the entire 26 weeks. In this manner, it was hoped that an accumulating set of measurements would eventually be able to predict, far in advance, the point at which a visibly detectable change could be reasonably expected. As a result of this work, the museum was able to avoid more stringent light reduction methods.

The museum lighting designers would normally have lighted the exhibit with (34) Sylvania 60W PAR38 30° Flood 120V halogen lamps, "screened down" to reduce the light output to the desired light levels (i.e., using layers of metal window screen to reduce light output without changing the color temperature). Three track lights, with one Sylvania 60W PAR38 30° Flood 120V halogen lamp each, were used to provide fill light on the floor of the galleries. Although the halogen lamps were still used for the floor fill light, the designers used (34) Cree 12W PAR38 20° lamps, 2700K for the displays. Although the luminous intensity of the LED PAR38 lamps was lower than the incumbent 60W halogen lamps, the designers still had to use some screening to reduce the light levels on the photographs to an acceptable level for conservation. Figure 2 shows an albumen silver print from the exhibit.

Figure 2. The Damascus Gate [1880's], Felix Bonfils (1831–1885). One of the albumen silver prints from the exhibit. (Ken and Jenny Jacobsen orientalist photography collection, The Getty Research Institute, Los Angeles, 2008.R.3)

This report describes the process and results of this demonstration of solid-state lighting (SSL) technology in the Getty Villa, and the results of GCI research on the fading effects from LED replacement lamps on museum artifacts and materials.

2.0 Methodology

The museum and PNNL agreed on the following procedure for this LED demonstration:

- Procure a limited set of LED replacement lamp samples for visual evaluation of the photographs in the gallery by the museum staff. Select one manufacturer's lamps for use in the track luminaires. All lamps were new (museum staff).
- Document the condition of the photographs before installing them for viewing, to establish baseline color data (GCI staff).
- Lamp, install, and aim track luminaires for the exhibit (museum staff).
- Document the layout of lighting for the exhibit, "In Search of Biblical Lands," with drawings and photographs. Collect information on hours of operation for the lighting system in the museum. (GCI staff).
- Calculate energy use in gallery and measure illuminances (PNNL).
- Document the spectral power distribution (SPD) of the LED replacement lamps so that this could be compared with lamps for which damage functions were known (GCI staff).
- Perform color measurements of selected exhibit photographs every two weeks to monitor any color changes or fading (GCI staff).
- Interview museum staff for visitor reactions to the LED lamping (PNNL).
- Perform a life-cycle cost study (PNNL).
- Document the relative performance of the lamps, as well as results of the ongoing fading studies at the GCI, in a GATEWAY report (PNNL).

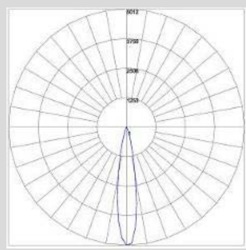
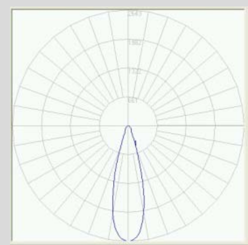
3.0 Demonstration Gallery Description and Measured Light Levels

The photographs of the "In Search of Biblical Lands" exhibit were displayed in four contiguous galleries at the Getty Villa. The LED replacement lamps were used in three of the four spaces, where ceiling heights were 15 to 16 feet. (The fourth gallery had a ceiling height of 8 feet 5 inches and was much more suited to a smaller, lower-output MR16 halogen lighting system.) Figure 3 shows one of the galleries with the lighting installed. Figure 4 provides a close-up photograph of the LED track lighting used in the galleries. There were no dimmers controlling the lighting circuits. The most sensitive images in the exhibit would be rotated at the halfway point, but one important photograph would be exhibited for the full 26 weeks.

Figure 3. One of the galleries of "In Search of Biblical Lands: From Jerusalem to Jordan in Nineteenth-Century Photography." (Not to be reproduced without written permission of the J. Paul Getty Museum.)

According to the exhibit's lighting designer, Scott Hersey, the goal in lighting the gallery for "In Search of Biblical Lands" was to choose lamps that were as similar in correlated color temperature (CCT) to the existing halogen lamps, and as close to the blackbody locus (measured in Duv) as possible, to minimize any apparent visual differences from halogen-lighted to LED-lighted galleries. Museum staff received sample lamps from local vendors, and these were visually tested in a mockup gallery by the Preparations staff, the GCI conservation scientist, and Thomas Kren, the museum's Associate Director of Collections. The Cree LED Par38 lamp's beam qualities, warm 2700K color appearance, and high (93) color rendering were deemed almost indistinguishable from the incumbent halogen PAR38 lamp. The museum opted to try this lamp for "In Search of Biblical Lands." The comparative characteristics are noted in Table 1.

Table 1. Comparison of characteristics of the LED PAR38 lamp used in the exhibit (Cree, left) and the halogen incumbent lamp (Sylvania, right). Data were derived from an LM-79 photometric report for the Cree LED lamp, and manufacturer's data sheet and LM-79 photometric report for the Sylvania halogen lamp.

Lamp description and nominal power	Cree 12W PAR38 LED 20° 2700K	Sylvania 60W PAR38 halogen/SPL reflector, 30° beam, 120V
Center beam candlepower	4648	2643
Beam angle (to 50% candlepower)	18° (20° nominal)	30°
Lumens	601	850
Power (watts) at 120V	10.2	60
Efficacy (lumens per watt)	58.9	14.2
Published lamp life	50,000 hr (to 70% lumen output)	3000 hr to 50% lamp survival
Polar plot showing candlepower distribution from lamp. Plot scales vary		
Photo of lamp		
CCT, CRI, Duv	2638K, 93, 0.002	2875K, 100, 0.001

CRI = color rendering index
CCT = color correlated temperature
Duv = difference above (+) or below (-) black body locus

Figure 4. Track luminaires installed in the gallery with Cree 12W PAR38 LED replacement lamps.

The maximum target vertical illuminance on the light-sensitive works in this exhibit was 50 lux (5 footcandles [fc]), although the vertical illuminance was lowered to 25 lux on one especially sensitive photograph. To compensate for extremely low illuminances, the display lighting in rooms leading to the gallery deliver only 100 to 200 lux (10 to 20 fc) vertical on art, so that the visitor's visual system can progressively adapt to very low illuminances. The walls of the gallery were painted dark red to reduce reflected light and wall luminance. The ambient illuminance in the exhibit gallery averaged less than 2.5 lux (0.25 fc) horizontal and vertical, which allowed the works to stand out and appear "bright" because of the high luminance contrast ratio between object and background. See Table 2.

To achieve the best visual effect on the artwork, the lighting designer used a combination of light screens and cross baffles to reduce the light output and shape the beam. The lighting designer estimated that the same number of lamps would have been used for display lighting with either the LED or halogen option, and screens would have been used for either lamp type to reduce the illuminances to the level prescribed by the conservators. When illuminances on the artwork are this low, perceived color saturation and color contrast are diminished, making it harder for the viewer to see details. This is called the Hunt Effect.[1] The LED lamps, having more blue energy than the filtered halogen lamps normally used in such an exhibit, may compensate better for the Hunt Effect by enhancing color contrast slightly in comparison to halogen. (Color contrast can be an advantage, even in viewing black-and-white photographs.) Note that the SPD data below shows that the LED lamps deliver more radiant power in the short wavelength portions of the spectrum.

Although there was concern about color perception at such low light levels, the faint pink toning on the photograph exhibited for 26 weeks below 30 lux was still easily visible to the visitors.

