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SSL Adoption by Museums: Survey Results, Analysis, and Recommendations

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Solid-State Lighting Program
Building Technologies Office
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Prepared by:

Pacific Northwest National Laboratory

SSL Adoption by Museums: Survey Results, Analysis, and Recommendations

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

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy
Getty Conservation Institute

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Preface

The GATEWAY Program

This document is a report of observations and results obtained from a lighting evaluation project conducted under the U.S. Department of Energy (DOE) GATEWAY Program. The program supports evaluations and 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 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 evaluation 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 used 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

This report stems from an initial collaboration between Jim Druzik of the Getty Conservation Institute (GCI) and Stefan Michalski of the Canadian Conservation Institute (CCI) over three years ago. Their goal was to simplify the process of selecting SSL products for museums with a document which established the *status quo* and addressed many levels of need, from the museum lighting designer to the facilities manager to the collections curator to the small museum owner who does it all (or at least tries). In the past year, the GATEWAY program collaborated with Michalski on the intent behind and creation of the survey used for this report – his insight on behalf of the CCI was very helpful. Additionally, there are almost fifty people whose responses provided the data for this report – their experiences and willingness to take the time to complete an exhaustive questionnaire form the foundation and content of this report. An extended thank you goes out to them all!

Executive Summary

Since 2011, Jim Druzik and Stefan Michalski's "Guidelines for Assessing Solid-State Lighting (SSL) for Museums" has been a pivotal resource for those seeking guidance in converting to SSL, which currently implies the use of light-emitting diodes (LEDs). In June 2014, the Pacific Northwest National Laboratory (PNNL), on behalf of the U.S. Department of Energy (DOE), the Getty Conservation Institute (GCI), and the Canadian Conservation Institute (CCI), investigated the use of the Guidelines for the benefit of both the museum and SSL communities. 979 questionnaires were successfully sent to members of the museum community who had requested a copy of the Guidelines, yielding 46 sets of responses (a 4.7% response rate). These responses provided real-world insight into how LEDs are being incorporated into museums, and what successes and hurdles have been encountered in the process.

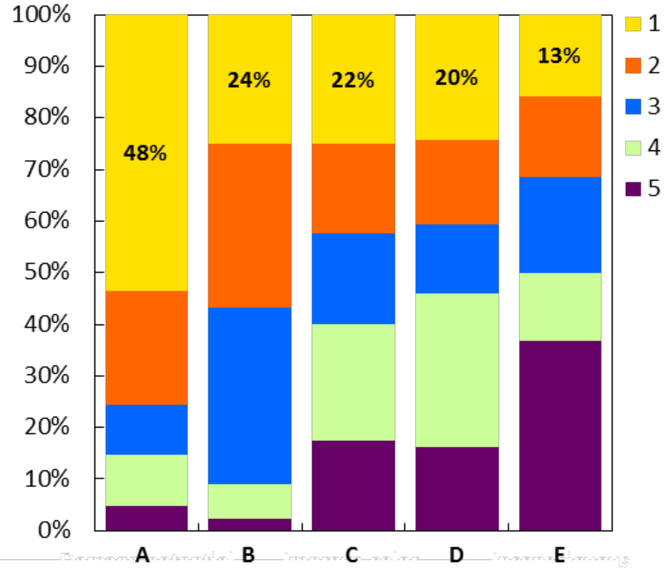
Of those who responded to the questionnaire, 30% were international and the majority were museum directors, designers, conservators, curators, and those involved in collections care and registration. A combination of question types and open-ended responses provided information on how well the Guidelines have served their purpose (to inform), which SSL products have been selected and where they have been applied, and what lessons were learned from the process. In addition, the respondents provided constructive criticism of the Guidelines themselves. This GATEWAY report, instead of focusing on one demonstration site, emphasizes the questionnaire's international scope, providing a picture of global adoption from the data and responses.

KEY TERMS

CCT	correlated color temperature
CFL	compact fluorescent
CRI	color rendering index
DALI	Digital Addressable Lighting Interface
DMX	Digital Multiplexing
FL	linear fluorescent
HVAC	heating, ventilating, and air conditioning
LCC	life-cycle cost
LED	light-emitting diode
SPD	spectral power distribution
SSL	solid-state lighting

Museum Lighting

This report provides background information on museum lighting and conservation science based largely on the questionnaire responses, but also draws from the knowledge of the authors in order to provide context. Included are museum requirements and goals, integrating sustainability and energy savings issues related to lighting; initial concerns and resolved misconceptions about LED technology; and the current lighting used in museums in consideration of how the Guidelines have been adopted to date. 68% of survey responders placed a high priority on energy efficiency. However, despite the savings in energy and the reduced cost of operation gained by a source with high luminous efficacy, respondents indicated that their museums would not risk potential damage on their works of art nor sacrifice lighting quality in their galleries solely for the sake of energy efficiency (Figure ES-1).

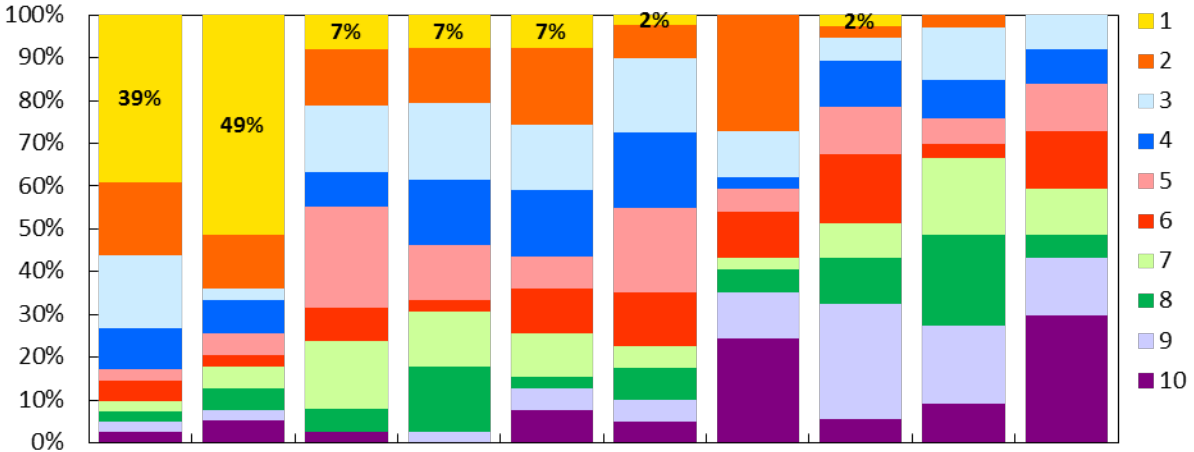


Ranking					
Mean	1.9	2.3	2.9	3	3.4
Mode	1	3	1	4	5
Min	1	1	1	1	1
Max	5	5	5	5	5
Mean rank	**1**	**2**	**3**	**4**	**5**

A Use a lighting source with equal if not lower damage potential
B Save energy and reduce cost/maintenance
C Improve color quality compared to standard
D Match color quality of standard museum lighting
E Inconspicuous transition from incandescent to LED lighting

Figure ES-1 Summary of the results for ranking lighting goals: The conservation benefits and energy savings from LEDs were prioritized more highly than improved color quality. (A rank of one was the most favorable and a rank of five was the least favorable.)

Compared with over 55% of museum workplaces still using incandescent in 2009, 51% of the responders also identified incandescent as the principal lighting type, with LED at 40%, compact fluorescent (CFL) at 13%, linear fluorescent (FL) at 11%, and others (including metal halide, halogen, daylight) at 22%. The main difference between 2009 and 2014 lies in the higher percentage of LED adoption, now up to 40% compared to almost none. When asked whether they would consider and implement another LED installation, 71% indicated they would, only 6% would not, and 32% of the responders said they already had. When evaluating the “success” of the installed lighting, responders solicited feedback from groups of observers – from the public there was a unanimously favorable response; from museum staff there was a 97% favorable response.



Ranking	A	B	C	D	E	F	G	H	I	J
Mean	2.9	3.1	4.6	4.6	4.7	5.1	5.9	6.6	6.8	7.3
Mode	1	1	5	3	2	5	2	9	8	10
Min	1	1	1	1	1	1	2	1	2	3
Max	10	10	10	9	10	10	10	10	10	10
Mean rank	**1**	**2**	**3**	**3**	**5**	**6**	**7**	**8**	**9**	**10**

A Color and spectral power distribution (SPD)
B Damage potential
C Lamp efficacy (lumens per watt)
D Initial cost
E Lamp size and shape
F Lifespan/lumen maintenance
G Dimming range/compatibility with dimmers
H Return on investment (ROI) or simply payback period
I Input power (W)
J Warranty

Figure ES-2 Summary of the results for ranking considerations when selecting lamps: Using mean rank, option A (color and SPD) was the consideration ranked first with B (damage potential) as the second. However, damage potential received a higher percentage of 1st and 2nd rankings. Many of the options were very closely ranked (especially options C-E). Option J (warranty) was the least considered. (A rank of one was the most favorable and a rank of ten was the least favorable.)

In the selection of lamps, color, spectral power distribution (SPD), and damage potential were the main considerations, with lamp efficacy, initial cost, and form factor (lamp size and shape) following (Figure ES-2). Some museums also prioritized the reliability of the manufacturer. Although 75% of responders experienced early LED product failures, the maximum failure rate reported was only 2.5% of the installed lamps or fixtures. Of the noted sources of failure, included were electronic components such as drivers and power supplies, but not the LED source itself.

Barriers to Adoption

The report highlights the main barriers to LED adoption, namely:

- Potential high cost, especially for dedicated LED fixtures;
- Difficult selection process, due to the confusing variety of products and difficulty keeping up with rapid advancements in technology;
- Resistance to change especially from conservators and university administration; and
- Technology limitations, such as poor dimming performance and potentially problematic performance of LED replacement lamps in enclosed fixtures.

Less than half (42%) of the responders conducted a life-cycle cost (LCC) analysis on their own projects, but of those who did, the following factors were considered:

- Maintenance costs, 87%;
- Years until payback, 77%;
- Warranty, 50%;
- Future drop in LED lamp costs, 40%;
- Other, 17%.

The questionnaire responses and comments showed that there is still confusion about different LED products, what museum staff should be asking for, and concerns about maintenance. It was clear from the responses that education and experience is needed at multiple levels.

In the discussion of perceived technology limitations, responders had no strong preference for replacement lamps versus dedicated LED fixtures. Instead, the decision was dependent on the application and the pressure exerted by existing luminaire stock. One responder said controls will drive the conversion to dedicated LEDs. When evaluating color, almost all considered color rendering index (CRI), with target values greater than 85, two-thirds considered correlated color temperature (CCT), with 2700 and 3000 K listed as target values, and 60% evaluated the light source SPD. Only 26% required a color warranty. To resolve color inconsistencies, luminaires of similar color shift were grouped together or replaced by manufacturers. Two-thirds of responders trialed expected lux levels and light sources in the actual gallery while less than half used a reserved space for mock-ups only.

When evaluating potential damage, the majority considered UV and IR content and about half considered short-wavelength emissions in the SPD. Other considerations included limiting the duration of exposure, CCT, heat output from LEDs, and the composition of displayed materials. Almost all responders considered light exposure recommendations based on the sensitivity of the materials displayed, along with the annual hours of operation of the lighting system. Dimming was generally deemed important to achieve required low light levels down to 5 fc (50 lux) incident on the object. 42% of respondents used DALI/DMX (Digital Multiplexing)/or 0-10V dimming protocol, 39% used dimmers designed for incandescent loads, and 33% had no dimming capabilities in galleries (12% used a combination of dimming methods). For dimmers not designed for incandescent loads, problems included flickering or failing to turn on. Almost two-thirds (over 65%) of the questionnaire responders would use lighting controls if they worked with their existing lamp-based infrastructure and afforded lamp-by-lamp control of light output—and chromaticity, if possible. They would also like the ability to monitor lux levels on an object-by-object basis.

Responder Recommendations on Speeding LED Adoption

The report lists constructive suggestions from the responders on how to speed LED adoption. Survey responders also discussed the overarching activities they recommend for government and industry, including utilizing alternate communications platforms to inform and educate. They suggested regional workshops, webinars, more GATEWAY demonstrations, and online forums. Additionally, more guidelines were requested: simple guidelines for museums of all sizes, including a version for a “layperson”; ones with a more international scope that address current product ranges and availability; and executive summaries of research to-date.

Exploration of Technology Limitations and Hope for the Future

The report also discusses current museum issues, possible solutions, and the current state of LED technology. In general, white LEDs pose no special color issues (in rendering nor increased damage potential) for works of art, compared to an equivalent CCT halogen or fluorescent source. Regarding damage, at equal lux levels, the photochemical, thermal, and hygrometric stresses posed by LEDs are lower than halogen and (photochemically) much lower than daylight. Figures ES-3 and ES-4 below show the strong linear correlation between damage potential and CCT for all products and minimal (if any) correlation between damage potential and CRI for a recent set of LED products.

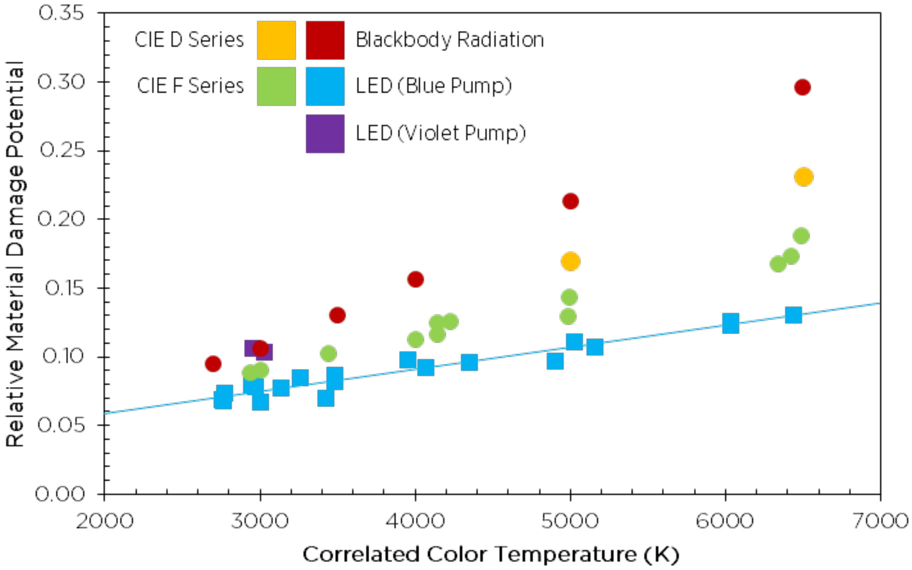


Figure ES-3 CIE spectral damage potential (S_{df}) versus CCT: The linear correlation between damage potential and CCT is high for all product types. The plot above is normalized for equal lumens from each light source. However, it is important to note that standard blue-pump LEDs have the lowest damage potential at a given CCT compared to unfiltered incandescent and halogen sources (approximated using blackbody radiation). Even violet-pump LEDs pose no more risk than a typical incandescent or halogen lamp.

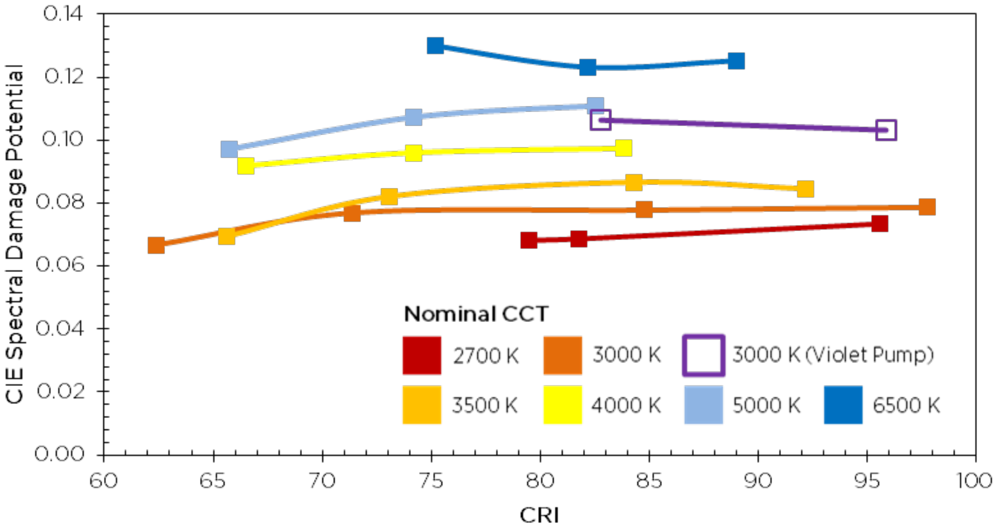


Figure ES-4 CIE spectral damage potential (S_{df}) versus CRI: The graph above shows minimal correlation between CRI and damage potential. (The damage is normalized for equal lumens from each light source.) However, as explained in the previous figure, there is a strong linear correlation between damage potential and CCT. It is important to note that standard blue-pump LEDs have the lowest damage potential at a given CCT compared to unfiltered incandescent and halogen sources (approximated using blackbody radiation). Even violet-pump LEDs pose no more risk than a typical incandescent or halogen lamp.

Flicker can result from an incompatible pairing of a LED driver and a dimmer, an incompatible driver and transformer, or a combination of all three. The likelihood of introducing annoying flicker to gallery spaces can be considerably reduced if manufacturer dimming compatibility tables are heeded. Lighting controls can eliminate 60% or more of the wasted lighting energy in buildings and would enable the museum lighting designer to specify lighting exposure (illuminance, spectrum, time) to minimize damage while providing optimal viewing conditions. A growing and more sophisticated set of controllable LED light sources and complementary control technologies are becoming available.

