GATEWAY DEMONSTRATIONS

Demonstration Assessment of Light-Emitting Diode (LED) Accent Lighting

Host Site: Field Museum, Chicago, Illinois

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
Field Museum of Natural History
Lighting Services, Inc.
Xicato

November 2010

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

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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) Solid-State Lighting Technology Demonstration GATEWAY 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 parking structure and application under examination. Each GATEWAY demonstration compares one SSL product against the incumbent technology used in that location. Depending on available information and circumstances, the SSL product may also be compared to alternative lighting technologies. Though products demonstrated in the GATEWAY program have been prescreened and tested to verify their actual 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.

Summary

This report describes the process and results of a demonstration of solid-state lighting (SSL) technology in an accent lighting application in a museum, under the U.S. Department of Energy GATEWAY Solid-State Lighting Technology Demonstration Program. In this project, an entire enclosed gallery originally used 32 halogen (various lamps) track luminaires to light an exhibit. The exhibit operated for roughly 2 months, and then the lighting was replaced with a light-emitting diode (LED) system that used 26 track fixtures. Both the halogen and the LED luminaires and track were manufactured by Lighting Services, Inc.

The LED system resulted in 63 percent energy savings compared to the halogen system. Energy savings resulted from the LED system being more efficacious on a per-fixture basis, greater centerbeam intensity for similar beam angles, and different distributions allowing for fewer luminaires to be installed. In terms of illumination, the LED system produced comparable illuminance on the lighted artifacts.

Aside from energy savings and illuminance, the LED system was demonstrated to examine the quality of the lighting from a source expected to be less detrimental to the artifacts. The mere act of lighting an artifact damages it, so museums are constantly balancing damage with visibility. The LED luminaires demonstrated do not emit light in the infrared or ultraviolet regions of the visible spectrum. Energy in these regions can be detrimental to the artifacts.

In terms of cost, the simple payback for the LED system compared to that of the halogen system is roughly 3 years. However, that is not typical of a luminaire-for-luminaire replacement scenario. In the scenario of comparing one LED luminaire against one halogen luminaire, the payback ranged from 5 to 11 years. Factors affecting the payback in a museum application include equipment used to filter the light, maintenance costs, and the effect of the lighting system on the air-conditioning system.

Two different groups of professionals evaluated the lighting systems: (1) museum exhibit design staff, who evaluated both the halogen and the LED systems, and (2) a group of lighting professionals, who only had the opportunity to evaluate the LED system. Each group responded differently based on their areas of expertise, but overall feedback from both groups was positive for the LED system.

Overall, the LED system was a success. However, the LED system could only provide beam angles from 20° to 60°. Depending on the lighting installation other (e.g., smaller) beam angles might be needed. The advantage of halogen sources is the myriad of beam angles and wattage combinations of the various lamps. The unique design of the LED luminaires makes smaller beam angles unrealistic because smaller angles would require the overall size of the luminaire to get disproportionately larger.

Another issue that arose during the demonstration, which is somewhat common to LED systems, was the LED system's interaction with the dimming system. As the LEDs were dimmed to a lower setting by the lighting control system, the illuminance continued to decrease but the measured current (and thus the power of the system) did not. The interaction between LED drivers and lighting control systems is an ongoing research activity in the lighting industry.

Acronyms and Abbreviations

A	ampere(s)
AFF	above the finished floor
Btu	British thermal unit(s)
CBCP	centerbeam candlepower
CCT	correlated color temperature
cd	candela(s)
CRI	color rendering index
DOE	U.S. Department of Energy
fc	footcandle(s)
ft	foot, feet
HVAC	heating, ventilation, and air-conditioning
IES	Illuminating Engineering Society
in.	inch(es)
IR	infrared
K	kelvin
kWh	kilowatt-hour(s)
LED	light-emitting diode
LLD	lamp lumen depreciation
lm/W	lumen(s) per watt
mm	millimeters
nm	nanometer(s)
PNNL	Pacific Northwest National Laboratory
SSL	solid-state lighting
Std. Dev.	standard deviation
UV	ultraviolet
V	volt(s)
VL	visible light
W	watt(s)

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1.0 Introduction

This report describes the process and results of a demonstration of solid-state lighting (SSL) technology in an interior application of museum lighting in Chicago, IL conducted by Pacific Northwest National Laboratory (PNNL) in late 2009. The project was supported under the U.S. Department of Energy (DOE) Solid-State Lighting GATEWAY Demonstration Program. Other participants included the Field Museum for Natural History (Field Museum), Lighting Services, Inc., and Xicato. PNNL conducted the measurements and analysis of the results.

PNNL manages several GATEWAY demonstrations for DOE and represents DOE's perspective in the conduct of the work. DOE supports such demonstration projects to develop real-world experience and data with SSL products in general illumination applications. DOE's approach is to carefully match applications with suitable products and form teams to carry out the project work. Other project reports and related information are available via DOE's SSL website at http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html.

Lighting Services, Inc. is one of the oldest track lighting manufacturers in the country and supplies products to museums across the United States and around the world. The Field Museum, one of the largest and oldest museums for natural history, is actively seeking methods to reduce damage to artifacts from lighting while increasing sustainability within the museum. When Lighting Services, Inc. contacted the Field Museum about a possible installation of new light-emitting diode (LED) sources for lighting a gallery, the museum was interested.

The museum dates back to the World's Columbian Exposition of 1893, which was one of the first major demonstrations of electric lighting. Fittingly, the exhibit selected to be test-lighted by the LEDs was of an architectural design competition for a memorial celebrating Daniel Burnham—the architect of the museum, developer of the master plan for the Exposition, and the author of the *Plan of Chicago*, a prominent document in the history of city planning (Chicago Historical Society 2005).

A second factor making the Burnham exhibit an excellent subject for testing a new light source is that the exhibit contained only one genuine artifact: a book displayed in a case at the back of the room. Other displays were either recent reproductions of the model of the memorial or new displays printed on foam core. Ultraviolet (UV), visible, and infrared (IR) wavelengths of light all have potentially negative effects on items in museums, so limiting the number of items that required particular attention to conservation was helpful.

In addition to electromagnetic radiation (i.e., UV, visible light [VL], IR), humidity and temperature can hasten the degradation of artifacts. For this reason, museums have elaborate cooling systems. All forms of electric lighting produce heat, and any technology drawing less power correlates to less work for the heating, ventilation, and air-conditioning (HVAC) system when cooling, but could require more work when heating is needed. However, because the museum cools the spaces year round to limit the degradation of the artifacts, the possible effects on the heating system did not need to be considered in this demonstration.

Required maintenance is another extremely important consideration for museums. Because the ambient lighting in most exhibits is very low (≈ 5 footcandles [fc]) and the accent lighting specifically exists to highlight and model key features of the artifact for the public, quick and timely maintenance of failed lamp sources is imperative. However maintenance can be difficult because (1) the accent fixtures are focused for a specific purpose and should not be altered through relamping, and (2) replacement requires bringing either a lift or a ladder into the museum space.

For these reasons, light sources with a long life that meet the other needs of the museum (e.g., provide accent lighting, limit damage from UV and IR light) are highly desirable. Fiber optic systems, typically with metal halide sources, have been used in some museums. The fiber optic systems typically require a mechanical douser for dimming, but don't actually save energy when "dimming." The systems can be used effectively in some gases, but have limitations when providing accent lighting for walls and other elements. In contrast, LEDs are directional, offer a potentially long life, and have low UV and IR content, making them very suitable for accent lighting.

2.0 Methodology

2.1 Site Description

The installation is located in the T. Kimball and Nancy N. Brooker Gallery (Brooker Gallery) of the Field Museum. The room is 17 ft wide × 32 ft long with a 14-ft-high ceiling. The walls in the space are neutral gray or white.

The south wall in the space displays sixteen 2 ft × 2 ft vertical graphics of submissions for an architectural competition to design a memorial to Chicago architect Daniel Burnham. Also mounted on this wall are two signs that show an aerial view of the coast of Lake Michigan and a sign about Burnham's vision for Chicago.

The east wall has a window that is almost always covered by a screen. A display box containing a book of Burnham's original drawings is located along this wall.

The north wall contains very large panels featuring the first through third place entries of the architectural competition. Also mounted on this wall are two signs that show information about the competition and the finalist.

In the center of the gallery are two large display tables and a triangular vertical display board. The display tables contain a model of the site of the memorial and a detailed model of the memorial.

Finally, there is a vestibule airlock that provides background information on the competition and separates the gallery from the main museum.

The display in the Brooker Gallery has changed since the start of this demonstration to display different artifacts, a common practice in certain museum galleries.

2.2 Typical Luminaires

The Field Museum's lamp inventory has to be limited yet versatile. Since most items in the museum are lighted to conservation levels (e.g., low illuminance), most of the halogen lamps in the space are low-wattage (e.g., under 60W). Furthermore, most lighting within the museum, and everything in the Brooker Gallery, is track-mounted accent lighting.