[1] Hunt RW. 1952. "Light and dark adaptation and the perception of color." *Journal of the Optical Society of America* 42(3): 190–9.

Table 2. Illuminances measured in gallery during the "In Search of Biblical Lands" exhibit. Values were measured using a Littlemore Scientific handheld light meter.

	Minimum illuminance	Maximum illuminance
Vertical illuminance on artwork	25 lux (2.5 fc)	50 lux (5.0 fc)
Ambient illuminance on floor and walls (vert. and horiz.)	2.5 lux (0.25 fc) avg.	

Figure 5 shows the SPD of the Cree LED PAR38 display lamps used in the exhibit galleries, and Figure 6 shows the SPDs of the LED test lamps used in GCI laboratory fading tests. Figure **7** shows, by contrast, a filter designed for use with halogen lamps during earlier research carried out principally by Professor Carl Dirk (University of Texas at El Paso) and Jim Druzik (GCI). The coated glass filter is intended to optimize energy, color rendering, and lumens/optical watt, while minimizing risks for artwork. Named the "Mark 2" and designed to be used with a variety of tungsten halogen lamp types, these filters have been successfully installed at the Georgia O'Keeffe Museum in Santa Fe, New Mexico. They limit energy radiated to the surface of artworks even more than LEDs do, but it is striking how close the SPD of the most successful (i.e., those producing the least damage) warm-color LEDs are to these filters when each were developed independently.

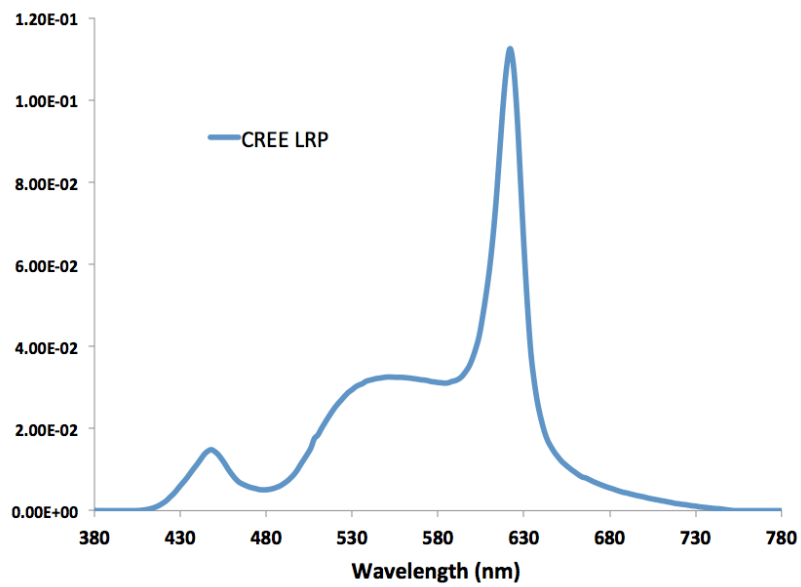


Figure 5. Spectral power distribution of the Cree LED PAR38 lamp selected for the "In Search of Biblical Lands" exhibit. Note that the LED spectrum emits no radiation below 400 nm (violet and ultraviolet) and no radiation above 760 nm (infrared). Also note a small peak of radiant power from 430 to 470 nm (blue) and a peak at 625 nm (orange-red), which may help enhance color contrast.

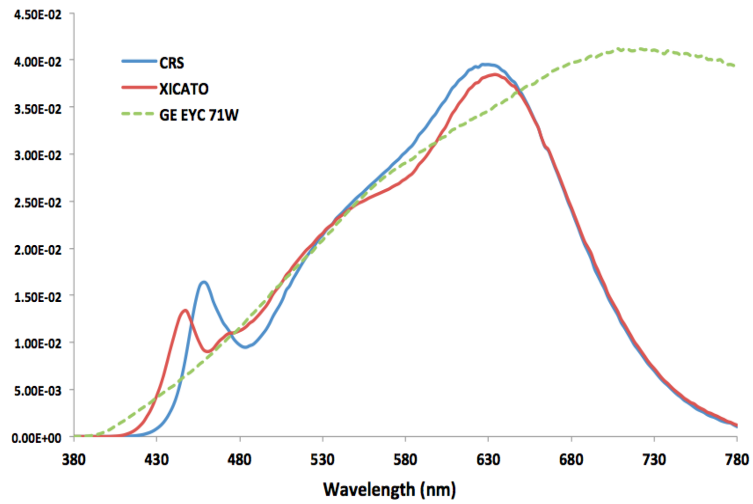


Figure 6. Spectral power distribution of the filtered halogen lamp (GE 71W MR16 halogen) that was compared to two 3000K white LEDs during the laboratory-based light aging study.

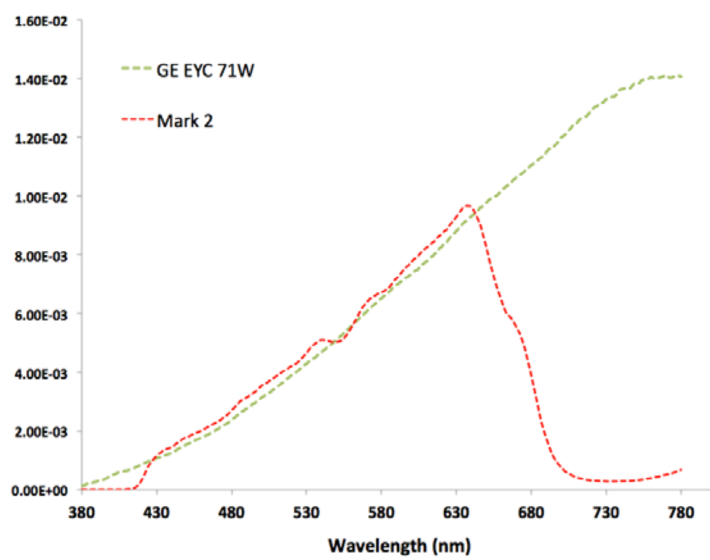


Figure 7. Spectral power distribution (dashed red line) of a halogen lamp with special filter to minimize UV and short-wavelength blue (<410 nm) as well as long-wavelength red (>700 nm). The "Mark 2" filter for halogen lamps was developed to optimize energy, color rendering, and lumens/optical watt, while minimizing risk of damage to artwork.

4.0 Monitoring the Photographs for Light Damage

Staff of the Getty Conservation Institute and the Getty Research Institute performed in situ color measurements of selected photographs in the exhibit. As noted, each monochromatic photograph had a faint pink tint that was highly light-sensitive, and the conservators were concerned about fading, even with a maximum vertical illuminance of only 25–50 lux. A Mylar template identified five locations on the target photographs so that color measurements could be made at identical points each time measurements were performed. Five replicate measurements of each point on a total of three photographs were taken at two-week intervals during the run of the exhibit.

Figure 8. Getty Conservation Institute staff measuring the color on five areas of two photographs in the exhibit gallery. (Photo courtesy The Getty Conservation Institute.)

Figure 9. GCI staff measuring color data from a Holy Land photograph to test for fading or color change. (Photo courtesy The Getty Conservation Institute.)