Lessons Learned

Finally, in a world of information overload, what LED technical requirements are really needed for museum lighting? The museum lighting survey elicited many telling responses from individuals who had experience with LED products, and the report includes lessons learned from their trials and tribulations.

Contents

1. Introduction and Background

Over the last two years 1,113 individuals, including conservators, registrars, preparators, curators, museum directors, facilities managers, lighting designers, manufacturers, consultants, and students requested a copy of "Guidelines for Assessing Solid-State Lighting for Museums" by Druzik[1] and Michalski[2] (2011). Originally prepared for a lighting workshop conducted at the Canadian Conservation Institute in the summer of 2011, the Guidelines are a working document keeping pace with evolving SSL technology. The Guidelines recognize the process of selecting SSL products for museums can be intimidating—3 years after publication, it still can be. The first section outlines how LEDs work, their performance parameters, and potential sources of failure; the second section educates the reader in how to review the applications for SSL in museums and provides additional resources appropriate for museum staff, facilities managers, and lighting specialists alike. Underscoring all decisions are evaluating all products in person and agreeing on appropriate warranties.

It has been Druzik and Michalski's objective, as conservation scientists, to supply relevant information for selecting SSL to decision makers as efficiently as possible and to learn more about how museums have fared adapting to LED display lighting. The U.S. Department of Energy's SSL program has been involved in a select number of these case studies (e.g., the Field Museum of Natural History, the Jordan Schnitzer Museum of Art, the J. Paul Getty Museum, the Smithsonian American Art Museum, and, most recently, the Burden Museum) through the GATEWAY demonstration program.

In June 2014, the Pacific Northwest National Laboratory (PNNL), on behalf of the Department of Energy (DOE), the Getty Conservation Institute (GCI), and the Canadian Conservation Institute (CCI), collaborated to investigate the use of Druzik and Michalski's Guidelines for the benefit of both the museum and SSL communities. Currently, most SSL implies the use of light-emitting diodes (LEDs). The introduction of LEDs initially had facilities managers worried about the reality of recovering from steep initial costs despite promised energy efficiency, conservators wary of potential damage, and curators questioning the color quality compared to traditional lighting—concerns that are still valid. As the Guidelines were distributed to a wide selection of the museum demographic, impressions and application feedback from those recipients were expected to be valuable because it would cover the spectrum of use and success. 466 recipients had indicated to the GCI that they were planning to replace lamps or luminaires in older incandescent display lighting, and another 560 were seeking to expand their understanding of SSL. A questionnaire was sent to all recipients of the Guidelines to learn what projects the Guidelines had been applied to and how useful they were in application.

Out of 979 questionnaires successfully sent, 55 responded, 46 of which completed questionnaires—a 4.70% response rate. 35% of the Guidelines recipients and 30% of those who completed the questionnaire were international. Of those who responded to the questionnaire, the majority were museum directors, designers, conservators, curators, and those involved in collections care and registration. A combination of question types (e.g., rank, select, yes/no) and open-ended responses provided invaluable insight into the museum community's selection of SSL products and use of the Guidelines. The results provide insight into how well the Guidelines have served their purpose (to inform), where LEDs have been adopted (at a variety of institutions), and what

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[1] James Druzik, Senior Conservation Scientist, Getty Conservation Institute (GCI)

[2] Stefan Michalski, Senior Conservation Scientist, Canadian Conservation Institute (CCI)

lessons were learned from the process. In addition, the respondents provided constructive criticism of the Guidelines themselves. Woven throughout all sections of the document are photographs from the various responders; their processes in converting to SSL are described in depth in the “Anecdotal Demonstrations” section in Appendix E.

This GATEWAY demonstration report, instead of having one focus site, emphasizes the questionnaire’s international scope, providing a picture of global adoption by analyzing the data and drawing together example applications from the questionnaire responses. The original plan was to provide all questionnaire responders with a database of LED lamps and luminaires suitable for museum display lighting use in exchange for their time in responding to the questionnaire. However, with programs like LED Lighting Facts®, a searchable web tool with current LED lamp listings, the authors instead hope to educate both responders and those in the museum community to use available resources. This will help designers and facilities experts keep up with the technology and compare available options as the market evolves. In addition, a revised set of guidelines for selecting SSL for museums will be drafted in the near future, since the SSL industry has advanced in the 3 years since its publication.

2. Questionnaire

A six-page questionnaire was sent to all those who requested a copy of the Guidelines. See Appendix B for the complete questionnaire. An analysis of the response data is found in Sections 2.1 through 2.3 and Appendix D.

2.1 Participants

Table 1 **Questionnaire distribution and response:** Of the 1,113 people who requested a copy of the Guidelines from Jim Druzik of the GCI, 55 were selected to be part of an initial trial group to test the format and content of the designed questionnaire. The remaining 1,058 were sent the final version of the questionnaire. Out of both groups, 55 people responded, of which 46 completed the questionnaire—a 4.70% response rate. If an email was bounced back, the questionnaire was deemed "unsuccessfully sent."

	TRIAL GROUP	FINAL GROUP	SUM
TOTAL sent	55	1,058	1,113
Unsuccessfully sent	2	132	134
Successfully sent	53	926	979
Response	6	49	55
% response of successfully sent	11.32%	5.29%	5.62%
Completed questionnaires	5	41	46
% completed of successfully sent	9.43%	4.43%	4.70%

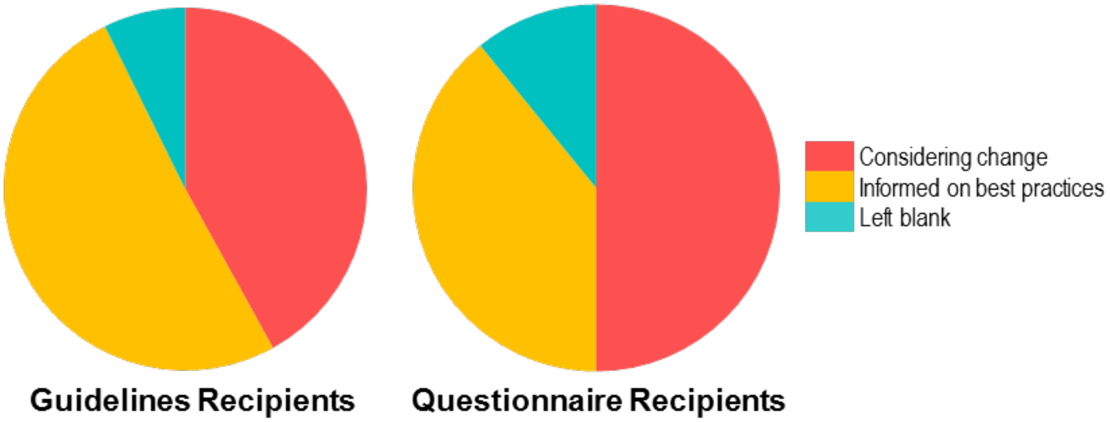

Figure 1 **Purpose of inquiry:** In order to keep track of who requested a copy of the Guidelines, anyone interested had to request a copy through the GCI. The charts above compare the purpose of inquiry for both those who received the Guidelines (1,113 people) and those who responded to the questionnaire (46 people).[3]

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[3] For Figures 1 through 3, the legends are read on the corresponding pie charts from 0 degrees clockwise.

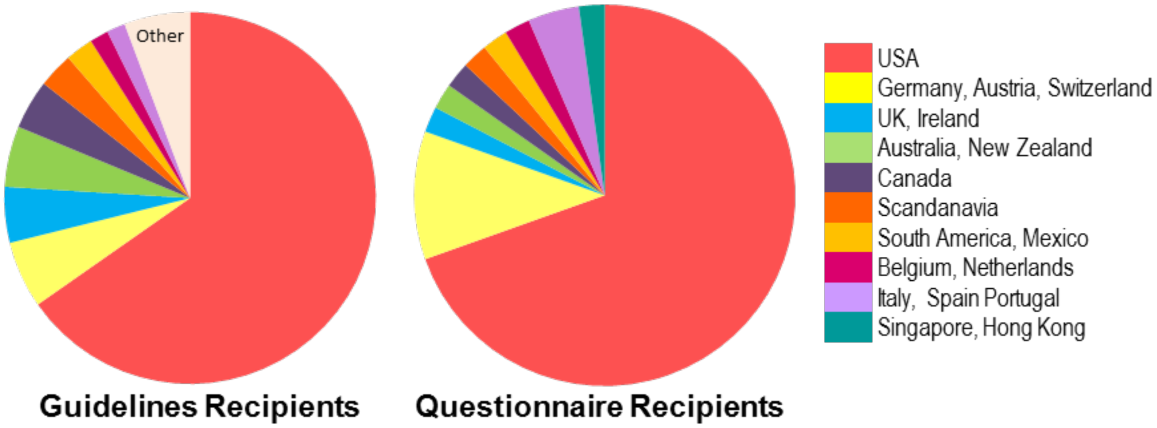

Figure 2 **Geographic distribution:** The charts above present and compare where both the Guidelines recipients and questionnaire responders are employed. Although the predominant audience was the USA, the international recipients and responders totaled 35% and 30%, respectively. In the pie chart on the left, the "other" wedge includes the following countries: India, Sri Lanka, Israel, Africa, Saudi Arabia, Poland, Romania, Lithuania, Singapore, Hong Kong, Malaysia, Philippines, Thailand, France, Greece, China, Near East, Slovenia, Servia, Caribbean, and Japan.

Figure 3 **Professional distribution:** Those who requested the Guidelines represent a wide range of professions related to museum lighting. Of those who responded to the questionnaire, the majority comprised museum directors, designers, conservators, curators, and those involved in collections care and registration.

2.2 Evaluation Methods

The questionnaire was designed to include a mix of question types, all with space for additional comments. (See Appendix C for the complete analysis.) Responders were encouraged to attach additional information (e.g., plans, photos, specifications), as the more information gathered, the better. The question types included:

Rank-order:

A list of choices was provided to be ranked, with the highest rank assigned the value of 1. Additionally, an "X" delineated the responder was either unfamiliar with the choice (question A1) or did not find the source useful (C4). Ties were allowed and the option of "Other" (A1, B4) allowed the responder to provide and rank additional choices. (However, these additional choices were not included in the rank-order analysis.) The responses were converted to a numerical scale and statistically evaluated using "mean rank". In the examples provided in Appendix C, question B4 asked the responder to rank a list of lighting goals from 1-5. The response rate was calculated to determine which goals were not selected and the response frequency per ranking (1-5) was tallied per goal. For example, choice four ("Use a lighting source with equal if not lower damage potential") was ranked first 22 times. The min and max ranking per choice were identified and the mean and mode calculated. As the mean for choice four was 1.9, the lowest mean of all the options, this was the highest ranked choice and thus assigned a mean rank of 1.

Select:

For the majority of the questions, a list of options was specified for the responder to select (as many as applicable). The option of “Other” allowed the responder to provide additional input and, unlike the rank-order questions, these were evaluated. The responses were converted to a binary scale: 1 was assigned to selected options; 0 assigned to those not selected. The responses per choice were summed and divided by the number of responses per question – the resulting percentage represented the percent selected. In the example provided in Appendix C, the most selected choices were incandescent (52%) and LED (41%) with the other choices below 25%.

Prioritize:

A list of rankings from 1 to 5 (5 signifying the highest priority for A4, or most important option for B12) forced the responder to either not respond to the question or select one number. Similar to the “select” type questions, the responses were converted to a binary scale per ranking: 1 was assigned to the selected option; 0 assigned to those not selected. The responses per ranking were totaled and divided by the number of responses per question – the resulting percentage represented the percent who selected each ranking. In the example provided in Appendix C, the highest percentages were 34% for rankings 4 and 5 – thus, the majority of responders (68%) placed high priority on energy efficiency.

2.3 Data

The data are summarized in Appendix D and a select number of responses are written up as “anecdotal demonstrations” in Appendix E.

3. Museum Lighting

This section will provide a background on museum lighting based largely on the questionnaire responses, but also drawing from the knowledge of the authors about museum lighting and conservation science to provide sufficient context. Included are museum requirements and goals, integrating how sustainability and energy savings are important and related to lighting; initial concerns and resolved misconceptions about LED technology; and the current lighting used in museums in consideration of how the Guidelines have been adopted to date.

3.1 Potential Damage

Because museums vary widely in content and object type, gallery scale, and atmosphere, display lighting will also vary from tiny lumen packages for fiber optics inside display cases for butterfly wings to large lumen packages for lighting airplanes in hangars. Beam angles required range from very narrow (4°) to very wide (60° or more). Lighting products may be less than an inch in diameter to 24" or more in diameter. LED lighting can be applied to that wide range of applications. The best design manages the presentation of daylight and electric lighting, so that illuminance levels, spectrum, and time are used to minimize damage while providing good viewing conditions for the visitor.

All lighting can be damaging to art objects, so museum lighting designers and conservation experts often design gallery lighting based on an acceptable rate of change over time. The first practical approaches are to limit light exposure to the object altogether. This is often achieved by storing the object in the dark whenever it is not on display, exhibiting artifacts at or near the levels of illumination that comply with long-standing recommendations (50 lux for known or suspected light-sensitive materials, 150 lux for paintings, and 300 lux for works considered stable to light, while limiting the UV content to 75 microwatts per lumen or lower), and using controls to switch off or dim down lighting when no observer is in the gallery. The next consideration to light exposure is the light source itself, choosing a spectral power distribution (SPD) that will limit the damage.

3.2 Sustainability and Energy Savings

There is a critical scarcity of knowledge, financial, and human resources in museums; such scarcities are a global problem prevalent in the preservation of cultural heritage. Because of these limitations, minimal intervention is often required—doing as much as necessary but as little as possible.[4] There are many motivations for considering LED light sources in museums, and some of them are derived from concerns about sustainability. "Sustainability" has many facets, environmental (water, air, land, plant, and animal), human health and quality of life, preservation of cultural heritage, economic, etc. To the International Association of Lighting Designers (IALD), sustainable lighting design "meets the qualitative needs of the visual environment with the least impact on the natural environment." In other words, the use of a minimum of environmental resources now, in order to enable use of resources and quality of life for future generations, is sustainability.

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[4] Australia International Council of Monuments and Sites (ICOMOS), *The Burra Charter*, 1999 (http://australia.icomos.org/wp-content/uploads/BURRA_CHARTER.pdf).

Figure 4 **Alberni Valley Museum, Vancouver, BC** – see Appendix E for more information on the museum's conversion to SSL (©Alberni Valley Museum 2009).

Figure 5 **Alberni Valley Museum, Vancouver, BC** – see Appendix E for more information on the museum's conversion to SSL (©Alberni Valley Museum, Joshua Berson 2009).

68% of survey responders placed a high priority[5] on energy efficiency (such as the Alberni Valley Museum shown in Figures 4 and 5 above). However, despite the savings in energy and the reduced cost of operation gained by a source with high luminous efficacy, respondents indicated that their museums would not sacrifice lighting quality in their galleries nor risk potential damage on their works of art solely for the sake of energy efficiency. Energy efficiency was noted as a key design criterion for museums seeking sustainability certification through international programs including Leadership in Energy & Environmental Design (LEED, US), Building Research Establishment Environmental Assessment Method (BREEAM, international), and Qatar Sustainability Assessment System (QSAS, Qatar).

3.3 Lighting Goals

Survey responders ranked a list of lighting goals for their projects – the following is in order of descending preference:

- Use a lighting source with equal if not lower damage potential than the incumbent light source (usually a halogen lamp);
- Save energy and reduce cost/maintenance;
- Improve or at least match color quality compared to the incumbent lighting;
- Provide an inconspicuous transition from incandescent to LED lighting.

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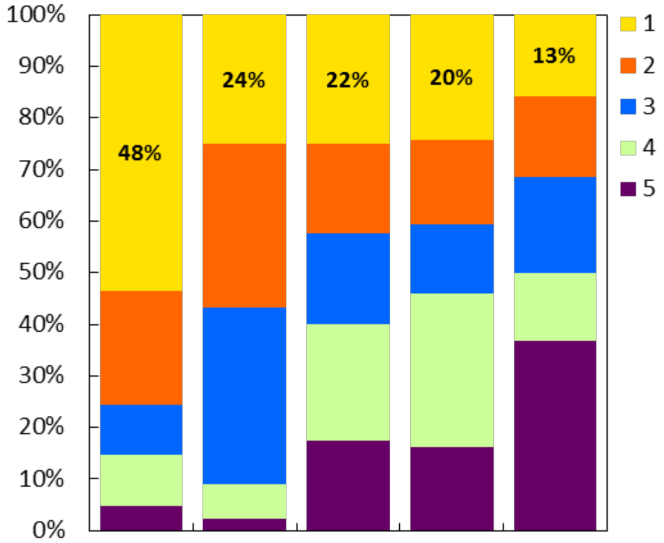
[5] A high priority was established as a ranking of 4 or 5 on a 5-point scale.



Ranking	A	B	C	D	E
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Mean rank	**1**	**2**	**3**	**4**	**5**

A Use a lighting source with equal if not lower damage potential
B Save energy and reduce cost/maintenance
C Improve color quality compared to standard
D Match color quality of standard museum lighting
E Inconspicuous transition from incandescent to LED lighting

Figure 6 **Summary of the results for ranking lighting goals:** Option A (use a lighting source with equal if not lower damage potential) was the most important goal with B (save energy and reduce cost/maintenance) as the second. Options C and D (improving and matching color quality compared to standard) were closely ranked. Option E (inconspicuous transition) was the least important goal. (A rank of one was the most favorable and a rank of five was the least favorable.)

