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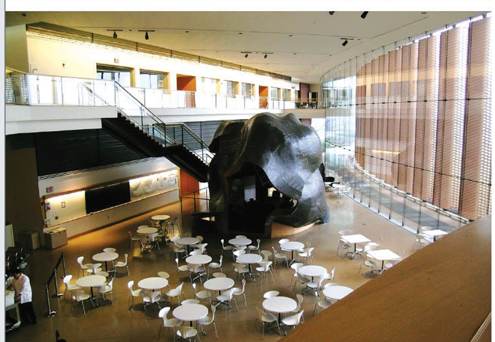
Demonstrations






Long-Term Evaluation of SSL Field Performance in Select Interior Projects

February 2017

Prepared for:

Solid-State Lighting Program
Building Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by:

Pacific Northwest National Laboratory

Long-Term Evaluation of SSL Field Performance **in Select Interior Projects**

Prepared in support of the DOE Solid-State Lighting Technology GATEWAY Program

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy
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St. Anthony Hospital
Princeton University
University of Maryland

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Preface

The U.S. Department of Energy's Solid-State Lighting program documents the performance of SSL products and systems based on standardized laboratory test results, additional specialized testing, mock-up studies, and real-world field evaluations. This information is provided publicly for several purposes: 1) to track SSL technology performance improvement over time; 2) to identify technology challenges that impact performance and application of SSL; 3) to spur continued advancements in SSL technology, product design, and application; and 4) to maximize energy efficiency and decrease U.S. energy use, while improving lighting quality. DOE does not endorse any commercial product or in any way provide assurance that other users will achieve similar results through use of these products. SSL technology continues to evolve quickly, so evaluation results should always be understood in the context of the timeframe in which products were acquired, tested, installed, and operated. Especially given the rapid development cycle for SSL products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products. The two programs primarily involved in product evaluations are CALiPER and GATEWAY.

CALiPER

When CALiPER was launched, its role was largely to test products and compare actual performance to manufacturer claims and to benchmark technologies. Early CALiPER testing also contributed fundamentally to the development of standardized photometric test methods specifically for SSL and the associated accreditation of testing laboratories. As the SSL market has matured, CALiPER has transitioned its evaluations to new products and functions, such as OLED-based luminaires and color tunable products, as well as long-term product performance. CALiPER continues to support the development of new test procedures and application guidance, with DOE investigations providing data that is essential for understanding the most current issues facing the SSL industry. Data are gathered primarily through laboratory testing and mock-up installations.

GATEWAY

GATEWAY conducts field evaluations of high-performance SSL products to collect empirical data and document experience with field installations. GATEWAY provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. GATEWAY typically documents pre- and post-installation light levels, color characteristics, energy intensity, and other performance attributes, and addresses application and maintenance of SSL products. In some cases, GATEWAY returns to projects after months or years of operation to take additional site measurements or remove luminaires and send to accredited laboratories for testing. While not possible for every project, such follow-up measurements have yielded useful data on dirt depreciation, color shift, luminous intensity distribution changes, and lumen depreciation over time.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

Acknowledgements

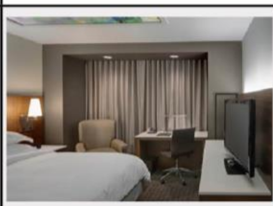
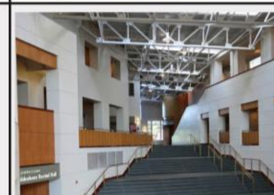
This project would not have been possible without the full collaboration and cooperation of the following individuals, whose support is gratefully acknowledged:

- Kevin Barman Sr., Director of Property Operations, Hilton Columbus Hotel, Columbus OH.
- Jason Henricksen, Maintenance Engineer, Facilities Engineering Department, St. Anthony Hospital, Gig Harbor WA.
- Arthur Murphy, Project Energy Engineer, Facilities Engineering, Princeton University, Princeton NJ.
- Tom Abell, Coordinator, Area Maintenance, Facilities Management, University of Maryland, College Park MD.

Executive Summary

This GATEWAY project evaluated four field installations to better understand the long-term performance of a number of LED products, which can hopefully stimulate improvements in designing, manufacturing, specifying, procuring, and installing LED products. Field studies provide the opportunity to discover and investigate issues that cannot be simulated or uncovered in a laboratory, and the installed performance over time of commercially available LED products has not been well documented. Beyond the energy savings made possible by SSL's higher efficacies, improving long-term performance can provide additional savings by reducing the need to over-light initially to account for later light loss, and by increasing SSL's market penetration. The projects evaluated for this report, outlined in Table ES-1, illustrate that SSL use is often motivated by advantages other than energy savings, including maintenance savings, easier integration with control systems, and improved lighting quality.

Table ES-1. Summary of each project. The following information is included for each site: technology platform, types of products and applications included, details of the lighting installation, and the motivation.

	HILTON DOWNTOWN COLUMBUS, OH	ST. ANTHONY HOSPITAL GIG HARBOR, WA	ICAHN LABORATORY PRINCETON, NJ		PERFORMING ARTS CENTER COLLEGE PARK, MD
DEMONSTRATION PROJECTS	NEW LUMINAIRES	INTEGRAL LAMPS	RETROFIT KITS		RETROFIT KITS
					
BUILDING DETAILS & ANNUAL ENERGY SAVINGS					
	• Occupancy in 2012 • 450,000 ft²	• Retrofit completed in 2014 • 250,000 ft²	• Retrofit completed in 2015 • 98,000 ft²		• Retrofit completed in 2014 • 342,000 ft²
	203,331 kWh 50% savings vs CFL	**131,279 kWh 59% savings vs CFL**	**61,025 kWh 60% savings vs CFL**	**57,050 kWh 24% savings vs FL**	**990,756 kWh 80% savings vs halogen**
LIGHTING INSTALLATION	• Dedicated LED downlights: Eaton's Cooper Lighting Business Portfolio® LED downlights • 3,700 installed in hotel guest rooms	• Integral LED lamps in CFL downlights: Lunera® Helen LED lamps • 1,262 installed in public spaces throughout the hospital	• LED retrofit kits for CFL downlights, using TerraLUX® DR8 LED retrofit kits • 245 installed in corridors, lobbies, and conference areas	• LED retrofit kits for 2×2 troffers, using MaxLite® LED retrofit kits • 815 installed in open and enclosed laboratories, corridors, and offices	• LED refrofit kits in halogen wall washers, using TerraLUX® Linear Line Voltage LED modules • 135 LED modules installed in 87 luminaires in public corridors
MOTIVATION	• Provide high quality, flexible lighting with familiar dimming capabilities • Satisfy task and ambient lighting needs with a high efficacy, low power solution • Reduce operational costs with long lifetimes, energy savings, and low maintenance needs	• Reduce maintenance costs and achieve substantial energy savings • Provide modest up-front investment, including relatively minimal labor costs for installation along with ease of installation • Achieve sustainability goals	• Achieve energy savings and the associated carbon reduction • Allow for maintenance and operational savings • Improve lighting quality	• Reduce power substantially • Achieve favorable pricing and warranty terms • Integrate with control system • Meet dimming performance requirements	• Reduce maintenance costs • Achieve a low-cost solution while providing an acceptable quality of light • Retain visual appearance of space • Benefit from energy savings • Solve melting conductor insulation issue by reducing heat

Pacific Northwest National Laboratory (PNNL) on behalf of the U.S. DOE collected two or three sets of illuminance and/or color data at each site. Figure ES-1 shows the range in chromaticity change (Δu'v') for each site based on the estimated hours of operation at the time measurements were taken. Although the data collected for the downlights at the Hilton Hotel did not allow the calculation of the Δu'v' values, these products showed very little change in their CCT, CRI, and R_9 values after more than 12,000 hours of use. The retrofit kits installed in the downlights and troffers at the Icahn Lab similarly show stable color performance after 7,400 hours; the downlight retrofit kits and the troffer retrofit kits in the corridor had an average Δu'v' of 0.0018 while the troffer retrofit kits installed in the small lab had an average Δu'v' of 0.0007. After 8,800 hours of use, the integral LED lamps used at St. Anthony had Δu'v' values of 0.0062 (surgery waiting area) and 0.0017 (imaging changing rooms) on average.

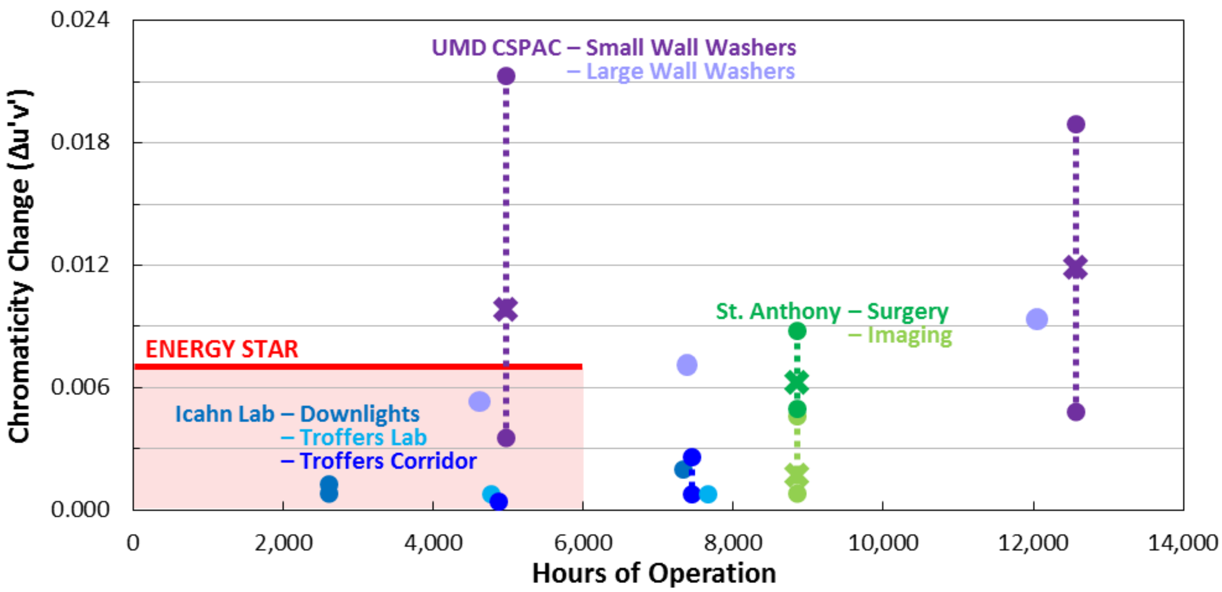


Figure ES-1.Overall chromaticity change for UMD CSPAC wall washer retrofit kits, Icahn Lab troffer and downlight retrofit kits, and St. Anthony replacement lamps based on the hours of operation at the time the measurements were collected. The average chromaticity change is marked by an X, while the minimum and maximum values are marked with circles, connected by a dotted line. If the range in performance is small, the average may not be marked and the circles may overlap.

For all measurement times, each site has measurement points that are below the red horizontal line in Figure ES-1, indicating the chromaticity change is less than the ENERGY STAR standard of 0.007. (This standard was used as a reference for comparison; the product manufacturers did not necessarily claim that their products met this standard.) The retrofit products in UMD's CSPAC exhibited substantially greater color shift than the other products; most of the measurement points are above the 0.007 line. After the third round of measurements (at least 12,000 hours of operation), the small wall washer products had an average Δu'v' value of 0.0118 compared to the initial set of measurements. Although the chromaticity shift measured for the LED retrofit kits at the UMD's CSPAC was greater than expected, the fact that the products have operated for more than 17,000 hours without any required maintenance satisfied the project goals for the university. The incumbent halogen lamp system would have required numerous lamp replacements during the same period, with much greater energy use.

Figure ES-2 shows the overall maintained illuminance for each of the sites based on the estimated hours of operation at the time measurements were collected. At the Hilton Hotel, the LED downlights provided sufficient lighting to satisfy IES task requirements after both sets of measurements, and all maintained illuminance values were significantly greater than the benchmark 70%; in fact, all of the values increased. In comparison to other downlight options, CFLs typically have a 10,000 hour rated life; thus, at least half of the lamps would have been expected to be replaced within the first 12,100 hours of data. At the Icahn Lab, illuminance levels after 7,400 hours of operation were also the same if not slightly greater than the initial levels with a maintained uniformity ratio. The average illuminance for the integral LED lamps at St. Anthony Hospital decreased but still met the relevant IES requirements after 8,800 hours. While the illuminance produced by the retrofit kits installed in

UMD's CSPAC decreased, it remained above 70% of initial after an estimated 5,000 operating hours. Although additional illuminance data was not collected, after 17,000 hours of operation only one of the 135 modules may need to be replaced, whereas the incumbent halogen lamps with a 1,500 hours rated life would have been replaced 11 times within the first 17,000 hours. Thus, from an energy and maintenance savings standpoint, the conversion was worthwhile.