The original assessment for light sensitivity was made using a technique called "microfading".[2] Prior to monitoring the photographs in the exhibit, a Minolta ChromaMeter CR-221 was tested for 6 months, taking repeated measurements of a British Ceramic Research Association (BCRA) Deep Blue calibration tile and a blue wool test sample. The geometry was 45/0 over 3 mm area using a pulsed xenon light source. This geometry indicates the angles of the incident light source and detector over the measured spot with 0 degrees being perpendicular, or "normal," to the surface. This established that the instrument's 6-month stability was 0.16 CIEDE2000 ±0.07. Assuming no other sources of variability than those created by the instrument and the measurement methodology - the 95% confidence level will be met - by a 0.3 CIEDE2000 of color difference. For the purposes of this study the acceptable threshold for a just-visible color difference was set at 1.5 units. Figure 8 and Figure 9 show Getty staff during one measurement campaign on the day of the week that the museum is closed to the public.

At the end of 26 weeks, the color changes measured were fitted to a mathematical model that projected 1.5 CIEDE2000 at 110 weeks. (See Section 5 for an explanation of these units.) However, this probably should be considered the conservative estimate since other models predicted at least twice that length of exposure time to the same amount of change. The monitoring program fully supported the more conservative estimate.

5.0 Principles of Conservation of Museum Materials

Color change is unavoidable with exhibition, and compromises will always be made between a museum's mandate to display and educate the public and its obligation to preserve its collections. Conservators and curators understand that all light is damaging no matter how fleeting the exposure, and they design exhibition frequency and duration based on what is considered an acceptable long-term rate of change. Frequently, the goal is to prolong the onset of visual change to a predetermined target. This is called a "preservation target" (PT) and is often set between 50 and 100 years. This puts the responsibility on the museum professional to understand how light-sensitive their artifacts are and to make the best effort possible to forestall the onset of a just noticeable change until that PT has been achieved.

A PT of 100 means the conservator is working to avoid any visible change for a century, so the conservator must then ration out the light exposure based on the estimate of the object's light sensitivity (e.g., X number of weeks of exposure at 50 lux, per year or decade). Damage is gauged in Just Noticeable Differences (JND), measured as 1 to 1.5 CIEDE2000 units, a metric for calculated color difference. Appendix D explains more about how JNDs in color are defined and PTs managed.

[2] Whitmore PM, X Pan, et al. 1999. "Predicting the fading of objects: identification of fugitive colorants through direct nondestructive lightfastness measurements." *Journal of the American Institute for Conservation* 38: 429–441.

6.0 GCI Laboratory Testing for Fading of Museum Materials

A paper published in 2008 warned about the potential fading hazard of LED light sources.[3] The paper suggested that the SPD power peaks in LEDs could accelerate the fading of certain colors. This was coined "hole-burning" in the museum community, borrowing a term from photophysics, and there were many internet discussions and warnings about LED use. The GCI began evaluating LED lamp spectra to see if all LEDs exhibited dramatic peaks in the blue portion of the spectrum. GCI also built accelerated-fading booths for testing light (Figure 10) from different light sources on standard museum test materials, given an exposure measured in lux-hours (i.e., illuminance × time).

GCI then began accelerated fading tests in the GCI laboratories. The ISO Blue Wools are industrially dyed textile swatches used by conservators to determine the amount of light exposure at a given location and lighting scenario. Although these Blue Wools were originally intended as radiometric standards and not photometric dosimeters, studies over the years have established their response to typical museum lighting. These responses have been generally accepted, and Table 3 shows these values for light free of ultraviolet radiation (hence, "no UV"). They involve measuring the degree of fading in eight swatches of wool, each one colored with a different mixture of blue dyes.

Figure 10. Accelerated-fading boxes. The photo on the left shows eight LED luminaires installed in the top of the box to deliver high light levels inside the box. The photo on the right shows the interior of the box lit with filtered halogen lamps. The diffuser helps deliver uniform light on the Blue Wool samples on the floor of the box. (Photo courtesy Getty Conservation Institute.)

[3] Ishii 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." *Journal of Light and Visual Environment* 12(4).

Table 3. ISO Blue Wool responses. Time to achieve a Just Noticeable Difference (JND) by correlation with an established color difference formula, or in the absence of such a visual comparison, to Grey Scale 4 (GS4). Light exposure is given in megalux-hours (Mlx h), e.g., 50 lux for a period of 20,000 hours equals 1,000,000 lux hours or 1 Mlx h, a light dose easily achieved in as little as 6 ½ years of continuous exhibition.[a]

Blue Wool Category	1	2	3	4	5	6	7	8
Mlx h with no UV	0.3	1	3	10	30	100	300	1000

[a] Table adapted primarily from data compiled in Michalski S, "Damage to Museum Objects by Visible Radiation (Light) and Ultraviolet Radiation (UV)," *Lighting,* (London: UKIC) 1987, 3–16; and in Michalski S, "The Lighting Decision," *Fabric of an Exhibition* (Ottawa: Canadian Conservation Institute) 1997, 97–104.

Initially the three most sensitive ISO Blue Wools were arrayed in a pattern to confirm that diffuse light was being evenly distributed over the bottom surface of the exposure boxes and to serve as one of the colorants in a comparison between two types of LEDs and tungsten halogen lighting. The second exposure, using 15 colorant systems, natural dyes on silk and artists' materials on paper, comprised the main body of the study.

Since SSL is such a new technology and the spectral power distribution of LEDs can vary from those of traditional light sources, its fading risks had not yet been evaluated experimentally. One of GCI's goals was to determine those risks for the LED lamp options considered most successful in terms of color appearance, and recalibrate, if necessary, the Blue Wool test for LED lamps, accordingly. The first two LED products evaluated were an MR16 LED retrofit lamp manufactured by CRS Electronics and a custom-designed source made by Xicato. Both LED light sources were approximately 3000K.[4]

Druzik has found in this study that most of the dyes fade at the same rate, regardless of which light source is being assessed, no doubt due to the similarity in the SPD of the sources.

But in addition to the dyes used in the first three Blue Wool swatches, 6 of 15 dyes known to have been available and used by artists in the past actually faded somewhat more slowly under LEDs than under halogens (Table 4). However, it should be noted that the observed benefits with LEDs always occurred *long after visible fading had begun on all samples*. In other words, the preservation target (PT) was always exceeded before there was a demonstrable difference between the light sources. Since the goal of risk management in applying preventive conservation to museum collections is to delay reaching the PT for as long as possible, this benefit is minor at best.

[4] The Cree lamps were not tested in this series because at the time of this study a Cree lamp that was both small enough (MR16) to fit into existing exposure GCI booths and suitable for museum use did not exist.

Table 4. Fading rates of 16 natural dyes and ISO Blue Wool Standards exposed to 880,000 lux-hours (at 11,000 lux) of two 3000K MR16 LED replacement lamps, compared to equivalent lux-hours of halogen MR16 lamps with Mark 2 filter. (Source: Getty Conservation Institute)

Name	Type	LED Fading Rate
ISO Blue Wools 1–3		Slower
Ukon	Japanese Dye/Silk	Slightly Slower
Zakuro	Japanese Dye/Silk	No Difference
Kihada	Japanese Dye/Silk	No Difference
Weld	European Dye/Silk	No Difference
Old Fustic	European Dye/Silk	No Difference
Onion Skin	European Dye/Silk	No Difference
Annatto	European Dye/Silk	No Difference
Safflower	Japanese Dye/Silk	Slightly Slower
Sappan wood	Japanese Dye/Silk	Slightly Slower
Erythrosine B	Modern/Paper	No Difference
Rose Bengal	Modern/Paper	Slightly Slower
Tartrazine	Modern/Paper	No Difference
Patent Blue	Modern/Paper	No Difference
Crystal Violet	Modern/Paper	No Difference
Rhoduline	Modern/Paper	No Difference
Rhodamine B	Modern/Paper	Slightly Slower

As new SSL products are developed, research on their fading effects will continue. For the moment, none of the sample dyes under study fade faster under LEDs than under the halogen control, with one notable exception: crystal violet—which may also be an anomalous result because the increased fade rate with LED does not occur until the dye is almost destroyed by the light sources.