Although the response was not predominantly from conservators, the conservation benefits and energy savings from LEDs were prioritized more highly than improved color quality (Figure 6). This seems unusual because museums are typically more vocal about color because color differences can be seen immediately whereas a conservation problem can remain hidden for an unknown period of time into the future. Thus, museums get feedback on aesthetics far more than conservation even though the latter is a higher priority. It is encouraging to see the changing focus on potential damage and energy savings. The inconspicuousness of the transition depended greatly on the museum's renovation plan – museums that were phasing out luminaires in stages needed LEDs to blend in whereas those that undertook complete renovations had greater flexibility.

Other lighting goals included the ease of use and lamp replacement, especially in small museums with non-specialist staff who have to know where to buy replacements easily and what to ask for. Also, the reduced operating temperature of the lighting is of benefit, especially where halogen lighting tended to radiate heat onto objects or gallery surroundings. One responder saw the potential of LEDs, specifically color-tunable, for enhancing the visitor's experience in order to illuminate each artwork with a specifically designed spectrum representative of the lighting conditions under which the work was created (predominantly daylight). This level of color specification is typically directed under the guidance of an art historian, conservator/restorer, curator, and museographer.

3.4 Historical Misconceptions about LEDs

In 2008, the problem of “hole-burning” surfaced due to a letter and posting submitted to the Green Task Force warning about the potential fading damage caused by LED light sources if the spectral power distribution (SPD) peaks were narrow and large enough at the critical wavelength at which an art object was sensitive. At that time, all white LED sources generally used LED chips (or photon pumps) that delivered a blue peak, with a phosphor covering that converted much of the energy into longer wavelengths. Because it was suggested by early Japanese researchers that at least some of the early white LEDs (even at lower CCTs) had very high blue peaks that caused accelerated aging of natural yellow dyes on silk, the GCI began evaluating white LEDs with lower blue peaks. In addition to evaluating lamp spectra, the GCI started accelerated aging (of ISO Blue Wool standards and a suite of dyes on silk) on a variety of light sources. It found that some test samples actually faded more slowly (very slightly) or at exactly the same rate under LEDs compared to halogen lamps.

In December 2012, a press release from a series of papers published in *Analytical Chemistry* went viral, warning against the use of LEDs on Van Gogh paintings containing chrome yellow paint, as they would cause accelerated darkening of the yellow paint on the canvas. However, the spectrum of the xenon light source the researchers used for the accelerated aging was not comparable to that of LEDs known to be used in museums, the blue band included UV (which normal architectural-application LEDs do not emit), paint samples were used instead of actual paints on canvas, and the experiment duration was 800 hours at 500 W/m^2 (roughly equivalent to a century of exposure for an object illuminated at 150 lux).[6]

As a consequence, LEDs were incorrectly attributed with high damage potential because of poor experimental comparisons. Furthermore, the LEDs originally implicated in these studies were early products of LED technology. The dramatic technological improvements since that time have reduced the damage potential of LED sources even lower, and made LEDs a light source ripe with possibility for museums.[7]

3.5 What does museum lighting look like today?

"Now, that we have a virtually unlimited amount of different 'lights' at the tip of our fingers, a whole new way of conceiving an 'art exhibition' may be developed." – Giancarlo Castoldi, Business Development Director (Targetti Sankey SpA, Italy). Figures 7 and 8 show two example exhibitions that used Targetti’s SSL products.

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[6] Assuming operating hours of 10 hours a day, 6 days a week, 52 weeks a year, 100 years of exposure at 150 lux is approximately 50 million lux-hours. By estimating the exposure of a xenon source (a daylight simulator whose illuminance capabilities are similar to noon summer daylight) at 75 - 150,000 lux, an 800 hour experiment would equate to 1 - 2 centuries of exposure at 150 lux.

[7] For more information related to evaluating SPD curves for potential damage, refer to the National Gallery’s resource created and maintained by Joseph Padfield: http://research.ng-london.org.uk/scientific/spd/?page=info.

Figure 7 **El Greco exhibition at the Museo de Santa Cruz, Toledo, Spain (March to June 2014)** – this exhibition is part of a series in Toledo for the 400th anniversary of El Greco's death. Around 30 cities internationally contributed to the exhibition of some 125 original works, the largest collection of to date. El Greco was one of the greatest masters of color so each painting was illuminated with tunable white light LED fixtures designed by Targetti to provide the best spectrum for the work. See Appendix F for more information on where Targetti's SSL products have been used (©Targetti 2014).

Figure 8 **El Greco exhibition at the Museo de Santa Cruz, Toledo, Spain (September to December 2014)** – this exhibition is part of a series in Toledo for the 400th anniversary of El Greco's death. El Greco was one of the greatest masters of color so each painting was illuminated with tunable white light LED fixtures designed by Targetti to provide the best spectrum for the work. See Appendix F for more information on where Targetti's SSL products have been used (©Targetti 2014).

3.5.1 Status Quo and Guidelines Adoption

Compared with over 55% of museum workplaces still using incandescent in 2009,[8] 51% of the responders also identified incandescent as the principal lighting type, with LED at 40%, CFL at 13%, linear fluorescent (FL) at 11%, and others (including metal halide, halogen, daylight) at 22%. (Some responders called out "halogen" separately from "incandescent" sources, although it is likely that all display lighting described was halogen, a higher efficacy form of incandescent.) The main difference between 2009 and 2014 lies in the higher percentage of LED adoption, now up to 40% compared to almost none. Some responded that they applied the Guidelines to all exhibit spaces in their museum. Others were planning to apply them to future installations, waiting mainly due to prohibitive LED cost and limited budget availability. A few have used the Guidelines in their teachings to discuss the different types of lighting available with both museum studies students and staff with little to no conservation experience. When asked whether they would consider and implement another LED installation, 71% indicated they would, only 6% would not, and 32% of the responders said they already had.

To evaluate the "success" of the installed LED lighting, responders indicated they solicited feedback from groups of observers. The majority consulted museum staff and approximately half reached out to lighting professionals, visitors, and others, including clients, photographers, and miscellaneous *ad hoc* reactions. From the public there was a unanimously favorable response. For many museums, no response was included in this "favorable" category as this implied the transition in lighting technology was not noticeably different. From the staff there was a 97% favorable response.

3.5.2 Product Selection

The museum lighting survey asked responders to consider best practices in museum lighting, and to rank the following sources for relevance and significance. The following is in order of descending preference, followed by the percentage of responders who selected the source.

- "Guidelines for Selecting SSL for Museums", Druzik & Michalski (2011), 89%;[9]
- Canadian Conservation Institute (CCI), 80%;[10]
- Illuminating Engineering Society (IES)/American National Standards Institute (ANSI) RP-30 (Recommended Practices for Museum and Art Gallery Lighting), 59%;
- CIE 157:2004 (Control of Damage to Museum Objects by Optical Radiation), 44%;
- "Lighting by Design", Christopher Cuttle (2008), 40%;
- "Light for Art's Sake: Lighting for Artworks and Museum Displays", Christopher Cuttle (2007), 39%.

Other sources listed included studies such as the DOE GATEWAY Demonstration program studies, periodical articles through the IES, and the AIC report on LEDs for gallery lighting (2009); information from lighting hubs, such as the California Lighting Technology Center (CLTC: http://cltc.ucdavis.edu/); presentations by experts, such as the Lunder Conservation Center's conference on gallery lighting, "LED Lighting in Today's Museums" (Washington DC, 2013), and Jim Druzik's presentation at the Preparation, Art Handling, and Collections Care

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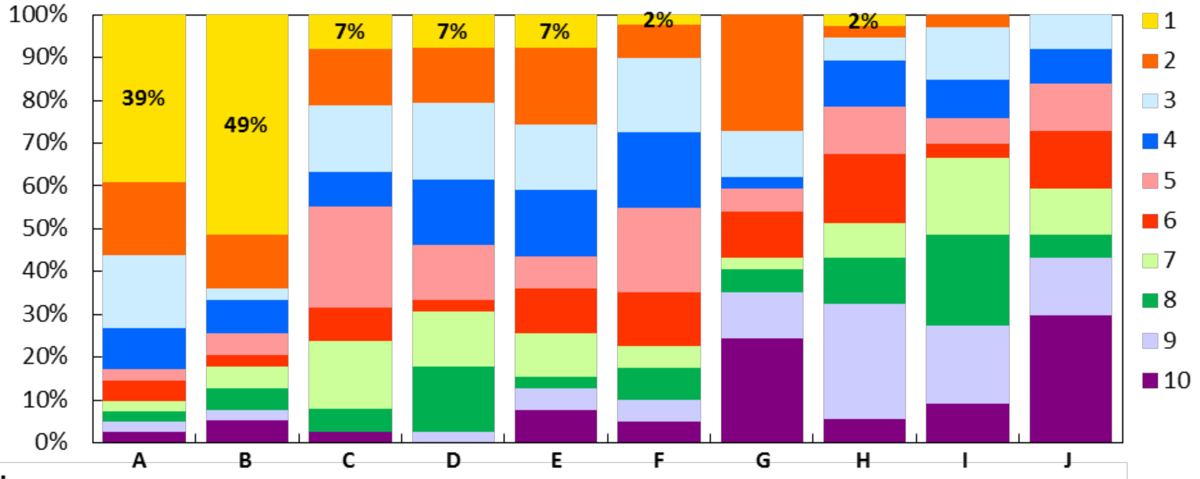
[8] American Institute for Conservation of Historic and Artistic Works (AIC), *Green Task Force Survey Summary Report*, May 2009 (http://www.conservation-us.org/publications-resources/surveys/green-task-force#.VC132_ldWSo).

[9] Since the survey group was selected based on their familiarity and use of the Guidelines, the high ranking of the Guidelines is not surprising and is not necessarily indicative of the broader museum community.

[10] For the Canadian Conservation Institute's resource, *Agents of Deterioration: Light, Ultraviolet and Infrared*, refer to the following link: http://www.cci-icc.gc.ca/resources-ressources/agentsofdeterioration-agentsdedeterioration/chap08-eng.aspx.

Information Network (PACCIN) Conference (Getty Villa, 2012); and experience from personal practice, observation, and research.



Ranking	A	B	C	D	E	F	G	H	I	J
Mean	2.9	3.1	4.6	4.6	4.7	5.1	5.9	6.6	6.8	7.3
Mode	1	1	5	3	2	5	2	9	8	10
Min	1	1	1	1	1	1	2	1	2	3
Max	10	10	10	9	10	10	10	10	10	10
Mean rank	**1**	**2**	**3**	**3**	**5**	**6**	**7**	**8**	**9**	**10**

A Color and spectral power distribution (SPD)
B Damage potential
C Lamp efficacy (lumens per watt)
D Initial cost
E Lamp size and shape
F Lifespan/lumen maintenance
G Dimming range/compatibility with dimmers
H Return on investment (ROI) or simply payback period
I Input power (W)
J Warranty

Figure 9 **Summary of the results for ranking considerations when selecting lamps:** Using mean rank, option A (color and SPD) was the consideration ranked first with B (damage potential) as the second. However, damage potential received a higher percentage of 1st and 2nd rankings. Many of the options were very closely ranked (especially options C-E). Option J (warranty) was the least considered. (A rank of one was the most favorable and a rank of ten was the least favorable.)

In the selection of lamps, aesthetic performance (namely color and SPD) and damage potential were the main considerations, with lamp efficacy, initial cost, and form factor (lamp size and shape) following (Figure 9). The remaining factors listed in order of preference included lifespan/lumen maintenance, dimming range/compatibility, return on investment (ROI) or simple payback period, input power, and warranty. Others included uniformity (of color and light distribution) and manufacturer reputation/reliability. As expected, the prioritization of variables depended on the application. For example, Grant McDonald, the Administration Services Manager for the Dunedin Public Art Gallery (New Zealand), said the gallery (Figures 10 and 11) prioritized the form factor and reliability of the manufacturer: "Our goal was to buy fittings that produced the best solution to our spaces and that included the look of the fitting and the manufacturer being able to continue to produce the same looking fitting over the next 20 plus years so we didn't end up with different types of fittings throughout the building." When narrowing down options, 55% considered what LED product manufacturers covered in their warranties, 50% considered published life, and 25% considered predicted actual life, based on either experience or speculation.

Figure 10 **Dunedin Public Art Gallery, NZ** – see Appendix E for more information on the museum's considerations when selecting SSL products (©Dunedin Public Art Gallery 2014).

Figure 11 **Dunedin Public Art Gallery, NZ** – see Appendix E for more information on the museum's considerations when selecting SSL products (©Dunedin Public Art Gallery 2014).

Product selection involved a broad set of museum departments, essentially any and all parts of the museum community: exhibits design (64%), conservation (57%), curatorial (55%), director (40%), consultant (33%), preparation (24%). Although the museum building facilities staff were not specifically listed, the initial push to convert to SSL often stemmed from many of them, particularly university galleries, museums, and libraries where campus-wide conversions were being made and sustainability is a high institutional priority [Druzik personal communication, 2014].

3.5.3 Product Performance

Although 75% of responders experienced early LED product failures, the maximum failure rate reported was only 2.5% of the installed lamps or fixtures. Of the noted sources of failure, included were electronic components such as drivers and power supplies, but not the LED source itself. Luminaires specifically designed for color critical applications were found to be less likely to fail – this was speculated by the responders, based on their experiences, to be due to better heat management in the higher quality products. Generally, failures occurred immediately upon start-up or within the first 100 hours of operation and products were replaced by the manufacturer. When selecting products, many used GATEWAY project reports that described SSL conversions in museums as models, and often contacted the project institution, asked for recommendations, and visited the installations before proceeding with their own installations.

4. Barriers to Adoption

"We're still in the 'wild west' era of LED companies rushing to produce marketable lighting components. Continuing evolution of products and dropping prices are helping, but [it's] still a bewildering selection." – Curtis Morris, Exhibits Manager (Shiloh Museum of Ozark History, Arkansas)

There are several barriers to LED lighting adoption, namely:

- High cost, especially for dedicated LED fixtures;
- Difficult selection process, due to the confusing variety of products and difficulty keeping up with rapid advancements in technology;
- Resistance to change especially from conservators and university administration; and
- Technology limitations, such as limitations in dimming performance and performance of LED replacement lamps in enclosed fixtures.

4.1 Cost

The museum lighting survey responses showed that cost was a considerable issue in the use of LEDs. In general, responders wanted more case studies of both retrofit and dedicated LED installations to document savings from the use of LEDs and the additional savings gained from the use of dimming and controls. Table 2 below summarizes the life-cycle cost (LCC) analysis conducted by the GATEWAY demonstration program for three different museums.

Table 2 **Life-cycle cost (LCC) analysis conducted by the GATEWAY demonstration program for three different museums:** The Smithsonian American Art Museum, [11] The Getty Museum, [12] and the Jordan Schnitzer Museum of Art. [13] For all examples, the following were specified: 10 year study period, 3% discount rate, and end-of-year discounting convention.

	Smithsonian American Art Museum		Getty Museum		Jordan Schnitzer Museum of Art	
	Incumbent	LED	Incumbent	LED	Incumbent	LED
Initial Capital Costs for All Components	$466	$5,610	$184	$3,398	$266.00	$5,832
Average Annual Electrical Energy Usage (kWh)	21,317	5,832	5,410	920	9851	1403
Average Electricity Cost per kWh	$0.14	$0.14	$0.12	$0.12	$0.06	$0.06
First Year Energy Consumption Cost	$2,984	$816	$649	$110	$591	$84
Net Energy Savings from LED Lamping (PV^1)	Baseline	$19,041	Baseline	$4,621	Baseline	$7,561
Net Savings from LED Lamping (PV)	Baseline	$27,891	Baseline	$9,843	Baseline	$4,545
Savings-to-Investment Ratio	Baseline	6.42	Baseline	6.31	Baseline	1.82
Adjusted Internal Rate of Return	Baseline	24.05%	Baseline	23.83%	Baseline	6.12%
Estimated Simple Payback Occurs in Year	Baseline	2	Baseline	3	Baseline	9

^{1}Present value

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[11] U.S. Department of Energy, *Demonstration of LED Retrofit Lamps at the Smithsonian American Art Museum, Washington, DC*, June 2012 *(*http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_gateway_smithsonian.pdf).

[12] U.S. Department of Energy, *Demonstration of LED Retrofit Lamps at an Exhibit of 19th Century Photography at the Getty Museum*, March 2012 *(*http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/getty_museum_gateway_final.pdf).

[13] U.S. Department of Energy, *Demonstration of LED Retrofit Lamps in the Jordan Schnitzer Museum of Art*, September 2011 (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2011_gateway_schnitzer.pdf).

The general process for conducting a LCC analysis includes comparing the energy input required for the LED system with the existing system. That value difference is then multiplied by the number of fixtures in use and the cost per kWh. Although there is some discussion about the benefit of having less heat for HVAC cost savings, along with the savings associated with not having staff up ladders frequently changing out bulbs, the general consensus is that these savings are negligible. Grant McDonald (Dunedin Public Art Gallery, New Zealand) pointed out that “the staff savings could only be argued if we ceased employing someone to change the bulbs and that was not going to be the case.” Less than half (42%) of the responders conducted a LCC analysis on their own projects, but, of those who did, the following factors were considered (a few relevant comments from questionnaire responders are added for illustration.)