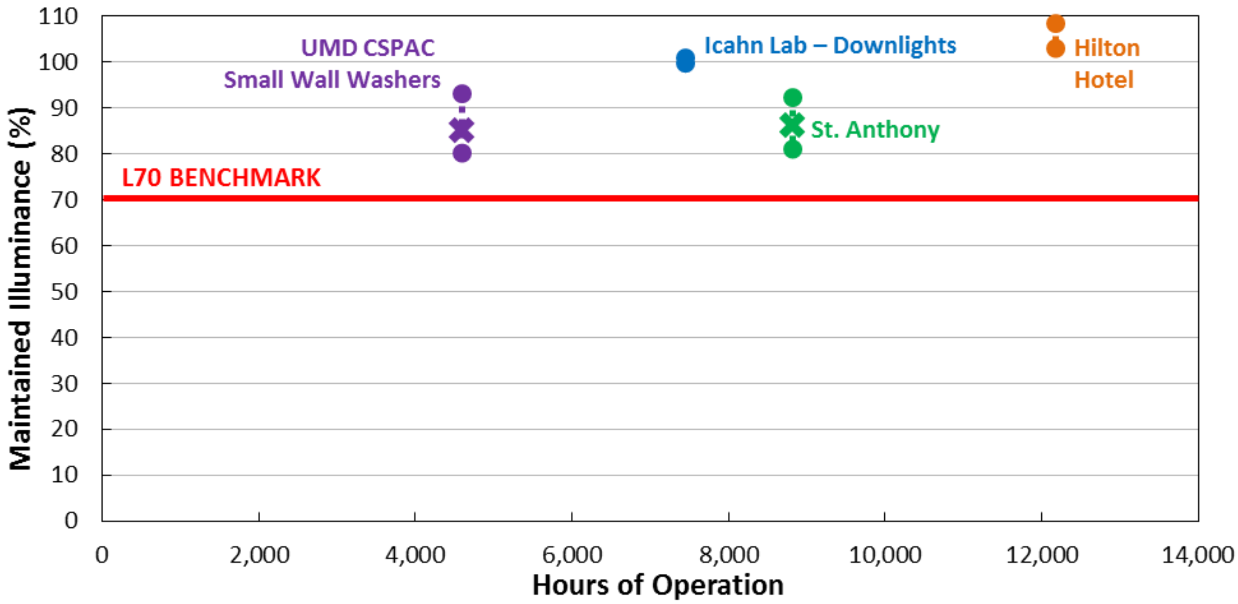


Figure ES-2.Overall maintained illuminance for the Hilton Hotel new downlights, UMD CSPAC wall washer retrofit kits, Icahn Lab downlight retrofit kits, and St. Anthony replacement lamps based on the hours of operation at the time the measurements were collected. The average maintained illuminance percentage is marked by an X, while the minimum and maximum values are marked with circles, connected by a dotted line. If the range in performance is small, the average may not be marked and the circles may overlap.

The evaluations reported here demonstrate that the success of any lighting implementation cannot only be determined by a simple review of technical performance data, but instead depends on full consideration of the individual project goals and priorities:

- The installation of new dedicated LED downlight luminaires at the Hilton Columbus Downtown Hotel was primarily motivated by architectural and lighting design goals, with light distribution and quality improvements compared to incumbent technologies. In addition, the LED lighting provided both greater control for the hotel guests, and substantial energy and operational savings for Hilton. The LED luminaires have maintained their performance over the time of this study.
- The replacement of existing CFLs with integral LED lamps at St. Anthony hospital was the lowest cost option to convert the five-year old luminaires to LED and reduce the system's maintenance burden. The retrofit continues to make sense because of the attractive economics and the maintenance savings, despite a few performance and operational issues. The economics of the system may need to be re-evaluated as the CFL ballasts reach their rated lifetimes.
- The conversion to LED retrofit kits at the Princeton University Icahn Lab was initiated based on the University's energy and sustainability goals, and the results showcase the economic, energy, and sustainability opportunities with LED conversions. The LED retrofit kits installed in 2x2 fluorescent troffers and in CFL downlights have maintained their performance over the time of this study. The use of controls demonstrates the additional savings that can be gained from controls strategies but also illustrates the difficulties that can be encountered in commissioning controls systems.

- The incumbent halogen wall wash luminaires at the University of Maryland CSPAC had high energy and operational costs due to the high wattage lamps and the long operating hours, but addressing these issues by converting the system to LED was made problematic by the unusual luminaire shape and also by the architectural constraints. Despite some performance concerns in color shift and maintained illuminance, the LED retrofit kits have provided a cost-saving solution due to the low initial cost, ease of installation, and energy and maintenance savings.

Glossary of Metrics

Δu'v':
Color shift is most appropriately documented as the difference or change in (*u*', *v*') coordinates, written Δu'v', because the (*u*', *v*') chromaticity diagram is the most visually uniform.

ANSI Chromaticity Bins:
Chromaticity "bins" demarcate areas on a chromaticity diagram, and are often used by manufacturers to sort products and convey nominal performance. Quadrangular bins for nominal CCT are defined by the American National Standards Institute (ANSI) Lighting Group and National Electrical Manufacturers Association (NEMA) document C78.377-2015. These quadrangles only roughly represent color appearance, and the variation within a bin is noticeable and unsatisfactory for almost all applications. That is, a source at one edge of the bin will appear very different from a source at the other end. Accordingly, manufacturers often establish much finer bins for sorting their products.

Color Rendering Index (CRI, R_a):
CRI is the common name for the CIE's general color rendering index, R_a. CRI is a measure of average color fidelity. R_1 through R_{14} provide supplemental information about specific color samples, which may be important in color-critical applications; for example, R_9 is a fidelity measure based on a saturated red color sample.

Correlated Color Temperature (CCT):
CCT is a measure of light source color appearance derived from chromaticity coordinates. CCT is calculated using the International Commission on Illumination (CIE) 1960 (*u*, *v*) chromaticity diagram and roughly describes the color appearance of a source from yellow to blue.

D_{uv}:
D_{uv} is a measure of light source color appearance derived from chromaticity coordinates. D_{uv} is calculated using the CIE 1960 (*u, v*) chromaticity diagram and roughly describes the color appearance of a source from purple to green.

TM-30 Fidelity Index (R_f):
R_f is the TM-30 measure for average color fidelity. It is analogous to the CIE CRI, but uses significantly more modern color science and a more comprehensive sample set, which makes it more accurate. The TM-30 R_f calculations are based on a (theoretical) comparison of how 99 color samples are rendered by the test source (the source in question) and the reference illuminant, which for TM-30 is a blackbody (Planckian) radiator, a model of daylight, or a blend of the two. TM-30 R_f values range from 0 to 100, with 100 indicating an exact match with the reference.

TM-30 Gamut Index (R_g):
R_g is the TM-30 measure for relative gamut area. In illumination engineering (as opposed to displays), gamut is the area enclosed by the chromaticity of a set of color samples. The range of values for TM-30 R_g does not have specific limits and is dependent on the TM-30 R_f value. Values greater than 100 indicate an average increase in gamut area, whereas values less than 100 indicate an average decrease in gamut area.

Contents

1 Introduction

To realize their full potential, solid-state lighting (SSL) products must prove their ability to perform over long operating times. Data available so far indicate that high lumen and chromaticity maintenance are possible and that estimated energy and operating savings can be achieved, but the installed performance of commercially available products has not been well documented. Beyond the energy savings made possible by SSL's higher efficacies, improving long-term performance can provide additional savings by reducing the need to over-light initially to account for later light loss, and by increasing SSL's market penetration. The projects evaluated for this report illustrate that SSL use is often motivated by advantages other than energy savings, including maintenance savings, integration with control systems, and improved lighting quality.

Field studies lend the opportunity to discover and investigate issues that cannot be simulated or uncovered in a laboratory. Although some manufacturers conduct long-term lab testing, the data are rarely made public. Other case studies and demonstration programs rarely, if ever, document ongoing performance of the installed lighting systems. This GATEWAY project evaluates several field installations to better understand the long-term performance of a number of different light-emitting diode (LED) products, which can hopefully stimulate improvements in designing, manufacturing, specifying, procuring, and installing LED products. This project complements other long-term GATEWAY investigations of exterior LED systems, such as the roadway lighting at the I-35W Bridge in Minneapolis, MN, and the security area lighting installation at the U.S.-Mexico border near Yuma, AZ.[1] In addition to these GATEWAY field studies, DOE has published several reports on the long-term performance of LED lamps. Each is summarized briefly here:

- **L Prize: *Lumen Maintenance Testing of the Philips 60-Watt Replacement Lamp L Prize Entry*[2]**: The L Prize testing involved continuous operation and frequent measurement of 200 A-type lamps submitted for the competition. Testing began in 2010, and after 25,000 hours of operation, the average lumen output was greater than 100% of the initial, and the average Δu'v' was less than 0.002. A reduced sample continues to be operated and measured, and after 50,000 hours of operation, the average lumen output was 93% of initial, with an average Δu'v' still at 0.002. The ambient temperature was maintained at 45°C for the duration of the test.
- **CALiPER Report 20.4: *Lumen and Chromaticity Maintenance of LED PAR38 Lamps*[3]**: With a setup and procedure similar to the L Prize testing, this experiment examined the performance of 38 different PAR38 lamps (32 LED, 2 CFL, 1 CMH, and 3 halogen) over 14,000 hours of operation at an ambient temperature of 45°C. On average, the lumen and chromaticity maintenance of the LED products was as good as or better than the competitors, but there was substantial variability.
- **CALiPER Report 20.5: *Chromaticity Shift Modes of LED PAR38 Lamps Operated in Steady-State Conditions*[4]**: This report utilized the dataset from CALiPER Report 20.4, but examined specific shifts in u' and v' coordinates, rather than the aggregated Δu'v'. The chromaticity shifts were linked to specific physical features and underlying causes.

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1 For completed outdoor projects, see the GATEWAY Demonstration Outdoor Projects webpage: https://energy.gov/eere/ssl/gateway-demonstration-outdoor-projects.

2 http://www.lightingprize.org/pdfs/lprize_60W-lumen-maint-testing_2016.pdf

3 http://energy.gov/eere/ssl/downloads/report-204-lumen-and-chromaticity-maintenance-led-par38-lamps

4 http://energy.gov/eere/ssl/downloads/report-205-chromaticity-shift-modes-led-par38-lamps-operated-steady-state

- **CALiPER Retail Lamps Study 3.2:** ***Lumen and Chromaticity Maintenance of LED A Lamps Operated in Steady-State Conditions***[5]: Like the L Prize and CALiPER Report 20.4, this investigation relied on PNNL's Automated Long-term Test Apparatus (ALTA). Ten samples each of 17 different retail-available A lamps were monitored over 7,500 hours. Again, the results showed variability in the results. Seven of the 15 LED products tested showed sufficiently low output at 7,500 hours that they would not be expected to be above 70% output at their rated lifetimes.

This report documents the evaluation of the long-term performance characteristics of SSL systems (lumen maintenance, chromaticity stability, operations and maintenance) in the following four field installations, each of which was previously documented in a DOE report[6]:

- Hilton Columbus Downtown Hotel, Columbus, OH (new construction: dedicated LED downlights)
- University of Maryland (UMD) Clarice Smith Performing Arts Center (CSPAC), College Park, MD (retrofit: LED retrofit kits in halogen wall washers)
- Princeton University Icahn Lab, Princeton, NJ (retrofit: LED retrofit kits in 2x2 troffers and downlights)
- St. Anthony Hospital, Gig Harbor, WA (retrofit: LED replacement lamps in compact fluorescent lamp [CFL] downlights)

Table 10 (page 24) summarizes each project in the grayed-out sections, including the technology platform installed, the types of products and applications, highlights of the initial performance and estimated energy savings, and the motivations for the initial SSL implementation at each site. For the current project, Pacific Northwest National Laboratory (PNNL) on behalf of the U.S. DOE collected two or three sets of illuminance and/or color data at each site. Figure 1 depicts the measurements collected at each project site and the approximate hours of operation at each collection time.