This space was lighted by a total of 32 fixtures from Lighting Services, Inc. Three different lamps were used: (1) OSRAM SYLVANIA CAPSLYTE 45PAR38/HAL/FL30 (herein referred to as PAR 38); (2) GE 35PAR36/NSP (herein referred to as PAR 36); and (3) an OSRAM SYLVANIA 50MR16/T/SP10/C (EXT) (herein referred to MR-16). The luminaires had only UV filters and no other accessories (i.e., baffles, filters, or color media).

2.2.1 Track Fixtures with PAR 38 lamps

The PAR 38 lamp has a nominal voltage of 130V. When operated at this voltage, the lamp draws 45W and produces approximately 560 lumens, and has a centerbeam candlepower (CBCP) of 1500 candelas (cd), a correlated color temperature (CCT) of 2825 K, a color rendering index (CRI) of 100, and rated life of 2500 hours. However, when operated on a 120V system, these values all shift accordingly.[1] According to the manufacturer, when operated at this voltage, the lamp draws approximately 40 watts and produces approximately 425 lumens, with a rated life of 5000 hours. Although the manufacturer provides no information about CBCP, CCT, or CRI at 120V, it can be assumed that if the lumen output has decreased by 24 percent (425/560) there will be a linear affect on CBCP, reducing it to 1138 cd. It is also well known that as halogen lamps dim (or in this case are operated at 120V rather than 130V), the CCT shifts lower. It is unknown how CRI changes when operated at a lower voltage. The 30° beam angle should not change at any voltage.

Using a nominal 130V lamp in a 120V system is a standard option for extending lamp life. In fact, several manufacturers market halogen PAR 38 lamps as “long life” when in essence they are just nominal 130V lamps. It should be noted, however, that most current 130V PAR lamps will not meet the new federal rulemaking regarding this technology when the requirement becomes effective in 2012 (DOE EERE 2009). The manufacturer also provides a footnote in its product catalog about operating this lamp on a different voltage than designed:

> Approximate life for 130 volt tungsten halogen lamps operated at 120 volts is within the value calculated using the recommended equations for standard incandescent lamps, as set forth in the IES Handbook, 8th edition. Because of the uncertain nature of the halogen cycle on the coil when operated at less than rated voltage, life of tungsten halogen lamps varies considerably and unpredictably. OSRAM SYLVANIA does not recommend operation at other than rated voltage (OSRAM SYLVANIA 2008).

2.2.2 Track Fixtures with PAR 36 Lamps

The PAR 36 lamp is a low-voltage lamp with a nominal voltage of 12V. When operated at this voltage, the lamp draws 35W and produces approximately 250 lumens, and has a CBCP of 8000 cd, a CCT of 3050 K, a CRI of 100, and a rated life of 4000 hours. See Figure 2.1 for intensity distribution. Similar to the PAR 38, when dimming, all of these lamp properties shift. This lamp has a beam angle of 8°, which should not change as voltage varies.

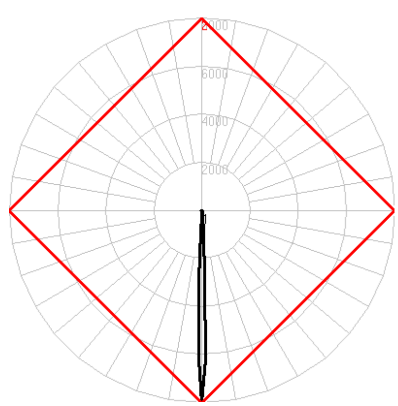

Figure 2.1. PAR 36 Trackhead Distribution

[1] See the *IESNA Lighting Handbook*, 9th Edition (IESNA 2006), section 6, regarding the applicable formulas for converting CCT, lumens, lm/W at different voltages than designed.

Being a low-voltage lamp, this fixture requires a step-down transformer, in this case an electronic transformer. This transformer adds some load (power) to the fixture, assumed to be between 3 and 5W.

2.2.3 Track fixtures with MR16 lamps

The MR-16 lamp is a low-voltage lamp with a nominal voltage of 12V. When operated at this voltage, the lamp has a CBCP of 11,500 cd, a CCT of 2900 K, a CRI of 100, and a rated life of 4000 hours, and draws 50W. Again, when dimming, all of the lamp properties will shift. The lamp has a beam angle of 11°, but this should not change as the lamp is operated at any voltage.

Since this is a low-voltage lamp, this fixture uses an electronic step-down transformer. This transformer is a 50 volt-ampere transformer. This transformer will add some load to the fixture, assumed to be between 3 and 5W.

2.2.4 New Luminaires

Two Lighting Services, Inc. trackheads using Xicato LED modules were installed for the LED system. Most of the trackheads were the Lighting Services, Inc. LX2024-D3M2-00-W. According to the manufacturer cutsheet, this luminaire produces 860 lumens at CCT of 3000 K and a CRI of 80. The input power to the luminaire is 26W. Therefore, the luminaire efficacy is 33 lumens per watt (lm/W). The luminaires use Lighting Services, Inc.'s 94 millimeter (3.70 in. (outside diameter)) LED module with a 20° beam angle. The CBCP of the luminaire is 4737 cd. See Figure 2.2 for intensity distribution.

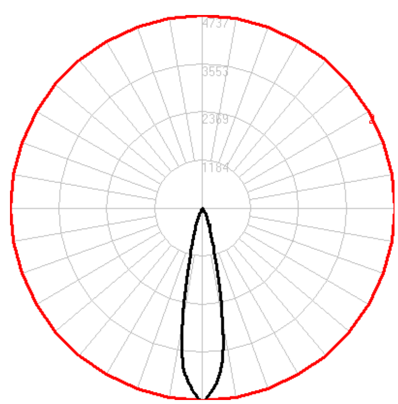

Figure 2.2. LED Trackhead with 20° Distribution

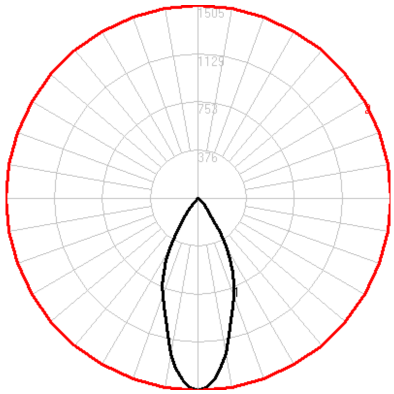

Figure 2.3. LED Trackhead with 40° Distribution

A smaller number of the new trackheads were the Lighting Services, Inc. LX2024-D3M4-00-W. According to the manufacturer cutsheet, this luminaire produces 860 lumens at a CCT of 3000 K and a CRI of 80. The input power is 26W, for a luminaire efficacy of 33 lm/W. The luminaires use Lighting Services, Inc.'s 70 millimeter (2.75 in. (outside diameter)) LED module with a 40 ° beam angle. The CBCP of the luminaire is 1505 cd. See Figure 2.3 for intensity distribution.

2.2.5 Materials Degradation

Museums must balance preserving the artifacts/pieces with displaying them for the betterment of the public. To allow future generations to view a piece, museums take many steps to limit material degradation. Electromagnetic radiation degrades sensitive materials and is a concern in a museum environment. Two processes by which light-induced degradation occurs include (1) photochemical reaction, and (2) radiant heating effect. Of these, photochemical reaction is the greater concern.

2.2.5.1 Electromagnetic Radiation

The spectra of electromagnetic radiation emitted by electric sources include UV, VL, and IR. UV light is composed of three subgroups, and each group affects people or objects differently. UV-C consists of wavelengths from 100 to 280 nanometers (nm), UV-B is from 280 to 315 nm, and UV-A is from 315 to 400 nm. VL extends from 380 to 780 nm. IR light, like UV, is composed of three subgroups: Near IR (770 to 1400 nm); Intermediate IR (1400 to 5000 nm); and Far IR (5000 to 1,000,000 nm). Because different molecules have different photon energy thresholds, some molecules are affected by only UV radiation while others are affected by radiant energy in the visible spectrum. For museum applications, the ideal light contains neither UV ($\lambda \leq$ 400nm) nor IR ($\lambda \geq$ 770nm) components. However, too much attention to reducing UV or IR may lead to needless damage to precious artifacts from visible radiation (380 to 770 nm). Emphasis must be continuously placed on controlling the visible radiation (IESNA RP-30-96).

Table 2.1 provides the light exposure recommendations in an illuminance-time unit. More information about material responsiveness classification can be found in Appendix E. As the sensitivity of the material increases (R0 low, R3 high) the total number of illuminance-hours decreases. To meet the values in Table 2.1, the artifact can be illuminated at high illuminance for a few hours, illuminated at very low illuminance for many hours, or illuminated by a special combination of these.

Table 2.1 Limiting Illuminance

Material responsiveness classification	Limiting illuminance	Limiting Exposure [lx h/y (fc h/y)]
R0. Non-responsive	No limit	No limit
R1. Slightly responsive	200 lx (20 fc)	600,000 lx h/y (60,000 fc h/y)
R2. Moderately responsive	50 lx (5 fc)	150,000 lx h/y (15,000 fc h/y)
R3. Highly responsive	50 lx (5 fc)	15,000 lx h/y (1500 fc h/y)

Source: Cuttle 2007, Table 3.3.