Compared to earlier generation LEDs, current warm white LEDs use more phosphors to convert energy from the blue wavelengths into warmer areas of the visible spectrum. The SPD of a given unit then shows much less of a blue spike in the short-wavelength region, and is probably a major contributor to the similar fading rates of LED and halogen. The weaker long-wavelength region may also benefit the few colorants that fade more slowly, including the three ISO Blue Wools. Such impacts should reduce museums' concerns about the use of similar LED light sources, given that until now LED's effect on art objects was largely unknown. In the future, GCI will extend this work to colorants of a more intermediate light sensitivity.

It must be reiterated that the conservation benefits found for the LED products studied are *very long range*, with impacts only becoming evident after decades. It would be fallacious to say the LEDs reduce damage enough to allow an increase in the lux-hours of exposure on an object without inflicting greater damage. Rather, carefully selected LED light sources can be one tool that helps align damage to objects of art with their existing Preservation Targets.

Further details of the study are summarized in Appendix D.

7.0 Energy Comparison

The LED replacement lamp lighting system with 34 track heads uses 920 kWh per year, compared to 5410 kWh for the comparable halogen lighting system. The lamps are never dimmed. At $0.12 per kWh, the display lighting in the three gallery spaces costs the J. Paul Getty Museum about $650 per year using their standard 60W halogen lamps, compared with only $110 using the LED replacement lamps. Table 5 shows the corresponding reductions in annual emissions based on the electrical generation fuel mix for California.

7.1 Life-Cycle Cost Analysis

The higher upfront costs of LED retrofit lamps are often offset by reduced electricity and maintenance costs over their relatively long life. The LED integral replacement lamps used in this retrofit project are on automatic control circuits, operated 51 hours per week, 52 weeks per year for a total of 2652 hours per year. The LED PAR38 lamps have an L_{70} life of 50,000 hours, according to the manufacturer, or 18.8 years at this usage rate. The incumbent halogen lamp has an expected average life of 3000 hours (the point at which 50% of the lamps are expected to have failed), or about 13 months.

This economic analysis uses the National Institute of Standards and Technology's Building Life-Cycle Cost (BLCC) software,[5] which calculates the life-cycle costs for energy conservation projects. The BLCC software was used to model the present value life-cycle cost of the (34) Cree 12W PAR38 LED lamps, compared to the life-cycle costs had the museum's standard 60W halogen lamps been installed. Both the halogen and LED scenarios are based on a 10-year analysis of each system's respective costs. This retrofit project is evaluated in terms of annualized spot-relamping costs (including labor at $30 per lamp) and projected 10-year energy costs, taking into account projected real fluctuations in energy prices. A 3.0% discount rate was assumed. Full details can be found in Appendices A through C.

In the United States, commercial electricity prices vary greatly from state to state and region to region. As a reference point, the U.S. Energy Information Administration publishes the Average Retail Price of Electricity to Ultimate Customers by End-Use Sector by State.[6] The national average retail price of electricity to ultimate commercial customers in April 2011 was approximately $0.10/kWh, and commercial electricity prices ranged from a high of $0.284/kWh in Hawaii to a low of $0.066/kWh in Utah. The melded retail rate that the J. Paul Getty Museum pays the local utility is above the national average at $0.12/kWh. In general, LEDs are more likely to be economically viable in places where electricity costs are high enough that the energy savings they generate contribute significantly to paying back the high initial cost of LED products.

BLCC comparisons are based on "contractor-level" commercial lamp prices as reported by the J. Paul Getty Museum, and confirmed by an online search of comparable prices. The Cree PAR38 LED lamps cost $99.95 each at the time of this study, replacing halogen PAR38 lamps that cost $5.40 each. No labor was included in the initial installation cost of the BLCC model because labor would be identical for both lamp types. It was assumed that all lamps would be spot-relamped when one failed. It was further assumed that there would be a 40% residual value of the LED lamps at the end of the 10-year analysis period, since the lamp is expected to provide almost 19 years of service at the calculated hours of use.

[5] Available online at http://www1.eere.energy.gov/femp/information/download_blcc.html.
[6] Available online at http://www.eia.gov/cneaf/electricity/epm/chap5.pdf .

While the LED lamps are not expected to require maintenance or to fail during the 10 years of life-cycle analysis, to build a conservative scenario, GATEWAY assumed an annual lamp replacement value of

$$= \frac{(34 \text{ lamps per exhibit} \times \text{cost per lamp} \times 2652 \text{ hours operation per year})}{\text{Rated lamp life}}$$

The museum's annualized halogen PAR38 lamp replacement cost for the three exhibit galleries is $1,064 per year, including labor, while the LED PAR38 lamp annualized replacement cost is $234 (see Appendix A).

7.2 Payback Horizons and Economic Feasibility

Table 5 summarizes the input data and life-cycle cost analysis for the incumbent halogen lamps and the replacement LED lamps. Although this exhibit will run for only 6 months, the same track lighting will be used for future exhibits. The economic analysis is based on a 10-year operation in the museum.

Table 5. Getty Museum display lighting life-cycle cost analysis (including relamping labor) – input data and summary.

	(34) Incumbent Sylvania 60W Halogen PAR38 30° Beam, 120V	(34) Cree "LRP38" 12W PAR38, 20° Beam LED Replacement
Initial Capital Costs for All Components	$184	$3,398
Average Annual Electrical Energy Usage	5410.08 kWh	919.71 kWh
Average Electricity Cost per kWh	$0.12	$0.12
First Year Energy Consumption Cost	$649.21	$110.37
Study Period	10 years	10 years
Discount Rate	3.0%	3.0%
Discounting Convention	End-of-year	End-of-year
Present Value (PV), Energy Consumption Costs	$5,568	$947
Annual Value, Energy Consumption Costs	$653	$111
Present Value, Relamping and Lamp Cost	$9,076	$1,999
Annual Value, Relamping and Lamp Cost	$1,064	$234
Present Value, Total Life-Cycle Cost	$14,828	$4,985
Annual Value, Total Life-Cycle Cost	$1,738	$584
Total Annual Emissions		
CO_2	1423 kg	242 kg
SO_2	0.35 kg	0.06 kg
NOx	0.58 kg	0.10 kg
Comparative PV Data over 10-Year Study Period for 12W PAR38 LED Lamps vs. 60W Halogen PAR38 Lamps		
Net Energy Savings from LED Lamping (PV)	Baseline	$4,621
Net Savings from LED Lamping (PV)	Baseline	$9,843
Savings-to-Investment Ratio	Baseline	6.31
Adjusted Internal Rate of Return	Baseline	23.83%
Estimated Simple Payback Occurs in Year	Baseline	3

In this gallery space with 34 display lights, the LED replacement lamp compares favorably against the 60W PAR38 halogen lamp, since the higher initial cost of the LED is recovered in year three of operation. At $0.12/kWh melded[7] electric rate, the total PV energy savings are $4,621 and the total PV life-cycle cost savings are $9,843.