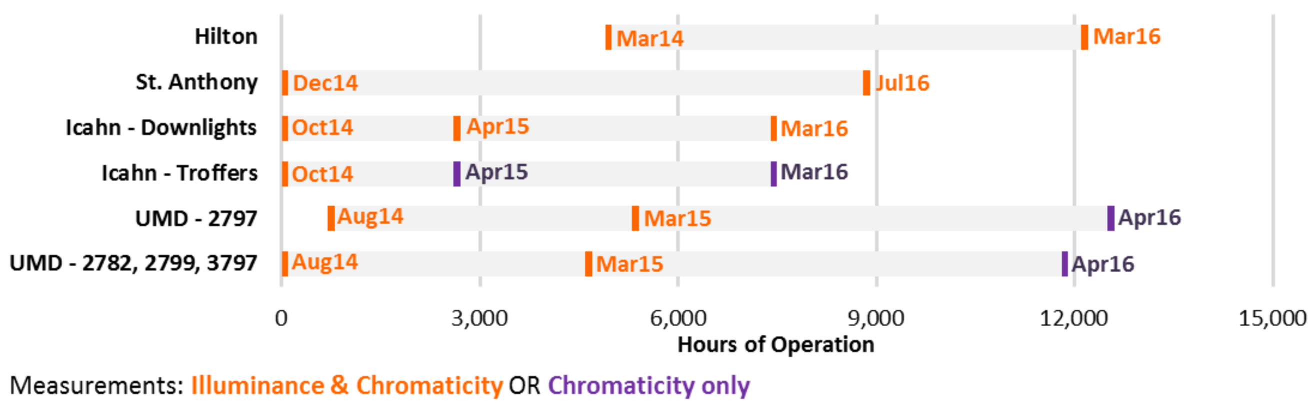

Figure 1. Timeline of data collection. Hours of operation are delineated for each set of measurements at each site. An orange bar indicates that both illuminance and chromaticity were measured, whereas a purple bar indicates that only chromaticity was measured. The date of each measurement is shown adjacent to each bar. For Icahn, the two product types are differentiated (downlights versus troffers), whereas for UMD, the installation locations are distinguished (2797 versus 2782, 2799, and 3797).

This report is organized primarily by the type of performance data evaluated for each site. Section 2 focuses on color, Section 3 on illuminance, and Section 4 on operations and maintenance costs. The discussion in each

5 http://energy.gov/eere/ssl/downloads/retail-lamps-study-32-lumen-and-chromaticity-maintenance-led-lamps-operated

6 For the original reports, see the GATEWAY Demonstration Indoor Projects webpage: http://energy.gov/eere/ssl/gateway-demonstration-indoor-projects.

section is organized by technology platform—new luminaires, replacement lamps, and retrofit kits.[7] Section 5 discusses the colorimetric and photometric performance, synthesizing the individual results from the four project sites. Section 6 summarizes the findings and highlights the lessons learned from these evaluations.

[7] For more information about these product categories, see the following fact sheets:
Updating Troffer Luminaires to LED: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_troffer-upgrades_fs.pdf
Recessed LED Downlights: https://energy.gov/sites/prod/files/2017/01/f34/led_downlight-upgrades_fs.pdf

2 Colorimetric Performance

The colorimetric performance of the LED products used in each project was documented at least twice during the first few years of operation.[8] Hours of operation were estimated based on information from facilities staff at each location and rounded to the nearest hundred hours. Colorimetric data measured in the field may be affected by application-specific conditions, and as a result may differ from manufacturer-rated data, which is measured under standard laboratory conditions; however, the focus of the report is to compare field measurements over time, not to the laboratory measurements conducted by the manufacturer.

2.1 Dedicated LED Luminaires at the Hilton Columbus Downtown Hotel, Columbus, OH

Of the 3,700 installed dedicated LED downlights, seven were evaluated in a guest room at the Hilton Columbus Downtown Hotel. Initial measurements were taken on March 11, 2014, approximately 17 months after installation, or after about 4,900 hours of operation, using the Hilton's assumed 3,500 annual operating hours.[9] Follow-up measurements were taken on March 28, 2016, approximately 7,200 operating hours after the previous measurements, for a total of 12,100 estimated hours of use. Table 1 summarizes the color data for the Hilton Columbus Downtown Hotel luminaires.

Table 1. Colorimetric data for seven LED downlights at the Hilton Columbus Downtown Hotel. Other color metrics could not be calculated since the full spectral power distributions for the LED1 and LED2 measurements were not recorded.

DATE		CCT	D_{uv}	CRI	R_9
LED1	min	3052	–	81	37
Mar 2014	**avg**	**3069**	**–**	**83**	**40**
(4,900 hrs)	max	3091	–	85	43
LED2	min	3064	-0.0003	81	36
Mar 2016	**avg**	**3087**	**0.0003**	**83**	**39**
(12,100 hrs)	max	3114	0.0010	84	42

After 4,900 operating hours, the seven LED downlights had an average correlated color temperature (CCT) of 3069 K with a range of 39 K and an average color rendering index (CRI) of 83; after 7,200 additional operating hours, or 12,100 total hours, these luminaires had an average measured CCT of 3087 K with a range of 50 K and the same average CRI of 83. The R_9 values averaged 40 initially and 39 in the second data set. These changes in color appearance and rendering are within measurement error and indicate that the color properties of the dedicated LED downlights at the Hilton remained stable over the study period.

2.2 Integral LED Lamps in CFL Downlight and Wall Sconce Luminaires at St. Anthony Hospital, Gig Harbor, WA

St. Anthony Hospital replaced CFLs with integral LED lamps in over 1,200 luminaires, the majority of which were recessed downlights. DOE staff visited the facility on December 10, 2014, about 1 month after the installation was completed, to document the baseline lighting conditions of seven downlights in a surgery waiting area along with six downlights and four wall-mounted uplight sconces in a patient changing room area near the diagnostic

[8] Color properties were measured using a Konica Minolta CL-500A Illuminance Spectrophotometer (serial number 10002008). This meter has a rated wavelength precision of +0.3 nm and a rated chromaticity accuracy in xy coordinates of +0.0015. The meter was within calibration specifications for each set of measurements.

[9] Estimated operating time for the lighting in a hotel guest room depends on occupancy rates and guest behavior, and is less reliable than estimates of spaces where lighting usage is more regular. The Hilton's estimate was based on their past experiences.

imaging department. Follow-up measurements were taken on July 18, 2016, approximately 8,800 operating hours after the initial visit. The operating hours in the changing room area are assumed to be less than the estimated 8,800 hours for other public areas at the hospital given the space has individual switches. Table 2 summarizes the color measurements.

Table 2. Color properties for seven downlights lamped with LED replacement lamps in a surgery waiting area (top) and for 10 fixtures in an imaging changing room area (bottom) at St. Anthony Hospital. The operating hours in the changing room area are not known since the space has individual switches, but are assumed to be less than the estimated 8,800 hours for the other public areas at the hospital.

	DATE		CCT	D_{uv}	CRI	R_9	R_f	R_g	Δu'v'
Surgery (7 fixtures)	**LED0**	min	3319	-0.0024	83	22	82	95	N/A
	Dec 2014	**avg**	**3329**	**-0.0020**	**84**	**23**	**82**	**95**	**N/A**
	(initial)	max	3343	-0.0014	84	24	82	96	N/A
	LED1	min	3439	-0.0046	84	25	82	95	0.0047
	Jul 2016	**avg**	**3484**	**-0.0037**	**85**	**27**	**82**	**95**	**0.0062**
	(8,800 hrs)	max	3550	-0.0030	85	30	82	95	0.0085[a]
Imaging (10 fixtures)	**LED0**	min	3396	-0.0013	84	22	82	95	N/A
	Dec 2014	**avg**	**3431**	**-0.0020**	**84**	**25**	**82**	**95**	**N/A**
	(initial)	max	3458	-0.0026	85	28	82	96	N/A
	LED1	min	3370	-0.0004	83	20	82	95	0.0004
	Jul 2016	**avg**	**3439**	**-0.0017**	**84**	**24**	**82**	**95**	**0.0017**
	(<8,800 hrs)	max	3567	-0.0027	85	27	82	96	0.0045

[a] Red text indicates Δu'v' values greater than the ENERGY STAR® maximum of 0.007.

The downlights in the surgery waiting area had an initial average CCT of 3329 K with a range of 24 K and an average D_{uv} of -0.0020; after 8,800 estimated operating hours, these luminaires had an average measured CCT of 3484 K with a range of 111 K and an average D_{uv} of -0.0037. The same model of LED replacement lamps were used in the changing room area. The products had an initial average CCT of 3431 K with a range of 62 K and an average D_{uv} of -0.0020; after less than 8,800 estimated operating hours, these luminaires had an average measured CCT of 3439 K with a range of 197 K and an average D_{uv} of -0.0017. For both spaces, the CRI and R_9 values remained relatively consistent, on average 84 to 85 and 23 to 27, respectively.

Figure 2 shows the chromaticity coordinates for 17 fixtures in both areas of the hospital, at each of the two measurement times, and illustrates that the chromaticity coordinates for all of the luminaires fall below the Planckian curve (as indicated by the negative D_{uv} values).[10] For the seven downlights in the surgery waiting area, the average change in chromaticity, Δu'v', was 0.0062 over 8,800 operating hours, and only one of the seven downlights had a Δu'v' greater than the ENERGY STAR maximum of 0.007.[11] ENERGY STAR specifies the maximum value at 6,000 hours, while the lamps at St. Anthony had operated for almost 9,000 hours at the time of the second measurements. The tight clustering of the chromaticity coordinates at each of the two measurement times shows that, although the average chromaticity shifted over time, it shifted consistently among the luminaires measured.

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[10] Although preference is highly individualized, some studies have shown a preference for light sources with chromaticity below the blackbody locus (i.e., negative D_{uv}). See K. Houser and M. Wei, "What Is the Cause of Apparent Preference for Sources with Chromaticity below the Blackbody Locus," *Leukos*, 2015: http://www.tandfonline.com/doi/abs/10.1080/15502724.2015.1029131?journalCode=ulks20.

[11] The ENERGY STAR program requires the change of chromaticity (Δu'v') over the minimum lumen maintenance test period (6,000 hours) to be within 0.007 on the CIE 1976 (*u*',*v*') diagram.

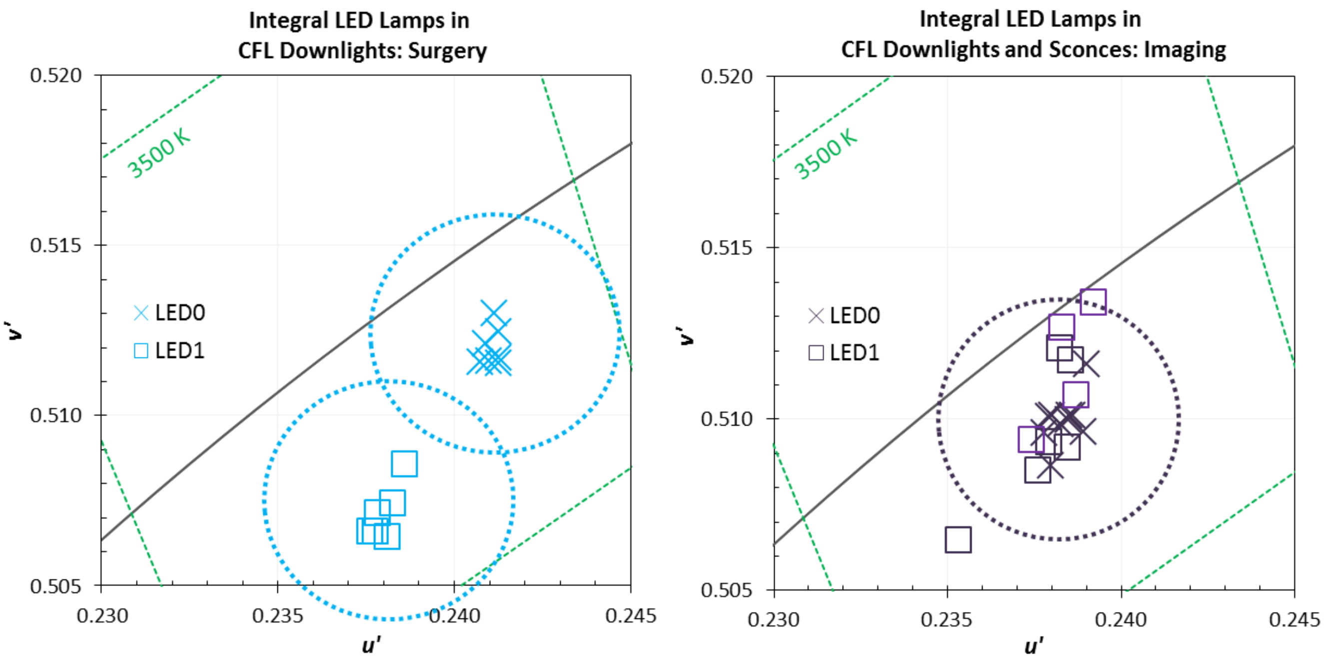


Figure 2. Chromaticity coordinates for 7 downlights in a surgery waiting area (left) and 10 fixtures in the imaging changing rooms (right) at St. Anthony Hospital plotted on 1976 CIE uniform color space (UCS) (*u'*,*v'*) chromaticity diagram with MacAdam ellipses. The circles have a radius of 0.0035 in the (*u'*, *v'*) chromaticity diagram to approximate a 3.5-step MacAdam ellipse, where the step size refers to the distance from the center of the ellipse to the perimeter. The circles are centered on the average *u*' and *v*' coordinates for each set of measurements. For the surgery downlights, the tight clustering of the chromaticity coordinates at each of the two measurement times shows that, although the average chromaticity shifted over time, it shifted consistently among the luminaires measured and remained within the 3500 K ANSI bin.[12] Unlike the downlight luminaires in the surgery waiting area, the LED1 measurements for the downlight and sconce luminaires in the imaging rooms are not tightly clustered; instead, the follow-up measurements indicate a range in color performance, with a spread that is greater than seven steps (i.e., outside of a 3.5-step ellipse). Despite this variation, all of the fixtures remained within the 3500 K ANSI bin.