2.2.5.2 Temperature/Humidity

Temperature and humidity can also affect the material. Warm temperatures and dry environments are undesirable for many museum pieces. The museum needs the air-conditioning system to maintain the temperature in the space between 66 and 70° F year round.

The load of the lighting system adds to the air-conditioning system load. One watt of electrical power, regardless of the device drawing the power (e.g., refrigerator, television, light fixture), is equal to 3.412 British thermal units (Btu). Therefore, any reduction in electrical power of the lighting system reduces the Btu needs of the air-conditioning system.

2.3 Installation

Prior to the LED installation, the space was designed and outfitted with a standard halogen-based lighting system. Both power and illuminance measurements were taken for the baseline installation. The baseline luminaires were then removed, and LED luminaires were installed and focused in the gallery. Illuminance and power measurements were repeated for the LED lighting system.

The baseline system operated for about 2 months before the LED installation. GATEWAY demonstrations typically use new lamps in the baseline installation to eliminate effects of lamp lumen depreciation (LLD), but this was not the case in this installation. The museum dims many of the lamps for conservation levels, which delays the effects of LLD. Furthermore, because halogen lamps are generally acknowledged to have only minimal lumen depreciation over their lifetime, the usual process of relamping was deemed unnecessary.

The new LED system produced more lumens and, in some cases, a slightly wider beam angle than the baseline halogen, which allowed the total number of luminaires to be reduced from 32 to 24, as detailed in Table 2.2.

Table 2.2. Number and Type of Luminaires Installed

	Original Installation			LED Installation	
	# of PAR 38	# of PAR 36	# of MR-16	70 mm	90 mm
Zone 1 (Track 1)	1	0	0	0	3
Zone 2 (Track 2)	0	0	0	0	0
Zone 3 (Track 3)	0	2	0	0	4
Zone 4 (Track 4)	2	2	0	0	3
Zone 5 (North Wall)	9	2	0	8	0
Zone 6 (South Wall)	8	2	0	6	0
Zone 7 (Vestibule)	3	0	1	0	2
Total	23	8	1	14	12

The space has a stand-alone lighting control system. This system is a Leviton a-2000 Dimming Control Equipment.[2] Dimming the LEDs produced mixed results. One run of track with only one LED fixture was connected to one dimming module in the control system. This LED fixture flickered as it was dimmed past 60 percent. To combat the flicker issue, additional fixtures had to be installed on the track to increase the load of the track. Another issue with the dimming was that it did not necessarily track linearly in terms of energy savings. After the LEDs were dimmed below 50 percent, measurements showed that the light on the wall continued to decrease but the current at the dimming panel did not change. During the measurements, the LEDs were dimmed from 50 percent to 15 percent in terms of dimming level at the dimming panel. The dimming was verified by the illuminance meter. However, the current draw at the panel remained constant over the range. This phenomenon was mostly likely a result of the specific LED driver and specific dimming module combination.

2.4 Power and Energy

Power measurements for both the baseline (halogen) and LED luminaires were taken at the same points on the lighting control panel. Each track inside the main gallery and the vestibule is connected to a single module on the panel. The voltage for the gallery is 120V, and the current (amperage) was measured at the individual wires to each module.

2.4.1 Power Measurements

Table 2.3 provides the baseline halogen lighting current measurements and the calculated power of the different control zones of the control system at full (100 percent) setting. The number of luminaires on each zone affects the load of that zone. When operating at full output, the baseline system drew 1209W.

[2] http://www.leviton.com/OA_HTML/ibeCCtpSctDspRte.jsp?section=15363.

Table 2.3. Load of Lighting System (Baseline, Halogen) at Full Setting

	Voltage (V)	Current (A)	Power (W)	# of PAR 38	# of PAR 36	# of MR-16	Output Level (%)
Zone 1 (Track 1)	120	0.32	38.4	1	0	0	100
Zone 2 (Track 2)	120	---	---	---	---	---	---
Zone 3 (Track 3)	120	0.62	74.4	0	2	0	100
Zone 4 (Track 4)	120	1.24	149.8	2	2	0	100
Zone 5 (North Wall)	120	3.45	414.0	9	2	0	100
Zone 6 (South Wall)	120	3.18	381.6	8	2	0	100
Zone 7 (Vestibule)	120	1.26	151.2	3	0	1	100
Total			1209.4	23	8	1	---

Table 2.4 provides the current measurements and the calculated power of the different control zones of the control system at the various settings needed to balance the lighting appearance of the different artworks in the gallery. When operating at the different output levels, the baseline system drew 894.0W.

Table 2.4. Load of Lighting System (Baseline, Halogen) at Dimmed Setting

	Voltage (V)	Current (A)	Power (W)	# of PAR 38	# of PAR 36	# of MR-16	Output Level (%)
Zone 1 (Track 1)	120	0.32	38.4	1	0	0	100
Zone 2 (Track 2)	120	---	---	---	---	---	---
Zone 3 (Track 3)	120	0.42	50.4	0	2	0	65
Zone 4 (Track 4)	120	0.71	85.2	2	2	0	45
Zone 5 (North Wall)	120	2.67	320.4	9	2	0	75
Zone 6 (South Wall)	120	2.45	294.0	8	2	0	75
Zone 7 (Vestibule)	120	0.88	105.6	3	0	1	65
Total			894.0	23	8	1	---

Table 2.5 provides the current measurements and the calculated power of the different control zones of the control system at full (100 percent) setting for the LED lighting system. When operating at full output, the LED system drew 836W.

Table 2.5. Load of Lighting System (LED) at Full Setting

	Voltage (V)	Current (A)	Power (W)	70 mm	90 mm	Output Level (%)
Zone 1 (Track 1)	120	0.76	91.2	---	3	100
Zone 2 (Track 2)	120	---	---	---	---	0
Zone 3 (Track 3)	120	1.01	121.2	---	4	100
Zone 4 (Track 4)	120	0.77	92.4	---	3	100
Zone 5 (North Wall)	120	2.12	254.4	8	---	100
Zone 6 (South Wall)	120	1.57	188.4	6	---	100
Zone 7 (Vestibule)	120	0.45	54.0	---	2	100
Total			836.4	14	12	

Table 2.6 provides the current measurements and the calculated power of the different control zones of the control system for the LED lighting at the various settings needed to balance the lighting of the different artworks in the gallery. When operating at the different output levels, the LED system drew 335W.

Table 2.6. Load of Lighting System (LED) at Dimmed Setting

	Voltage (V)	Current (A)	Power (W)	70 mm	90 mm	Output Level (%)
Zone 1 (Track 1)	120	0.29	34.8	---	3	45
Zone 2 (Track 2)	120	---	---	---	---	0
Zone 3 (Track 3)	120	0.44	52.8	---	4	45
Zone 4 (Track 4)	120	0.29	34.8	---	3	15
Zone 5 (North Wall)	120	0.94	112.8	8	---	40
Zone 6 (South Wall)	120	0.66	79.2	6	---	45
Zone 7 (Vestibule)	120	0.17	20.4	---	2	43
Total			334.8	14	12	

2.4.2 Annual Load Profile

The scene set in the LED installation draws 335W compared to the baseline installation's draw of 894W. Since this space is windowless, no daylighting controls are possible, and no occupancy-based controls are used. Therefore, annual energy savings are estimated by assuming system operation from 9:00 am to 5:00 pm daily at the power levels specified in each scene, 364 days per year (The Field Museum 2010). The annual scheduled operation of the system is 2912 hours.

2.4.3 Annual Lighting Energy Usage

Resulting annual energy use would be 2603 kilowatt-hours (kWh) (894W × 2912 hours) for the halogen installation and 975 kWh (335W × 2912 hours) for the LED installation. The LED system therefore uses 63 percent less energy than the halogen system.

2.5 Horizontal Illuminance

Illuminance for the halogen (baseline) installation was measured between 10:00 am and 12:00 pm and illuminance for the LED installation was measured between 2:00 pm and 4:00 pm on October 2, 2009. Since museum (accent) lighting is specific to the artifact and the exhibit to help tell the story, lighting for several museum pieces was measured. For each case (summaries shown below), illuminance measurements were taken on the top of the display case for the halogen system and the LED system.

2.5.1 Display Case – "Model of Site"

This display case was 50 in. wide × 60 in. long and the top of the case was 48 in. above the finished floor (AFF). A grid 6 in. × 6 in. centered across the top of the display case was measured, providing a total of 63 points. Detailed illuminance data can be found in Appendix B. Table 2.7 summarizes the results of these measurements. The LED installation provided slightly more (≈25 percent) average illuminance than the baseline installation, along with higher minimum and maximum values.

