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GATEWAY
Demonstrations

LED Lighting in a Performing Arts Center

Host Site: University of Maryland, College Park, Maryland

July 2015

Prepared for:

Solid-State Lighting Program
Building Technologies Office
Office of Energy Efficiency and Renewable Energy
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Prepared by:

Pacific Northwest National Laboratory

University of Maryland Wall Washer Retrofit
LED Modules Replace Halogen Lamps in a Performing Arts Center

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

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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 field evaluations of high-performance solid-state lighting products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Program provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Though products used in the GATEWAY program may have been prescreened for performance, 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.

Executive Summary

The University of Maryland (UMD) retrofit of halogen wall washers in the Clarice Smith Performing Arts Center (CSPAC) was documented by the U.S. Department of Energy (DOE) Solid-State Lighting (SSL) GATEWAY program, beginning with mock-ups in the spring of 2014 through final installation in March 2015. The wall washers illuminate hallways lining the atrium, providing task illuminance for transitioning between spaces and visual interest to the atrium boundaries. The main goals of the retrofit from halogen to light-emitting diode (LED) were to retain the visual appearance of the space while reducing maintenance costs – energy savings was considered an additional benefit by UMD Facilities Management staff. Measurements were recorded before and after the retrofit from halogen to LED to capture any changes in the lighting quality, as well as long-term performance of the LED technology.

The 87 halogen wall washers, operating 7300 hours per year, required continual maintenance. In areas where the wall washers are 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. Hoping to reduce maintenance, UMD Facilities Management considered all known LED alternatives in the spring of 2014, but viable options remained limited. The LED options were initially evaluated based on several factors, including initial cost and size. Two distinct options were considered financially feasible, and both were mocked-up: a complete LED wall washer and a retrofit of the internal components of the existing wall washer with an LED module.

The LED module was selected because it was a low-cost solution that provided an acceptable quality of light. In this particular application there were some visual changes after the retrofit, the largest being the amount of light reaching the walls and the floor, with some smaller changes in distribution. Flicker was noticeable and considered acceptable for this application, but may not be acceptable for other applications. There were also some changes in the color appearance of the light, which was a reminder of the care that must be taken when ordering and receiving products.

As the efficacy and lifetime of LED technology continues to improve, more demands are being placed on the visual appearance of the light. The visual appearance is a concern for many retrofits, even when maintenance or energy efficiency is the primary concern, because often facilities personnel do not want to go through the process of getting approvals for any appearance changes. If a new luminaire can deliver a quality of light similar to the incumbent product, the retrofit process can often move more quickly.

All installed LED modules were operational and required no maintenance as of the writing of this report, so the benefits of the LED module wall washer retrofit are already being realized. UMD Facilities Management is pleased with the results of this retrofit, and continues to initiate LED retrofit projects across the UMD campus.

Acronyms and Abbreviations

AFF	above finished floor
CIE	International Commission on Illumination
CRI	color rendering index
CSPAC	Clarice Smith Performing Arts Center
DOE	U.S. Department of Energy
HID	high-intensity discharge
IES	Illuminating Engineering Society
LDD	luminaire dirt depreciation
LED	light-emitting diode
SPD	spectral power distribution
SSL	solid-state lighting
UCS	uniform chromaticity scale
UMD	University of Maryland

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1 Introduction

The University of Maryland (UMD) began retrofitting halogen wall washers in the Clarice Smith Performing Arts Center (CSPAC) in April 2014. The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) GATEWAY program documented this process through the final installation in March 2015, summarized in this report. The wall washers illuminate hallways lining the atrium, providing task illuminance for transitioning between spaces and visual interest to the atrium boundaries. The main goals of the retrofit were to retain the visual appearance of the space while reducing maintenance costs – energy savings was considered an additional benefit by UMD Facilities Management.