For the six downlights and four wall sconces in the imaging rooms (right graph, Figure 2), the average Δu'v' from the initial to follow-up measurements was 0.0017 and the maximum was 0.0045, well within ENERGY STAR requirements. In terms of Δu'v', these fixtures are shifting less in chromaticity over time than those in the surgery waiting area, perhaps because they have operated for fewer hours since the area is individually controlled and the lights are turned off after hours. However, they are not shifting as homogeneously as the waiting area, thus their color difference may be more noticeable. The variability in fixture types and corresponding measurement techniques are also possible (even likely) explanations for the differences from the surgery area.

2.3 LED Retrofit Kits in CFL Downlights at the Princeton University Icahn Lab, Princeton, NJ

At the Icahn Lab at Princeton, 245 LED retrofit kits were installed in CFL downlights located in corridors, lobbies, and conference areas. To evaluate these retrofit kits, color data were documented for seven downlights in an open conference area. Initial readings were taken in October 2014, shortly after the installation was completed, with follow-up measurements in April 2015 (after 2,600 operating hours) and in March 2016 (after 7,400 operating hours). Table 3 summarizes the color performance.

[12] ANSI Lighting Group and National Electrical Manufacturers Association document C78.377-2015: http://www.nema.org/Standards/Pages/American-National-Standard-for-Electric-Lamps-Specifications-for-the-Chromaticity-of-Solid-State-Lighting-Products.aspx.

Table 3. Summary of color measurements for seven downlights with LED retrofit kits in the Icahn Lab at Princeton.

DATE		CCT	D_{uv}	CRI	R_9	R_f	R_g	Δu'v'[a]
LED0	min	3475	-0.0038	85	29	82	96	N/A
Oct 2014	**avg**	**3496**	**-0.0036**	**85**	**30**	**82**	**96**	**N/A**
(initial)	max	3504	-0.0033	85	30	82	96	N/A
LED1	min	3471	-0.0031	84	28	82	96	0.0007
Apr 2015	**avg**	**3485**	**-0.0030**	**85**	**28**	**82**	**96**	**0.0010**
(2,600 hrs)	max	3497	-0.0027	85	28	82	96	0.0014
LED2	min	3436	-0.0033	84	27	82	96	0.0015
Mar 2016	**avg**	**3454**	**-0.0030**	**84**	**27**	**82**	**96**	**0.0018**
(7,400 hrs)	max	3467	-0.0026	85	28	82	96	0.0021

[a] These values were calculated relative to the initial measurements in all cases.

The average CCT changed from 3496 K initially to 3454 K after 7,400 operating hours, and the average D_{uv} changed from -0.0036 to -0.0030. These changes in CCT and D_{uv} are very small, likely within the measurement uncertainty, and would probably not be noticed by most building occupants. The Δu'v' values were, on average, 0.0010 after 2,600 hours and 0.0018 after 7,400 hours, confirming that the color properties have remained stable. Figure 3 shows the *u*' and *v*' chromaticity coordinates of the seven downlights at each of the three measurement times. The graph illustrates that the chromaticity changes are small.

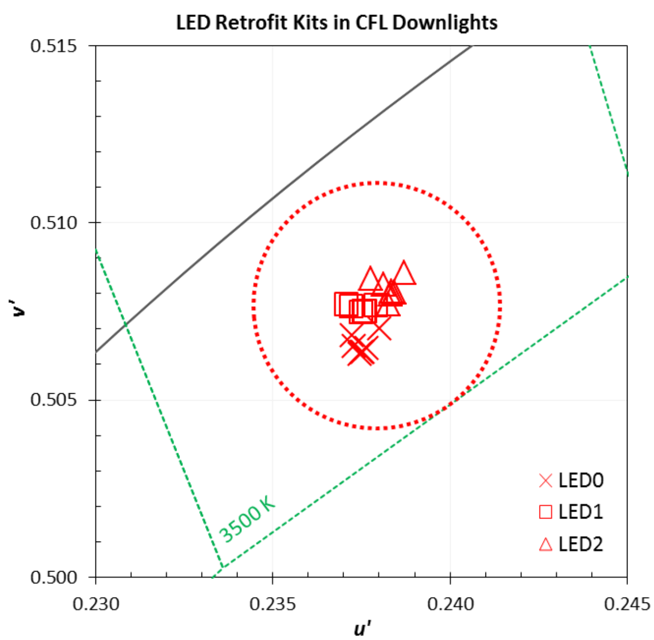


Figure 3. Chromaticity coordinates for the LED downlight retrofit kits in the Icahn Lab plotted on 1976 CIE uniform color space (UCS) (*u'*,*v'*) chromaticity diagram with MacAdam ellipses. The diagram shows the coordinates for the seven measured downlights at each of the three measurement times, in relationship to the ANSI bin for 3,500 K products. The circle has a radius of 0.0035 in the (*u'*, *v'*) chromaticity diagram to approximate a 3.5-step MacAdam ellipse, where the step size refers to the distance from the center of the ellipse to the perimeter. The circle is centered on the average *u*' and *v*' coordinates. The tight clustering of the chromaticity coordinates at each of the measurement times shows that all products remained fairly well grouped.

2.4 LED Retrofit Kits in Fluorescent Troffers at the Princeton University Icahn Lab, Princeton, NJ

Separate from the downlights, 815 LED retrofit kits were installed in 2x2 recessed troffer luminaires in labs, corridors, and offices at the Icahn Lab. To evaluate these retrofit kits, color data were documented for 11 of the products, installed in luminaires that were easily accessible for data collection. Of these 11 luminaires, four were in a corridor within a large open lab space and the other seven were in a small enclosed lab. Initial measurements of the recessed troffer luminaires were taken in October 2014, shortly after the installation was completed, with follow-up measurements in April 2015 (after 2,600 operating hours in the corridor, based on Princeton's assumed 5,000 annual operating hours) and in March 2016 (after 7,400 operating hours in the corridor). The operating hours for the small lab are not known since the lab had a separate switch, but are assumed to be less than the hours for the open lab and corridor areas.

Table 4 summarizes the color metrics, which show that the overall change in average CCT and D_{uv} was relatively small for these LED retrofit kits. The average CCT changed from 4390 K initially to 4471 K (corridor) and from 4313 K to 4341 K (lab) after 7,400 operating hours. The average D_{uv} changed from -0.0041 to -0.0043 in the corridor and remained at -0.0031, on average, in the lab. The Δu'v' values for the corridor luminaires after 7,400 hours were all below the ENERGY STAR specification of 0.007.

Table 4. Summary of color measurements: initial (October 2014) and follow-up (April 2015, March 2016).

	DATE		CCT	D_{uv}	CRI	R_9	R_f	R_g	Δu'v'[a]
CORRIDOR (4 luminaires)	**LED0**	min	4309	-0.0048	85	33	82	100	N/A
	Oct 2014	**avg**	**4390**	**-0.0041**	**85**	**34**	**82**	**100**	**N/A**
	(initial)	max	4468	-0.0033	85	36	83	100	N/A
	LED1	min	4310	-0.0040	85	32	82	100	0.0002
	Apr 2015	**avg**	**4369**	**-0.0037**	**85**	**33**	**82**	**100**	**0.0004**
	(4,800 hrs)	max	4399	-0.0033	85	34	83	100	0.0005
	LED2	min	4364	-0.0051	85	33	82	100	0.0011
	Mar 2016	**avg**	**4471**	**-0.0043**	**85**	**34**	**82**	**100**	**0.0018**
	(7,400 hrs)	max	4553	-0.0038	85	36	82	100	0.0025
LAB (7 luminaires)	**LED0**	min	4299	-0.0037	85	32	82	99	N/A
	Oct 2014	**avg**	**4313**	**-0.0031**	**85**	**32**	**83**	**100**	**N/A**
	(initial)	max	4336	-0.0027	85	33	83	100	N/A
	LED1	min	4328	-0.0035	85	31	82	99	0.0006
	Apr 2015	**avg**	**4350**	**-0.0029**	**85**	**32**	**83**	**100**	**0.0008**
	(<4,800 hrs)	max	4386	-0.0025	85	32	83	100	0.0011
	LED2	min	4321	-0.0038	85	32			0.0003
	Mar 2016	**avg**	**4341**	**-0.0031**	**85**	**33**	**82[b]**	**100[b]**	**0.0007**
	(<7,400 hrs)	max	4375	-0.0028	86	34			0.0013

[a] These values were calculated based on the initial measurements in all cases.
[b] Only one measurement point was used for these calculations.

Figure 4 illustrates the shift in chromaticity for the troffer retrofit kits in the corridor luminaires (left) and the lab luminaires (right). The Δu'v' values for both sets of fixtures after 7,400 hours were below the ENERGY STAR specification of 0.007, but there was a greater shift in chromaticity for the corridor luminaires.

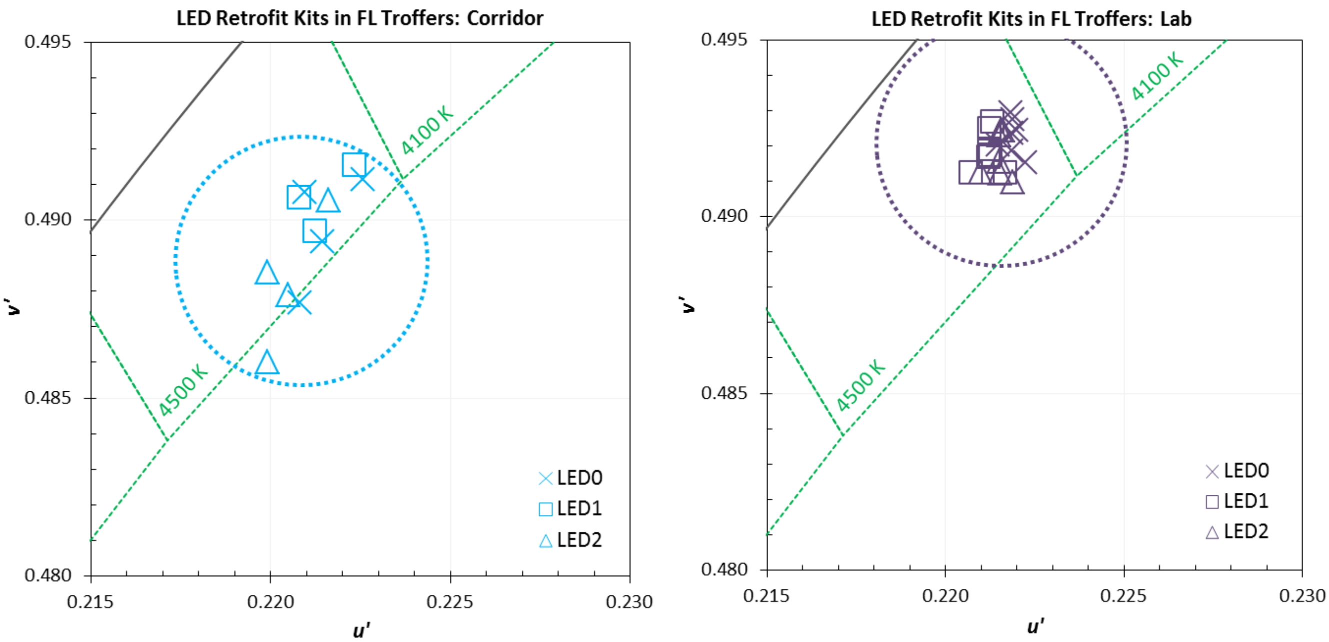


Figure 4. Chromaticity coordinates for the LED troffer retrofit kits in the Icahn Lab plotted on 1976 CIE uniform color space (UCS) (*u'*,*v'*) chromaticity diagram with MacAdam ellipses. The diagram on the left shows the coordinates for the corridor luminaires at each of the three measurement times, while the diagram on the right is for the lab luminaires. The circles have a radius of 0.0035 in the (*u'*, *v'*) chromaticity diagram to approximate a 3.5-step MacAdam ellipse, where the step size refers to the distance from the center of the ellipse to the perimeter. The circles are centered on the average *u*' and *v*' coordinates for each set of measurements. The circles indicate that for both sets of luminaires, the shift in chromaticity is within seven steps. The lab hours are assumed to be less than those in the corridor, which could explain the more tightly grouped performance in the diagram on the right.