- Maintenance costs, 87%;
- Years until payback, 77% - “To estimate a realistic life of LED bulbs, we are using a lower life estimate (around 5,000 hours) than that supplied by the manufacturers.” (Lucy Commoner, Head of Conservation, Cooper Hewitt – Smithsonian Design Museum, NY, Figure 12);
- Warranty, 50%;
- Effect on HVAC costs, 50%;
- Future drop in LED lamp costs, 40%;
- Other, 17% - comments included expected effects on wellbeing, other human factors, and the environment; the look of fittings given predicted long life; and potential failure (e.g., color shift with age).

Figure 12 Cooper Hewitt, Smithsonian Design Museum, NY, NY – see Appendix E for more information on the museum’s conversion to SSL and their use of controls (©Cooper Hewitt 2014).

The Guidelines claimed many manufacturers provide a 3 or even 5-year warranty, which rang true in the survey results. However, even if a manufacturer provides a warranty, one of the biggest difficulties with the performance criteria covered in warranties was specifying the level of performance warranted, including how to monitor the criterion and operational limits. Few institutions were capable of monitoring total lumen output or illuminant color characteristics. The following were components responders listed as covered by LED product warranties:

- LED chip and mechanical/electrical parts of lamp, 91%;
- Color consistency, 64%; and
- Return on investment (ROI) shorter than warranty period, 14%.

The Frist Center for the Visual Arts in Tennessee (Figure 13) was able to negotiate a longer warranty with their distributor due to the approach outlined in the Guidelines. Previously they had never thought to negotiate for a longer warranty, and since then have passed the advice along to museum colleagues. As higher luminous efficacy can equate to greater energy savings, museums established benchmark efficacies (LPW) for LED replacement lamps to ensure needed light levels for less input power. Although industry has established the "end of life" of an LED as the point in time when the LED's lumens drop to 70% of its initial output, some museums used shorter life spans (e.g., 5,000 hours instead of 50,000 in the example listed above) to account for potential issues.

Figure 13 Frist Center for the Visual Arts, Nashville, TN – see Appendix E for more information on the museum's recently completed retrofit to SSL (©Frist Center).

4.2 Difficult Selection Process

“Sustainability education is preservation.” As stated in the Guidelines, lighting is an arena where informed adoption of SSL will amount to preservation. However, with such a rapidly evolving industry,[14] there is a lot to keep up with: the variety, quality, and difference of LED products among manufacturers; the complexity in making choices without knowing how long replacements will be available; and the uncertainty of the spectral content of the emitted light and whether the color will shift over time. Professionals responding to the questionnaire all seemed aware that LEDs emit virtually no UV and little IR, but expressed concern that spectral information was not always available (specifically SPDs), lamp-to-lamp consistency was uncertain, and durability was unknown because LED manufacturers were unfamiliar. Many expressed questions about evaluating LED lamp quality, including whether purchasing from a reputable brand ensures quality. Fortunately, as shown in Figure 4 above, there are many products available that are both high quality and perform comparably to both one another and at least as well as incumbent technology.

The questionnaire responses and comments showed that there is still confusion about different LED products, what museum staff should be asking for, and concerns about maintenance. Some museums had experienced failures or problems that were probably due to using LED replacement lamps inside luminaires that didn’t allow for adequate thermal management, or used LED lamps with inappropriate color specifications. This can give SSL products a bad reputation. There were several generalizations (of the technology as a whole) expressed in the responses, including: LED sources appeared hazy regardless of lumen output; color rendering was poor, due to their discontinuous/spike-y SPDs; higher artwork damage potential; higher UV content; color shifts; discrepancy between advertised and actual life. While some of these generalizations could well be valid, it was clear from the responses that education and experience is needed at multiple levels: of museum staff, museum administration, museum facilities engineers, maintenance staff, and even visitors. Some museums created lighting review teams to insure the highest quality product possible consistent with the user’s specifications.

4.3 Resistance

“Waiting for a better variant (an excuse for inaction) ignores the reality that what we call a ‘technology’ is rather a large set of product development cycles that began at different times, will mature at different rates, and demonstrate different degrees of product durability in the market.” This statement from the Guidelines illustrates some of the uncertainty in dealing with LED products. After three years, some of what was once viewed as impractical or impossible in the world of LED is now practical and possible. The main reasons for not converting museum gallery lighting to LED were:

- Resistance from conservators, mainly due to the unknown damage potential.
- Inertia and habit from facility and museum staff, including the tendency to reproduce what they had in halogen rather than make the full shift to LED, embracing its differences and opportunities.
- Aesthetic bias against LED, although several responders noted that people's attitudes about the aesthetic of LED lighting seemed to have shifted.
- Considerable perceived difficulty in changing over from CFL to LED. In one example, all lamps used on a university’s campus (Figure 14) had to be available through state contract bids, which limited the availability of certain LED options.

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[14] Using Cree’s PAR38 lamp, which was well-received by museums, as an example, a Cree representative called it “a dinosaur” after only a few years (Druzik pers. comm. 2014).

Figure 14 1938 Techionery, Arkansas Tech University Museum, Russellville, AR – the museum above is on the National Register of Historic Structures and, originally, was used as the campus's first student union. See Appendix F for more information on the museum's process of converting from fluorescent technology and selecting LED lamps (©Arkansas Tech University 2009).

4.4 Technology Limitations

The following subsection will discuss the perceived technology limitations, as shared by the survey responders. Section 6 will go into further exploration.

4.4.1 Form Factor (Retrofit vs. Dedication LED Design)

When considering different lamp types, the responders had no strong preference for replacement lamps versus dedicated LED fixtures. Instead, the decision was dependent on the application and the pressure exerted by existing luminaire stock. If replacement lamps were used, it was often dictated by the perceived ease of replacement, the flexibility of interchangeable lamping, and/or budget constraints due to the prohibitive costs of new dedicated fixtures. However, replacement lamps posed some issues as well. Although here are now LED form factors that mimic most incandescent lamp options, some found LED replacement lamps didn't fit into existing fixtures; others found the light output and beam characteristics were similar to halogen lamps, but seldom identical to the lamp being replaced. Consequently, the museum lighting designer had to re-lamp and re-aim multiple luminaires with multiple types of LED replacement lamps in order to produce the ideal intensity and pattern of light on the objects. Most museums could not afford to do this. There were also incompatibilities with transformers and the low-voltage retrofit LED lamps, which were impossible to identify from product literature, so they were not noticed until the full-scale mockup stage. Better photometric performance, color rendition, and versatility drove many to select dedicated LED fixtures despite the potential reduction in flexibility. One responder said controls will drive the conversion to dedicated LEDs: "It is expected over time that integrated luminaires may replace the majority of non-integrated luminaires due to a change toward more reliable LED control systems such as DALI" (more on controls in section 4.4.5).

4.4.2 Color

Responses to the questionnaire indicated color was a significant factor in making a final aesthetic decision on what to buy and what to illuminate in galleries. Many responders thought color quality was inversely proportional to source efficacy. Although this can be true, it is speculated by the authors that this was because, at the time of purchase, higher efficacy was associated with higher CCT which didn't meet expectations of color rendering, especially for track lighting. When evaluating color, almost all considered CRI, with target values greater than 85. The Shelburne Museum (Burlington, VT, Figures 15 and 16) even reported that it specified values greater than 92 in an effort to achieve a spectrum that renders both reds and blues well. However, despite its ubiquitous use, many questioned the use of the metric, especially the use of an incandescent source as a low CCT reference for CRI. Two-thirds considered CCT in choosing LED lamps, with 2700 and 3000 K listed as target values, but the CCT of the source was not considered an important factor of potential damage by all. 60% evaluated the light source SPD and wished manufacturers made SPDs more available. 26% required a color warranty, and 20% used the color quality scale (CQS), with target values greater than 90. D_{uv} as a metric of how green or pink the light source appeared compared to the blackbody curve was not used.

Figure 15 Pizzagalli Center for Art and Education, Shelburne Museum, Shelburne, VT – see Appendix E for more information on the museum's conversion to SSL and difficulty with controls (©Shelburne Museum 2013).

Figure 16 **Shelburne Museum's Round Barn, Shelburne Museum, Shelburne, VT** – see Appendix E for more information on the museum's conversion to SSL and difficulty with controls (©Shelburne Museum 2012).

Although all responders said that LED color quality held up over time, to resolve any color inconsistencies that did occur, luminaires were visually evaluated and those with similar color shift were grouped together. This was done at the Art Gallery of New South Wales (Australia); it was deemed an entirely unsatisfactory solution and the manufacturers were notified. In other cases, the manufacturer replaced the product or the products were simply returned. When conducting a visual assessment of the lamps, two-thirds of responders trialed expected lux levels and light sources in the actual gallery while less than half used a reserved space for mock-ups only, either in house or off site. The majority compared several options and used multiple observers. A color-checker card was the predominant object used for performance comparison, but others used a neutral grey background and white card. One responder conducted source evaluations outside the gallery with large color swatches of over 100 colors ranging in hue and chromaticity. Others considered the artist's original intent and tuned each lamp or luminaire specifically for that painting to match the original conditions, under the guidance of an art historian and/or restorer.

4.4.3 Damage[15]

Simm Steel, a conservator for the Art Gallery of New South Wales (Australia, Figure 17) claimed one of the barriers to LED adoption was the widespread ignorance of the facts about potential damage to light sensitive materials by SSL sources. "The last three years has been rife with information released to the general public and the museum world that has proven to be either poorly researched, misinterpreted, misunderstood, or already outdated by its release date. Unfortunately this includes statements presented by highly regarded and trusted sources, which only serves to make matters worse. I am still getting fretful queries from conservators all over the world who are frightened of very old images floating about on the internet about the damaging effects of the royal blue spike of LEDs."

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[15] For more information on damage, see the discussion in section 3.1.

Figure 17 **Art Gallery of New South Wales, Sydney, Australia** – see Appendix E for more information on the museum's conversion to SSL and adjustments made due to color shift (©AGNSW).

When evaluating potential damage, the majority of responding museum professionals considered UV and IR content and about half considered short-wavelength (e.g., blue) emissions in the SPD. Other considerations included limiting the duration of exposure, CCT, heat output from LEDs, and the composition of displayed materials. For artificial sources, many specified a CCT no greater than 3,000 K and, for matching to daylight, less than 6,000 K, as damage was believed to increase with increasing CCT – this will be addressed in more depth in section 6.2.

Almost all responders considered light exposure recommendations based on the sensitivity of the materials displayed, along with the annual hours of operation of the lighting system. Target illumination values were not generalized as they depended on the installation (object and selected light sources) and most followed IES recommendations. In the documentation of initial conditions of artwork, the main step practiced by all responders was to take lighting condition measurements. However, less than 25% took object color measurements (e.g., spectrophotometry), used ISO Blue Wool dyes, or conducted microfading tests. Many claimed there is simply no budget for sophisticated testing so they used recommendations from the GCI and others. However, they hoped to have the capability to identify individual light fastness of single items in the future. When monitoring illuminated objects during installation, almost all periodically monitored illuminances with hand-held meters along with temperature and relative humidity. Less than 20% took color measurements throughout the duration of display or monitored illumination passively with ISO Blue Wool scales – one responder even remarked, a view shared by a few, "I don't know of any museum that conducts this kind of evaluation." Instead, most exhibition monitoring was done visually.

4.4.4 Dimming

Dimming was generally deemed important to achieve required low light levels down to 5 fc (50 lux) incident on the object (Figure 18). Some responded that they looked for dimming down to 1% of maximum output. Many considered dimming to be a part of their energy efficiency measures. Some respondents preferred dimming at the fixture level (tracks and individual lamps) for flexibility of illuminance control on an object-by-object basis using controls, although some (including the Getty Museum) still preferred to adjust individual luminaire light output using screens/lenses/reflectors/filters. Those who preferred the former option viewed screens and other media as inefficient and not sustainable. Those using dedicated LED fixtures were keener to require dimming than those using a retrofit approach.

42% of respondents used DALI/DMX/or 0-10V dimming protocol, 39% used dimmers designed for incandescent loads, and 33% had no dimming capabilities in galleries (responders could select more than one response). For dimmers not designed for incandescent loads, problems included flickering (both during the undimmed and dimmed states) or failing to turn on (especially when the dimming circuit was lightly loaded). These problems were often not noticed during mock-up stages, and had to be dealt with in the ultimate installation. There was little to no color change from the reduction of line voltage on dimming systems designed for LED loads (probably due to pulse width modulation techniques used in the dimming drivers). However, some LEDs are now being designed to mimic incandescent dimming by decreasing their CCT as illuminance decreases – "dim-to-warm."

Figure 18 **Abbe Museum, Bar Harbor, ME** – see Appendix E for more information on the museum's conversion to SSL and preference for dedicated fixtures (©Abbe Museum, Peter Vanderwarker 2014).

Another dimming method used a system that transmits radio signals to circuits or luminaires with built-in receivers. Some museums had used trailing edge phase-cut dimmers but were upgrading to DALI dimming systems. Some were working with dimming suppliers to continually rewrite dimmer firmware to enhance the compatibility of the new LED technologies to their installed analogue dimming systems. Explained by Simm Steel, a conservator at the Art Gallery of New South Wales (Australia), "Trailing edge dimming issues had to be resolved with a temporary transition to on-board dimming until the dimmer firmware could be re-written to smooth the dimming curve and resolve flicker at certain dimming regions. Existing display area trailing edge systems are being replaced with DALI after it was found that trailing edge phase-cut dimming and LED products were not reliably compatibility. 0-10V dimming protocol is also used for non-display lighting areas such as the bookshop." Feedback from the museum community through the responses suggests that dimming is a rarity in museum buildings, but is specified more regularly for new museum projects.

4.4.5 Controls

All lighting can be damaging to art objects, so museum lighting designers and conservation experts often design gallery lighting based on an acceptable rate of change. The best design coordinates and manages the presentation of daylight and electric lighting. Historically, lighting in museums has been controlled through the spatial (beam shape, spill light) and spectral (UV, visible, IR) distribution of light, primarily through lamp selection. A variety of tools have been adopted for manipulating the output of installed lamps, including various forms of lenses, filters, diffusers, and baffles. As LEDs are transforming the lighting market, their inherently electronic nature is opening the door for the use of lighting control in new applications. Almost two-thirds (over 65%) of the questionnaire responders would use lighting controls if they worked with their existing lamp-based infrastructure and afforded lamp-by-lamp control of light output—and chromaticity, if possible. They would also like the ability to monitor lux levels on an object-by-object basis. This would be a big time saver, keep illuminances constant and within conservation parameters, and allow for tracking lux-hours per object. Steel Simm said, “Individual monitoring of lux levels per object would be particularly useful for tracking lux hours and would not only be highly instructive data, it would also give conservators and curators the ability to schedule the display of artworks according the CIE recommendations far more accurately, but to do such a thing may not be logistically possible for many museums.”

5. Responder Recommendations on Speeding LED Adoption

Questionnaire responders offered constructive suggestions on how to speed LED adoption. The overarching activities they recommended for government and industry included utilizing other communications platforms to inform and educate, through regional workshops, webinars, more GATEWAY demonstrations, and online forums. Additionally, more guidelines were requested: simple guidelines for museums of all sizes, including a version for a "layman", and ones with a more international scope that include current product ranges and availability, along with executive summaries of research to-date.

Recommendations to manufacturers:

- Stop trying to retrofit SSL technology into luminaires with reflector designs that are still based on halogen lamp form-factors and distributions;
- Increase cross-communication between luminaire and dimming system manufacturers;
- Provide easier access to SPDs and test reports (LM-79 and LM-80).

Recommendations to governments:

- Provide grants to support LED purchases, especially for small organizations, from utilities or mixed utility/government programs;
- Offer tax incentives for energy-efficiency improvements;
- Produce additional assessments of lighting installations (not just in the U.S.);
- Sponsor practical demonstrations/workshops.

Recommendations to IES/CIE:

- Change CCT and CRI metrics for easier and more accurate selection of LEDs;
- Develop D_{uv} standards.

Education topic recommendations for lighting professionals and members of the museum community:

- Recommended practice for lighting museums;
- Current lamp/luminaire product features and market availability;
- Information on lighting and photodegradation issues;
- Potential SSL challenges.

6. Exploration of Technology Limitations and Hope for the Future

This section moves beyond the background information on SSL and the museum questionnaire responses in order to discuss current museum issues, possible solutions, and the current state of LED technology.

6.1 Color[16]

Color is the agony in Scott Rosenfeld's *The Agony and the Ecstasy of LED Lighting*.[17] For uniform lighting, the color of each lamp has to be the same, meaning visually matched initially and over time (color maintenance). However, lamps with the same chromaticity (CCT, D_{uv}) do not necessarily visually match; the color of the illuminated objects could look different due to different spectral properties. Looking specifically at the color performance of LEDs, color consistency between identical products is improving. Designers are not likely to find dramatic variations among identical lamps at this point in time, although two MR16 products of different output or beam angle, for example, may vary. Furthermore, there may be some color change in a single product over time, specifically phosphor degradation or aging of phosphor substrates. This most often appears as slight yellowing of the light.