The energy savings plus the savings due to reduced relamping labor costs will pay back even more quickly when LED replacement lamp costs decrease in the near future. For example, the same life-cycle cost comparison using half the lamp cost ($50 per LED lamp) will show a simple payback in year two.

Table 6 reports the present-value annual energy cost, total life cycle cost, and payback periods for a range of electric rates, assuming the lamp cost were to remain fixed at $99.95. Higher utility rates yield greater cost savings and reduce payback periods.

[7] The melded (or blended) electric rate is the average rate charged by the utility per kilowatt-hour, including time-of-use rate variations, demand charges, taxes, and fees.

Table 6. Comparative present value cost and energy of the LED lamps over 10-year analysis period, according to average electrical rate. Simple payback values are compared to the baseline 60W halogen PAR38 lamping. Note that simple payback periods are shorter when energy prices are higher.

	Average Cost of Electricity			
	$0.06/kWh	$0.12/kWh	$0.18/kWh	$0.24/kWh
PV Energy Consumption Cost	$473	$947	$1,420	$1,893
Total PV Life-cycle Cost	$4,511	$4,985	$5,458	$5,931
Simple Payback	2.9 yrs	2.3 yrs	2.0 yrs	1.7 yrs

Many factors influence whether an LED system is cost-effective for a given site. This report focuses only on the initial investment, energy, and maintenance costs. In general, where their initial cost premium remains high, LED lighting systems can be cost-effective when electric utility rates are higher than average, hours of operation are long, and labor costs for relamping are high. Other factors could affect the calculation of value and payback, such as embedded energy cost or the cost of lamp disposal and increased waste. At this point, these factors are difficult to quantify, and they will vary according to location, so GATEWAY has not included them. Note that reduced fading damage effects were determined to be slight, so these are similarly ignored.

8.0 Comments from the Museum Staff and Visitors

After the exhibit lighting was installed, a group of museum department heads toured the exhibit and responded favorably to the visual results. During the 6-month run of the photograph exhibit, there was no detected color shift in the lamps, and no lamp failures. The museum did not publicize the use of the LED technology for this exhibit, so it is unlikely that most visitors even noticed the difference in the light sources. There was no reaction, positive or negative, from the viewing public about the lighting, and the lighting designer believes this indicates that even frequent visitors did not perceive the change.

At the conclusion of the exhibition, the LED lamps were moved to another exhibit, titled "Modern Antiquity," in the same gallery spaces. The museum plans to continue to use LEDs in exhibits where they produce desired visual results. The museum has expanded the use of the Cree lamp retrofits to the photo galleries at Getty Center based on the favorable results of the testing at the GCI. The Getty is anticipating using the lamps also in the Drawings galleries, which feature light-sensitive objects.

9.0 References for Museum Lighting and Artifact Conservation

Druzik JR and SW Michalski. 2011. Guidelines for Selecting Solid-State Lighting for Museums. Canadian Conservation Institute and the Getty Conservation Institute. Accessed March 6, 2012 at http://www.getty.edu/conservation/our_projects/science/lighting/lighting_component8.html (last updated December 2011).

CIE Publication 157:2004, *Control of Damage to Museum Objects by Optical Radiation*. International Commission on Illumination, Vienna, Austria.

IES RP-30, *Museum and Art Gallery Lighting: A Recommended Practice* (in press). Illuminating Engineering Society, New York.

Cuttle C. 2007. *Light for Art's Sake: Lighting for Artworks and Museum Displays*. Butterworth-Heinemann, Oxford.

The Canadian Conservation Institute maintains a website with information for building a comprehensive lighting policy for museums:

SW Michalski. 2011. Light, Ultraviolet, and Infrared. The Canadian Conservation Institute. Accessed March 6, 2012 at http://www.cci-icc.gc.ca/caringfor-prendresoindes/articles/10agents/chap08-eng.aspx (last updated August 2, 2011).

10.0 Lessons Learned and Best Practices for Museum Lighting

It is well established that light damages objects over time. This damage can be minimized with careful attention to the light sources and lighting techniques used.

- Know the light sensitivities for the classes of materials in your collection. Many vulnerabilities are well known and published. Training courses are offered by organizations such as the Canadian Conservation Institute and the Getty Conservation Institute. They review these vulnerabilities and offer "best practices" for assessing objects.
- Establish and document the Preservation Target (PT) for objects and collections of objects, and adhere to policy. Damage or fading is a function of the SPD of the illuminant, illuminance on the object multiplied by time (i.e., measured in lux-hours), and varies according to the spectral sensitivity of the specific object
- The curator and the conservator are the authorities on viewing conditions for specific objects in a collection, especially those that are especially rare, involve organic materials, or involve especially fugitive pigments. If risk to an object is suspected, it is best to cease all light exposure until a conservator can confirm safe levels of exposure.
- Keep the object in the dark when it is not actively being observed
- Know the light source SPD. This shows where energy is emitted, whether ultraviolet (UV) and infrared (IR) are emitted, and whether there are peaks of energy in the short wavelengths (400–500 nm) that could pose a risk to specific colors or dyes. The light source includes both electric lighting and any daylighting.
- Eliminate UV (< 400 nm) and IR (> 700 nm) wavelengths through filtering or choice of light source, because they can cause damage while contributing nothing to seeing. (Most LEDs do not emit UV and IR and therefore do not need that filtering.)
- Minimize short-wavelength visible radiation because for many objects that radiation can produce greater damage than middle or long wavelengths. Warm CCT white LEDs (< 3200K) are less likely to radiate significant power in the short wavelengths, and therefore are likely to cause less damage over time than a high-CCT light source. As a rule of thumb, look for lamps where the blue peak in the SPD is less than 1/2 of the maximum power in the SPD. Lamps with lower peaks are even more desired.
- It may be possible to "tune" the LED spectrum for displaying a specific object, to maximize visibility and color rendering, while minimizing damage.[8]
- For further advice, consult the web site of the Canadian Conservation Institute at http://www.cci-icc.gc.ca/caringfor-prendresoindes/articles/10agents/chap08-eng.aspx

[8] Cuttle C. 2009. "New Opportunities for LEDs in Museum Lighting." In *Proceedings of the 2nd PLDC Professional Lighting Design Convention*, pp. 38–44, Berlin.

It is still critical to evaluate the LED lamps in person during the selection process

Although documentation of color metrics can help narrow down the options, it is important to mock up the light sources with similar light levels, similar paint finishes, and on similar artwork in a test gallery. There is no substitute for the human eye in spaces with critical seeing applications.

Energy savings from LED replacement lamps are significant when compared to halogen incumbents

The nominal 12W Cree PAR38 LED lamp (10.2W actual) was able to replace a 60W PAR38 halogen lamp one-for-one. Economic payback rates depend on several factors, including a significant power difference between the incumbent system and the replacement system. This museum gallery showed an 83% reduction in power, and the simple payback occurs in year three of operation because of the above-average power rates in the Los Angeles area (12c/kWh), and relatively high labor costs for replacing the museum's display lighting, in spite of the high cost of the LED replacement lamp. In general, payback times will be shorter when

- electric rates are higher (e.g., greater than the U.S. average $0.10/kWh melded rate),
- labor costs for relamping are high because of hard-to-reach locations, areas where skilled labor is costly, the need for access outside of normal work crew hours, access to the space is limited because of special security clearance, clean room requirements, etc., and
- hours of operation are extensive (e.g., longer than 40 hours per week).

Higher values in any one of these factors will shorten payback times and make the project more economically viable.