The 87 halogen wall washers, operating 7300 hours per year, required continual maintenance. The frequent spot re-lamping also required re-aiming of the fixtures to retain the desired distribution of light on the gray walls. In areas where the wall washers are 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. The supply conductor insulation melted in some of the wall washers, which was another maintenance concern.

The retrofit occurred over the course of a year in several stages (Figure 1), beginning with examining potential alternatives to the incumbent halogen wall washers, then mocking-up options, and finally retrofitting all wall washers. The options selected as a result of the mock-ups remained installed.

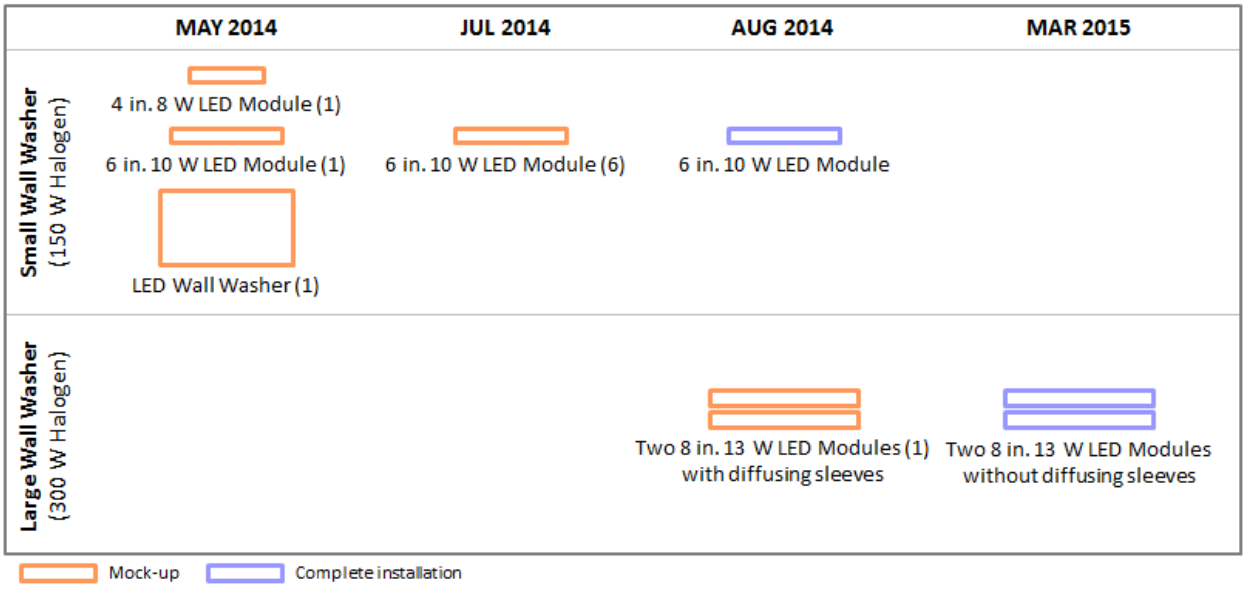

Figure 1. UMD CSPAC Wall Washer Retrofit Timeline: Mock-up and Installation. After potential alternatives to the incumbent halogen wall washers were assessed, the selected options were mocked-up in various stages, delineated above by the orange outline. The installation was completed for the small wall washers in August 2014 and for the large wall washers March 2015, shown by the purple outline. The numbers in parentheses indicate how many of a given option were installed for the mock-up.

Hoping to reduce maintenance, UMD Facilities Management staff considered all known light-emitting diode (LED) alternatives in the spring of 2014, but viable options remained limited. The LED options were initially evaluated based on several factors, including initial cost and size. The only two financially feasible options were mocked-up: a new LED wall washer and an LED retrofit module for the existing luminaire. The mock-up provided an opportunity to visually evaluate light on the wall and floor, glare, color, dimming behavior, and

flicker. Many of these factors were unfavorable for the LED wall washer, while the LED module cost less and delivered the desired quality of light. Due to the low cost and ease of installation, the LED module provided a cost-saving solution even if it only lasts a couple of years, according to UMD Facilities Management. Additionally, energy savings were approximately 80% compared to the halogen wall washers.