In general, white LEDs pose no special color issues (in rendering nor increased damage potential) for works of art, compared to an equivalent CCT halogen or fluorescent source. CCT, CRI, D_{uv}, and other color metrics are intended to help designers select lamps and luminaires. However, each has assumptions built into the metric that may not apply to the needs of a specific museum or collection so they should be used as rough guidelines. There is no substitute for evaluating LED products with the human eye. As an example of this, Figures 19 and 20 show a painting illuminated by similar CRI light sources, but with varying CCT and D_{uv} values. The background image is the painted surface illuminated with a 2875 K halogen PAR38 lamp. Overlaid onto that image are patches showing the same art illuminated by a series of LED lamps of a variety of form factors (e.g., PAR38, PAR30, MR16). It's obvious that some patches appear too blue or yellow or green or pink, which is a consequence of the color point of the individual LED product and how far its color point strays from the blackbody locus. As colors are also more difficult to see under low light levels (the Hunt Effect), some light sources can increase or decrease the perceived saturation of some colors, and that saturation characteristic can increase contrast, colorfulness, and visibility of an object when it is lighted to low light levels. The highest possible CRI value is not necessarily a goal as there can be much variability and the performance depends on the object being lighted.

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[16] For background information and questionnaire responses regarding color, see section 4.4.2.

[17] S. Rosenfeld, *Lighting Art at The Smithsonian American Art Museum*, DOE's Tenth Annual SSL R&D Workshop, Long Beach, CA, January 29-31, 2013 (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/rosenfeld_smithsonian_longbeach2013.pdf).

Figure 19 A patchwork of halogen and LED sources with CRI values between 80 and 90. This illustrates that even with similar CRI values, varying chromaticity (CCT) changes visual appearance, depending on whether the color coordinates lie above or below the blackbody locus. The metric for measuring the distance from the blackbody locus is D_{uv} (©Perrin 2013).[18]

Figure 20 A patchwork of halogen and LED sources with CRI values greater than 90 (©Perrin 2013).

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[18] Figures 19 and 20 do not reflect the chromatic adaption (changes in the visual system that approximately compensate for changes in the spectral quality of illumination) available to the viewer – the "patchwork" images were created in Adobe Photoshop® with a halogen-lighted image as the background and other LED lamp –lighted images overlaid in sections. The images were not color balanced but were captured in "camera raw" so no camera-based calculations were applied to what the charge-coupled device (CCD) "saw". To white balance the images would have added the camera equivalent of "super chromatic adaptation" in a way the human eye cannot achieve, despite the adjustments our visual system makes (e.g., color constancy).

6.2 Damage[19]

Light-induced damage is due to photochemical reactions and radiant heating effect. Looking at visible light, UV, and IR, the types of deterioration caused by the three bands in museums are:

- Light fades color, induces shifts in hue, and darkens some pigments;
- UV causes yellowing, chalking, weakening, and/or disintegration of materials;
- IR heats the surface, reducing moisture content, which may induce physical stresses.

Often fading is attributed to UV; however UV contributes less than half of the fading, sometimes as little as one tenth of the total fading. At equal lux levels, the photochemical, thermal, and hygrometric stresses posed by LEDs are lower than halogen and (photochemically) much lower than daylight. According to Steven Weintraub (AIC), “damage calculations predict that a warm white phosphor-based LED has a lower damage potential and is therefore less damaging than a UV-filtered tungsten halogen lamp.” Even 3,000 K LEDs can be found with enough energy in the 300-400 nm range to make blue pigments stand out thus making them even more comparable to daylight rendering while posing less of a threat. Figures 21 and 22 below show the strong linear correlation between damage potential and CCT for all products and minimal (if any) correlation between damage potential and CRI. Standard blue-pump LEDs have the lowest damage potential compared to unfiltered incandescent and halogen sources at the same CCT; even violet-pump LEDs pose no additional risk than a typical unfiltered incandescent or halogen lamp. However, this is only a generalized model of relative damage and cannot predict true damage rates that depend upon the physical chemistry of the colorant/substrate system.

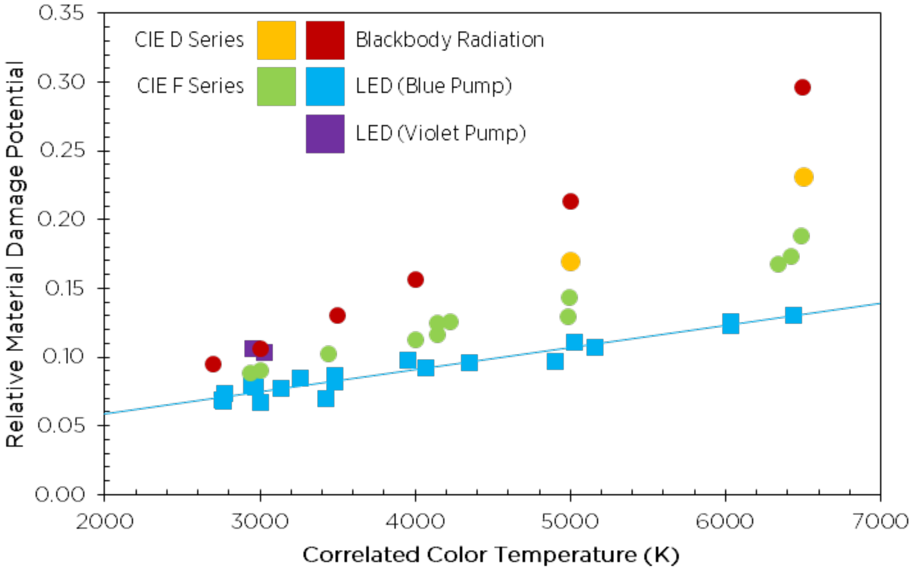

Figure 21 CIE spectral damage potential (S_{df}) versus CCT: The linear correlation between damage potential and CCT is high for all product types. The plot above is normalized for equal lumens from each light source. However, it is important to note that standard blue-pump LEDs have the lowest damage potential at a given CCT compared to unfiltered incandescent and halogen sources (approximated using blackbody radiation). Even violet-pump LEDs pose no more risk than a typical incandescent or halogen lamp.[20]

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[19] For background information and questionnaire responses regarding damage, see section 4.4.3.

[20] U. S. Department of Energy, *True Colors: LEDs and the relationship between CCT, CRI, optical safety, material degradation, and photobiological stimulation*, October 2014 (http://www1.eere.energy.gov/buildings/ssl/pdfs/true-colors.pdf).

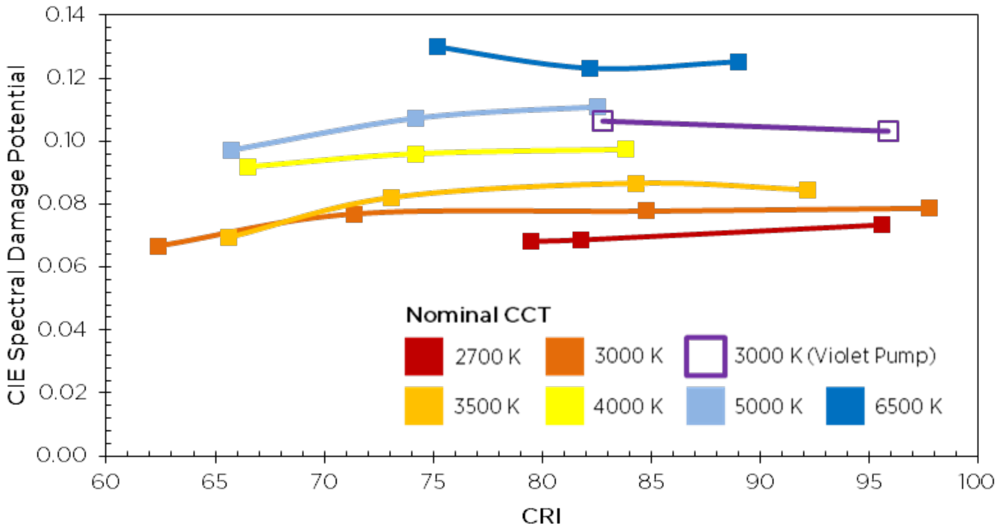

Figure 22 CIE spectral damage potential (S_{df}) versus CRI: The graph above shows minimal correlation between CRI and damage potential. (The damage is normalized for equal lumens from each light source.) However, as explained in the previous figure, there is a strong linear correlation between damage potential and CCT. It is important to note that standard blue-pump LEDs have the lowest damage potential at a given CCT compared to unfiltered incandescent and halogen sources (approximated using blackbody radiation). Even violet-pump LEDs pose no more risk than a typical incandescent or halogen lamp.[21]

For risk assessment and limiting deterioration, the predominant problem with LEDs is their newness in the market. The technique of microfading means bombarding a very small area of a material with high illuminance, over a known period of time, to predict the change in material appearance according to its lux-hours of light exposure. Microfading tests done in museum labs are conducted to rank order materials by light sensitivity only, not to mimic real performance or scale results down to museum light levels (e.g., 50 lux) which results in high inaccuracy. Microfading tests are expected to be just as predictive of damage performance of LEDs as they have been for halogen sources. Normal 'macro' scale exposures of colorant materials to LEDs still need to be carried out.

6.3 Dimming[22]

Dimming can be applied to an individual lamp or luminaire, or to an electrical circuit, to reduce light output from a lamp or lighting system. The lumen output of some LEDs can be reduced with other methods as well: for example, the "powerband technology" of a PAR38 LED lamp by MSi uses an adjustable ring for 10, 12, or 16 W to produce 550, 650, and 800 lumens, respectively. Flicker can result from an incompatible pairing of LED driver and a dimmer, an incompatible driver and transformer, or a combination of all three.[23] Compatibility tables are available from manufacturers for certain combinations, and the likelihood of introducing annoying flicker to the emitted light can be considerably reduced if that manufacturer's report guidance is heeded.

Are energy savings now realized when LEDs are dimmed? At the Field Museum, the LEDs were dimmed by the control system, which resulted in a decreased illuminance but not measured current.[24] Thus the museum didn't save significant energy. Rist-Frost-Shumway Engineering, P.C. (RFS), a firm based in Laconia, NH since 1972,

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[21] (http://www1.eere.energy.gov/buildings/ssl/pdfs/true-colors.pdf).

[22] For background information and questionnaire responses regarding dimming, see section 4.4.4.

[23] U.S. Department of Energy, *CALiPER Report 20.2: Dimming, Flicker, and Power Quality Characteristics of LED PAR 38 Lamps*, March 2014 (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20-2_par38.pdf).

[24] U.S. Department of Energy, *Demonstration Assessment of Light-Emitting Diode (LED) Accent Lighting at the Field Museum in Chicago, IL*, November 2010 (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/gateway_field-museum.pdf).

deals with a range of projects specifying lighting for museums – dedicated fixtures with dimming capability are always specified due to their energy saving potential. However, despite its claimed importance, dimming is rarely implemented in the museum community in order to saving energy. As controls are more utilized and dedicated LED fixtures are selected, dimming will become more common.

6.4 Controls[25]

As the building industry moves slowly toward zero net energy—key in the roadmap of the U.S. DOE—the industry is recognizing that lighting controls play a crucial role in energy conservation. According to the DOE, lighting is by far the largest end user of electricity in commercial buildings; it consumes 38% of a building's total electricity use. Museums use approximately half the electricity compared to other commercial buildings due to the increased HVAC use to regulate the interior relative humidity (Druzik personal communication, 2014). Lighting controls can eliminate 60% or more of the wasted lighting energy in buildings.[26]

Lighting controls would enable the museum lighting designer to specify lighting exposure (illuminance, spectrum, time) and attempt to minimize damage while providing optimal viewing conditions for the visitor. Different exposure conditions could be scheduled, or enacted automatically through sensors in response to changing time of day, daylight levels, and even the presence of observers. Wireless lighting control holds the promise of integrating more easily with existing lamp-based infrastructure. Networked lighting control systems can communicate or log cumulative light exposure (lux-hours) per object, thereby increasing conservator knowledge of light exposure effects in the long term for an individual artifact. A growing and more sophisticated set of controllable LED light sources and complementary control technologies are becoming available. Simple light switches and optical devices, still preferred by some, are no longer the museum designer's only option.

However, many view controls as too complicated or ineffective or counterproductive. This stems from experiences with controls that were incorrectly specified, poorly installed, incorrectly commissioned or never commission, and poor user education. The user interface is often poorly designed or intimidating, and frequently controls end up being disabled or else programmed to be less intrusive. There are so many studies that show the potential of controls but when scrutinized, the controls seldom live up to that potential. Furthermore, even if they are properly commissioned and functional at the beginning of a project, control settings can drift over time, implying that controls may need a tune-up periodically. The cost of that re-commissioning may negate the energy savings, depending of course on how much the controls are saving, and what the electric rates are. Ideally, controls have to be dirt simple, durable, and adaptable to changing gallery displays and hours of operation, etc. All museums, regardless of endowment, have funding limitations for lighting equipment, so controls most often also need to work with existing track systems and luminaires. That said, controls that are well thought out, designed for ease of use, and which are installed and commissioned properly, can be a boon to museum operations, can reduce light exposure hours for gallery objects, and can result in energy savings that can be applied to other parts of the museum.

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[25] For background information and questionnaire responses regarding controls, see section 4.4.5.

[26] *Illumination in Focus*, Fall 2014, Volume 3, Issue 2 (http://digital.illuminationinfocus.com/illuminationinfocus/fall2014?sub_id=pNiRT0RgsNb6&u1=DAIIF0914#pg13).

6.5 Energy Savings: Means and Potential

This list was taken from the Guidelines and tailored to reflect the survey responses**.** The following are avenues for achieving energy savings:

- Recycling and reduction in energy use. LEDs, if adopted, have the potential to save 80% or more in electric power use, with further savings from the use of controls.
- Reducing the use and disposal of mercury by minimizing the use of mercury-containing lamps (fluorescent, CFL, metal halide), as mandated by states and the US Environmental Protection Agency (EPA).
- Reducing greenhouse gas emissions and carbon footprint by cutting down electric energy use in buildings, especially power generated by fossil fuel plants.
- Reducing operating costs to the museums through more energy-efficient LED sources and longer-life lamps that reduce maintenance; also through reduced heating, ventilation, and air conditioning (HVAC) costs due to lighting systems that produce less heat.
- Facing the imminent reduction in availability of older incandescent lamps as mandated by the U.S. Energy Independence and Security Act (EISA) energy conservation standards. The California Energy Commission (CEC) has introduced LED lamp standards to ensure a high performance that will create a positive perception of LEDs among the California homeowners.[27]

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[27] A. McAllister, California Energy Commission, *California Quality Light Emitting Diode (LED) Lamp Specification* (http://www.energy.ca.gov/appliances/led_lamp_spec/).

7. Lessons Learned

In a world of information overload, what LED technical requirements are really needed for museum lighting? Does anyone but a lighting engineer really want or need to know all the information provided by an IES LM-79 report? The museum lighting survey elicited many telling responses from individuals who had experience with LED products. Below is a distillation of lessons learned from the trials and tribulations of their installations.

- Museums place a high priority on **energy efficiency** but will not sacrifice light quality/aesthetics to achieve energy savings. Survey responders acknowledged that lighting quality is not necessarily diminished by higher source efficacy: it is possible to achieve both a high LPW and high quality LED performance.

- Color/SPD, damage potential, cost, and form factor are the biggest considerations in **product selection.** High performing products with attractive fixtures that will not become obsolete are key.

- Users are skeptical about **predicted life** due to the lack of "real" proof (e.g., the relatively newness of LED technology and performance in "real time"). Although the point of 70% lumen maintenance (30% **lumen depreciation**) is often accepted as the typical failing criterion by some users,[28] this is not always adopted by the museum community; significantly shorter lifespans, such as 5,000 hours, are frequently used in economic analysis.

- Be cautious of **CCT and CRI** claims because lamp-to-lamp consistency may be poor. Museums should agree with manufacturers to have replacements lamps supplied when consistency is inadequate, either out-of-the-box or over operation hours.

- The most noted **sources of failure** were electronic components (drivers, power supplies), not the LED source itself. Museums are looking for **warranties** that cover LED chips and electronics, lumen depreciation, and color shift, and some are even looking for warranties that are longer than their return on investment (ROI) period.

- **Dimming** incompatibilities still exist and, due to the added challenge, older systems (like screens) are still being used to modify lamp light output because they are simple, inexpensive, and effective. Dimming is not as straightforward as it seems – all luminaires need to be trialed in both undimmed and dimmed states for **flicker** potential, acceptability of dimming smoothness and low-end performance.

- **LED retrofit lamps** are easiest to install in existing tracks and fixtures but don't discount **dedicated LED luminaires**, especially if accompanied with easy and effective dimming. The higher upfront costs of dedicated LED luminaires can be offset by reduced power and energy use. The greatest energy cost savings occur in geographic areas with higher-than-average electric rates and installations with longer operating hours.

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[28] For more information on lumen maintenance criteria, see the DOE SSL Program's fact sheet *Lifetime and Reliability*: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/life-reliability_fact-sheet.pdf.

- Museums would use **controls** if they were user-friendly and not prohibitively expensive. **Wireless controls** would be easier to retrofit because no additional control wires need be run between the dimmer and the load and luminaires equipped with a wireless receiver could be individually dimmed to customize light output for a specific object. This would allow for setting and maintaining illuminances within conservation parameters (thus more easily tracking lux-hours on an object-by-object basis) and provide additional energy savings compared to using screens to reduce output. However, survey responders indicated that at this point in time, controls are too complicated. This is likely to change in the coming years.

- GATEWAY project reports are a good **benchmark** for selecting products. Other commonly used **resources** for product selection include guidelines published by experts in the museum lighting industry (e.g., resources put out by the GCI and the CCI) along with other recommended practices published by the IES.