2.5 LED Retrofit Kits in Halogen Wall Wash Luminaires at the University of Maryland CSPAC, College Park, MD

In August 2014, March 2015, and April 2016, color data were documented for some of the LED retrofit kits installed in halogen wall washers at UMD CSPAC. Of the 87 luminaires that were converted to LED, 31 were measured.[13] Of those 31, 16 small wall washers were measured in hallway 2782, two in area 2799, and six in hallway 2797; seven large wall washers were measured in hallway 3797. In August 2014, 18 of the modules in hallway 2782 and area 2799 along with one of the modules in hallway 3797 had just been installed while six in hallway 2797 had been operating for 700 hours—the differences due to mock-ups prior to the full retrofit of the small wall washers. In March 2015, the small wall washers had been operating an additional 4,600 hours when the rest of the large wall washers were installed. In April 2016, the wall washers had been operating an additional 7,400 hours (for 12,000 to 13,000 hours in total). Table 5 summarizes the results of the color measurements. Most of the points are an average of two to three spectral power distribution measurements per wall washer.

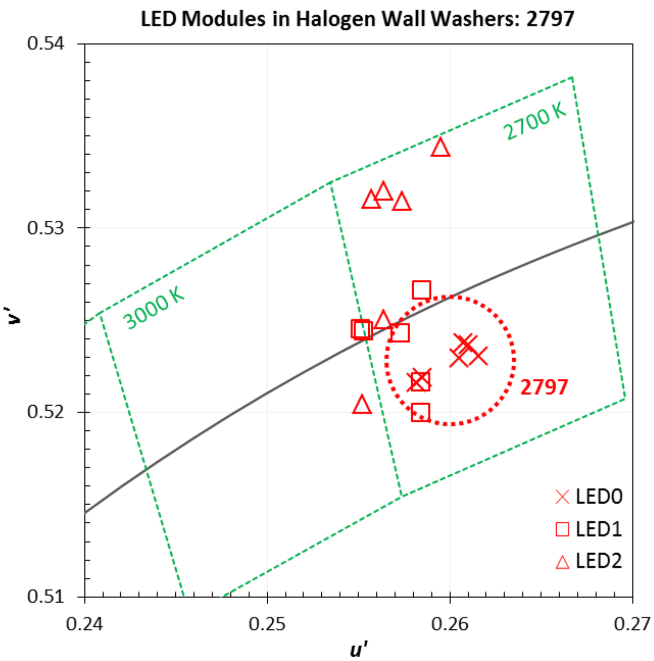
[13] Six luminaires in hallway 2797 were installed on July 11, 2014. All luminaires in hallway 2782 and area 2799, along with one fixture in hallway 3797, were installed on August 14, 2014. The rest of the fixtures in hallway 3797 were installed on March 31, 2015.

Table 5. Summary of color measurements for the small wall washer luminaires (top) and large wall washer luminaires (bottom): initial (August 2014) and follow-up (March 2015, April 2016).

	DATE		CCT	D_{uv}	CRI	R_9	R_f[a]	R_g[a]	Δu'v'[b]
Small Wall Washers (2782, 2799, 2797)	**LED0[c]**	min	2652	-0.0026	82	14			–
	Aug 2014	**avg**	**2718**	**-0.0017**	**82**	**16**	**81**	**98**	**–**
	(0 or 700 hrs)	max	2819	-0.0007	83	17			–
	LED1	min	2779	-0.0043	82	16			0.0033
	Mar 2015	**avg**	**2927**	**-0.0015**	**83**	**20**	**82**	**98**	**0.0098**
	(4,600 or 5,300 hrs)	max	3181	0.0007	85	25			0.0212
	LED2	min	2733	-0.0023	80	6			0.0046
	Apr 2016	**avg**	**2930**	**0.0016**	**82**	**15**	**83**	**95**	**0.0118**
	(12,000 or 12,700 hrs)	max	3106	0.0058	84	22			0.0187
Large Wall Washers (3797)	**LED0[d]**	min							
	Aug 2014, Mar 2015	**avg**	**2701**	**-0.0028**	**83**	**28**	**83**	**98**	**–**
	(0 hrs)	max							
	LED1[e]	min							
	Mar 2015	**avg**	**2814**	**-0.0009**	**83**	**–**	**82**	**96**	**0.0049**
	(4,600 hrs)	max							
	LED2[f]	min							
	Apr 2016	**avg**	**2857**	**-0.0005**	**83**	**17**	**81**	**97**	**0.0073**
	(7,400 hrs)	max							
	LED3[e]	min							
	Apr 2016	**avg**	**2801**	**0.0038**	**82**	**11**	**82**	**93**	**0.0092**
	(12,000 hrs)	max							

[a] Only the average values are shown since a subset of measurement points was used.
[b] These values were calculated based on the initial measurements in all cases. Red text indicates Δu'v' values greater than the ENERGY STAR maximum of 0.007.
[c] Eighteen luminaires were just installed (0 hrs) and six luminaires had been operating 700 hrs; data were combined for these comparisons.
[d] Data are shown for four luminaires, one installed in Aug 2014 and three in Mar 2015.
[e] Data are shown for the one luminaire that had been installed in Aug 2014.
[f] Data are shown for the three luminaires at 7,400 hrs.

The small wall washers had an initial average CCT of 2718 K with a range of 167 K and an average D_{uv} of -0.0017; after 4,600 estimated operating hours, these luminaires had an average measured CCT of 2927 K with a range of 402 K and an average D_{uv} of -0.0015. The third set of measurements, after an additional 7,400 hours (12,000 hours total), revealed an average CCT of 2930 K with a range of 383 K and an average D_{uv} of -0.0016. The CRI and R_9 values remained relatively consistent, as delineated in Table 5. However, the chromaticity shift, Δu'v', ranged from 0.0033 to 0.0212 after 4,600 operating hours with 16 modules exceeding the ENERGY STAR maximum of 0.007; Δu'v' ranged from 0.0046 to 0.0187 after 12,000 hours with all but three of the 24 modules exceeding 0.007. For the large wall washers, the average CCT increased from 2701 to 2801 K, with the average D_{uv} changing from -0.0028 to 0.0038. The chromaticity shift (Δu'v') ranged from 0.0049 to 0.0081 after the first follow-up measurements and increased to 0.0092 after 12,000 hours. Figure 5 and Figure 6 show the chromaticity coordinates for the light exiting the small and large wall washers at the three different measurement times. After the second round of measurements (LED1), the small wall washers in hallway 2782 and area 2799 were generally shifting toward blue, while those in hallway 2797 remained relatively stable. Despite the initial blue shift, the third round of measurements (LED2) indicated a yellow shift, shown more clearly in Figure 5. The large wall washers in hallway 3797 (Figure 6) indicated trends similar to those in hallway 2797.



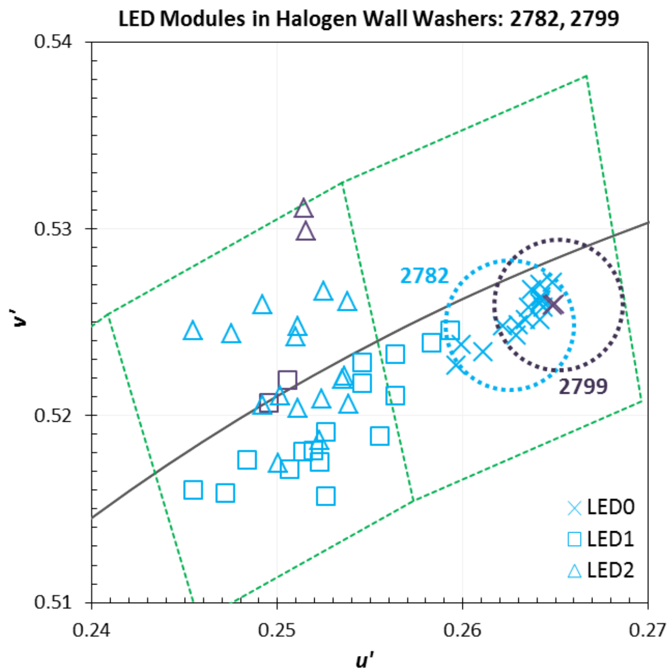


Figure 5. Chromaticity coordinates for the small wall washers at UMD CSPAC plotted on 1976 CIE uniform color space (UCS) (*u′*,*v′*) chromaticity diagram with MacAdam ellipses. The diagram on the left shows the chromaticity coordinates of the light exiting the wall in hallway 2797 while the diagram on the right is for hallway 2782 and area 2799. In August 2014, the six modules in hallway 2797 (graphed on the left) had been operating for 700 hours whereas 18 of the modules in hallway 2782 and area 2799 (on the right) had just been installed. The circles have a radius of 0.0035 in the (*u′*, *v′*) chromaticity diagram to approximate a 3.5-step MacAdam ellipse, where the step size refers to the distance from the center of the ellipse to the perimeter. The circles are centered on the average *u*' and *v*' coordinates for each set of measurements.

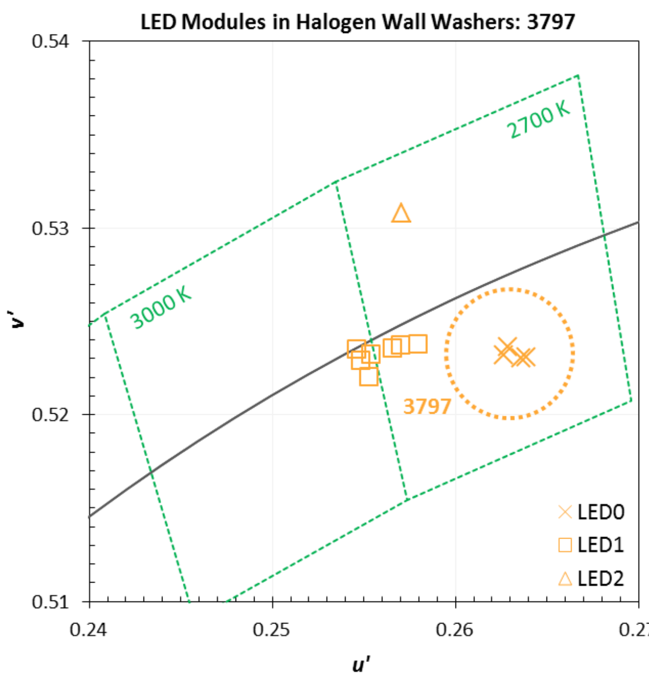


Figure 6. Chromaticity coordinated for the large wall washers at UMD CSPAC plotted on 1976 CIE UCS (*u′*,*v′*) chromaticity diagram with MacAdam ellipses. The diagram shows the chromaticity coordinates of the light exiting the wall in hallway 3797. In August 2014, two modules were installed in one fixture; the rest were installed in March 2015 with follow-up measurements taken in March 2016.

The 3.5 step MacAdam ellipses indicate that the products generally shifted more than the diameter of the ellipses (seven steps) from the original measurements and also inconsistently, causing noticeable color differences. The color shift crossed the blackbody in both directions, indicated by the negative and positive D_{uv} values, which visually manifest as pink and green tints (demonstrated in the photo in Figure 7).

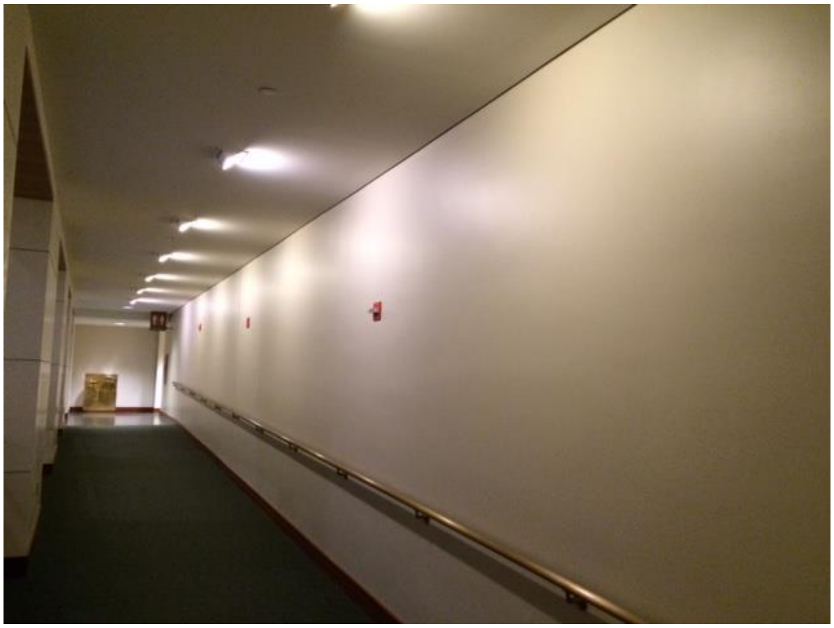


Figure 7. Disparity in color shift shown in a photograph taken during the LED2 measurements. Note: While photographs do not ensure exact replication of the conditions, this image gives an idea of the noticeable color difference.