Color consistency is very important when selecting luminaires to illuminate a plain, smooth wall. This is one of the more difficult applications because any change in color is easily noticeable. Distribution of light on the wall is also a challenge because often the goal of wall washing is to create a smooth gradient, which typically requires luminaires specifically designed for wall washing. The wall washers installed in the CSPAC have reflectors designed to distribute luminous flux from a tubular halogen lamp onto a wall, providing a smooth gradient of light on the wall. When the LED modules were installed, shown in Figure 2, they blocked the wall washer reflector that had directed the flux from the halogen lamp. DOE recorded illuminance and color measurements before and after the retrofit to better understand the performance of the LED module in the existing wall washers, particularly the distribution of light on the walls.

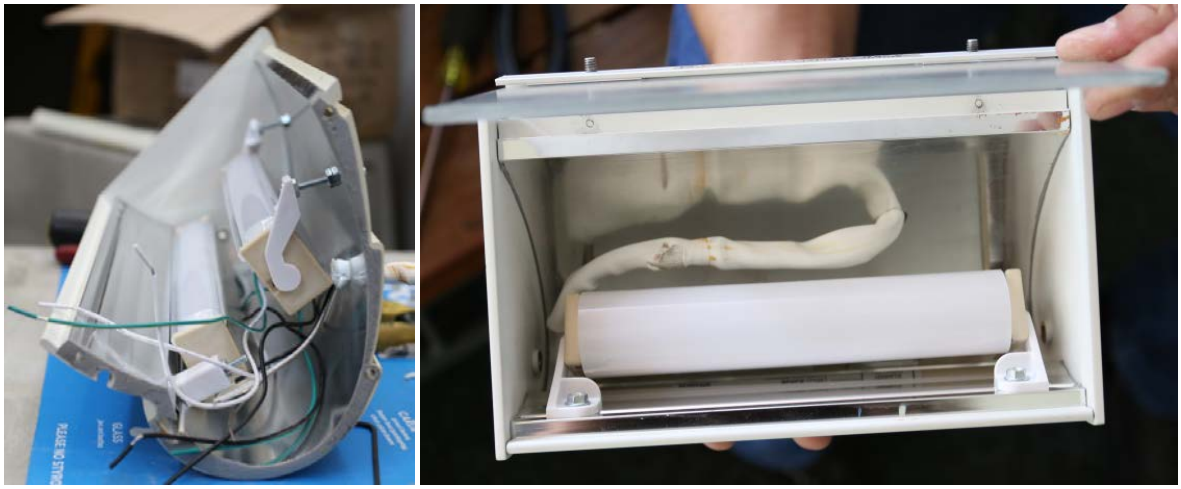

Figure 2. LED Modules in Existing Wall Washer Housings. The left image is a side view of the large wall washer housing with two LED modules and the right image is a front view of the small wall washer housing with one LED module.

2 Background

The Clarice Smith Performing Arts Center (CSPAC) sits on 17 acres of land on the University of Maryland (UMD) campus, opening to the public in 2001. This 341,996 ft² building, shown in Figure 3, was the largest single building ever constructed by UMD at the time it was built, housing six performance venues, rehearsal rooms, a library, and other spaces that serve students and the surrounding community. The architecture firm Moore Ruble Yudell envisioned the building as an academic village, each major hall with its own portico in the atrium that serves as a main street, greeting those who enter the CSPAC.

Figure 3. Exterior View of the University of Maryland (UMD) Clarice Smith Performing Arts Center (CSPAC). The varying shapes and sizes composing the exterior hint at the diversity of the interior spaces.