To be informed of further museum-related and other SSL efforts, please subscribe to the DOE postings at http://www1.eere.energy.gov/buildings/ssl/postings.html and email postings@akoyaonline.com to be added to the mailing list. Alternatively, please check the following pages:

- The publications page of the CCI: www.cci-icc.gc.ca;
- The GATEWAY demonstrations homepage: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html;
- The Museum Lighting Research page of the GCI: http://www.getty.edu/conservation/our_projects/science/lighting/lighting_component8.html.

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U.S. Department of Energy, *True Colors: LEDs and the relationship between CCT, CRI, optical safety, material degradation, and photobiological stimulation*, October 2014 (http://www1.eere.energy.gov/buildings/ssl/pdfs/true-colors.pdf).

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U.S. Department of Energy, *Demonstration of LED Retrofit Lamps at an Exhibit of 19th Century Photography at the Getty Museum*, March 2012 (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/getty_museum_gateway_final.pdf).

U.S. Department of Energy, *Demonstration of LED Retrofit Lamps in the Jordan Schnitzer Museum of Art*, September 2011 (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2011_gateway_schnitzer.pdf).

Appendix A: Questionnaire Cover Email

Hello,

Over the last two years almost 1200 individuals including conservators, registrars, preparators, curators, museum directors, facilities managers, lighting designers, manufacturers, consultants, and students have requested a copy of “Guidelines for Assessing Solid State Lighting for Museums” by James Druzik and Stefan Michalski.

It has been our objective to supply relevant information to decision makers as efficiently as possible and to learn more about how museums have fared adapting to LED display lighting. As they have become available, we have also provided museum case studies created under the GATEWAY program for the U.S. Department of Energy believing that these would also assist project planners.

466 of you have told us that you were planning to replace old display lighting, usually incandescent track lighting. Another 560 were seeking to expand their understanding.

It is now time to learn from you a number of valuable lessons. We want to know how well these resources served you and if you did proceed to adapt LED lighting to your institution, what did you learn from the process?

This is an incredibly important step to take and we hope for a significant response rate. The attached questionnaire is self-explanatory and all questions provide space for unlimited text comments. We strongly encourage you to make use of this space. Please save the PDF in its original, interactive form so we can scroll through all of your comments.

Questionnaires that are returned will be sent a small token of our appreciation. Since you may have LED projects in the future we’d like to offer you a listing of 1,800 lamps that qualify for consideration in museums. It can be sorted by color rendering index, light output, bulb-type, color temperature, efficacy, warranty, and brand name.

Please return your completed questionnaire to Tess.Perrin@pnnl.gov at your convenience.

Thank you very much for your help!

Tess Perrin
Naomi Miller
Jim Druzik
Stefan Michalski

Appendix B: Questionnaire

QUESTIONNAIRE ON THE "GUIDELINES FOR SELECTING SOLID-STATE LIGHTING FOR MUSEUMS" (DRUZIK AND MICHALSKI, 2011)

The Pacific Northwest National Laboratory (PNNL), on behalf of the Department of Energy (DOE), Getty Conservation Institute (GCI), and Canadian Conservation Institute (CCI) are collaborating to investigate the use of Druzik and Michalski's guidelines for the benefit of both the museum and solid-state lighting (SSL) communities. Currently, most solid-state lighting implies the use of light-emitting diodes (LEDs).

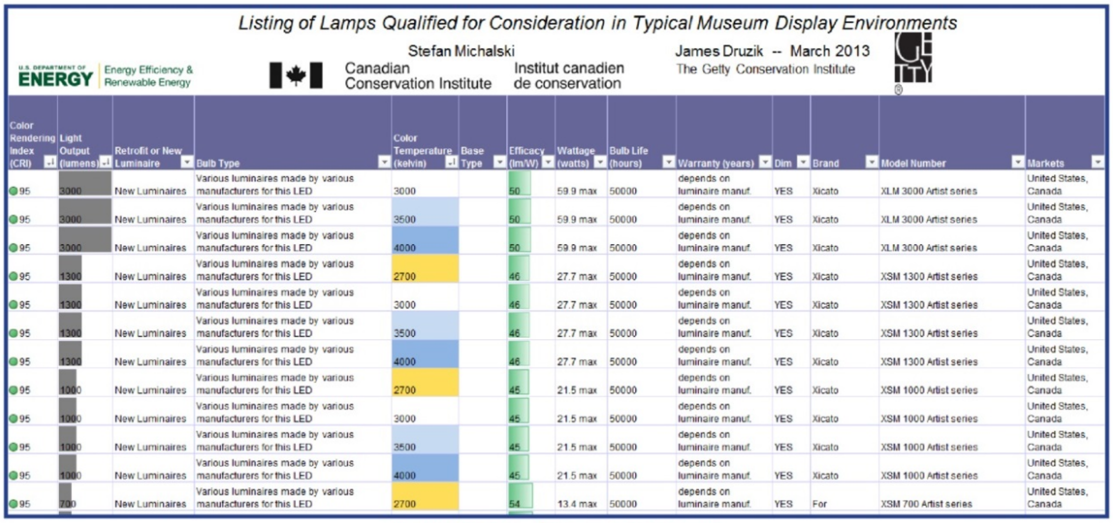
We are interested in the projects you have been involved in and your assessment of how useful the guidelines were in application. For many of you, upon request of the guidelines, access to the GATEWAY demonstration reports was also provided to show examples of previous SSL application. These included:

- Field Museum for Natural History, Chicago, IL (November 2010);
- Jordan Schitzer Museum of Art (JSMA), Eugene, OR (September 2011);
- J. Paul Getty Museum, Malibu, CA (March 2012); and
- Smithsonian American Art Museum, Washington, DC (June 2012).

The introduction of LEDs initially had facilities managers worried about the reality of recovering from steep initial costs despite promised energy efficiency, conservators wary of potential damage, and curators questioning the color quality compared to traditional lighting. As the guidelines were distributed to a wide selection of the museum demographic, please answer the questions which you find relevant to your experience. Your impressions and application feedback will help us improve future lighting guidelines.

There is no word limit to your comments so please feel free to be as elaborate as you wish and time allows - if you would like to attach plans, photos, specifications, etc. to the questionnaire, please do as it could save you time and potentially provide us with more information. The more the merrier!

Thank you for taking the time to help with this project. For some extra incentive, your "free gift" upon return of the questionnaire will be a searchable spreadsheet of specifications for approximately 1,800 lamps. See the figure below for a sneak peak!



Listing of Lamps Qualified for Consideration in Typical Museum Display Environments

Stefan Michalski
Canadian Conservation Institute
Institut canadien de conservation

James Druzik -- March 2013
The Getty Conservation Institute

Color Rendering Index (CRI)	Light Output (lumens)	Retrofit or New Luminaire	Bulb Type	Color Temperature (kelvin)	Base Type	Efficacy (lm/W)	Wattage (watts)	Bulb Life (hours)	Warranty (years)	Dim	Brand	Model Number	Markets
● 95	3000	New Luminaires	Various luminaires made by various manufacturers for this LED	3000		50	59.9 max	50000	depends on luminaire manuf.	YES	Xicato	XLM 3000 Artist series	United States, Canada
● 95	3000	New Luminaires	Various luminaires made by various manufacturers for this LED	3500		50	59.9 max	50000	depends on luminaire manuf.	YES	Xicato	XLM 3000 Artist series	United States, Canada
● 95	3000	New Luminaires	Various luminaires made by various manufacturers for this LED	4000		50	59.9 max	50000	depends on luminaire manuf.	YES	Xicato	XLM 3000 Artist series	United States, Canada
● 95	1300	New Luminaires	Various luminaires made by various manufacturers for this LED	2700		46	27.7 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1300 Artist series	United States, Canada
● 95	1300	New Luminaires	Various luminaires made by various manufacturers for this LED	3000		46	27.7 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1300 Artist series	United States, Canada
● 95	1300	New Luminaires	Various luminaires made by various manufacturers for this LED	3500		46	27.7 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1300 Artist series	United States, Canada
● 95	1300	New Luminaires	Various luminaires made by various manufacturers for this LED	4000		46	27.7 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1300 Artist series	United States, Canada
● 95	1000	New Luminaires	Various luminaires made by various manufacturers for this LED	2700		45	21.5 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1000 Artist series	United States, Canada
● 95	1000	New Luminaires	Various luminaires made by various manufacturers for this LED	3000		45	21.5 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1000 Artist series	United States, Canada
● 95	1000	New Luminaires	Various luminaires made by various manufacturers for this LED	3500		45	21.5 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1000 Artist series	United States, Canada
● 95	1000	New Luminaires	Various luminaires made by various manufacturers for this LED	4000		45	21.5 max	50000	depends on luminaire manuf.	YES	Xicato	XSM 1000 Artist series	United States, Canada
● 95	700	New Luminaires	Various luminaires made by various manufacturers for this LED	2700		54	13.4 max	50000	depends on luminaire manuf.	YES	For	XSM 700 Artist series	United States, Canada

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

YOUR NAME: ☐ **TITLE:** ☐

INSTITUTION: ☐

A. MUSEUM PRACTICE

1. When considering the best practices in museum lighting today, please rank the following resources you are familiar with in terms of relevance and significance (1=highest rank, 2=2nd highest rank, etc.). If you are not familiar with a source, please mark with an 'X'.

- ☐ IES/ANSI RP-30 (Recommended Practices for Museum and Art Gallery Lighting)
- ☐ CIE 157:2004 (Control of Damage to Museum Objects by Optical Radiation)
- ☐ "Lighting by Design" Christopher Cuttle (2008)
- ☐ "Light for Art's Sake: Lighting for Artworks and Museum Displays" Christopher Cuttle (2007)
- ☐ CCI (Canadian Conservation Institute)
- ☐ "Guidelines for Selecting SSL for Museums" Druzik & Michalski (2011)
- ☐ Other(s): ☐

Comments:

☐

2. Select the predominant lighting currently used for *gallery* and *display cases* in your workplace:

- ☐ LED
- ☐ Compact fluorescent
- ☐ Linear fluorescent
- ☐ Incandescent
- ☐ Other: ☐

3. What priority does your institution place on energy efficiency?

Low ☐ *1* – ☐ *2* – ☐ *3* – ☐ *4* – ☐ *5* *High*

Comments:

☐

B. APPLICATION OF THE GUIDELINES TO YOUR PROJECT:

1. What project(s) did you apply the guidelines to?

☐

2. What lighting products did you choose?

☐

3. What department(s) was involved in the selection of light sources?

- ☐ Exhibits design
- ☐ Preparation
- ☐ Conservation
- ☐ Curatorial
- ☐ Director
- ☐ Consultant
- ☐ Others: ☐

4. Rank the following lighting goals:

☐ Match color quality of standard museum lighting
☐ Improve color quality compared to standard lighting
☐ Inconspicuous transition from incandescent to LED lighting
☐ Use a lighting source with equal if not lower damage potential
☐ Save energy and reduce cost/maintenance
☐ Other: ☐

Comments:

☐

5. Issues considered in gallery beyond lighting fixtures:

☐ Annual hours of operation of lighting system: ☐ hrs
☐ Light exposure recommendations appropriate for sensitivity of materials displayed taken into consideration
☐ Target llumination values (fill in any target value): ☐ / ☐ / ☐ lux
VERTICAL FLOOR AMBIENT

Comments:

☐

6. Which of the following were included in your documentation of initial conditions of artwork?

☐ Microfading tests
☐ ISO blue wool dyes
☐ Lighting condition measurements
☐ Object color measurements (e.g., spectrophotometry)
☐ Other: ☐

Comments:

☐

7. Please rank the following factors in your selection of lamps (1-10):

☐ Damage potential
☐ Lamp size and shape
☐ Color and spectral power distribution (SPD)
☐ Lamp efficacy (lumens per Watt)
☐ Input power (W)
☐ Lifespan/lumen maintenance
☐ Dimming range/compatibility with dimmers
☐ Initial Cost
☐ Return on investment (ROI) or simple payback period
☐ Warranty

Comments:

☐

8. When evaluating potential damage, please check factors considered:

☐ Short wavelength emissions in spectral power distribution (SPD)
☐ UV content
☐ IR content
☐ Other: ☐

Comments:

☐

9. Did you consider the following in your color evaluation? Please check if you did and list any values if appropriate:

- ☐ Spectral power distribution (SPD)
- ☐ Correlated color temperature (CCT): ☐ K
- ☐ Color rendering index (CRI): ☐
- ☐ Other Ri values: ☐
- ☐ Color Quality Scale (CQS): ☐
- ☐ ANSI standard for acceptable variation (Duv): ☐
- ☐ Color warranty: ☐

Comments:

10. Did you conduct a visual assessment of the lamps? Please check if you did and list any values if appropriate:

- ☐ Mocked-up expected lux levels and light source in actual gallery
- ☐ Mocked-up expected lux levels and light sources in mock-up space
- ☐ Comparison of options (if yes, select one): ☐ single fixture ☐ multiple fixtures
- ☐ White card
- ☐ Color-checker card
- ☐ Used neutral grey wall color for background
- ☐ Other background color used:
- ☐ Multiple observers
- ☐ Who conducted the color evaluation?

Comments:

11. Lamp type:

- ☐ Preference for replacement LED lamps
- ☐ Preference for dedicated LED fixtures
- ☐ No preference

Comments:

12. How important was it that the lighting system be dimmable?

Not important *1* – *2* – *3* – *4* – *5* *Important*

Comments:

13. What method of dimming did you use?

- ☐ Dimmer designed for incandescent loads
- ☐ DALI, DMX, 0-10V, or similar dimmer
- ☐ None

Comments on dimming success (e.g., flicker? color change? erratic behavior?):

14. Cost and return on investment (ROI)

☐ Life-cycle cost study conducted
If yes, type of analysis: ☐

Please select the following factors you considered:

☐ Years until payback
☐ Maintenance costs
☐ Future drop in LED lamp costs
☐ Warranty
☐ Effect on HVAC costs
☐ Other: ☐

Please select what your warranty covered:

☐ LED chip and mechanical/electrical parts of lamp
☐ Color consistency
☐ Return on investment (ROI) shorter than warranty period
☐ Additional coverage: ☐

Comments:

☐

15. How was your exhibition monitored?

☐ Color measurements taken throughout duration of display
☐ Illumination periodically monitored with electronic hand-held meter
☐ Illumination passively monitored with ISO Blue Wool scales
☐ Temperature/humidity appropriately regulated
☐ Other: ☐

Comments:

☐

16. Lifespan and lumen maintenance

☐ Were there early failures?
If yes, number of lamps: ☐ / ☐ (TOTAL LAMPS)
☐ Published life: ☐ hrs
☐ Actual life: ☐ hrs
☐ Warranty coverage: ☐ yrs

Comments:

☐

17. Has the color quality held up over time?

☐ Yes ☐ No

Comments:

☐

18. If there was any undesirable color change, how was it resolved?

☐

19. Whom did you interview for reactions to lighting?

☐ Museum staff
☐ Lighting professionals
☐ Visitors
☐ Other:

Comments on response(s):

20. In general, how has the public responded?

☐ No response
☐ Negative response
☐ Favorable response

21. How has the staff responded?

☐ No response
☐ Negative response
☐ Favorable response

22. Would you consider and implement another SSL installation?

☐ Yes ☐ No ☐ Already have

Comments:

C. FUTURE RESEARCH

1. What activities do you recommend for government and industry to speed the adoption of quality SSL products and their specification for museum/gallery use?

☐ GATEWAY demonstrations
☐ Additional guidelines
☐ Regional workshops
☐ Webinars
☐ Online forum
☐ Other:

Comments:

2. Select the following you want/would use and explain:

☐ Wireless programmable lighting control networks on track lighting
☐ The ability to monitor lux levels on an object by object basis

Comments:

3. What are the barriers to adoption of SSL products in museums/galleries?

4. For the next set of SSL guidelines, please rank the following sections in terms of relevance and significance (1=highest rank, 2= 2nd highest rank, etc.). If you did not find a section useful, please mark with an 'X'.