3 Photometric Performance

The photometric performance for each project was documented by recording illuminance values at two or more times during the first few years of operation.[14] Although illuminance can serve as a proxy for luminaire light output, many other factors can also affect illuminance levels, so the exact relationship to luminaire light output is not known. Any changes in the spaces that would affect illuminance are noted. The measurement times were the same as for the colorimetric performance unless otherwise noted.

3.1 Dedicated LED Luminaires at the Hilton Columbus Downtown Hotel, Columbus, OH

Illuminances in the three areas documented increased on average from 3% to 7%, as shown in Table 6. An increase in light output is common during the early operating hours for many LED packages, and the small amount of change documented could be caused by other sources of field measurement variability. After both sets of measurements, the LED downlights provided sufficient lighting to satisfy Illuminating Engineering Society (IES) task requirements, in most cases exceeding the IES recommended values for guests of any age.[15]

Table 6. Horizontal illuminance values for the first (LED1) and follow-up (LED2) measurements at the Hilton Columbus Downtown Hotel.

		Illuminance (lx)		Percent Difference (LED2 to LED1)
		LED1 Mar 2014 4,900 hrs	**LED2 Mar 2016 12,100 hrs**	
Entry area	min	120	126	
	avg	**168**	**176**	**+5%**
	max	204	215	
	max:min	1.7	1.7	
Sink	min	415	429	
	avg	**535**	**550**	**+3%**
	max	584	603	
	max:min	1.4	1.4	
Desk area	min	177	187	
	avg	**240**	**257**	**+7%**
	max	275	294	

14 Unless otherwise noted, illuminances were measured using a Konica Minolta T-10A meter (serial number 207839) with an attached standard receptor head (serial number 30011584). This meter has rated linearity of ±2%, ±1 digit, rated cosine response within 3%, and rated spectral response within 6% of the CIE spectral luminous efficiency function, V(λ). The meter was within calibration for each set of measurements.

15 DiLaura et al., IES 10th Edition Lighting Handbook.

3.2 Integral LED Lamps in CFL Downlight and Wall Sconce Luminaires at St. Anthony Hospital, Gig Harbor, WA

Table 7 shows that the horizontal illuminance values in the surgery waiting area at St. Anthony Hospital ranged from 107 to 231 lx compared to 124 to 276 lx originally, a 13% reduction on average, with essentially the same max:min ratio of 2.2.[16] Even with this reduction, the average illuminance in this area still satisfies the relevant IES requirements, as does the max:min illuminance uniformity ratio. The space also has large windows that provide abundant daylight during the normal operating hours. As discussed in the original report on this project, the integral LED lamps changed the distribution of light in the space compared with the original CFLs, with the LEDs producing more light directly under the downlights than the original CFL downlights.

Table 7. Horizontal illuminance measurements in the surgery waiting area (top) and in the hallway joining the imaging changing rooms (bottom) at St. Anthony Hospital.

		Illuminance (lx)		Percent Difference (LED1 to LED0)
		LED0 Dec 2014 (initial)	**LED1 Jul 2016 (8,800 hrs)**	
Surgery Waiting Area	min	124	107	-7%
	avg	**186**	**161**	**-13%**
	max	276	231	-17%
	max:min	2.2	2.1	
Imaging Hallway	min	129	105	-9%
	avg	**155**	**136**	**-13%**
	max	185	165	-19%
	max:min	1.4	1.6	

Horizontal illuminance values in the hallway joining the changing rooms ranged from 105 lx to 165 lx after 8,800 hours, with a uniformity ratio (maximum to minimum) of 1.6, compared to a range of 129 lx to 185 lx and a uniformity ratio of 1.4 when originally installed. On average, this was a 13% reduction in illuminance. The illuminances and illuminance ratios produced by the LED systems continued to meet IES recommended values, even with the observed reduction in illuminance.

3.3 LED Retrofit Kits in CFL Downlights at the Princeton University Icahn Lab, Princeton, NJ

To evaluate the performance of the CFL downlights converted to LED retrofit kits at Icahn Lab, illuminances in an open conference area were initially measured in October 2014, after the LED retrofit had occurred. Horizontal illuminances were measured on a grid across the conference table, with an average of 584 lx and a max:min uniformity ratio of 1.3. These satisfy IES recommended values for conference areas. Follow-up measurements were taken at approximately 7,400 hours of operation. The average horizontal illuminance was 588 lx, an increase of 1% from the original measurements, with a maintained uniformity ratio of 1.3 (Table 8). The small differences in measured values are within the expected measurement error for field measurements; thus, the illuminances can be considered equivalent for the two measurements.

[16] Three measurement points from the original data set were excluded from the set of comparison data due to a change in a nearby fluorescent luminaire that also contributed to those three points.

Table 8. Horizontal illuminance measurements in a conference area at the Icahn Laboratory.

	Illuminance (lx)		Percent Difference (LED1 to LED0)
	LED0 Oct 2014 (initial)	LED1 Mar 2016 (7,400 hrs)	
min	505	502	-1%
avg	**584**	**588**	**+1%**
max	659	664	+2%
max:min	1.3	1.3	

3.4 LED Retrofit Kits in Fluorescent Troffers at the Princeton University Icahn Lab, Princeton, NJ

Changes in illuminance were not documented in the spaces illuminated by the troffer retrofit kits in the Icahn Lab due to changes in those spaces that would affect illuminance measurements, such as changes to the walls and substantial changes in laboratory equipment present.

3.5 LED Retrofit Kits in Halogen Wall Wash Luminaires at the University of Maryland CSPAC, College Park, MD

The 10th Edition of the IES Lighting Handbook recommends that public transition spaces that are independent passageways (e.g., not encompassed by surrounding task areas) have an illuminance of 25 lx on horizontal surfaces and 15 lx on vertical surfaces, when the majority of occupants are under the age of 25.[17] This is appropriate for the hallways at the CSPAC because they serve to transition students between classroom spaces, and do not connect to performance venues or other areas frequently visited by the public in the evenings. The initial illuminance measurements (LED0) in the area near one of the small wall washers in hallway 2782, captured with the Konica Minolta T-10A meter, showed the average horizontal and vertical illuminance values exceeded IES recommendations (see Table 9). After the follow-up measurements (LED1), the illuminance levels still met IES recommendations. For the small wall washer, the values decreased by 15% and 13% on average, for the horizontal and vertical measurements, respectively. Illuminance levels decreased, even with the dimming level set at 100% instead of the 80% level set at the time of the initial measurements. The interaction between the dimming level and lumen output of the LED module is unknown, so although the change in dimming level would be expected to increase the illuminance on the wall, this was not verified or quantified.

Table 9. Horizontal and vertical illuminance measurements for the area near one of the small wall washers in hallway 2782.

		Horizontal Illuminance (lx)		Percent Difference (LED1 to LED0)	Vertical Illuminance (lx)		Percent Difference (LED1 to LED0)
		LED0 14-Aug (0 hrs)	LED1 15-Mar (4,600 hrs)		LED0 14-Aug (0 hrs)	LED1 15-Mar (4,600 hrs)	
2782-14	min	32	30	-6%	19	16	+8%
	avg	**38**	**32**	**-15%**	**46**	**40**	**-13%**
	max	42	37	-21%	128	123	-32%
	max:min	1.3	1.2		6.9	7.8	

17 DiLaura et al., IES 10th Edition Lighting Handbook, pp.10.26-10.27.

4 Operations and Maintenance of the LED Systems

In addition to visiting each facility for follow-up colorimetric and photometric data collection, DOE requested operations and maintenance information from the facilities staff at each project. The information requested included details about any product failures and replacements, user complaints, lighting control operations, and other related topics. The information obtained for each project is summarized below.

4.1 Dedicated LED Luminaires at the Hilton Columbus Downtown Hotel, Columbus, OH

As of December 2016 (after 14,500 hours of operation), there have been very few issues with the 3,700 new LED downlight luminaires installed at the Hilton Columbus Downtown Hotel, according to the property operations staff. Less than six required driver replacements during the first few months of operation, and four additional luminaires have been replaced since then. These luminaires would flicker on and off before catastrophic failure, leading to guest complaints and subsequent replacement.

Dimming controls are the only element of the LED lighting solution that has caused guests to complain. Guests occasionally are confused about the dimming capability, maybe because the slide dimmer that controls the downlights in the seating area is relatively small and located alongside a conventional rocker switch (see Figure 8). Hilton staff believes that a different style of dimmer with more obvious functionality would make it easier for guests to adjust the lighting.

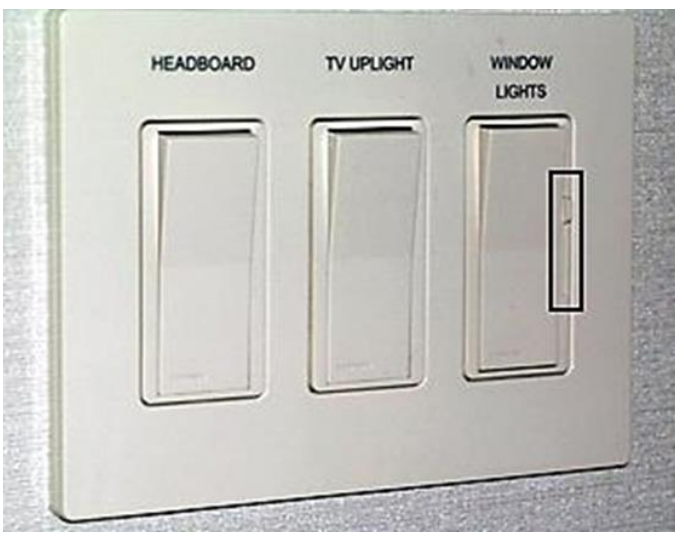


Figure 8. Lighting controls in the guest rooms at the Columbus Downtown Hilton. The switch marked “Window Lights” controls two LED downlights with an on/off rocker switch and a small slide dimmer located next to the rocker switch (outlined in a box in the photo). Some guests are confused by the controls and do not understand the dimming functionality and control.

As described in the original report, a passive infrared ceiling-mounted wireless vacancy sensor was implemented in the Hilton guest room bathrooms to enhance energy savings. DOE verified that the vacancy sensor was operating properly during the initial site visit, when it consistently extinguished the bathroom lights after 15 minutes of vacancy during three different trials. However, during the follow-up visit, three trials showed the vacancy sensor appeared to not be functioning properly, as it did not switch the bathroom lights off after 30 minutes of vacancy. This was most likely the result of a guest disabling the sensor to keep the bathroom light on. Although an inoperable sensor would likely reduce energy savings (if guests fail to turn the light off when leaving the bathroom), it would be unlikely to cause any guest complaints that would initiate a response from Hilton operations staff. Hilton operations confirmed that their engineering staff test the sensors during periodic maintenance checks and sometimes find that a sensor has been disabled by a guest, in which case they re-set it for proper operation.

The estimated annual energy savings of more than 200,000 kWh combined with the low system maintenance requirements have yielded significant cost savings for the hotel, and have fully satisfied the initial expectations of the operations staff. According to Kevin Barman, Director of Property Operations for the Hilton Columbus Downtown Hotel:

> "The LED fixtures and controls are meeting our overall expectations for guest room lighting and for energy savings. This project has proven again the ability of LEDs to be a cost-efficient lighting solution, that provides the required amount and quality of light, while saving energy overall."

4.2 Integral LED Lamps in CFL Downlight and Wall Sconce Luminaires at St. Anthony Hospital, Gig Harbor, WA

For the initial installation at St. Anthony Hospital, the economic arguments for integral LED lamps were very persuasive, mainly due to material and labor costs that were much lower than those for new luminaires or retrofit kits. The lamp replacements were performed by the in-house facilities staff and any additional electrical work, such as re-wiring or replacing ballasts, was done by the hospital's in-house licensed electrician. The hospital also received a $13 rebate per lamp from its electric utility, which further reduced the initial material costs.