Table 2.7. Summary of Model of Site Illuminance Values

	Baseline	LED Installation	LED: Baseline
Average	5.58 fc	7.00 fc	125%
Max	6.96 fc	8.49 fc	121%
Min	3.80 fc	5.58 fc	146%
Avg:Min	1.47:1	1.25:1	
Max:Min	1.83:1	1.52:1	
Std. Dev	0.71 fc	0.83 fc	
Coefficient of Variation	0.13	0.12	

2.5.2 Display Case – "Detail of Memorial"

This display case was 39 in. wide × 36 in. long and the top of the case was 65 in. AFF. A grid 6 in. × 6 in. centered across the top of the display case where the lighting was oriented was measured, providing a total of 20 points. Detailed illuminance data can be found in Appendix B. Table 2.8 summarizes the results of the measurements. Notice that the LED installation provided significantly less (≈40%) average illuminance than the baseline installation, along with lower minimum and maximum values.

Table 2.8. Summary of Detail of Memorial Illuminance Values

	Baseline	LED Installation	LED:Baseline
Average	37.10 fc	22.46 fc	61%
Max	65.5 fc	29.7 fc	45%
Min	14.8 fc	11.42 fc	77%
Avg:Min	2.51:1	1.97:1	
Max:Min	4.43:1	2.60:1	
Std. Dev	14.14 fc	5.83 fc	
Coefficient of Variation	0.38	0.26	

2.5.3 Display Case – "Burnham Sketch Book"

Illuminance measurements were taken on the top of the display case showing the model of the entire site. This display case was 39 in. wide × 36 in. long and the top of the case was 65 in. AFF. A grid 6 in. × 6 in. centered across the top of the display case where the lighting was oriented was measured for a total of 9 points. Detailed illuminance data can be found in Appendix B. Table 2.9 summarizes the results of the measurements. The LED installation provided significantly more (64 percent) average illuminance than the baseline installation, along with higher minimum (almost twice) and maximum illuminance values.

This increased illuminance of the LED system was an unintentional byproduct of the fixtures attached to that specific piece of track and the needs served by the other fixtures on that track. The desired illuminance for the artifact was 5 fc, whereas the conventional system was providing only about 4 fc (average) while the LED increased this to about 6 fc. Issues had been encountered with flicker of the LEDs at illumination levels below this due to insufficient loading of the dimming system, so this level was as low as the LED could manage with the given configuration. The higher illuminance could have been an issue had the installation been a permanent exhibit, but the relatively short run planned in this instance eliminated any illuminance/exposure limit concerns for the artifact.

Table 2.9. Summary of Book Values

	Baseline	LED Installation	LED:Baseline
Average	3.71 fc	6.08 fc	164%
Max	5.95 fc	7.67 fc	129%
Min	2.04 fc	4.03 fc	198%
Avg:Min	1.82	1.51	
Max:Min	2.92	1.90	
Std. Dev	1.39 fc	1.33 fc	
Coefficient of Variation	0.38	0.22	

2.6 Vertical Illuminance

Vertical illuminance is also critical in a museum. Several pieces in the gallery were mounted on the wall or in vertical cases on the wall. Vertical measurements were taken on the face (if a glass surface) or as close to the face of the object as possible without causing damage. Summaries of the illuminance measurements are below.

2.6.1 South Wall – "Submissions that Did Not Place"

Illuminance measurements were taken on the architectural competition submissions located on the south wall. The 16 entries were arranged in 2 rows with a total of 8 columns. To get a sense of how the lighting on this wall compared, vertical illuminance measurements normal to the wall were taken at every other diagonal submission following a checkerboard pattern (e.g., starting at top left, then to the bottom to the right, then to the top right). This provided for a total of 8 entries to be measured and effectively provided the most data without having to measure every submission. A grid 6 in. × 6 in. in the center of each 2 ft × 2 ft submission was measured for a total of 9 points per submission. Detailed illuminance data can be found in Appendix C. All of the values for both installations were tabulated and the results are in Table 2.10. The LED installation provided virtually the same average illuminance as the baseline installation. In addition, the maximum and minimum values in both cases differed within 10 percent of the baseline, which is well within tolerances for comparable values.

Table 2.10. Summary of South Wall Illuminance Values

	Baseline	LED Installation	LED:Baseline
Average	4.25 fc	4.35 fc	102%
Maximum	6.20 fc	5.70 fc	92%
Minimum	2.75 fc	3.02 fc	110%
Avg:Min	1.54:1	1.44:1	
Max:Min	2.25:1	1.89:1	
Std. Dev	1.04 fc	0.64 fc	
Coefficient of Variation	0.25	0.15	

2.6.2 Triangular Vertical Display – "Visions of a White City"

Illuminance measurements were taken on the submission displays on the south wall. A total of 8 measurements points were measured on this face of the triangular vertical display. The points corresponded to parts of the graphic. Detailed illuminance data can be found in Appendix C. All of the values for both installations were tabulated and the results are in Table 2.11. The LED installation provided 50 percent more than the average illuminance of the baseline. Both the maximum and minimum values also increased, with the minimum values being twice that of the baseline installation.

Table 2.11. Summary of "White City" Illuminance Values

	Baseline	LED Installation	LED:Baseline
Average	4.02 fc	6.29 fc	157%
Maximum	6.10 fc	5.34 fc	120%
Minimum	2.62 fc	7.31 fc	204%
Avg:Min	1.53	1.18	
Max:Min	2.33	1.37	
Std. Dev	1.17 fc	0.77 fc	
Coefficient of Variation	0.29	0.12	

2.6.3 Triangular Vertical Display – "Visions of a Plan of Chicago"

Illuminance measurements were taken on the submission displays on the south wall. A total of 8 measurements points were measured on this face of the triangular vertical display. The points corresponded to parts of the graphic. Detailed illuminance data can be found in Appendix C. All of the values for both installations were tabulated and the results are in Table 2.12. The LED installation provided the twice the average and twice the minimum values compared to the baseline.

Table 2.12. Summary of Plan of Chicago Illuminance Values

	Baseline	LED Installation	LED:Baseline
Average	2.05 fc	3.96 fc	193%
Maximum	3.08 fc	4.98 fc	162%
Minimum	1.54 fc	3.12 fc	203%
Avg:Min	1.33:1	1.27:1	
Max:Min	2.00:1	1.60:1	
Std. Dev	0.50 fc	0.58 fc	
Coefficient of Variation	0.25	0.15	

2.6.4 Signage – "About the Finalists" (Vertical Illuminance)

Illuminance measurements were taken on the submission displays on the south wall. A total of 20 measurements points were measured on this face of the wall-mounted signage, corresponding to parts of the graphic. Detailed illuminance data can be found in Appendix C. All of the values for both installations were tabulated and the results are in Table 2.13. The LED installation provided illuminance values similar to those of the baseline across the board.

Table 2.13. Summary of About the Finalists Illuminance Values

	Baseline	LED Installation	LED:Baseline
Average	5.50 fc	5.57 fc	101%
Max	7.88 fc	6.90 fc	88%
Min	3.2 fc	3.92 fc	123%
Avg:Min	1.72	1.42	
Max:Min	2.46	1.76	
Std. Dev	1.28 fc	0.84 fc	
Coefficient of Variation	0.23	0.15	

2.7 Illuminance Summary

In total, more than 200 different illuminance points were measured within the gallery. For a majority of those points, the LED installation either met or exceeded the illuminance provided by the baseline installation. Of the 7 subsets of points measured (Table 2.7 – Table 2.13), the LED installation provided more light in 4 cases, equal illumination in 2 cases, and less illumination in only a single case.

More light is not always preferable in a museum setting, where illumination levels must be balanced against the potential for fading or other damage. In this case, matching the existing illuminance values was the most critical metric for the LED system, and the incumbent source was exceeded by no more than 2 fc at most.

The vast majority (75 percent) of the halogen fixtures in the baseline installation were line-voltage (120V) PAR 38 fixtures, and the LED product performed quite well compared to these. Against the PAR 36 fixture used in the "Detail of Memorial" display case, however, the LED did not perform as well. This low-voltage lamp produces a significant amount of CBCP and concentrates most of the intensity into a relatively small beam angle. In contrast, the LED product produces less intensity and has a beam angle (20°) approximately twice that of the PAR 36 halogen lamp. Thus, the LED installation could neither match nor exceed the illumination of the baseline for this unique combination of case+application+technology+geometry. Lighting Services, Inc. has since developed a 12° spot (see section 5.0, Discussion, for more information).

3.0 Cost Effectiveness

3.1 Expenses and Inputs to Calculations

Many factors influence the cost effectiveness of a lighting installation. The factors considered in this analysis include the initial cost of the system, its operating schedule, the price of electricity, and projected maintenance costs.

3.1.1 Operating Hours/Electricity Tariffs/Maintenance Costs

The Field Museum is open 364 days per year, from 9:00 am to 5:00 pm. For this report the lighting is assumed to operate 2912 hours per year. Although the lighting probably operates more than that for cleaning, special events, maintenance, and other needs, those hours are inconsistent and that time is assumed to be insignificant.

The Field Museum pays $0.12/kWh.