☐ LED Decision-Making in a Nutshell
☐ Example of survey used in the evaluation of lighting used at Field Museum
☐ Suggested outline for a warranty review
☐ Recap: Getting the Most Out of Your LED Products
☐ Sources for Solid-State Lighting Products Described in this Document
☐ U.S. Department of Energy Internet Resources

Comments:

Appendix C: Data Analysis

	A1						B4					B7										C4					
	When considering the best practices in museum lighting today, please rank the following resources you are familiar with in terms of relevance and significance (1=highest rank, 2=2nd highest rank, etc.). If you are not familiar with a source, please mark with an 'X'.						Rank the following lighting goals:					Please rank the following factors in your selection of lamps (1-10):										For the next set of SSL guidelines, please rank the following sections in terms of relevance and significance (1=highest rank, 2= 2nd highest rank, etc.). If you did not find a section useful, please mark with an 'X'.					
	IES/ANSI RP-30 (Recommended Practices for Museum and Art Gallery Lighting)	CIE 157:2004 (Control of Damage to Museum Objects by Optical Radiation)	"Lighting by Design" Christopher Cuttle (2008)	"Light for Art's Sake: Lighting for Artworks and Museum Displays" Christopher Cuttle (2007)	CCI (Canadian Conservation Institute)	"Guidelines for Selecting SSL for Museums" Druzik & Michalski (2011)	Match color quality of standard museum lighting	Improve color quality compared to standard	Inconspicuous transition from incandescent to LED lighting	Use a lighting source with equal if not lower damange potential	Save energy and reduce cost/maintenance	Damage potential	Lamp size and shape	Color and spectral power distribution (SPD)	Lamp efficacy (lumens per Watt)	Input power (W)	Lifespan/lumen maintenance	Dimming range/compatibility with dimmers	Initial Cost	Return on investment (ROI) or simple payback period	Warranty	LED Decision-Making in a Nutshell	Example of survey used in the evaluation of lighting used at Field Museum	Suggested outline for a warranty review	Recap: Getting the Most Out of Your LED Products	Sources for Solid-State Lighting Products Described in this Document	U.S. Department of Energy Internet Resources
	🟥	🟥	🟥	🟥	🟥	1	🟥	2	🟥	1	3	1	4	1	7	🟥	5	🟥	3	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	3	🟥	🟥	4	2	1	1	🟥	🟥	3	2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	1	X	5	6	2	4	4	3	5	1	2	1	5	4	6	🟥	2	3	7	9	5	🟥	🟥	🟥	🟥	🟥	🟥
	3	1	6	4	X	5	🟥	1	2	1	1	1	2	1	3	🟥	3	2	3	5	4	🟥	🟥	🟥	🟥	🟥	🟥
	2	🟥	🟥	🟥	1	🟥	2	5	1	4	3	9	2	1	7	🟥	8	🟥	4	3	5	🟥	🟥	🟥	🟥	🟥	🟥
	X	3	X	X	1	2	4	3	5	1	2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	1	3	4	2	6	5
	🟥	🟥	🟥	🟥	2	1	5	4	3	1	2	1	3	4	5	9	10	8	2	6	7	1	3	5	2	4	6
	2	1	X	X	X	3	🟥	2	🟥	🟥	🟥	🟥	🟥	1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	X	X	2	3	1	4	2	4	3	1	5	1	4	6	5	4	7	2	3	9	8	2	1	5	3	4	6
	🟥	🟥	🟥	🟥	1	1	4	3	5	1	2	1	6	3	7	8	9	4	5	2	10	🟥	🟥	🟥	🟥	🟥	🟥
	1	2	X	3	X	X	2	5	3	4	1	4	10	1	7	8	5	2	3	6	9	🟥	🟥	🟥	🟥	🟥	🟥
	X	3	X	X	2	1	5	4	3	2	1	2	9	3	1	8	4	10	7	6	5	1	2	4	3	6	5
	🟥	1	5	3	2	4	1	3	4	5	2	4	7	3	2	8	5	6	1	9	10	2	1	X	3	X	X
	🟥	🟥	🟥	🟥	🟥	🟥	🟥	1	🟥	🟥	1	🟥	🟥	1	🟥	🟥	1	🟥	1	1	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	X	X	3	4	2	1	5	4	3	1	2	1	7	8	5	9	3	2	5	4	10	1	3	X	2	4	X
	X	X	3	4	2	1	2	5	4	1	3	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	1	5	6	4	2	3
	1	X	X	X	3	2	3	1	4	5	2	10	6	1	4	3	5	2	8	7	9	2	4	6	3	1	5
	🟥	1	🟥	🟥	1	1	1	🟥	1	1	1	3	3	1	3	3	3	2	3	3	3	1	🟥	🟥	🟥	🟥	🟥
	X	X	X	X	X	1	1	1	1	1	1	8	1	2	3	4	6	5	7	9	10	1	3	4	5	2	🟥
	4	3	X	X	2	1	5	1	4	2	3	2	10	1	8	9	3	7	5	4	6	4	5	X	3	1	2
	5	X	4	X	1	2	4	2	5	3	1	2	7	1	8	9	3	10	5	6	4	1	5	3	2	4	6
	2	X	X	X	3	1	🟥	3	1	🟥	2	1	4	2	5	10	7	3	8	9	6	🟥	🟥	🟥	🟥	🟥	🟥
	X	X	X	X	2	1	1	4	5	3	2	1	2	3	7	9	5	10	4	5	6	1	4	6	2	3	5
	🟥	🟥	🟥	🟥	🟥	🟥	4	2	5	1	3	1	7	3	2	4	9	6	5	8	10	🟥	🟥	🟥	🟥	🟥	🟥
	X	1	3	3	4	2	4	3	5	1	2	1	5	9	6	7	3	10	2	4	8	1	4	3	5	2	6
	🟥	🟥	🟥	🟥	🟥	🟥	3	1	🟥	2	4	1	2	7	6	5	4	8	9	10	3	🟥	🟥	🟥	🟥	🟥	🟥
	🟥	🟥	🟥	🟥	🟥	1	3	2	5	1	4	1	5	3	4	10	8	6	2	9	7	1	2	6	3	4	5
	2	3	X	4	X	1	4	2	5	1	3	1	2	4	7	6	5	3	8	9	10	1	4	5	6	2	3
	2	3	🟥	🟥	5	2	3	4	5	2	1	1	6	2	5	7	4	10	8	9	3	1	4	2	3	6	5
	🟥	🟥	🟥	🟥	🟥	🟥	1	🟥	🟥	1	1	7	6	5	3	8	4	2	1	9	10	🟥	🟥	🟥	🟥	🟥	1
	3	X	X	X	X	2	4	5	2	3	1	10	4	2	1	5	8	3	7	6	9	1	4	6	2	3	5
	🟥	🟥	🟥	🟥	🟥	1	1	5	2	4	3	4	2	10	1	3	5	6	7	8	9	1	5	4	3	2	6
	X	X	4	2	3	1	2	4	5	1	3	2	1	3	5	7	6	10	4	8	9	1	2	X	4	3	5
	1	X	X	X	1	1	🟥	3	🟥	1	2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	1	🟥	🟥	🟥	🟥	🟥
	🟥	🟥	🟥	🟥	🟥	🟥	4	5	2	1	3	1	3	4	10	8	6	9	2	7	5	1	4	3	5	2	6
	X	X	X	X	2	1	5	2	4	1	3	1	3	2	5	9	4	10	8	7	6	1	6	2	4	5	3
	2	3	X	X	4	1	5	4	1	2	3	6	3	1	5	10	4	2	8	9	7	🟥	🟥	🟥	🟥	🟥	🟥
	X	X	1	X	X	X	1	5	2	4	3	7	9	1	2	8	3	10	4	5	6	1	3	2	4	5	6
	2	X	X	X	2	1	2	🟥	🟥	1	3	1	4	2	3	🟥	6	5	🟥	🟥	🟥	X	1	X	X	2	3
	X	X	X	X	1	2	3	4	5	2	1	8	1	6	5	7	2	9	3	4	10	1	X	X	X	X	X
	4	1	4	4	🟥	4	🟥	1	3	1	2	1	4	1	2	3	2	2	4	5	4	1	2	6	3	4	5
	X	X	X	X	1	X	1	🟥	3	2	4	5	2	1	3	7	4	9	6	8	10	1	X	X	2	3	4
	🟥	🟥	🟥	🟥	🟥	🟥	4	1	5	2	3	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	1	X	3	X	2	X	4	1	5	2	3	1	8	2	4	7	5	9	3	6	10	1	3	6	4	2	5
	🟥	🟥	🟥	🟥	🟥	1	🟥	1	2	🟥	🟥	2	10	1	2	2	10	10	2	10	10	1	2	X	3	4	X
	2	2	X	X	1	1	🟥	🟥	1	🟥	2	5	3	1	🟥	🟥	6	2	4	🟥	7	2	1	5	4	3	6
# responses	40						46					41										32					
% response (per choice)	41%	33%	28%	28%	63%	76%	80%	87%	83%	89%	96%	85%	85%	89%	83%	72%	87%	80%	85%	80%	80%	65%	59%	46%	59%	59%	54%
% Xs	41%	55%	58%	59%	19%	10%																3%	7%	28%	7%	7%	14%
response frequency																											
1	5	6	1	0	10	22	9	10	6	22	11	20	3	16	3	0	1	0	3	1	0	25	4	0	0	2	1
2	8	2	1	1	12	7	6	7	6	9	14	5	7	7	5	1	3	10	5	1	0	4	5	3	7	8	1
3	3	6	4	4	3	1	5	7	7	4	15	1	6	7	6	4	7	4	7	2	3	0	6	3	10	5	4
4	2	0	3	6	2	4	11	9	5	4	3	3	6	4	3	3	7	1	6	4	3	1	7	4	6	7	1
5	1	0	2	0	1	1	6	7	14	2	1	2	3	1	9	2	8	2	5	4	4	0	4	4	3	2	10
6	0	0	1	1	0	0						1	4	2	3	1	5	4	1	6	5	0	1	7	1	3	8
7												2	4	1	6	6	2	1	5	3	4						
8												2	1	1	2	7	3	2	6	4	2						
9												1	2	1	0	6	2	4	1	10	5						
10												2	3	1	1	3	2	9	0	2	11						
mean	2.3	1.9	3.3	3.4	1.9	1.7	3.0	2.9	3.4	1.9	2.3	3.1	4.7	2.9	4.6	6.8	5.1	5.9	4.6	6.6	7.3	1.2	3.2	4.4	3.3	3.3	4.7
mode	2.0	2.0	3.0	4.0	2.0	1.0	4.0	1.0	5.0	1.0	3.0	1.0	2.0	1.0	5.0	8.0	5.0	2.0	3.0	9.0	10.0	1.0	4.0	6.0	3.0	2.0	5.0
min	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	2	1	2	1	1	3	1	1	2	2	1	1
max	5	3	6	6	5	5	5	5	5	5	5	10	10	10	10	10	10	10	9	10	10	4	6	6	6	6	6
mean rank	3	2	4	5	2	1	4	3	5	1	2	2	4	1	3	8	5	6	3	7	9	1	2	4	3	3	5

	A2				
	Select the predominant lighting currently used for gallery and display cases in your workplace:				
	LED	Compact fluorescent	Linear fluorescent	Incandescent	Other:
	1	0	0	0	0
	1	0	0	1	0
	1	1	1	1	0
	1	0	1	1	1
	0	0	0	1	0
	0	0	0	1	0
	1	1	0	0	0
	1	0	0	0	0
	0	1	1	1	0
	1	0	0	0	0
	1	0	0	0	0
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	0	1
	1	0	0	1	0
	1	0	0	0	0
	1	0	0	0	0
	0	0	0	1	0
	1	0	0	0	0
	0	0	0	0	1
	0	0	0	0	1
	1	0	0	0	0
	0	0	1	1	0
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	1	0
	1	0	0	1	0
	0	0	0	1	0
	0	1	0	0	0
	1	0	0	0	1
	1	0	0	0	1
	0	1	0	0	0
	1	0	0	0	1
	0	0	0	0	1
	1	0	1	1	0
	0	0	0	1	0
	0	1	0	0	0
	1	0	0	0	0
	0	0	0	1	0
	0	0	0	0	1
	0	0	0	1	0
#responses	46				
sum (per choice)	19	6	5	24	10
% selected	**41%**	**13%**	**11%**	**52%**	**22%**

	A3				
	What priority does your institution place on energy efficiency?				
	1	2	3	4	5
	0	0	1	0	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	0	0	1
	0	1	0	0	0
	🟥	🟥	🟥	🟥	🟥
	0	0	0	1	0
	0	0	1	0	0
	0	0	1	0	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	0	0	1
	0	0	1	0	0
	0	0	0	0	1
	0	1	0	0	0
	0	0	0	1	0
	0	0	0	0	1
	0	1	0	0	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	0	1	0
	0	0	1	0	0
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	1	0	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	0	0	1
	0	0	1	0	0
	0	0	0	0	1
	0	0	0	1	0
	0	0	1	0	0
	0	0	1	0	0
	0	0	0	1	0
	0	0	0	1	0
	0	0	0	0	1
	0	0	0	0	1
	0	0	0	0	1
	0	1	0	0	0
	1	0	0	0	0
	🟥	🟥	🟥	🟥	🟥
#responses	**44**				
sum (per choice)	**1**	**4**	**9**	**15**	**15**
% selected	**2%**	**9%**	**20%**	**34%**	**34%**

Appendix D: Data Summary

A	Response Rate	Museum Practice						
1	100%	When considering the best practices in museum lighting today, please rank the following resources you are familiar with in terms of relevance and significance. (1 high - 6 low)	IES/ANSI RP-30 (Recommended Practices for Museum and Art Gallery Lighting)	CIE 157:2004 (Control of Damage to Museum Objects by Optical Radiation)	"Lighting by Design" Christopher Cuttle (2008)	"Light for Art's Sake: Lighting for Artworks and Museum Displays" Christopher Cuttle (2007)	CCI (Canadian Conservation Institute)	"Guidelines for Selecting SSL for Museums" Druzik & Michalski (2011)	
			4	2	5	6	2	1	
		Not familiar with source	41%	56%	60%	61%	20%	10%	
2	100%	Select the predominant lighting currently used for gallery and display cases in your workplace:	LED	Compact fluorescent	Linear fluorescent	Incandescent	Other:		
			41%	13%	11%	52%	22%		
3	96%	What priority does your institution place on energy efficiency? (1 low - 5 high)	1	2	3	4	5		
			2%	9%	20%	34%	34%		
B	**Response Rate**	**Application of the Guidelines to Your Project**						
3	93%	What department(s) was involved in the selection of light sources?	Exhibits design	Preparation	Conservation	Curatorial	Director	Consultant	Others:
			65%	26%	58%	56%	42%	35%	40%
4	100%	Rank the following lighting goals (1 high - 5 low):	Match color quality of standard museum lighting	Improve color quality compared to standard	Inconspicuous transition from incandescent to LED lighting	Use a lighting source with equal if not lower damage potential	Save energy and reduce cost/ maintenance		
			4	3	5	1	2		
5	89%	Issues considered in gallery beyond lighting fixtures:	Annual hours of operation of lighting system:	Light exposure recommendations appropriate for sensitivity of materials displayed taken into consideration	Target illumination values (fill in any target value):				
			63%	85%	34%				
6	70%	Which of the following were included in your documentation of initial conditions of artwork?	Microfading tests	ISO blue wool dyes	Lighting condition measurements	Object color measurements (eg. spectrophotometry)	Other:		
			13%	16%	75%	25%	19%		
7	100%	Please rank the following factors in your selection of lamps (1 high - 10 low):	Damage potential	Lamp size and shape	Color and spectral power distribution (SPD)	Lamp efficacy (lumens per watt)	Input power (W)		
			2	5	1	3	9		
			Lifespan/lumen maintenance	Dimming range/compatibility with dimmers	Initial Cost	Return on investment (ROI) or simple payback period	Warranty		
			6	7	3	8	10		
8	87%	When evaluating potential damage, please check factors considered:	Short wavelength emissions in spectral power distribution (SPD)	UV content	IR content	Other:			
			48%	93%	65%	23%			
9	76%	Did you consider the following in your color evaluation? Please check if you did and list any values if appropriate:	Spectral power distribution (SPD)	Correlated color temperature (CCT):	Color rendering index (CRI):	Other Ri values:	Color Quality Scale (CQS):	ANSI standard for acceptable variation (Duv):	Color warranty:
			60%	69%	91%	6%	20%	9%	26%
10	74%	Did you conduct a visual assessment of the lamps? Please check if you did and list any values if appropriate:	Mocked-up expected lux levels and light source in actual gallery	Mocked-up expected lux levels and light sources in mock-up space	Comparison of options (if yes, select one):	single fixture	multiple fixtures		
			68%	41%	65%	32%	78%		
			White card	Color-checker card	Used neutral grey wall color for background	Other background color used:	Multiple observers	Who conducted the color evaluation?	
			18%	32%	28%	38%	59%	45%	
11	83%	Lamp type:	Preference for replacement LED lamps	Preference for dedicated LED fixtures	No preference				
			34%	37%	32%				

12	96%	How important was it that the lighting system be dimmable? (1 not important - 5 important)	1	2	3	4	5	
			23%	9%	7%	16%	45%	
13	72%	What method of dimming did you use?	Dimmer designed for incandescent loads	DALI, DMX, 0-10V, or similar dimmer	None			
			39%	42%	33%			
14	59%	Cost and ROI (return on investment)	Life-cycle cost study conducted					
			42%					
	67%	Please select the following factors you considered:	Years until payback	Maintenance costs	Future drop in LED lamp costs	Warranty	Effect on HVAC costs	Other:
			74%	87%	42%	52%	48%	16%
	48%	Please select what your warranty covered:	LED chip and mechanical/ electrical parts of lamp	Color consistency	Return on investment (ROI) shorter than warranty period	Additional coverage:		
			91%	64%	14%	23%		
15	83%	How was your exhibition monitored?	Color measurements taken throughout duration of display	Illumination periodically monitored with electronic hand-held meter	Illumination passively monitored with ISO Blue Wool scales	Temperature/ humidity appropriately regulated	Other:	
			16%	76%	8%	71%	13%	
16	43%	Lifespan and lumen maintenance	Were there early failures?	Published life:	Actual life:	Warranty coverage:		
			75%	50%	25%	55%		
17	54%	Has the color quality held up over time?	Yes	No				
			100%	0%				
19	63%	Who did you interview for reactions to lighting?	Museum staff	Lighting professionals	Visitors	Other:		
			90%	45%	41%	31%		
20	63%	In general, how has the public responded?	No response	Negative response	Favorable response			
			48%	0%	55%			
21	65%	How has the staff responded?	No response	Negative response	Favorable response			
			17%	3%	80%			
22	76%	Would you consider and implement another SSL conversion?	Yes	No	Already have			
			71%	6%	31%			
C	**Response Rate**	**Future Research**						
1	80%	What activities do you recommend for government and industry to speed the adoption of quality SSL products and their specification for museum/gallery use?	GATEWAY demonstrations	Additional guidelines	Regional workshops	Webinars	Online forum	Other:
			46%	65%	65%	51%	35%	24%
2	70%	Select the following you want/would use and explain:	Wireless programmable lighting control networks on track lighting	The ability to monitor lux levels on an object by object basis				
			66%	69%				
4	100%	For the next set of SSL guidelines, please rank the following sections in terms of relevance and significance. (1 high - 6 low)	LED Decision-Making in a Nutshell	Example of survey used in the evaluation of lighting used at Field Museum	Suggested outline for a warranty review	Recap: Getting the Most Out of Your LED Products	Sources for Solid-State Lighting Products Described in this Document	U.S. Department of Energy Internet Resources
			1	2	5	3	3	6
		Did not find useful	3%	7%	28%	7%	7%	14%

Appendix E: Anecdotal Demonstrations

Smaller museums

Abbe Museum, Bar Harbor, ME – Curator

The Abbe Museum's collection comprises more than 50,000 objects representing 10,000 years of Native American culture and history in Maine. LED is now their predominant lighting. In January of 2014, the incandescent track lighting in the main gallery was replaced with an LED system consisting of a combination of LED fixture types. Additionally, in some of the smaller galleries and public spaces, the incandescent lamps have been replaced by MR16 LEDs. As opposed to wanting to be inconspicuous, the museum was rather very open about the fact that they were making the transition to LED lighting, with a primary focus on reduced damage potential and energy savings and reduced maintenance secondary. The lighting designer and installer had a strong preference for dedicated LED fixtures – the old fixtures were unattractive and starting to physically break with each exhibit change-over, along with being very difficult to work with (e.g., adjusting the individual track heads). The reduction in heat load was a significant factor, along with its effect on HVAC costs. Additionally, for certain objects and exhibits, dimming was a necessity in order to achieve 5 fc (50 lux). They initially had problems with flickering when only a few fixtures were installed, and tests showed incoming electrical supply wattage was fluctuating. When a full load of fixtures was installed, problems with flickering went away at all dimming levels. There was also much less to no color change at different dimming settings compared to the old incandescent system. The museum is planning on replacing the rest of their track lighting when funding allows, despite initial resistance from conservators.