As cited in the original project report, five of the 1,262 installed LED lamps failed upon initial installation and were replaced by the lamp manufacturer. In addition, some of the integral LED lamps initially operated erratically, usually flashing on and off or flickering noticeably. In some cases, this was caused by an incompatibility between the LED lamp and the CFL ballast, and in others, the downlight was found to be incorrectly wired. In response, the facility staff had all wiring problems corrected and replaced 25 of the existing CFL ballasts with newer model CFL ballasts. These steps resolved all of the initial issues with the LED replacement lamp installation.

However, the hospital has experienced some ongoing operational issues with the LED lamp and CFL ballast system. As of December 2016, after 11,000 hours of operation, the hospital's facility staff has replaced more than 60 of the integral LED lamps, with an additional 10 to 15 in need of replacement. The hospital also estimates that they have now replaced nearly 150 of the CFL ballasts. These changes were often made due to complaints about lamps flickering noticeably or not operating at all. The hospital reported that there have been no complaints about color quality, glare, or light levels with the LED lamps, but that users have complained about flicker. Replacing the CFL ballast and/or the LED lamp almost always resolves the flicker problem.

Another operational issue was related to the thermal environment in one luminaire type, the small wall sconce. While investigating a lamp failure in one of these wall sconce luminaires, the facilities staff observed indications of overheating at the lamp base, which was discolored and seemed partially melted. The facilities staff then conducted in situ testing to verify that the lamps were within manufacturer design specifications, but also noticed that the luminaire did not seem to provide adequate air flow to remove heat. Again, replacing the older CFL ballast with a newer model seemed to resolve the thermal issues within this luminaire type.

These operations and maintenance issues have resulted in the integral LED lamp installation requiring more attention than expected, with about 12% of the CFL ballasts and 6% of the LED lamps needing to be replaced. Because of this project and his further experiences with LED systems, Jason Henricksen from St. Anthony Hospital has observed:

> "LEDs are promoted as being maintenance free, but that's not necessarily true. The sensitivities of LED systems make them more nuanced as far as troubleshooting, since they seem to be much more sensitive to minor issues with the electrical system."

Another operational limitation encountered at St. Anthony was the lack of compatibility of the integral LED lamps with the existing dimming systems. In the few spaces where the CFL luminaires were operated on dimmers, the CFLs remained in place, since the LED lamps available at the time of the installation were not compatible with the dimming systems.

A long-term operational concern for this project is that the CFL ballasts that now operate the integral LED lamps will eventually fail. The ballasts had been operating for about five years before the retrofit, and in normal use will likely last 10 to 12 years total. At that time, the hospital will face further decisions regarding the downlights because replacing the 1,200+ ballasts may be costly or the CFL ballasts may no longer be available. Whether a new CFL ballast is installed or a dedicated driver for the LED lamps is selected, rewiring of the luminaires seems likely, which will result in higher labor costs than those of the initial lamp replacement described in this report. Under these circumstances, the installation of new LED luminaires may be economically attractive relative to ballast replacement, especially since the efficiency of LED luminaires is likely to increase while LED luminaire costs are expected to decrease.

Even with the operational issues encountered on this large project, the hospital found the return on investment from the effort attractive enough to continue with other LED implementations. Recent projects have focused on exterior lighting, with the parking lot, building perimeter, and some landscape lighting changed to LED, addressing locations that are difficult to access or would require additional rental equipment for maintenance. They continue to evaluate other opportunities for energy and maintenance costs savings through LED lighting. Annual energy savings for the facility from their initial LED implementations are estimated to be roughly $14,500.

4.3 LED Retrofit Kits in CFL Downlights and Fluorescent Troffers at the Princeton University Icahn Lab, Princeton, NJ

The retrofit kit conversions of the recessed 2x2 troffers and downlights at the Icahn Lab continue to show great success, from the operations and maintenance perspective, after 11,000 hours of operation. The 815 LED retrofit kits in the recessed troffers have had no failures requiring replacement of components, and the same is true for the 245 LED retrofit kits installed in the downlights. There have been no user complaints about the installation; in fact, the Princeton facility staff report that the only request was from an office worker who wanted to further dim the LED lighting in his office to save more energy while still meeting his needs for lighting.

At the time of the original report on this project, the wireless occupancy sensing system had not been fully deployed as planned, and that continues to be true. Communication and data management limitations with the occupancy sensors have prevented the implementation of the original plan to have the sensors communicate through the building automation system sub-network so that they could be used for controlling the HVAC and lighting systems.

As explained in the original report, the LED solutions implemented in the Icahn Lab were expected to save over 61,000 kWh annually and yield a simple payback of less than four years; the Princeton facility staff stated that the systems are delivering the savings as expected. Based on the success of the Icahn Lab project as well as earlier LED implementations at Princeton, the university has continued to aggressively pursue LED conversions as part of a campus-wide energy conservation and carbon reduction program.[18] According to Arthur Murphy, Princeton's Project Energy Engineer:

> "We continue to move full speed ahead with LED projects, since they almost always meet our economic, energy and carbon reduction objectives. While our short-term goals can in many cases be met with retrofit lamps in existing luminaires, we expect that longer-term efforts will move towards replacing luminaires and implementing connected systems that allow for communication and data exchange between the various energy and communication systems in our facilities."

4.4 LED Retrofit Kits in Halogen Wall Wash Luminaires at the University of Maryland CSPAC, College Park, MD

A main goal of the retrofit at CSPAC was to reduce maintenance costs, as the incumbent halogen wall washers, operating 7,300 hours per year, required continual maintenance. Energy savings of approximately 80% was considered an additional benefit by UMD facilities management. In areas where the wall washers were installed, the ceilings are as high as 41 ft, and in one area over stairs the distance from floor to ceiling ranges from 10 to 23 ft, requiring a scissor lift and scaffolding for maintenance of the lighting system. The LED retrofit kit implementation has fully satisfied the primary goals of reducing maintenance, while retaining the visual appearance of the CSPAC. Through early November 2016, after a total of 17,000 operating hours, there had been no product failures requiring replacement, a significant improvement compared to the frequent relamping that had been required with the halogen lamps.[19] In addition, there have been no user complaints about the LED system.

The substantial savings in operation and maintenance costs that were realized through the LED retrofit kit installation have informed future plans for LED implementation at UMD. According to the facility staff, the CSPAC project has demonstrated that converting existing luminaires to LED rather than replacing the luminaires can be an effective strategy in some applications. In the CSPAC project, significant installation cost savings were achieved through conversion of existing luminaires, and conversion was also less disruptive to the building than replacing the luminaires and repairing the drywall ceiling. In other applications, such as recessed troffers in grid ceilings, replacing the existing luminaires with new LED luminaires is considered.

As of January 2017, UMD has completed additional LED conversions in other buildings. Areas with pendants or fluorescent troffers have been re-lamped with integral LED lamps since the labor and material cost was lower than the cost of installing retrofit kits in the existing luminaires. Areas with self-ballasted CFLs installed to replace A19 and PAR38 incandescent lamps have been replaced with integral LED lamps. All installations are expected to achieve predicted energy savings, reduce maintenance costs, and maintain or improve lighting levels. Planning and scheduling further conversions is ongoing.

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[18] For a complete list of the projects at Princeton University, see the GATEWAY Demonstration University Projects page: http://energy.gov/eere/ssl/gateway-demonstration-university-projects.

[19] In November 2016, one module was reported to be operating erratically and is now being evaluated, but that has been the only reported product issue.

5 Discussion

5.1 Colorimetric Performance

Figure 9 shows the range in chromaticity change (Δu'v') for each site based on the estimated hours of operation at the time measurements were taken. Although the data collected for the downlights at the Hilton Hotel did not allow the calculation of the Δu'v' values, these products showed very little change in their CCT, CRI, and R_9 values after more than 12,000 hours of use. The retrofit kits installed in the downlights and troffers at the Icahn Lab similarly show stable color performance after 7,400 hours; the downlight retrofit kits had an average Δu'v' of 0.0018 while the troffer retrofit kits installed in the lab fixtures had an average Δu'v' of 0.0007, almost one-third less than the corridor fixtures (average Δu'v' of 0.0018) given the reduced hours of operation. After 8,800 hours of use, the integral LED lamps used at St. Anthony had Δu'v' values of 0.0062 (surgery waiting area) and 0.0017 (imaging changing rooms) on average. Similar to the Icahn troffers, the downlights in the changing rooms are assumed to operate for fewer hours that those in the surgery waiting area.

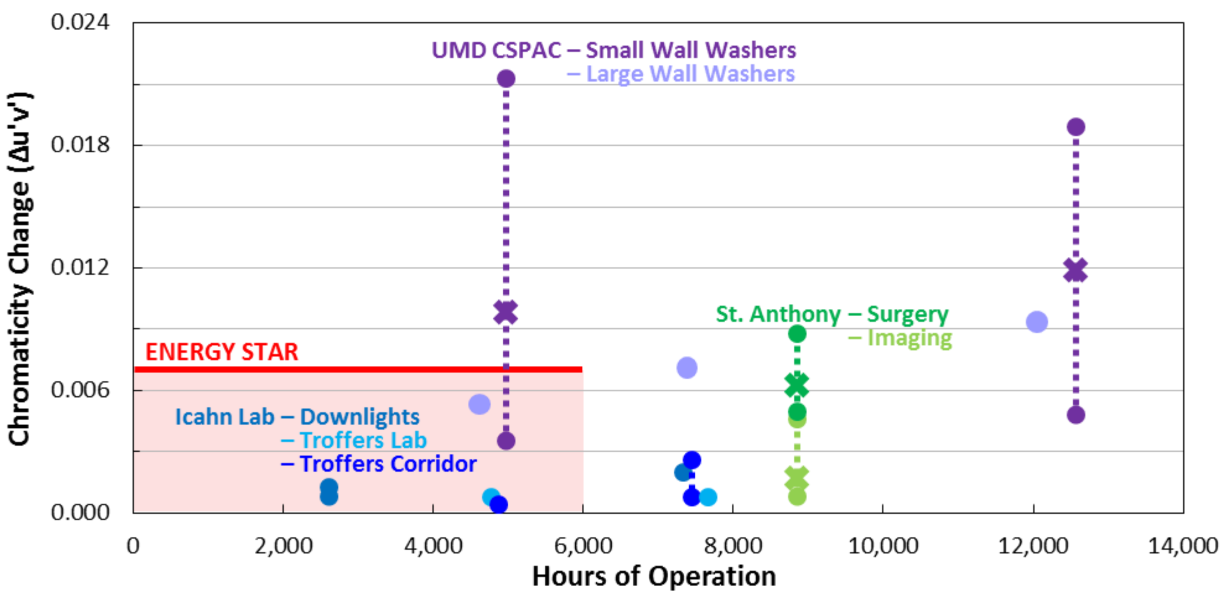

Figure 9. Overall chromaticity change for UMD CSPAC wall washer retrofit kits, Icahn Lab troffer and downlight retrofit kits, and St. Anthony replacement lamps based on the hours of operation at the time the measurements were collected. The average chromaticity change is marked by an X, while the minimum and maximum values are marked with circles, connected by a dotted line. If the range in performance is small, the average may not be marked and the circles may overlap.

For all measurement times, each site has measurement points that are below the red horizontal line in Figure 9, indicating the chromaticity change is less than the ENERGY STAR standard of 0.007. The ENERGY STAR criterion is perhaps the only defined criterion for chromaticity shift. It is a reasonable starting point, but may not be strict enough to ensure very high-quality lighting, especially since the lifetimes of LED products routinely far exceed 6,000 hours. This level of difference is readily noticeable in many interior lighting settings, if two lamps with that level of difference are viewed simultaneously and in relative proximity. However, if all the lamps in a room undergo a change of that magnitude—and in the same direction—over the course of several years, the occupants may not detect that the lighting has changed, at least not until one or more of the lamps is replaced.

The retrofit products in UMD's CSPAC exhibited substantially greater color shift than the other products; most of the measurement points are above the 0.007 line. After the third round of measurements (at least 12,000 hours of operation), the small wall washer products had an average Δu'v' value of 0.0118 compared to the initial set of measurements.[20] The LED module manufacturer made no claims about color consistency nor were the products ENERGY STAR qualified.

After the LED1 measurements, further investigation of the installed LED modules revealed that although the 6-inch LED modules installed in these wall washers had the same product specification, the dates on the labels were different. The LED modules installed in wall washer 2797 in May and July 2014 are dated 2013 while the modules installed in wall washers 2782 and 2799 in August 2014 are dated 2012. The LED1 measurements revealed only two of the 18 LED modules in hallway 2782 and area 2799 had a Δu'v' value less than 0.007, while all six of the LED modules in hallway 2797 had a Δu'v', value greater than 0.007. The differences in the chromaticity shift are illustrated in Figure 5, with hallway 2797 in the graph on the left and hallway 2787 and area 2799 in the graph on the right. The large wall washers, shown in Figure 6, perform similarly to the small wall washers in hallway 2797. Regardless, although the chromaticity shift measured for the LED retrofit kits at the UMD's CSPAC was greater than expected, the fact that the products have operated for more than 17,000 hours without any required maintenance satisfied the project goals for the university. The incumbent halogen lamp system would have required numerous lamp replacements during the same period, with much greater energy use.