2.1 Atrium Characteristics

In the atrium the main sources of lighting during the day are the sun and high-intensity discharge (HID) high-bay luminaires mounted on the ceiling at a height that decreases from 41 ft above the floor at the main entrance to 23 ft above the floor at the back of the atrium. Rows of clear skylights spanning the width of the atrium illuminate the space. In the future, the HID luminaires might be replaced with theatrical luminaires that allow for scenes and color changing as part of a larger retrofit. The photographs in Figure 4 show the atrium during the day and at night. The brightness of the hallways that define the atrium perimeter is faint during the day compared to the daylight washing the main walls of the atrium; however, after sunset these hallways appear brighter—adding a perimeter glow and depth to the atrium. This glow is from wall washers that illuminate the walls of the hallways, the focus of this report.

2.2 Incumbent Halogen Wall Washers

The goal for this interior wall washer retrofit was to retain the visual appearance while reducing maintenance costs. Maintenance costs were significant because 87 wall washers with halogen lamps, rated at a 2000 hour lifetime, operating 20 hours per day—7300 hours per year—require continual maintenance to retain the desired appearance of the atrium. The dimming level was set to 30% during the day and 80% in the evening, which extended the life of the lamps, but the maintenance burden remained. The maintenance technician regularly replaced the halogen lamps as necessary, instead of implementing a group re-lamping policy. The number of halogen lamps replaced annually was not tracked.

Figure 4. Interior View of the UMD CSPAC Atrium. The wall washers illuminate the hallways that line the atrium during the day (left) and evening (right) as well as some surrounding areas. The brightness of the hallways is faint during the day compared to the daylight washing the main walls of the atrium; however, in the evening these perimeter hallways play a more dominant role in the visual appearance of the space.

Another UMD Facilities Management maintenance concern is the aiming of the wall washers, which becomes more of a problem the more the wall washers require maintenance. Less maintenance reduces the supervision required to make sure the wall washers are aimed properly each time the lamps are replaced. UMD Facilities Management assumed that the retrofit would also solve another significant maintenance concern, melting conductor insulation. Some of the halogen wall washers had supply conductors with melted insulation, and since the LED modules dissipated much less heat than the halogen lamps, the concern was expected to be eliminated.

The existing halogen wall washers in the CSPAC included a family of Winona wall washers:

39 Small (150 W) Ceiling Semi-Recessed Halogen Wall Washers (P1-SS-Q150-SSRS-SGW-X-STD)
28 Large (300 W) Ceiling Semi-Recessed Halogen Wall Washers (LSRU-LS-Q300-120V-P1-SGW-X-STD)
20 Large (300 W) Single Simple Pendant Halogen Wall Washers (LP1-LS-Q300-120V-P1-SGW-X-STD)

The 150 W small semi-recessed wall washers are mounted in the ceilings at lower heights, generally less than 11 ft. The 300 W large semi-recessed and pendant wall washers are mounted in ceilings with heights ranging from 10 to 41 ft. The small wall washers used 120 V 150 W T4 halogen lamps and the large wall washers used 120 V 300 W T3 halogen lamps. The wall washers are on two circuits that are controlled together with a Strand CD80 Supervisor modular dimmer rack system.

3 Mock-up of LED Options

There were limited LED wall washer options available during the selection process in the spring of 2014. One significant consideration was the size of the housing opening in the ceiling because the existing wall washers are installed in a drywall ceiling and any options that required additional repair to the ceiling added to the overall cost and complexity of the project. A solution that could work for both the small and large wall washers was also a priority. One custom luminaire option that would have required no ceiling repair was initially considered, but was cost prohibitive and consequently never mocked-up. Two distinct options were considered financially feasible, and both were mocked-up: a complete LED wall washer and a retrofit of the internal components of the existing wall washer with an LED module.

The mock-ups took place over a few months and were valuable for determining if the retrofit options could provide a similar distribution of light and color as the existing halogen wall washer. The benefits of the mock-up included the visual evaluation of the distribution of luminous flux on the wall and the floor, glare, color, dimming behavior, and flicker. The small wall washer retrofit options were mocked-up beginning in April 2014.