If carefully chosen, LED replacement lamps can deliver an equivalent appearance of artwork, so similar that the viewing audience may not notice that the light source is different

LEDs are now available with a warm-color continuous spectrum that is remarkably similar to that of halogen lamps filtered to minimize their damage potential. This gives designers, curators, and conservators a new tool to illuminate critical museum objects, with a dramatic reduction in power and heat.

Appendix A: Getty Museum Exhibit - Input Data for Life-Cycle Cost Analysis

In Search of Biblical Lands exhibit - Input values for Life Cycle Cost Analysis *Incumbent halogen Lamping, LED Lamping*													
Area	Lamp Qty	Incumbent Manuf.	Lamp	Rated Life (hours)	Watts	Operating hours per year (8.5 hrs/day x 6 days/wk x 52 wks/yr)	Total Annual Energy Use (kWh)	Lamp Cost (Cree lamp prices from Getty, Sylvania lamp cost is averaged internet price from 5 retailers)	Initial cost for lamps for whole installation	Number of replacement lamps needed per year	Annualized lamp replacement cost for Gallery	Annual $30 per lamp spot replacement labor cost	Gallery Display Lighting - Annual spot relamping and lamp cost
Lobby													
Display Lighting Incumbent Halogen	34	Sylvania	60PAR38/FL30 reflector, 120V	3000	60	2652	5410.08	$ 5.40	$ 183.60	30.06	$162.30	$ 901.68	$1,063.98
Display Lighting (Cree LED lamp)	34	Cree	PAR38 LED 12W LRP38 2700K	50000	10.2	2652	919.71	$ 99.95	$ 3,398.30	1.80	$180.25	$ 54.10	$ 234.35

Appendix B: Summary Life-Cycle Cost Calculations

NIST BLCC 5.3-10: Summary LCC

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information

File Name:	C:\Documents and Settings\D3Y335\My Documents\Life-Cycle Cost Analysis\projects\Getty 10 year study\Getty Exhibit 10 year analysis 12c per kwh.xml
Date of Study:	Thu Dec 15 17:33:23 PST 2011
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Getty Villa Exhibit
Project Location:	California
Analyst:	Naomi Miller
Base Date:	March 1, 2011
Service Date:	March 1, 2011
Study Period:	10 years 0 months (March 1, 2011 through February 28, 2021)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are REAL (exclusive of general inflation)

Alternative: Cree LED Par38

LCC Summary

	Present Value	Annual Value
Initial Cost	$3,398	$398
Energy Consumption Costs	$947	$111
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Annually Recurring OM&R Costs	$1,999	$234
Non-Annually Recurring OM&R Costs	$0	$0
Replacement Costs	$0	$0
Less Remaining Value	-$1,359	-$159
	------------	------------
Total Life-Cycle Cost	$4,985	$584

Alternative: Sylvania 60W Par38 halogen

LCC Summary

	Present Value	Annual Value
Initial Cost	$184	$22
Energy Consumption Costs	$5,568	$653
Energy Demand Costs	$0	$0

Energy Utility Rebates	$0	$0
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Annually Recurring OM&R Costs	$9,076	$1,064
Non-Annually Recurring OM&R Costs	$0	$0
Replacement Costs	$0	$0
Less Remaining Value	$0	$0
	------------	------------
Total Life-Cycle Cost	$14,828	$1,738

Appendix C: Comparative Analysis of Life-Cycle Cost

NIST BLCC 5.3-10: Comparative Analysis
Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Sylvania 60W Par38 Kalogen

Alternative: Cree LED Par38

General Information

File Name:	C:\Documents and Settings\D3Y335\My Documents\Life-Cycle Cost Analysis\projects\Getty 10 year study\Getty Exhibit 10 year analysis.xml
Date of Study:	Thu Dec 15 16:38:43 PST 2011
Project Name:	Getty Villa Exhibit
Project Location:	California
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	Naomi Miller
Base Date:	March 1, 2011
Service Date:	March 1, 2011
Study Period:	10 years 0 months(March 1, 2011 through February 28, 2021)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$184	$3,398	-$3,215
Future Costs:			
Energy Consumption Costs	$5,568	$947	$4,621
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$9,076	$1,999	$7,077
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$1,359	$1,359
	------------	------------	------------
Subtotal (for Future Cost Items)	$14,644	$1,586	$13,058
	------------	------------	------------
Total PV Life-Cycle Cost	$14,828	$4,985	$9,843

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$11,699
- Increased Total Investment	$1,855

Net Savings	$9,843

Savings-to-Investment Ratio (SIR)

SIR = 6.31

Adjusted Internal Rate of Return

AIRR = 23.83%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 3

Discounted Payback occurs in year 3

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	5,410.1 kWh	919.7 kWh	4,490.4 kWh	44,897.6 kWh

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	18.5 MBtu	3.1 MBtu	15.3 MBtu	153.2 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	1,422.51 kg	241.83 kg	1,180.68 kg	11,805.22 kg
SO2	0.35 kg	0.06 kg	0.29 kg	2.91 kg
NOx	0.58 kg	0.10 kg	0.49 kg	4.85 kg
Total:				
CO2	1,422.51 kg	241.83 kg	1,180.68 kg	11,805.22 kg
SO2	0.35 kg	0.06 kg	0.29 kg	2.91 kg
NOx	0.58 kg	0.10 kg	0.49 kg	4.85 kg

Appendix D: Conservation Assessment

Table D.1. Measured and calculated summary values for fifteen colorants and three ISO Blue Wool Standards exposed to two 3000K white LED sources compared to tungsten halogen.