5.2 Photometric Performance

Figure 10 shows the overall maintained illuminance for each of the sites based on the hours of operation at the time measurements were collected. At the Hilton Hotel, the LED downlights provided sufficient lighting to satisfy IES task requirements after both sets of measurements; all maintained illuminance values were significantly greater than the benchmark 70%; in fact, all of the values increased. In comparison to other downlight options, CFLs typically have a 10,000 hour rated life; thus, at least half the lamps would have been expected to be replaced within the first 12,100 hours of data. At the Icahn Lab, illuminance levels after 7,400 hours of operation were also greater than the initial levels with a maintained uniformity ratio.[21] The average illuminance for the integral LED lamps at St. Anthony Hospital also still met the relevant IES requirements after 8,800 hours.[22] While the retrofit kits installed in UMD's CSPAC varied in performance, the illuminance was above 70% of initial after an estimated 5,000 operating hours.[23] Although additional illuminance data was not collected, after 17,000 hours of operation only one of the 135 modules may need to be replaced, whereas the incumbent halogen lamps with a 1,500 hours rated life would have been replaced 11 times within the first 17,000 hours. Thus, from an energy and maintenance savings standpoint, the conversion was worthwhile.

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20 The pattern of color shift seen in UMD's LED modules was similar in performance to the results in CALiPER Report 20.5. Refer to this report for more information: DOE SSL Program, *CALiPER Report 20.5: Chromaticity Shift Modes of LED PAR38 Lamps Operated in Steady-State Conditions*, February 2016: https://energy.gov/sites/prod/files/2016/03/f30/caliper_20-5_par38.pdf.

21 TerraLux performance claims: L70 at 60,000 hrs, 5-year warranty.
MaxLite performance claims as of 2013-12-04 (not discussed in this section): L70 at 50,000 hrs.

22 Lunera performance claims: L70 at 50,000 hrs.

23 TerraLux performance claims as of 2013-05-14: L70 at 60,000 hrs, 5-year warranty.

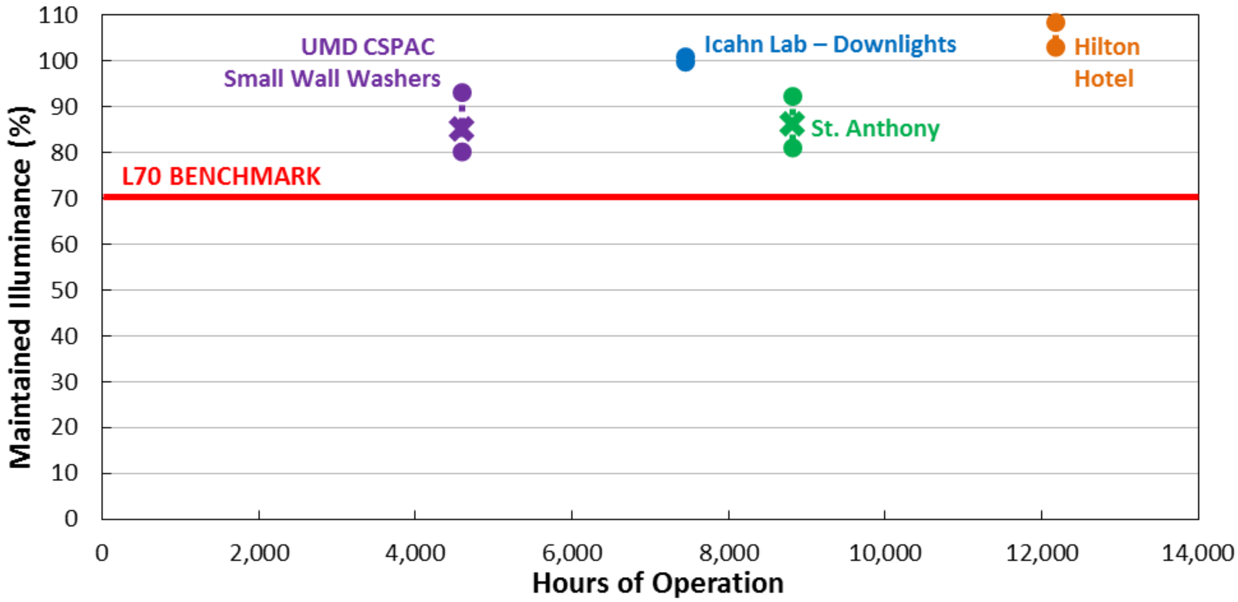


Figure 10. Overall maintained illuminance for the Hilton Hotel new downlights, UMD CSPAC wall washer retrofit kits, Icahn Lab downlight retrofit kits, and St. Anthony replacement lamps based on the hours of operation at the time the measurements were collected. The average maintained illuminance percentage is marked by an X, while the minimum and maximum values are marked with circles, connected by a dotted line. If the range in performance is small, the average may not be marked and the circles may overlap.

6 Conclusion

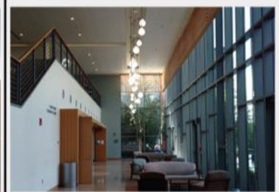
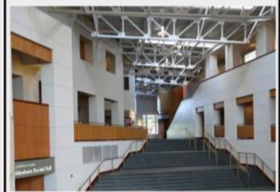
This GATEWAY project evaluated four field installations to better understand the long-term performance of a number of LED products, which can hopefully stimulate improvements in designing, manufacturing, specifying, procuring, and installing LED products. Field studies provide the opportunity to discover and investigate issues that cannot be simulated or uncovered in a laboratory, and the installed performance over time of commercially available LED products has not been well documented. Improving long-term performance can provide both direct energy savings by reducing the need to over-light to account for light loss and indirect energy savings through better market penetration due to SSL's competitive advantages over less-efficient light source technologies. The projects evaluated for this report illustrate that SSL use is often motivated by advantages other than energy savings, including maintenance savings, easier integration with control systems, and improved lighting quality.

The evaluations reported here demonstrate that the success of any lighting implementation cannot only be determined by a simple review of technical performance data, but instead depends on full consideration of the individual project goals and priorities:

- The installation of new dedicated LED downlight luminaires at the Hilton Columbus Downtown Hotel was primarily motivated by architectural and lighting design goals, with light distribution and quality improvements compared to incumbent technologies. In addition, the LED lighting provided both greater control for the hotel guests, and substantial energy and operational savings for Hilton. The LED luminaires have maintained their performance over the time of this study.
- The replacement of existing CFLs with integral LED lamps at St. Anthony hospital was the lowest cost option to convert the five-year old luminaires to LED and reduce the system's maintenance burden. The retrofit continues to make sense because of the attractive economics and the maintenance savings, despite a few performance and operational issues. The economics of the system may need to be re-evaluated as the CFL ballasts reach their rated lifetimes.
- The conversion to LED retrofit kits at the Princeton University Icahn Lab was initiated based on the University's energy and sustainability goals, and the results showcase the economic, energy, and sustainability opportunities with LED conversions. The LED retrofit kits installed in 2x2 fluorescent troffers and in CFL downlights have maintained their performance over the time of this study. The use of controls demonstrates the additional savings that can be gained from controls strategies but also illustrates the difficulties that can be encountered in commissioning controls systems.
- The incumbent halogen wall wash luminaires at the University of Maryland CSPAC had high energy and operational costs due to the high wattage lamps and the long operating hours, but addressing these issues by converting the system to LED was made problematic by the unusual luminaire shape and also by the architectural constraints. Despite some performance concerns in color shift and maintained illuminance, the LED retrofit kits have provided a cost-saving solution due to the low initial cost, ease of installation, and energy and maintenance savings.

Table 10 summarizes each project, including the technology platform installed, the types of products and applications included, highlights of the initial and follow-up results, and operations and maintenance performance.

Table 10. Summary of each project. The following information is included for each site: technology platform, types of products and applications included, highlights of the initial and follow-up results, and operations and maintenance performance.

	HILTON DOWNTOWN COLUMBUS, OH NEW LUMINAIRES	ST. ANTHONY HOSPITAL GIG HARBOR, WA INTEGRAL LAMPS	ICAHN LABORATORY PRINCETON, NJ RETROFIT KITS		PERFORMING ARTS CENTER COLLEGE PARK, MD RETROFIT KITS
DEMONSTRATION PROJECTS					
BUILDING DETAILS & ANNUAL ENERGY SAVINGS					
	• Occupancy in 2012 • 450,000 ft²	• Retrofit completed in 2014 • 250,000 ft²	• Retrofit completed in 2015 • 98,000 ft²		• Retrofit completed in 2014 • 342,000 ft²
	203,331 kWh 50% savings vs CFL	**131,279 kWh 59% savings vs CFL**	**61,025 kWh 60% savings vs CFL**	**57,050 kWh 24% savings vs FL**	**990,756 kWh 80% savings vs halogen**
LIGHTING INSTALLATION	• Dedicated LED downlights: Eaton's Cooper Lighting Business Portfolio® LED downlights • 3,700 installed in hotel guest rooms	• Integral LED lamps in CFL downlights: Lunera® Helen LED lamps • 1,262 installed in public spaces throughout the hospital	• LED retrofit kits for CFL downlights, using TerraLUX® DR8 LED retrofit kits • 245 installed in corridors, lobbies, and conference areas	• LED retrofit kits for 2×2 troffers, using MaxLite® LED retrofit kits • 815 installed in open and enclosed laboratories, corridors, and offices	• LED refrofit kits in halogen wall washers, using TerraLUX® Linear Line Voltage LED modules • 135 LED modules installed in 87 luminaires in public corridors
MOTIVATION	• Provide high quality, flexible lighting with familiar dimming capabilities • Satisfy task and ambient lighting needs with a high efficacy, low power solution • Reduce operational costs with long lifetimes, energy savings, and low maintenance needs	• Reduce maintenance costs and achieve substantial energy savings • Provide modest up-front investment, including relatively minimal labor costs for installation along with ease of installation • Achieve sustainability goals	• Achieve energy savings and the associated carbon reduction • Allow for maintenance and operational savings • Improve lighting quality	• Reduce power substantially • Achieve favorable pricing and warranty terms • Integrate with control system • Meet dimming performance requirements	• Reduce maintenance costs • Achieve a low-cost solution while providing an acceptable quality of light • Retain visual appearance of space • Benefit from energy savings • Solve melting conductor insulation issue by reducing heat
INITIAL RESULTS	• Light levels satisfied or exceeded IES recommendations • Dimming and control scheme provided flexibility for adjusting lighting • Improved color rendition • More consistent color than CFLs	• Substantial energy savings with slight increase in light levels • Small changes in distribution of light • Improved color rendition • More consistent color than CFLs	• Significant energy savings and better control of lighting • Light levels satisfied or exceeded IES recommendations • Improved color rendition • More consistent color than FL and CFLs		• Significantly reduced maintenance costs and hassle • Acceptable changes in light levels and distribution • Some flicker observed but deemed acceptable for transitional spaces
FOLLOW-UP RESULTS	• Light levels increased by 3% to 7% on average and continued to satisfy, if not exceed, IES recommendations • Color properties remained very stable	• Light levels decreased by 7% to 19% while maintaining the same uniformity ratios and meeting IES recommendations • Color performance was maintained with chromaticity shift within the specified ENERGY STAR recommendations	• Light levels for the downlight retrofit kits increased by 1% on average after 7,400 hours, while maintaining uniformity ratios and meeting IES recommendations • Color properties for both retrofit kits have remained very stable and stayed within ENERGY STAR recommendations		• The majority of the light levels decreased by 10% to 30%, with some fixtures decreasing greater than 30% • The chromaticity shift is significantly greater than the ENERGY STAR maximum
MAINTENANCE	• The lighting and controls have received positive online reviews for the hotel • Significant cost savings achieved due to the annual energy savings and low system maintenance requirements • Minor issues with the passive infrared wireless vacancy sensors	• Some incompatibility issues between the LED lamps and CFL ballasts (6% and 12% replaced, respectively) • Lack of compatibility of the integral LED lamps with the existing dimming system • Overall the retrofit is achieving energy and maintenance cost savings	• No failures requiring replacement of components for either the troffer or downlight retrofit kits • Wireless occupancy sensing system has not been fully deployed as planned due to communication and data management limitations with occupancy sensors • Systems are delivering the savings as expected and the university has continued to aggressively pursue LED conversions as part of a campus-wide energy conservation and carbon reduction program		• Substantial savings in operation and maintenance costs were realized • No product failures requiring replacement and no user complaints • University's staff is planning on pursuing future LED retrofit options, along with new LED luminaires when appropriate