3.1.2 Maintenance Costs

The Field Museum has in-house staff dedicated to moving, aiming, and maintaining the lighting system. In museums, maintenance staff must think beyond "two wires and a light bulb" to understand why a particular lamp and fixture were chosen (IESNA RP-30-96), adding to maintenance personnel labor costs. However, since Field Museum staff perform many functions, it is difficult to isolate a specific cost for lamp replacement. For this reason an hourly rate of $40 is assumed for the personnel replacing the light source. It is also assumed that each lamp can be replaced within 20 minutes on average. Each of the halogen sources in this demonstration has a rated life of either 5000 hours (MR-16 and PAR 38) or 4000 hours (PAR 36). Since the gallery operates 2912 scheduled hours per year, it is assumed that the lamps are replaced once every 2 years.

3.1.3 Initial Luminaire Costs

Table 3.1 provides the "list" prices for the Lighting Services, Inc. track luminaires used in the demonstration. Actual price varies by quantity, region, and relationship among the electrical distributor, the manufacturer's representative, and the manufacturer.

Table 3.1. List Price of Lighting Services Inc. Track Luminaires

	PAR 36 Luminaire	PAR 38 Luminaire	MR-16 Luminaire	LED Luminaire
Individual Luminaire Cost	$193	$143	$179	$316
Lamp Cost	$10	$10	$10	N/A
UV Filter	$73	$73	$50	N/A
Total Cost	$276	$226	$239	$316

At first glance the LED luminaire appears to be 1.5 to 2 times as expensive as the halogen luminaires. However, the total cost includes not only the trackhead (luminaire) but also lamps and the UV filters since these are essential to lighting the museum with halogen. A cost of $10 was assumed for each lamp, whereas the UV lens price increases with lamp diameter. Prices for the filters are from Lighting Services, Inc. and are typical costs paid by sites for these filters. Together these items constitute roughly 30 percent of the total cost and bring the cost of the halogen much closer to that of the LED luminaire.

Table 3.2 provides the quantity of luminaires installed in the gallery and the total costs of the two different types of lighting. The halogen system cost a total of $7645 compared to $8216 for the LED system. Thus, the premium paid for the LED system in this installation was only about 7.5 percent. However, the system premium is 7.5 percent only because fewer LED luminaires were needed compared to the halogen system. On a per-fixture basis the price premium is between 15 percent and 40 percent.

Table 3.2. Total Cost of Lighting System

	PAR 36 Luminaire	PAR 38 Luminaire	MR-16 Luminaire	LED Luminaire
Total Individual Fixture Cost	$276	$226	$239	$316
Quantity	8	23	1	26
Total Cost	$2208	$5198	$239	$8216

3.1.4 Effects on Heating, Ventilation, and Air-Conditioning Systems

Reducing the power of the lighting system has direct effects on the HVAC system. A rule of thumb in the lighting industry is that for every 3W of lighting power reduction, roughly 1W of cooling load is eliminated. In some buildings, heat generated from lighting is designed to assist the building heating system, so that a reduction in lighting power might be offset by an increased demand on the heating load. This is not the case for the Field Museum, however. The cooling load is a significant contributor to the Field Museum's overall operating expenses and the lighting system power reductions are thereby accounted for in the economic calculations.

3.2 Simple Payback

The demonstration examined the simple payback of the lighting system because this measure is commonly used and easily understood. Simple payback does not take into account the time value of money and therefore becomes less accurate as the timeframe of analysis increases.

3.2.1 Simple Payback of Installation in Gallery

Table 3.3 compares the simple payback of the entire halogen system and the LED system as installed in the Brooker Gallery. Because of the different beam angles and different products in this installation, the Field Museum lighting designer was able to achieve the desired results in the space using fewer luminaires. In this case the halogen system used 32 luminaires while the LED system required only 26 luminaires. The payback from HVAC savings in the table factors in $65.14 due to the reduction in the electrical power load of the lighting system on the HVAC system.

Table 3.3. Simple Payback of LED Replacement for Lighting System in this Demonstration

	Halogen System	LED System
Total Initial Cost	$7645.00	$8216.00
Annual Hours of Operation	2912	2912
Operating Power of Lighting System	836	335
Electricity Operating Cost from Lighting	$292.13	$116.99
Payback from Lighting alone (Years)	3.26	---
Payback from Lighting+HVAC (Years)	2.38	---

3.2.2 Simple Payback on a Per Luminaire Basis

Not every installation will allow for a reduction of luminaires as in the case here. Table 3.4 therefore compares the simple payback on a one-for-one basis of the halogen to the LED luminaire. This comparison is also useful because the Field Museum generally purchases equipment in bulk rather than to satisfy the needs of individual installations.

Table 3.4. Simple Payback of LED Replacement on a Per Luminaire Basis

	PAR 36 Luminaire	PAR 38 Luminaire	MR-16 Luminaire	LED Luminaire
Total Initial Cost	$276.00	$226.00	$239.00	$316.00
Operating Lamp Power (Watts)	38	45	55	22
Electricity Operating Cost from Lighting	$13.28	$15.72	$19.22	$7.69
Payback from Lighting Electricity Savings Only (Years)	8.81	11.20	6.68	---
Payback from Lighting w/ Annual Maintenance Savings (Years)	7.40	10.40	6.01	---
Payback from Lighting+HVAC Electricity Savings (Years)	6.60	8.40	5.01	---
Payback from Lighting+HVAC w/ Annual Maintenance Savings (Years)	5.55	7.80	4.51	---

4.0 User Feedback

In this demonstration, PNNL developed a 10-question survey on specific lighting and color qualities of the LED product. Care was taken to avoid the introduction of bias in the questions. The same survey was used for two separate groups, both of which possessed useful experience and backgrounds in lighting.

4.1 Museum Staff Survey

The survey was provided to 9 Field Museum staff members during September 2009. These staff members included exhibit designers, graphics designers, and conservators who were well-versed in qualities of lighting and color rendition and experienced in the perception of illuminated objects as well as overall aesthetics of the lighting system. Because the staff members had an opportunity to see both the baseline (halogen) system and replacement (LED) system, surveys were given for both the original system and the replacement system on two separate dates.

4.2 Lighting Practitioner Survey

In parallel with the ArchLED 2009 conference held in Chicago in October, Lighting Services, Inc. and Xicato hosted an event for lighting practitioners (lighting designers, manufacturer's representatives, architects, etc.) at the Brooker Gallery. During the event, the attendees were given a survey regarding the lighting in space. A total of 26 attendees completed the survey, which was focused solely on the LED system since attendees had not seen the original halogen system.

4.3 Survey Results

Results of both sets of surveys are discussed below, categorized by survey question. Appendix D and Appendix E provide a more complete list of the questions and tabulates the percentages of responses received.

4.3.1 "The uniformity of light across the various targets in the gallery is:"

Several objects measured in the gallery included signage or vertical displays where the primary need was readability. The halogen and LED systems had similar measured uniformity values across the different illuminance metrics.

Nevertheless, when the museum staff evaluated the halogen system, 8 of 13 responded to this question with "good." In evaluating the LED system, 5 selected "good" and 3 selected "excellent," suggesting that the museum staff perceived the LED uniformity to be equal to or better than the halogen system.

In evaluating the LED system, 19 lighting practitioners (73 percent of those who responded) selected "good" in response to this question.

4.3.2 "The color temperature of the lighting in this gallery is:"

In evaluating the 2900 K halogen system, 5 museum staff members selected "too low" as a response to this question and the other 4 selected "just right." In contrast, when the staff evaluated the 3000 K LED system, 5 selected "just right" and the remaining 4 selected either "too high" or "much too high." Based on the responses, the museum staff prefers a color temperature at or below 3000 K.

When the lighting practitioners evaluated the 3000 K LED lighting, 12 (46 percent of those that responded) selected "just right" and 9 (35 percent of those that responded) chose "too high."

Unlike halogen lamps, where CCT decreases (i.e., shifts down or becomes "warmer") as the lamp is dimmed, the CCT of the LEDs installed in this demonstration remain constant throughout dimming. Museum-goers and lighting professionals might normally associate sources below 2700 K with low lighting levels, and were thus not expecting to see color temperatures as high as 3000 K. The nearly even split in preference among respondents reflects the constant struggle designers face when selecting the optimal CCT for a given light source. In this case, some users may prefer LEDs to shift to lower CCTs as the source is dimmed to mimic the familiar incandescent lamp.

4.3.3 "The visible variation in color temperature among the different luminaires is:"

The museum staff was evenly split (3 responses or 33 percent each) when they evaluated the halogen system, with 1 selecting "not noticeable," 1 "barely noticeable," and 1 "noticeable." In comparison, when the museum staff evaluated the LED system, with 8 of the 9 responding "not noticeable." Since the color temperature of the LED system does not change as the LED system dims, it is understandable that variation caused by different levels of dimming is not visible. In contrast, the halogen fixtures were dimmed to different levels across the gallery and thus resulted in visible variation for the majority of respondents.

In evaluating the LED system, half of the practitioners (13) found the CCT variations among the luminaires to be "not noticeable." Six responded "barely noticeable" and another six "slightly noticeable." Variation in white LEDs is an issue the lighting industry is continuing to resolve. Xicato employs a technology "binless" concept which holds color point variation less than 2 MacAdams Ellipse to eliminate this issue. The color point is centered on the black body curve and all sources selected were from standard production.