Colorant (4) Name	Colorant Description	Form	Average (1) Uncertainty ΔE 2000 MCDM+2δ	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change (2) Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range
Exposure Duration (6)				52,000	105,000	210,000	445,000	883,000	1,700,000	6,420,000
Rose Tyrein	Rhodamine B aluminum lake	Gouache on Paper	0.42	**LED <HALOGEN (3)** **Ave ΔE=3.6** **ΔE Range=0.60**	**LED <HALOGEN** **ΔE=6.2** **ΔE Range=0.89**	**LED <HALOGEN** **ΔE=9.73** **ΔE Range=0.93**	**LED <HALOGEN** **ΔE=14.64** **ΔE Range=1.27**	**LED <HALOGEN** **ΔE=18.60** **ΔE Range=1.47**	**LED <HALOGEN** **ΔE=25.83** **ΔE Range=1.29**	**(6)**
Annatto	*Bixa Orellana L.*	Dye/Silk	2.1	LED=HALOGEN Ave ΔE=0.35 ΔE Range=0.06	LED=HALOGEN ΔE=0.64 ΔE Range=0.42	LED=HALOGEN ΔE=0.85 ΔE Range=0.34	LED=HALOGEN ΔE=1.2 ΔE Range=0.50	LED=HALOGEN ΔE=1.8 ΔE Range=0.55	LED=HALOGEN ΔE=3.1 ΔE Range=0.79	LED=HALOGEN ΔE=5.03 ΔE Range=1.07
Sappan	*Caesalpinia sapan L.*	Dye/Silk/Al	0.28	LED=HALOGEN Ave ΔE=0.31 ΔE Range=0.06	LED=HALOGEN Ave ΔE=0.74 ΔE Range=0.01	LED=HALOGEN Ave ΔE=0.98 ΔE Range=0.20	**LED <HALOGEN** **Ave ΔE=1.70** **ΔE Range=0.49**	**LED <HALOGEN** **Ave ΔE=2.30** **ΔE Range=0.90**	**LED <HALOGEN** **Ave ΔE=4.4** **ΔE Range=1.81**	**LED <HALOGEN** **Ave ΔE=9.17** **ΔE Range=3.59**
45440	Rose Bengal	Dye/Paper	0.54	LED=HALOGEN Ave ΔE=1.60 ΔE Range=0.20	LED=HALOGEN Ave ΔE=2.55 ΔE Range=0.25	LED=HALOGEN Ave ΔE=3.02 ΔE Range=0.24	LED=HALOGEN Ave ΔE=4.37 ΔE Range=0.48	LED=HALOGEN Ave ΔE=5.45 ΔE Range=0.43	LED=HALOGEN Ave ΔE=9.12 ΔE Range=0.23	**(6)**
45430	Erythrosine B	Dye/Paper	0.47	LED=HALOGEN Ave ΔE=1.15 ΔE Range=-0.09	LED=HALOGEN Ave ΔE=1.27 ΔE Range=-0.04	LED=HALOGEN Ave ΔE=1.68 ΔE Range=-0.26	LED=HALOGEN Ave ΔE=1.70 ΔE Range=-0.09	LED=HALOGEN Ave ΔE=2.24 ΔE Range=0.18	LED=HALOGEN Ave ΔE=1.93 ΔE Range=0.36	**LED>HALOGEN** **Ave ΔE=4.84** **ΔE Range=-1.07**
Kihada	*Phellodendron amurense*	Dye/Silk	1.65	LED=HALOGEN Ave ΔE=1.50 ΔE Range=0.44	LED=HALOGEN Ave ΔE= 2.66 ΔE Range=0.67	LED=HALOGEN Ave ΔE=4.31 ΔE Range=1.01	LED=HALOGEN Ave ΔE=6.45 ΔE Range=1.14	LED=HALOGEN Ave ΔE=8.05 ΔE Range=1.30	LED=HALOGEN Ave ΔE=9.97 ΔE Range=-0.65	LED=HALOGEN Ave ΔE=11.11 ΔE Range=-0.75
19140	Tartrazine	Dye/Paper	0.82	LED=HALOGEN Ave ΔE=0.29 ΔE Range=0.26	LED=HALOGEN Ave ΔE=0.23 ΔE Range=0.06	LED=HALOGEN Ave ΔE=0.35 ΔE Range=0.36	LED=HALOGEN Ave ΔE=0.44 ΔE Range=0.18	LED=HALOGEN Ave ΔE=0.55 ΔE Range=0.20	LED=HALOGEN Ave ΔE=1.0 ΔE Range=0.33	LED=HALOGEN Ave ΔE=1.60 ΔE Range=0.40
42555	Crystal Violet	Dye/Paper	0.64	LED=HALOGEN Ave ΔE=2.39 ΔE Range=0.42	LED=HALOGEN Ave ΔE=4.51 ΔE Range=0.63	LED=HALOGEN Ave ΔE=6.07 ΔE Range=0.40	LED=HALOGEN Ave ΔE=8.70 ΔE Range=0.67	**LED>HALOGEN** **Ave ΔE=10.43** **ΔE Range=-0.89**	**LED>HALOGEN** **Ave ΔE=15.58** **ΔE Range=-2.25**	**(6)**
42051	Patent Blue	Dye/Paper	0.76	LED=HALOGEN Ave ΔE=0.86 ΔE Range=0.22	LED=HALOGEN Ave ΔE=2.22 ΔE Range=0.66	LED=HALOGEN Ave ΔE=2.89 ΔE Range=0.62	LED=HALOGEN Ave ΔE=3.92 ΔE Range=0.73	LED=HALOGEN Ave ΔE=5.24 ΔE Range=1.22	LED=HALOGEN Ave ΔE=6.92 ΔE Range=0.35	LED>HALOGEN Ave ΔE=10.50 ΔE Range=-0.85

Colorant Name	Colorant Description	Form	Average Uncertainty ΔE 2000 MCDM+2δ	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change (2) Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range	Exposure (Lux-hrs) LED<=>HALOGEN Ave Change Range
	Exposure Duration (6)			52,000	105,000	210,000	445,000	883,000	1,700,000	6,420,000
Weld	*Reseda luteola*	Dye/Silk/Al	1.1	LED=HALOGEN Ave ΔE=0.51 ΔE Range=0.28	LED=HALOGN Ave ΔE=0.90 ΔE Range=0.25	LED=HALOGEN Ave ΔE=0.87 ΔE Range=0.14	LED=HALOGEN Ave ΔE=1.08 ΔE Range=0.11	LED=HALOGEN Ave ΔE=1.28 ΔE Range=0.21	LED=HALOGEN Ave ΔE=1.51 ΔE Range=0.12	LED=HALOGEN Ave ΔE=2.25 ΔE Range=0.02
Safflower	*Carthamus tinctorius*	Dye/Silk	0.37	LED=HALOGEN Ave ΔE=1.29 ΔE Range=0.21	**LED<HALOGEN Ave ΔE=1.97 ΔE Range=0.42**	**LED<HALOGEN Ave ΔE=3.23 ΔE Range=0.78**	**LED<HALOGEN Ave ΔE=5.23 ΔE Range=1.51**	**LED<HALOGEN Ave ΔE=7.46 ΔE Range=2.30**	**LED<HALOGEN Ave ΔE=11.48 ΔE Range=3.72**	**(6)**
Ukon	*Curcuma longa*	Dye/Silk	0.89	LED=HALOGEN Ave ΔE=1.99 ΔE Range=0.34	LED=HALOGEN Ave ΔE=3.34 ΔE Range=0.85	**LED<HALOGEN Ave ΔE=5.47 ΔE Range=1.32**	**LED<HALOGEN Ave ΔE=8.52 ΔE Range=1.82**	**LED<HALOGEN Ave ΔE=10.78 ΔE Range=2.82**	**LED<HALOGEN Ave ΔE=14.62 ΔE Range=2.46**	**(6)**
Zakuro	*Punica granatum*	Dye/Silk/Al	0.83	LED=HALOGEN Ave ΔE=1.48 ΔE Range=0.79	LED=HALOGEN Ave ΔE=2.72 ΔE Range=0.39	LED=HALOGEN Ave ΔE=3.40 ΔE Range=0.27	LED=HALOGEN Ave ΔE=3.68 ΔE Range=0.28	LED=HALOGEN Ave ΔE=4.15 ΔE Range=0.71	LED=HALOGEN Ave ΔE=4.66 ΔE Range=0.57	LED=HALOGEN Ave ΔE=5.99 ΔE Range=0.10
Old Fustic	*Chlorophora tinctoria*	Dye/Silk/Al	0.55	LED=HALOGEN Ave ΔE=0.32 ΔE Range=0.58	LED=HALOGEN Ave ΔE=0.95 ΔE Range=0.36	LED=HALOGEN Ave ΔE=1.23 ΔE Range=0.30	LED=HALOGEN Ave ΔE=1.60 ΔE Range=0.15	LED=HALOGEN Ave ΔE=2.09 ΔE Range=0.25	LED=HALOGEN Ave ΔE=3.03 ΔE Range=0.31	LED=HALOGEN Ave ΔE=3.88 ΔE Range=0.18
Onion Skin	*Allium cepa*	Dye/Silk/Al	0.86	LED=HALOGEN Ave ΔE=1.49 ΔE Range=0.50	LED=HALOGEN Ave ΔE=2.26 ΔE Range=0.34	LED=HALOGEN Ave ΔE=2.67 ΔE Range=0.30	LED=HALOGEN Ave ΔE=2.30 ΔE Range=0.37	LED=HALOGEN Ave ΔE=2.71 ΔE Range=0.36	LED=HALOGEN Ave ΔE=2.83 ΔE Range=0.31	LED=HALOGEN Ave ΔE=4.17 ΔE Range=0.55
ISO BLUE WOOL 1				LED=HALOGEN Ave ΔE≈0.5	LED=HALOGEN Ave ΔE≈0.7	LED=HALOGEN Ave ΔE≈3	**LED<HALOGEN Ave ΔE≈5**	**LED<HALOGEN Ave ΔE≈9**	**LED<HALOGEN Ave ΔE≈13**	**(6)**
ISO BLUE WOOL 2				LED=HALOGEN Ave ΔE<0.3	LED=HALOGEN Ave ΔE<0.5	LED=HALOGEN Ave ΔE<0.7	LED=HALOGEN Ave ΔE<1.5	**LED<HALOGEN Ave ΔE≈2.5**	**LED<HALOGEN Ave ΔE≈4.5**	
ISO BLUE WOOL 3				LED=HALOGEN Ave ΔE<0.3	LED=HALOGEN Ave ΔE<0.5	LED=HALOGEN Ave ΔE<0.5	LED=HALOGEN Ave ΔE≈0.5	LED=HALOGEN Ave ΔE<0.7	LED=HALOGEN Ave ΔE<1.0	~8,500,000 **LED<HALOGEN Ave ΔE≈3.0**