3.1 Small Wall Washer Mock-up

The small wall washer mock-up options included a complete replacement LED wall washer and an LED module that fit inside the existing wall washer housing. The LED wall washer was The Lighting Quotient elliptipar S222 with fraqtir optics, and it was mocked-up in both 2700 K and 4000 K. The LED module was the TerraLUX Linear Line Voltage LED module, with the 2700 K 4 in. and 6 in. long modules mocked-up along with a 3500 K 6 in. module. The LED module retrofit process is illustrated in Figure 5. The trim and mounting frame remained in the ceiling, and the adjustable luminaire housing was removed from the mounting frame. The halogen lamp and socket were removed from the luminaire housing, and the LED module was wired and then mounted to the housing with white plastic brackets. Prior to mounting the LED module, a plastic diffusing sleeve was slid over the lens and a thermal pad was attached to the aluminum heat sink on one of the sides of the module. The plastic diffusing sleeve and the white plastic brackets were both optional accessories.

The installation of the LED wall washer required the complete removal of the existing wall washer so the LED wall washer could be wired and mounted in the ceiling. The opening in the ceiling from the incumbent wall washer was larger than the LED wall washer, so tape was required to keep the wall washer in the ceiling during the mock-up.

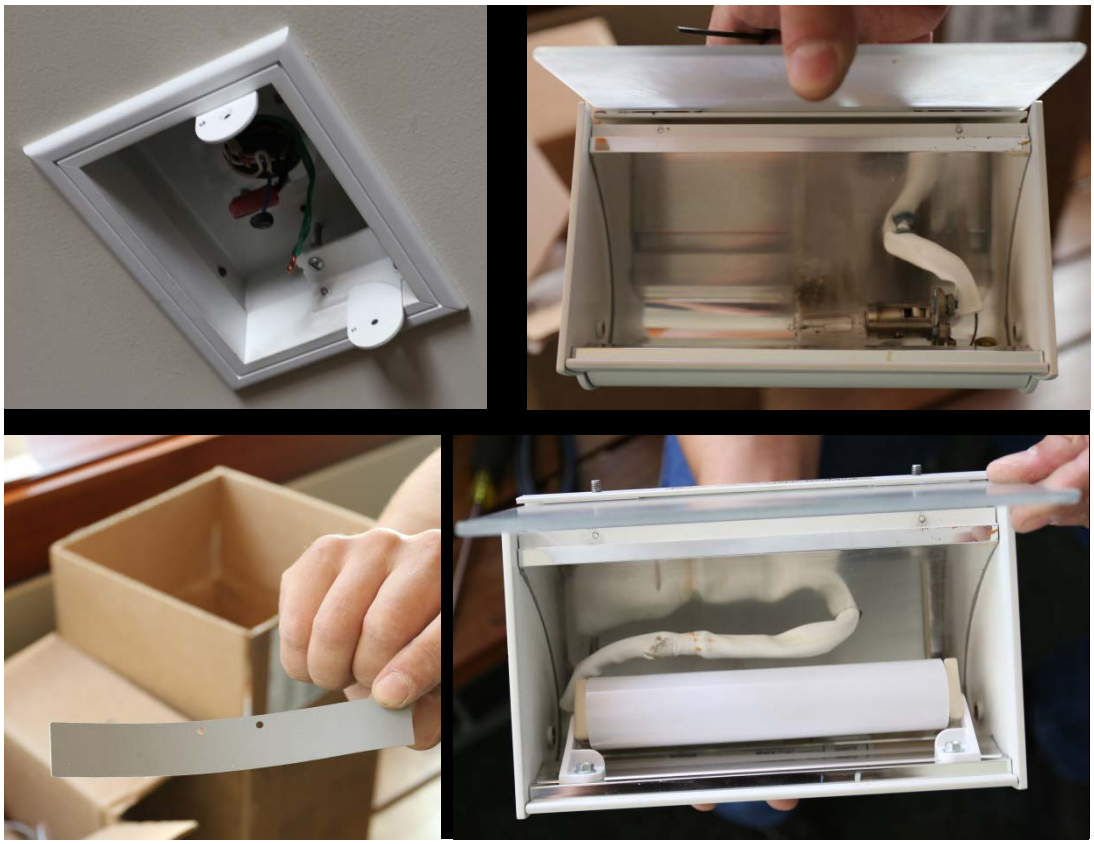