4.3.4 "Glare from the lights is:"

When evaluating the halogen system, the museum staff split between "noticeable, but acceptable" and "lower than most," with 4 responses each. When evaluating the LED system, 5 museum staff selected "noticeable, but acceptable" to this question. Glare is a geometry issue as much of a luminaire issue. Overall, the museum staff found the sources relatively equal in terms of glare.

Of the practitioners reviewing the LED system, 12 responded "lower than most" and 7 "noticeable, but acceptable." Glare is a difficult issue to manage. A point source is needed for accent lighting, but due to the geometry of the space, the lighting layout, and the needed "look" for the artifact, glare cannot always be avoided. Based on these responses, however, glare does not appear to be an issue for the Lighting Services, Inc. LED system for most reviewers.

4.3.5 "This lighting product shows _____ of the subject colors accurately."

For the halogen system evaluation, 5 museum staff members responded "most" to this question, while for the LED installation 4 selected either "most" or "all." The staffers also noted that they did not have a color point of reference for comparison.

For their LED evaluation, 11 practitioners responded "some," 7 responded "most," and another 7 responded "all." Although the majority of the respondents therefore felt that the lighting showed most or all the colors accurately, a remaining large number felt that only "some" of the colors were accurate. Each person perceives color differently, some better than others. Differences in perception could explain a portion of the "some" comments, or the artifact being lighted might have a rich color component corresponding to an area of low spectral energy in the output of the LED.

4.3.6 "This product shows _____ of the subject forms clearly."

For the halogen system, a slight majority of 5 museum staff members selected "all" to this question. For the LED system, a larger majority of 6 also selected "all." This is a situation where the lighting design as well as the luminaire affects the results. As the lighting design was completed by the same person, the responses suggest that the museum staff finds the LED system essentially equal to the halogen system in this regard.

For the LED system, 10 practitioners responded "all" and 9 responded "most" to this question. Again, proper display of form comes from a combination of the light source and its location. The positive responses give credit to the lighting designer in selecting the location, focusing the luminaire, and in selection of the luminaire, and also support the use of this luminaire for suitable museum applications.

4.3.7 "Overall, the lighting in the gallery is _____."

For the halogen system, 5 museum staffers selected "somewhat too dim" and the remaining 4 selected "just right." In stark contrast, all of the museum staff (100 percent) completing the evaluation for the LED system selected "just right." In terms of absolute illuminance, however, both systems produced virtually identical values for all three (average, maximum, minimum) illuminance metrics. This suggests the differing opinions of adequacy are probably less an issue of illuminance level than spectral power distribution or color shift associated with the dimming of the halogen system.

In comparison, 15 practitioners responded "somewhat too dim" to this question while reviewing the LED system.

The LED system was designed to match the halogen system's illuminance and was thus dimmed to match (as closely as possible) the illuminance on the artifacts. The perception of being too dim is common for museum lighting installations. Artifact preservation typically requires low lighting levels (e.g., the vertical displays in the space are lighted to less than 5 fc). The difference between perceptions of the museum staff and the practitioners may be because the museum staff members are more familiar with artifact lighting requirements while the practitioners have a more general lighting background. The museum staff also had a chance to compare the LED system with the previous halogen system and its associated color shift, whereas the practitioners did not.

4.3.8 "The artifact colors look _____ rich/saturated."

For both the halogen and LED systems, museum staff responses were mixed regarding the color saturation of the artifacts; 4 selected "somewhat" for the halogen system and 4 said "very" for the LED system. The remaining 5 responses for both halogen and LED system were distributed across the other three response options. Every option was selected at least once for both systems, suggesting that the responses were probably more affected by the contents of the exhibits themselves than by how well the lighting displayed them.

For the LED system, 9 practitioners responded "somewhat" and another 9 responded "not at all." Comparing the responses to this question to those in 4.3.5, along with the results above, suggests that the artifacts themselves may not have been very rich in color.

4.3.9 "The suitability of the lighting system for this gallery is:"

For the halogen system, 8 museum staff members found the suitability of the lighting to be "good." For the LED system, 7 staff members responded "good," 1 selected "superior," and 2 chose "adequate."

For the LED system, 9 practitioners responded "good," 7 responded "adequate," and 2 each were recorded for "superior," "marginal," and "no response."

In all, it appears that the two systems were judged relatively equal in their suitability for lighting the gallery.

4.3.10 "The overall impression of the gallery under this lighting is:"

For the halogen system, 7 museum staffers rated the overall impression as "favorable," 1 responded "adequate," and 1 selected "inadequate in some respects." The staff had similar responses for the LED system; 6 selected "favorable," 1 "exceptional," 1 "adequate," and 1 "inadequate in some respects."

For the LED system, 9 practitioners responded "favorable," 5 responded "adequate," and the other 5 responded "inadequate in some respects."

Based on these results, the majority of respondents found that both the halogen system and the LED system created a favorable lighting impression. Some of the practitioners may have negatively judged the LED system due to the dimmed lighting levels in the gallery that were driven by the need for artifact preservation.

5.0 Discussion

Overall the LED system successfully met the different aspects of museum lighting needs.

LEDs do not emit energy in the UV (unless designed to) or IR ranges of the electromagnetic spectrum. This is a plus in terms of reducing material degradation. However, museum pieces are still rated in terms of exposure-hours (e.g., fc-hours or lx-hours). Museum pieces will still need to be lighted to low illuminance levels to reduce possible degradation. Some artifacts react more to different parts of the visual spectrum. Therefore, it cannot be said unequivocally that the LEDs are better than halogen systems for museums. In the end, it comes down to identifying the light spectrum that will damage the item least.

The LED system saved a phenomenal 63 percent of the energy compared to the halogen system while producing the same or a slightly higher illuminance than the halogen system.

As a system, the LEDs had a short payback (around 3 years). However, when comparing on a one-for-one replacement basis, the payback on the LED fixture was much longer (between 4.5 and 11 years). The short payback on the system level was a result of (1) being able to reduce the total number of fixtures installed, and (2) the cost savings gained by eliminating UV filters from the halogen fixtures. Also, the LEDs are more efficacious than the halogen system, reducing the load on the air-conditioning system. This translates to energy savings that were factored into the payback calculation.

The incumbent lamps used were PAR 38 and MR-16 lamps. These lamps are well known for their versatility in terms of output and beam angle. The LEDs were competitive in lumen output compared to the low wattage incumbent systems, but were not competitive in terms of available beam angles. Due to the source size of the Xicato light engine, narrow beam angles were not available at the time of this installation. A 12° spot reflector (8010 CBCP) is now available for the Xicato light engine, although the reflector diameter is 130 mm (5.11 in.) because there is an inverse relationship between reflectors and beam angles. The smaller the desired beam angle, the larger the reflector required. At beam angles below 20°, the overall size of the LEDs and reflector would become unwieldy for retail and office applications but will most likely be fine for high ceiling applications like museums.

Dimming is not easy for any light source except incandescent and line voltage halogen lamps. For many lighting systems, pairing the dimming system with the power supply is often fraught with problems and compromises. The LED system dimmed smoothly from 100 percent to 50 percent output using silicon controlled rectifier (virtually only known within the industry by the abbreviation SCR) type dimming module. The lighting industry is actively working on dimming standards and compatibility issues. In time, LED driver design and dimmer compatibility will improve. In the short term, smooth dimming down to 50 percent output should be acceptable for museum applications for halogen lamps. After all, if the museum is going to set an illuminance level in a scene below 50 percent output, then a lower power lamp should be considered from the outset (e.g., use a 25W halogen lamp rather than a dimmed 50W halogen lamp). The same is true for LED luminaires, provided lower-wattage lamps are available in a matching color bin and desired beam angle.

The user feedback questionnaire did not include any questions about flicker, but a few references to flicker were mentioned in the free-response portion of the lighting practitioner survey. Flicker, when it occurs, is generally a result of dimming LEDs. The issues are complex and have multiple causes, and the symptoms do not apply equally across different LED and dimmer combinations. The industry is working on specifications and metrics to address flicker in LEDs.

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Appendix A

Material Responsiveness Classification

Appendix A - Material Responsiveness Classification

The tables below are from *Light for Art's Sake* (Cuttle 2007). The tables reflect Tables 3.1 and 3.2 (p. 46 and 47 respectively) and are themselves from CIE 157:2004.

Material responsiveness classification	Material description
R0. Non-responsive	The object is composed entirely of materials that are permanent, in that they have no response to light. Examples: most metals, stone, most glass, genuine ceramic, enamel, most minerals.
R1. Slightly responsive	The object includes durable materials that are slightly light-responsive. Examples: oil and tempera painting, fresco, undyed leather and wood, horn, bone, ivory, lacquer, some plastics
R2. Moderately responsive	The object includes fugitive materials that are moderately light-responsive. Examples: costumes, watercolors, pastels, tapestries, prints and drawings, manuscripts, miniatures, paintings in distemper media, wallpaper, gouache, dyed leather and most natural history objects, including botanical specimens, fur and feathers.
R3. Highly responsive	The object includes highly light-responsive materials. Examples: silk, colorants known to be highly fugitive, newspaper.