TEST COLOR CODES	
No Difference in Lamps	LED=HALOGEN
Statistically Significant & at or below JND	**LED<HALOGEN**
Statistically Significant & well above JND	**LED<HALOGEN**

Table Notes:

1. Over the course of 500 exposure hours and multiple withdraws, measurements and sample uncertainty were calculated in CIEDE 2000 using the MCDM method of Berns during "measurement with replacement." The overall uncertainty (shown here) was summed plus two standard deviations. From the work of Nadal and others this was expected to greatly exceed the 95% confidence level for each dye substrate combination (Berns 2000). See (Nadal, Miller et al. 2010) for a complete discussion of alternative methods for the statistical analysis of color difference.
2. "Average Change" presents the general level of appearance change for all three sets of samples (6–9 samples per colorant) at a given exposure in lux-hours. The "ΔE Range" was how broad changes were between the samples. Both of these then can be compared to the "Average Uncertainty." For example, using 45440, Rose Bengal, the overall uncertainty was 0.54 ΔE, which is more than twice as small as a visually detectable color change on a textile. Incrementally, Rose Bengal was measured periodically between 52,000 and 1,700,000 lux-hours for each light source. During that time, average sample color change went from no change at the start to 9.12 ΔE, a significant fade. This is 6–9 times a "just noticeable difference" (JND≈1.0-1.5 CIEDE2000), yet the color difference span ("Range") under all three light sources were ΔE 0.11 at 52,000, ΔE 0.14 at 105,000, ΔE 0.20 at 210,000, ΔE 0.45 at 445,000, ΔE 0.37 at 883,000, and ΔE 0.21 at 1,700,000 lux-hours—virtually no difference at all between the three light sources.
3. All entries in **BLACK** note "no difference" for the colorant and the three light sources in light-induced color damage. **BLUE** entries indicate where color change differences are statistically significant and in all cases the LEDs are slowing down the rate of change. Entries in **RED** indicate where the difference is both statistically significant and visually detectable. **For all colorants, visually detectable color change differences occurred long after all the samples would have visually faded. Therefore, from a risk management and preventive conservation point of view, none of the colorants represent a difference in terms of exhibition policy with respect to these three light sources. (See the text for a detailed explanation.)**
4. Dyes on silk were provided by Masako Saito of the Kyoritsu Woman's University in Japan and were identical to those samples prepared by Mie Ishii in her studies of lighting on traditional textile dyed colorants (Ishii, Moriyama et al. 2008). Number samples on paper were supplied by Luisa Casella, then of the Metropolitan Museum of Art, to represent the dyes used on autochrome photographs, known to be particularly sensitive.
5. Three exposure booths were each balanced to 13,200 lux over the sample exposure surface and periodically checked over a 7-point grid between February 17 and August 18, 2011. They were found to hold to within 1.6%. The exposure period of 490 hours was insufficient to experience lamp lumen depreciation for the halogen lamps that were supplied as GE 71W MR16. One of the two LEDs was a MR16 replacement lamp by CRS Electronics, the other was a small form factor light engine produced by Xicato. Both were CRI~95, CCT~2900K. For the ISO Blue Wool exposures, the booths were balanced to 12,200 lux. Colorimetry was recorded with a Minolta CR-221 checked against the BCRA blue tile standard bi-weekly. Five replicate measurements were made on 2 or 3 specimens for each color sample in each chamber at differing locations on the grid. Measurement was done "with replacement."
6. Colorants that had badly discolored by 1.7 million lux hours were discontinued.

References:

Berns, RS, ed. 2000. *Billmeyer and Saltzman's principles of color technology*. 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." *Journal of Light and Visual Environment* 32(4):8.

Nadal ME, CC Miller, et al. 2010. "Statistical methods for analyzing color difference distributions." *COLOR: Research and Application* 36(3):160-168.

Chamber 1			***Chamber 2***			***Chamber 3***		
Xicato LED light engine, 3000K, 95 CRI			**GE 71 W MR16 Tungsten-Halogen, 3000K, 94 CRI**			**CRS, MR16 LED, 2900K, 93 CRI**		
52,000 lux-hrs.			**52,000 lux-hrs.**			**52,000 lux-hrs.**		
Annatto	**Annatto**	**Annatto**	**Annatto**	**Annatto**	**Annatto**	**Annatto**	**Annatto**	**Annatto**
Measure Color			**Measure Color**			**Measure Color**		
L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*
L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*
L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*
L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*
L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*	L*a*b*
Average MCDM	Average MCDM	Average MCDM	Average MCDM	Average MCDM	Average MCDM	Average MCDM	Average MCDM	Average MCDM
NEXT Colorant: NEXT Exposure Interval								

CIEDE 2000   CIEDE 2000   CIEDE 2000

If Difference > Uncertainty & Differences > JND Then Difference is Significant Else Not

Figure D.1. Experimental design for testing LED and tungsten halogen lamps for their relative damage to light-sensitive colorants. Measurement periods: 0, 52,000, 105,000, 210,000, 445,000, 883,000, 1,700,000, 6,400,000 lux hours (± 1.6%).

Table D.2. Relative spectral sensitivity of several light sources determined with the method described in CIE Technical collection 1990, CIE 089-1991, ISBN 978 3 900734 36 8. The three sources used in this study are highlighted in gray. (Data adapted from Joseph Padfield, National Gallery, http://reseach.ng-london.org.uk/scientific/spd/).

Lamp Type	Type	CCT (K)	CRI	Relative Exposure (%)
Daylight Blackbody	DL	5600	100	100
Erco Eclipse - Blue Lens	TH	4060	95	92
Philips 50W MR16	TH	2700	98	63
GE EYC 71W MR16	**TH**	**3000**	**98**	**63**
Xicato, LSI LumeLEX	**LED**	**3000**	**95**	**59**
CRS SP12 MR16	**LED**	**2900**	**96**	**56**
Philips EnduraLED MR16	LED	3000	86	54
MSI PAR38	LED	2950	82	53
CREE LRP-38	LED	2600	93	46

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