Figure 5. Retrofit of Small Wall Washer from Halogen to LED Module. The trim and mounting frame remained in the ceiling (top left), and the adjustable luminaire housing was removed (top right) so the halogen lamp and socket could be replaced with the LED module (bottom right). A thermal pad (bottom left) was to be attached to the module.

The mock-up compared the LED wall washer, LED module, and the existing halogen wall washer. UMD Facilities Management coordinated the mock-ups and from the beginning sought feedback from key CSPAC staff. The LED module had two financial advantages over the LED wall washer. First, the initial cost of the LED module was one-third the cost of the LED wall washer. Second, the LED wall washer was slightly smaller than the existing halogen wall washer, so patching the ceiling or fabricating custom trim plates would have been necessary—adding considerable cost and the risk of noticeable repair marks on the ceiling. In order to justify the cost difference, the LED wall washer needed to perform better than the LED module in the visual evaluation of the distribution of luminous flux, glare, and color. The side-by-side mock-up of some of the options is shown in Figure 6.

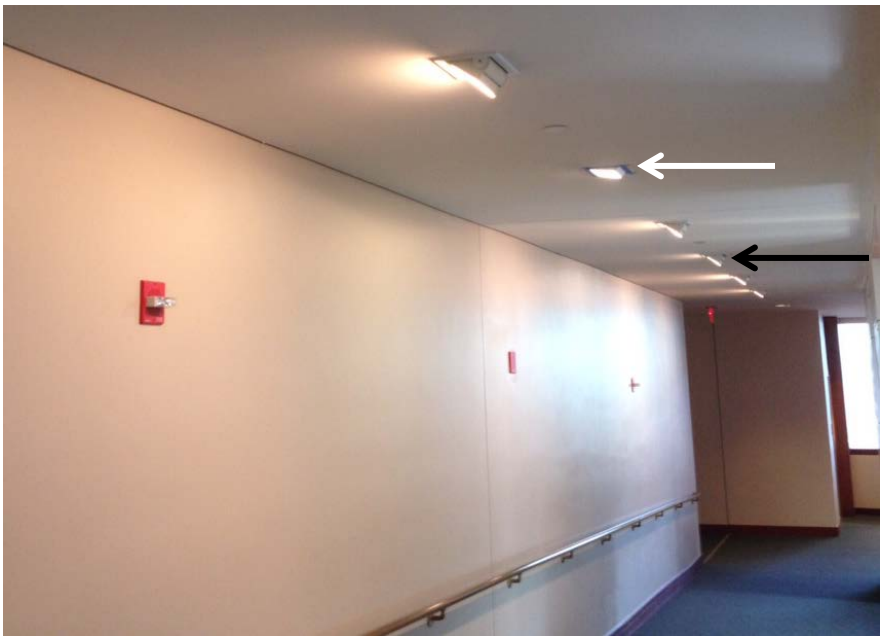

Figure 6. Initial Mock-up of the LED Wall Washer (white arrow) and the 6 in. LED Module (black arrow) with the Existing Halogen Wall Washers (no arrow). The dimming level was 30%. The LED wall washer did not provide light near the top of the wall, or distribute the light as widely on the wall, when compared to the halogen and LED module wall washers.