Material responsiveness classification	ISO Rating	Years for noticeable fade	
		UV rich	No UV
R3. Highly responsive	1	1.5	2
	2	4	7
	3	10	20
R2. Moderately responsive	4	23	67
	5	53	200
	6	130	670
R1. Slightly responsive	7	330	2000
	8	800	7300

Material responsiveness classification	Limiting illuminance (lx)	Limiting exposure (lx-hours/year)
R0. Non-responsive	No limit	No limit
R1. Slightly responsive	200	600,000
R2. Moderately responsive	50	150,000
R3. Highly responsive	50	15,000

Appendix B

Detailed Horizontal Illuminance Data

Appendix B - Detailed Horizontal Illuminance Data

The horizontal illuminance was measured for three horizontal displays. In the center of the room, there was a large model of the design that won the competition (Section B.1); a second horizontal display had an enlarged detail of the winning design (Section B.2); and finally a book containing original work by Daniel Burnham (Section B.3) was measured under both the halogen and LED systems.

B.1 Model of Winning Design

Table B.1. Halogen System Illuminance (fc) Values

3.80	4.30	4.58	4.83	4.90	4.84	4.81	4.70	4.51	3.80
4.27	4.80	5.04	5.27	5.29	5.22	5.13	5.00	4.81	4.27
4.72	5.24	5.49	5.67	5.72	5.58	5.47	5.28	5.03	4.72
5.14	5.65	5.87	6.00	6.05	5.92	5.78	5.56	5.24	5.14
5.46	5.93	6.18	6.32	6.38	6.25	6.11	5.72	5.30	5.46
5.70	6.20	6.40	6.59	6.69	6.50	6.34	5.80	5.34	5.70
5.95	6.27	6.57	6.80	6.96	6.79	6.39	5.87	5.28	5.95

Table B.2. LED System Illuminance (fc) Values

5.71	5.83	5.95	5.76	5.86	5.62	5.58	5.72	5.67	5.71
6.26	6.41	6.65	6.55	6.47	6.26	6.11	6.11	6.10	6.26
6.76	7.01	7.00	6.79	6.89	6.58	6.53	6.47	6.44	6.76
7.32	7.41	7.58	7.33	7.36	6.99	6.90	6.92	6.48	7.32
7.67	8.04	8.00	7.94	7.80	7.57	7.43	7.21	6.62	7.67
7.65	8.30	8.29	8.19	7.97	7.83	7.40	7.28	6.49	7.65
7.66	8.21	8.49	8.22	8.28	7.93	7.68	6.98	6.19	7.66

B.2 Detail of Winning Design

Table B.3. Halogen System Illuminance (fc) Values

19.10	28.47	29.70	27.40	23.79
25.12	41.80	48.20	45.20	42.30
25.77	38.80	50.00	54.80	65.50
14.80	24.36	32.70	43.60	60.60

Table B.4. LED System Illuminance (fc) Values

28.50	27.67	26.72	21.59	14.42
29.70	28.64	27.46	21.60	14.44
27.90	27.50	24.98	19.55	13.26
23.77	23.02	20.61	16.38	11.42

B.3 Book

Table B.5. Halogen System Illuminance (fc) Values

2.04	2.48	2.44
3.18	3.76	3.87
3.89	5.78	5.95

Table B.6. LED System Illuminance (fc) Values

4.03	4.58	4.86
5.78	6.54	6.69
7.08	7.67	7.54

Appendix C

Detailed Vertical Illuminance Data

Appendix C - Detailed Horizontal Illuminance Data

The vertical illuminance was measured for four sets of vertical displays. Signage about the competition was measured (Section C.1). The vertical illuminance from both the halogen and the LED systems was measured on two thin vertical sets of signage, one about Burnham's "White City" design (Section C.2) and another about Burnham's *Plan for Chicago* (Section C.3). Eight smaller displays for non-winning entries were mounted on the south wall. Most of these designs were from local architecture firms (Altamanu; Daniel P. Cofey & Associates; OWP/P; Peter Walker; Hammond Beeby; James McCrery; Stoneberg + Gross; and Wheeler Kearns). Rather than provide all the individual illuminance values for these displays, Section C.4 provides an illuminance summary for each entry. At the end of Section C.4, a comparison of the LED system to the halogen system is provided.

C.1 Competition Signage

Table C.1. Halogen System Illuminance (fc) Values

5.95	7.88	6.73	4.10
5.01	7.30	7.14	4.89
4.30	6.24	6.96	5.30
3.70	5.10	6.25	5.34
3.20	4.30	5.38	4.98

Table C.2. LED System Illuminance (fc) Values

6.18	6.9	6.88	6.54
5.65	6.19	6.39	6.33
5.04	5.7	5.84	5.67
4.72	5.2	5.28	4.92
3.92	4.69	4.82	4.52

C.2 "White City" Vertical Display Poster

Table C.3. Halogen System Illuminance (fc) Values

5.03	6.10
3.72	4.50
3.16	4.10
2.62	2.91

Table C.4. LED System Illuminance (fc) Values

7.25	7.31
6.05	6.16
5.78	6.92
5.34	5.53

C.3 "Plan of Chicago" Vertical Display Poster

Table C.5. Halogen System Illuminance (fc) Values

1.87	3.08
1.86	2.43
1.78	2.21
1.54	1.67

Table C.6. LED System Illuminance (fc) Values

4.54	4.98
3.94	4.00
3.78	3.65
3.64	3.12

C.4 South Wall

	Altamanu (#1)		Daniel P. Cofey & Associates (#2)	
	Halogen Values	LED Values	Halogen Values	LED Values
Average	3.82 fc	4.54fc	5.80 fc	4.42 fc
Max	3.92 fc	6.20 fc	6.2 fc	4.61 fc
Min	3.72 fc	4.32 fc	5.5 fc	4.14 fc
Avg:Min	1.03	1.03	1.05	1.07
Max:Min	1.05	1.40	1.13	1.11
Std. Dev	0.09 fc	0.6909 fc	0.19 fc	0.15 fc
Coefficient of Variation	0.02	0.15	0.03	0.03

	OWP/P (#3)		Peter Walker (#4)	
	Halogen Values	LED Values	Halogen Values	LED Values
Average	3.17 fc	3.88 fc	5.35 fc	4.17 fc
Max	3.38 fc	5.70 fc	5.70 fc	4.39 fc
Min	3.00 fc	3.38 fc	5.50 fc	3.92 fc
Avg:Min	1.06	1.15	1.07	1.06
Max:Min	1.13	1.69	1.14	1.12
Std. Dev	0.15 fc	0.83 fc	0.25 fc	0.15 fc
Coefficient of Variation	0.05	0.21	0.0521	0.04

	Hammond Beeby (#5)		James McCrery (#6)	
	Halogen Values	LED Values	Halogen Values	LED Values
Average	5.31 fc	5.50 fc	4.03 fc	4.68 fc
Max	5.62 fc	5.70 fc	4.36 fc	4.98 fc
Min	4.83 fc	3.93 fc	3.73 fc	4.48 fc
Avg:Min	1.10	1.40	1.08	1.04
Max:Min	1.16	1.45	1.17	1.11
Std. Dev	0.28 fc	0.73 fc	0.19 fc	0.17 fc
Coefficient of Variation	0.05	0.13	0.05	0.04

	Stoneberg + Gross (#7)		Wheeler Kearns (#8)	
	Halogen Values	LED Values	Halogen Values	LED Values
Average	3.50	4.36	2.99	3.22
Max	3.78	4.48	3.29	3.52
Min	3.28	2.75	2.75	3.02
Avg:Min	1.07	1.59	1.09	1.07
Max:Min	1.15	1.63	1.20	1.17
Std. Dev	0.17	0.69	0.17	0.17
Coefficient of Variation	0.05	0.16	0.06	0.05

The table below compares the average, maximum, and minimum illuminance values from the 8 displays above. Overall, the LED system produced very similar values to the baseline halogen system.

	#1	#2	#3	#4	#5	#6	#7	#8
Average Values LED:Halogen	119%	76%	123%	78%	104%	116%	125%	108%
Maximum Value LED:Halogen	121%	74%	169%	77%	101%	114%	119%	107%
Minimum Value LED:Halogen	119%	75%	113%	100%	81%	120%	84%	110%

Appendix D

Museum Staff Survey Questions

Appendix D – Museum Staff Survey Questions

The following are the museum staff survey responses for the halogen and LED systems.

1. The uniformity of light across the target is:

Response	Halogen System Percent Response	LED System Percent Response
Unacceptable	0%	0%
Poor	11%	0%
Fair	0%	11%
Good	89%	55%
Excellent	0%	33%
No response	---	---

Unsolicited responses:

- None.

2. The color temperature of the lighting in this gallery is:

Response	Halogen System Percent Response	LED System Percent Response
Much too high (i.e., blue)	0%	11%
Too high	0%	33%
Just right	44%	56%
Good	56%	0%
Much too low	0%	0%
No response	---	---

Unsolicited responses:

- Halogen System
  - Sides feel cooler, but maybe because 2nd material or cooler wall color.
  - Just a little yellow.
  - Yellow.
- LED System
  - Lighting feels right but different.
  - It's a little cool, but I don't mind it.