Alberni Valley Museum, Vancouver, BC – Curator

The Alberni Valley Museum in Vancouver, BC, is municipally owned and operated, with a profession staff of only four. As the museum is part of the city, which places a high priority on energy efficiency, new LED replacement bulbs (A19, PAR20, PAR38) were supplied for work spaces, pathway lighting, and artifact lighting in both the permanent and temporary galleries to replace the existing lighting (predominantly LED, fluorescent, and incandescent). A consultant and city maintenance manager were in charge of the selection, with the focus on saving energy, reducing costs and required maintenance, and matching, if not decreasing, damage potential compared to the incumbent sources. Dimming was very important – the pathway lighting used the existing incandescent dimmers but the temporary gallery required installation of new dimmers. Despite mocking-up the sources in the actual gallery at different light levels, the museum is not happy with the lighting choices which were made and is thus still working on the project. Although the museum finds not having to change the bulbs as frequently is a real bonus, the quality of light is too focused and casts too many shadows. Throughout the selection process, the museum found it difficult to select appropriate bulbs as, with the current cost of bulbs, testing is expensive.

Arkansas Tech University Museum, Russellville, AR – Museum Director

The Arkansas Tech University Museum, established in December 1989, provides a center for collection, conservation, interpretation, and research concerned with the history of the Arkansas Tech University. The museum serves as a gateway between the university and community by making this knowledge and interpretation available. The university is committed to using CFLs for track lighting campus-wide. In order to change the current CFLs wholesale, a limited number of LED bulbs had to be acquired as a test case to present to the University Plant as all bulbs used on campus must be available in state contract bids – the University

Facilities Management and Plant office makes all final selections on products. The project currently underway is to re-install two exhibits in one of the galleries that has track lighting with canisters for PAR38 fluorescent flood lamps, which are not dimmable – in June 2014, four gooseneck style track light canisters with accompanying PAR38 LED bulbs were purchased for testing. These lamps were selected based on their color performance, form factor, and efficacy. As of July 2014, the museum is closed for the LED installation.

Cooper Hewitt, Smithsonian Design Museum, NY, NY – Head of Conservation

The Cooper Hewitt, Smithsonian's Design Museum, has a diverse collection spanning 30 centuries of historic and contemporary design. The museum is housed in the former residence of Andrew Carnegie, a NYC and National Historic Landmark. Scheduled to reopen on December 12th of this year, Cooper Hewitt has been closed for several years for major renovation, which includes a new lighting system that will transition from using predominantly incandescent fixtures to LED – both retrofit lamps (including MR16s) and dedicated fixtures. This transition was prompted by the potential energy savings and, secondly, the lower potential damage afforded by LED technology. Museum objects are illuminated from 30 lux to 200 lux, with didactic labels at 100 lux. In evaluating color, the museum was looking for sources with a CCT of 3,000 K, a high CRI (e.g., 98), a high CQS (e.g., 90), and a warranty for potential color shift. Although they tested both replacement and dedicated LED fixtures, dimming was not prioritized as filters are used for dimming. In order to estimate a realistic life of LED bulbs, they are also using a lower estimate (e.g., around 5,000 hours) than the lifetime a manufacturer supplies – this is approximately one-tenth of the rated life, assuming 50,000 hours. In the new galleries, both wireless programmable lighting control networks and object-by-object lux level monitoring will be possible. When considering the barriers to adoption posed by SSL, initial cost, the complexity of making choices without having a road-map of the industry, and concerns about long-term reliability were at the forefront of Cooper Hewitt's list.

Shelburne Museum, Shelburne, VT – Director of Conservation

The Shelburne museum in Vermont's Lake Champlain Valley is home to over 150,000 works in 38 exhibition buildings, of which 25 were historic and relocated to the museum's grounds. The museum, supported by the Vermont Arts Council, was founded in 1947 as an "educational project, varied and alive", showcasing artifacts that date back to the 17th-century, with an annual attendance of 110,000 visitors. According to their director of conservation, the museum places a high priority on energy efficiency. Their target illumination values are 15 vertical lux. When judging the color rendering, paintings from their collection were used, with extra attention placed on representing the entire range of colors – only the LEDs with CRI values greater than 92 were found to render both reds and blues well. There is a preference for using dedicated LED fixtures due to their better color rendition (at the time of purchase) and the accompanying versatility in accessories and ability to change beam spread. However, despite the dimming capability, the museum prefers to control light output at the individual heads using screens, spread lenses, and reflectors.

Performance wise, 10 PAR20s out of the 500 installed base failed within the first 100 hours and were replaced under warranty. In one of the permanent exhibitions where PAR30 retrofit LEDs were placed in existing unvented cans, 14 out of 200 failed after 4,500 hours and warranty replacement is pending (both the PAR20s and PAR30s were installed in December 2010). The museum has had no comments by the public about the LED lighting since it was installed. They have not tried to mix halogen and LED as they found the LED bulbs have much better color consistency than the halogen bulbs, especially the MR16 halogen bulbs that are all over the spectrum out of the box, depending on the manufacturer. Although a Lutron automated lighting system for the new exhibition and education building was installed, it was deemed too complicated and simple light switches are preferred. The main barriers to adoption include the high cost, especially for dedicated LED fixtures, along with the lack of knowledge about UV content, color spikes, color shifting, and actual vs. rated life.

Larger museums

Art Gallery of New South Wales, Sydney, Australia – Lighting Technician/Designer

The Art Gallery of New South Wales in Sydney, Australia, was established in 1871 to showcase both Australian and international art. Their predominant lighting currently in use is incandescent with the hope that by the end of 2016, LED and metal halide will be the predominant source types. The gallery has its own lighting department which prioritizes improving the color quality, visual performance, and spectral damage control compared with their current, incandescent lighting. Vertical illumination is given priority in accordance with conservation and curatorial exhibition design concepts – “Ambient targets are then balanced in accordance with that exhibition concept and philosophy, transition zone requirements (particularly if there are adaptation needs), rest points and reading areas if in dark spaces. Floor lighting responds to the over-riding philosophy of each gallery space (i.e., 'white box', 'black box') and in the instance of dark exhibitions floor lighting is used in conjunction with source hierarchies to guide visitors through the exhibition space. Stairs/stairwells, if part of an exhibition transition, are maintained under the AS/NZ standards regardless.” When monitoring lux levels, they are done on an object by object basis.

Artificial source CCTs are limited to 3,000 K for display to ensure reduced high energy damage; day-lighted areas are limited to 6,000 K with the recommendation to never display light sensitive materials of any sort in these areas (if they are, the recommended lux hours should be followed or at the very least the potential consequences fully understood). The department does not agree with the use of incandescent as a low CCT reference and thus relies more on other values (e.g., maintaining color within 2 MacAdams ellipses for initial and L_{80} measurements), visual evaluation (including outside the gallery using large color swatches of over 100 colors ranging in hue and chromaticity), and comparative assessment. The gallery has found that, in an attempt to achieve high CRI and CQS values, manufacturers often focus on R_9 values often to the detriment of others (e.g., R_4 and R_{11}) which can leave the visible quality of whites under low 3,000 K sources looking the same as old incandescent sources. Thus, they see a need for new metrics with different referents and benchmarks to increase the quality of light, not just to match the old standards.

For their installed base of LEDs, although the initial color uniformity was not up to the standard required, the exhibition scheduling pushed a compromise so luminaires have been grouped according to visual shift. The gallery also found that the sources they preferred, due to their high color quality, had issues when integrated into existing luminaires: the fittings were generally too large, not efficient, and resulted in low uniformity for wall washing. Old luminaires are being used due to budget or design limitations but, as upgrades are planned to continue over the next few years, the gallery expects that over time integrated luminaires may replace the existing ones as they phase out trailing edge dimming systems to DALI. Wireless controls to date have not proved reliable for their dimming systems.

Only one LED lamp failed (after 16,000 hours of use) due to an electronic control component failure (not an LED chip or module failure) and was replaced under warranty. Masters students of lighting design from two different universities evaluated the installation – the response was extraordinarily positive, particularly concerning the whites achieved by the LED sources. Consequently, the gallery is continuing with upgrades and refurbishments along with maintaining very close relationships with professionals in the field, researchers, and manufacturers to stay up to date with any changes to current or emerging SSL technologies. They view the lack of distribution control (from an engineering standpoint) as one of the biggest barriers to adoption.

Dunedin Public Art Gallery, NZ – Administration Services Manager

The Dunedin Public Art Gallery's collection includes New Zealand works of art dating from the 1860s to the present, along with British and European paintings and works on paper, Western art, and other international pieces, all gifted by benefactors or purchased by the Dunedin Public Art Gallery Society. The gallery needed to replace their existing 17 year old fittings (new in 1995) and were very keen to replace their entire exhibition lighting in as tight a time frame as possible for continuity between spaces and consistency between purchased products (e.g., range and model of fitting). Funding for the project was first sought from the Dunedin City Council, the gallery' s "owner", before evaluating and purchasing products in 2012. As all LED fixtures with a predicted lifespan of 20 years achieve payback based on their energy savings, improved energy efficiency was taken for granted in the selection process. Additionally, the conservator accepted that LED technology has less damage potential than any other lighting solution.

Having decided upon a dedicated LED fixture, the 5 main contending manufacturers supported by New Zealand based companies were invited to the gallery and offered time to give the gallery's exhibition lighting review team their sales pitch and a visual evaluation. The review team included:

- The Administration Services manager (budget/running costs),
- The Exhibition Manager (staff resources and overall exhibition responsibilities),
- The Curator (how the LED impacted on the look of the work),
- The Designer (how the fitting body impacted the overall look of the spaces),
- The Conservator (the benefits of LED and how that impacted the conservation), and
- The Consultant (helped explain all the technical information).

These sessions were evaluated individually initially and then discussed as a group. A lensed wall washer was selected along with an assortment of lenses – the model has a fixed LED source and interchangeable lenses which alter the display characteristics of the fitting. Thus, it is very easy to change from a wall washer to a variety of spots and floods, saving a store room of spares. "The fittings we trialed all had similar power input requirements, warranty, and lifespan, and therefore payback on investment. Our goal was to buy fittings that produced the best solution to our spaces and that included the look of the fitting and the manufacturer being able to continue to produce the same looking fitting over the next 20 plus years so we didn't end up with different types of fittings throughout the building. We are lucky enough to have a sister department, Toitu Otago Settlers Museum, who have selected the same supplier and fitting as we did so we can borrow fittings if required." All fixtures had on-board dimmers as well and a 2-year manufacturer's warranty along with an additional 3 years warranty supplied by New Zealand. The gallery is now into year four of its purchase plan and everyone is happy with what was have chosen – this conversion is part of an ongoing program which will culmination in replacing approximately 350 fixtures.

Frist Center for the Visual Arts, Nashville, TN – Designer

The Frist Center for the Visual Arts in Nashville, TN is a nonprofit art-exhibition center housed in the city's U.S. Post Office building, which is listed on the National Register of Historic Places. The center recently completed a retrofit of the lighting system to SSL with monetary assistance from the TVA Energy Right Business Incentive Program – the "back of house" (e.g., non-art) lighting was completed first, main level galleries and security night lighting second, and upper galleries third. The retrofit has a predicted two-year payback. Although the center views cost as the biggest barrier to LED adoption, they think people's attitudes about the aesthetic performance of LEDs has shifted for the better. Now the predominant lighting in the galleries is LED retrofit PAR38 lamps (rated CRI of 94) used for wall washing (the existing fixtures were retrofitted for added ventilation) with MR16 halogens (narrow spot) used in select areas. MR16 6 W retrofit lamps are used in both the office area and as night lights – for the night lights, they are screened down. Although the LED MR16s only have a rated CRI of 80, they were low cost ($15/lamp) and used in areas where color rendering wasn't as important.

The center has no permanent collection and thus light levels and number of fixtures is exhibition dependent. In the evaluation of lighting, all evaluators (exhibits design, preparation, curatorial, director) were invited to view multiple LED retrofit options in the gallery space with a subsequent discussion. There were samples of dedicated LED fixtures but the cost was prohibitive so the decision to use a retrofit option was due to budget constraints. The choice to use retrofit options also mandated the continued use of screens and lenses to modify light levels instead of the dimming options dedicated fixtures would have afforded. In the past two years since the installation, the color quality has held up and only 2 of the 500 installed base have failed and been replaced under warranty, which is 5 years. In the future, the center hopes LM-79 /80 forms are easier to access instead of having to go through sales representatives.

Engineering firm

RFS Engineering, Laconia, NH – Electrical Designer

Rist-Frost-Shumway Engineering, P.C. (RFS), a firm based in Laconia, NH since 1972, deals with a range of projects from specifying museum grade display lighting to small commercial displays. To date, the predominant lighting used in their projects is incandescent but, as education about SSL is spreading to the end-user, LEDs are becoming more adopted. Their selection of lamp type is dependent on the situation but generally they go with dedicated LED fixtures and prefer a high dimming capability as this plays into energy efficiency measures – when considering dimming in a museum setting, they typically want down to the 1% level. They have specified a range of products in current use, from directional to track to color-changing LEDs, and subsequently a variety of dimming methods – DMX-512 is likely the best and most accurate for museum purposes. The firm is aware of the potential damage caused by UV and IR and thus considers this in the selection process. However, if significant detail regarding documenting initial conditions (e.g., of the art work) is to be undertaken, they typically hire a separate lighting consultant. When dealing with LED fixtures, it's generally been found that, if they're going to fail, it will happen upon start up or within the first 100 hours of operation. Otherwise, life expectancy is as stated by the manufacturer. Regarding wireless programmable lighting control networks on track lighting, they tend to hardwire new installations but, in retrofit applications, can see where wireless capability would make sense.

Manufacturer

Targetti, Florence, Italy – Director, Business Development

Targetti Poulsen SpA has been a manufacturer of both indoor and outdoor lighting products in Florence since 1928. Targetti's tunable LED products have been used to light various paintings including those by Lorenzo Lotto (Rome), Titian (Rome), and El Greco (Toledo) and many spaces, including Bronzino's Chapel of Eleonora in the Palazzo Vecchio (Florence) and the Galleria dell'Accademia (Florence). Their director of business development believes that there is no other source besides LED that can provide an appropriate spectrum for museum use. When working to design museum exhibitions, their main lighting goal is to use light to facilitate comprehension and understanding. Due to LED technology, there's a whole new way of conceiving how an art exhibition may be developed. The manufacturer's purpose should be to serve as an educator to the consumer just like an exhibition should pass knowledge on to the visitor.

In evaluating potential damage, the spectrum of the source (including short wavelength, UV, and IR emissions) along with the quantity of illumination (e.g., a maximum of 150 lux, vertical) are their only considerations as all other values are derived from the SPD. Each lamp is tuned according to the painting under the guidance of an art historian and restorer. Dedicated LEDs are preferred due to their dimmability– as dimming LEDs does not vary the spectra, dimming is of high importance as this is the only way to adjust to the right quantity of illumination required. Radio signals are viewed as the only dimming method without complications; however, this is a problem for videos as the frequencies often have conflicts with the equipment. Although higher quality in color rendering is believed to equate to lower efficacy (thus energy efficiency is compromised for quality), this is changing. With Targetti's fixtures, in order to adjust the color quality, if the diodes in the PCB fail, the fixture can be re-tuned by slighting increase the output of the others in the circuit to compensate for the other losses. "Normally the [visitor's] reaction is an incredible surprise to discover how paintings really are. Often they praise 'such a great restoration'...when they have not been restored at all."