3. The visible variation in color temperature among the different luminaires is:

Response	Halogen System Percent Response	LED System Percent Response
Not noticeable	33%	89%
Barely noticeable	33%	11%
Slightly noticeable	0%	0%
Noticeable	34%	0%
Very noticeable (Unacceptable)	0%	0%
No response	---	---

4. Glare from the light is:

Response	Halogen System Percent Response	LED System Percent Response
Disabling	0%	0%
Annoying	0%	0%
Noticeable, but acceptable	44%	56%
Lower than most	45%	22%
Nonexistent	11%	22%
No response	---	---

Unsolicited responses:

- Halogen System
  - Aware of it only on west-most vitrine.
- LED System
  - Only around center vitrine with small model and triangular column.

5. The lighting product shows __________ of the subject colors accurately.

Response	Halogen System Percent Response	LED System Percent Response
None	11%	0%
Some	22%	11%
Most	56%	44%
All	11%	45%
No response	---	---

Unsolicited responses:

- Halogen System
  - Not possible to say without comparison to master “accurate” color.
- LED System
  - Feel like most colors accurate, anyway—no standard for comparison.

- Trick question! I think the lighting is showing the colors clearly, but I can't tell how accurately the colors look….

6. This product shows ________ of the subject forms clearly.

Response	Halogen System Percent Response	LED System Percent Response
None	0%	0%
Some	22%	0%
Most	44%	33%
All	54%	67%
No response	---	---

Unsolicited responses:

- Halogen System
  - Easier to look at and see on smaller model than bigger model. Bigger model feels flatter.
- LED System
  - None.

7. Overall, the lighting in the gallery is ________.

Response	Halogen System Percent Response	LED System Percent Response
Too bright	0%	0%
Somewhat too bright	0%	0%
Just right	44%	100%
Somewhat too dim	56%	0%
Too dim	0%	0%
No response	---	---

Unsolicited responses:

- None.

8. The artifact colors look ___________ rich/saturated.

Response	Halogen System Percent Response	LED System Percent Response
Very	0%	44%
Somewhat	22%	33%
Slightly	44%	11%
Not at all	54%	11%
No response	---	---

Unsolicited responses:

- Halogen System
  - More saturated on small model and graphic column. Side wall graphics feel richer close up than from door.
- LED System
  - Blueprint looks “bluer”.
  - Very but could be better

9. The suitability of the lighting system for this gallery is:

Response	Halogen System Percent Response	LED System Percent Response
Superior	0%	11%
Good	89%	78%
Adequate	11%	11%
Marginal	0%	0%
Inadequate	0%	0%
No response	---	---

10. The overall impression of the gallery under this lighting is:

Response	Halogen System Percent Response	LED System Percent Response
Exceptional	0%	11%
Favorable	78%	67%
Adequate	11%	11%
Inadequate in some respects	11%	11%
Unacceptable	0%	0%
No response	---	---

10A. If you answered “inadequate in some respects” or “unacceptable”, please explain:

- Halogen System
  - I think the light is too yellow. Graphics in corners are unevenly lit.

- LED System
  - Cooler color temperature is noticeable and lessens experience in gallery

11. Please provide any additional thoughts you have about the gallery lighting:

- Halogen System
  - The lighting on the center vitrine and triangular graphic column feel more vibrant/inviting than on the west vitrine. Apart from the lighting – the east wall feels bit dingy – perhaps w/low light required by objects, a colored wall would feel more welcoming than the white?

  - The gallery is lit traditionally and within the museums conservation guidelines. Some artifacts are dark and uneven due to conservation requirements.
  - If lighting requirements permit, I would have liked the light to be brighter, more even and more neutral in temp.

- LED System
  - The lighting overall is very uniform and a bit too blue and cold. Lacking warmth and drama. But for this particular show it is fine. Don't like the shadows on the top of the kiosks but that is because the fixtures are too high up.
  - The gallery is lit non-traditionally by using LED light sources that fall within the museums conservation guidelines. Some artifacts are lit less due to conservation requirements. The improvements to the hall are with the quality of light and the evenness. The main noticeable change is the color of the light due to the 3000 K of the light source be improved by pushing LED CRI into the 90's.
  - This energy efficient lighting will no doubt be improved in time.
  - The brightness and temperature of the light suited this show [*The Daniel Burnham Memorial Competition*] in particular. The brighter light and cooler temp displayed the white models and graphics better. The "flooding" of the walls with the light might not always be appropriate.
  - Feels cleaner, more engaging.
  - I like the LEDs. I do wish there was more flexibility in the placement of the fixtures though.

Appendix E

Lighting Practitioner Survey Questions

Appendix E – Lighting Practitioner Survey Questions

The following are the survey responses provided by the lighting practitioners during the ArcLED event held in the gallery and **ONLY** apply to the LED system.

1. The uniformity of light across the target is:

Response	Percent Response
Unacceptable	0%
Poor	4%
Fair	15%
Good	73%
Excellent	8%
No response	0%

Unsolicited responses:
- If light was not dim as much, uniformity will look better.
- Need more bright spots.

2. The color temperature of the lighting in this gallery is:

Response	Percent Response
Much too high (i.e., blue)	12%
Too high	35%
Just right	46%
Good	4%
Much too low	0%
No response	4%

Unsolicited responses:
- A little high when dimmed.
- Just a little, better, if brighter.
- Just by a little.

3. The visible variation in color temperature among the different luminaires is:

Response	Percent Response
Not noticeable	50%
Barely noticeable	23%
Slightly noticeable	23%
Noticeable	4%
Very noticeable (Unacceptable)	0%
No response	0%

Unsolicited responses:

- None.

4. Glare from the light is:

Response	Percent Response
Disabling	0%
Annoying	8%
Noticeable, but acceptable	27%
Lower than most	46%
Nonexistent	19%
No response	0%

Unsolicited responses:

- Excellent.
- If you are not looking at them.

5. The lighting product shows __________ of the subject colors accurately.

Response	Percent Response
None	0%
Some	42%
Most	27%
All	27%
No response	4%

Unsolicited responses:

- If light level is higher, looks better.

6. This product shows ________ of the subject forms clearly.

Response	Percent Response
None	0%
Some	23%
Most	35%
All	38%
No response	4%

Unsolicited responses:

- None.

7. Overall, the lighting in the gallery is ________.

Response	Percent Response
Too bright	0%
Somewhat too bright	0%
Just right	27%
Somewhat too dim	58%
Too dim	8%
No response	8%

Unsolicited responses:

- "Just right" after 5 minutes.

8. The artifact colors look ___________ rich/saturated

Response	Percent Response
Very	8%
Somewhat	35%
Slightly	4%
Not at all	35%
No response	19%

Unsolicited responses:

- Light levels need to be increased at the wall.

9. The suitability of the lighting system for this gallery is:

Response	Percent Response
Superior	8%
Good	35%
Adequate	27%
Marginal	15%
Inadequate	0%
No response	15%

10. The overall impression of the gallery under this lighting is:

Response	Percent Response
Exceptional	12%
Favorable	35%
Adequate	19%
Inadequate in some respects	19%
Unacceptable	0%
No response	15%

Unsolicited responses:
- Very good.
- Surprisingly good.

10A. If you answered "inadequate in some respects" or "unacceptable", please explain:

- It needs louvers, it's too cool, flicker is out of control, don't like the light on the ceiling.
- The gallery seems dim & muddy. Turn up overall light levels.
- Crisp lighting would help pull out the graphics on everything.
- Dark areas, focus points are not on vitrines, gloomy.
- Don't wear glasses & still found reading difficult.
- Need more watts.

11. Please provide any additional thoughts you have about the gallery lighting:

- Flicker, white signs don't feel white.
- Light fixture should be lit a bit brighter. Colors looked a bit dull.
- The scalloping on the walls create a slight cave effect. There is shadowing. I would prefer to see some wall washing or uplighting.
- It is too monolithic – not enough contrast to draw my eye to anything.
- Lighting is too even, too dim. Dimming is making it seem cooler in color temperature.
- The colors were not vibrant – greyed out it seemed like when the fixtures were no dimmed it helped with color rendering.
- 1st display needs more light. Immediate impression dark spot in entry [spot in foyer is a difficult balance with lack of light upon entry into the room. Some flicker is noticeable overall color is good, consistency is good. Kick a spot on 1st display and I think that it is there (not to tell you your job, I know little…)] needs more light on 1st display as balance; it felt dark walking in and not enough highlight inside, giving dark impression or increase light at entry.
- Perhaps the lighting levels could be higher to fully appreciate the work.
- Love the glare-free track heads.
- Too much flicker!
- Good consistency.
- The Future!
- Reds seem weak – but there is not much red in the display.
- Overall light level looks a little "muddy" and could be improved with some contrast in levels. Needs brighter accent at walls. Overall color consistency is great!