The 17 W complete LED wall washer did not provide light near the top of the wall, or as widely on the wall as the halogen lamp or LED module in the existing wall washers. The distribution of light was similar between the 150 W halogen and the 10 W 6 in. LED module. The 10 W LED module provided less light on the ceiling than the existing halogen; however, it was barely noticeable and in some cases might be preferable. The 8 W 4 in. LED module did not provide enough light on the wall, so the 10 W 6 in. LED module was selected. There was a 13 W 8 in. LED module option that would have provided more light on the wall, but it was too long for the existing small wall washer housing. Although the 10 W LED module did not provide as much light on the wall as the 150 W halogen lamp, it was considered similar enough to be acceptable by UMD Facilities Management staff as well as key CSPAC staff.

The glare from the LED wall washer was noted by Facilities Management and CSPAC staff. Based on DOE observations, three factors seemed to contribute to the perception of glare:

- Individual LEDs were visible through the wall washer lens.
- Housing extended down about half as far as the existing wall washer (providing less shielding).
- LEDs were closer to the lens of the wall washer than the halogen lamps in the existing wall washer.

A louver was later added to the LED wall washer to mitigate the glare; however, it reduced the light on the wall about 20%, particularly on the edges, according to UMD Facilities Management staff. The LED wall washer would have likely been selected if the LED module was not considered to be a better option.

The 4000 K LED wall washer and 3500 K 10 W LED module were both considered too cool. Later, 2700 K versions of both were installed for comparison with the halogen lamps, which had a lower color temperature than their rating of 2900 K because the lamps were dimmed between 30% and 80% depending on the time of day. The color of the 2700 K LED module and LED wall washer were considered an acceptable match with the existing halogen.

Based on the similarity of the distribution of light and color of the LED module to the incumbent halogen lamp in the existing wall washer, in combination with the lower total cost, UMD Facilities Management decided to move

forward with the LED module. Lifetime of the LED module was not a principal concern given the low cost and ease of installation (requiring less than an hour to retrofit the existing wall washer during the initial mock-up). The LED module was considered a cost-saving solution even if it only lasted a couple of years, since the halogen lamps would have been replaced several times during that same time period. The long-rated lumen maintenance easily satisfied the project needs.

Initial dimming testing by UMD Facilities Management showed that the LED wall washer dimmed better than the LED module, dimming to less than 10%. The LED module was not rated for dimming, but according to the manufacturer it is compatible with a small number of phase dimmers—which explains why it dimmed on the Strand dimmer rack. Dimming performance can vary based on the number of LED luminaires installed, so the remaining six halogen wall washers in the mock-up hallway were retrofitted with the 10 W LED modules in early July 2014. The dimming performance of the seven 10 W LED modules was similar to just one 10 W LED module, with the LED modules flashing below a dimming level of 10% and off below 6%. UMD did not need to dim to less than 10% in the hallways, so LED module's inability to dim below 10% was not a considerable concern. Flicker was noticed, but was a minor concern in this transitional application where occupants do not spend extended periods of time. UMD is concerned about flicker in classrooms and other spaces where lectures are recorded (due to potential for interference caused by the camera and lighting), as well as spaces occupied by people who are sensitive to flicker.

3.2 Large Wall Washer Mock-up

The large wall washers in the CSPAC were lamped with a single 300 W halogen lamp. For the mock-up the halogen lamp and socket were removed and replaced with two 13 W 8 in. LED modules, shown in Figure 7. The same procedure used to retrofit the small wall washers was followed. The large wall washer mock-up in August 2014 occurred at the same time as the small wall washer retrofit of the remaining 32 incumbent halogen small wall washers in the CSPAC. Since TerraLUX was selected for the small wall washers, and offered a suitable product for the large wall washers, other manufacturers were not considered. The distribution of light and color from the wall washer with two 13 W LED modules was similar to the incumbent performance of the 300 W halogen lamp, and therefore, was considered acceptable by UMD Facilities Management staff.

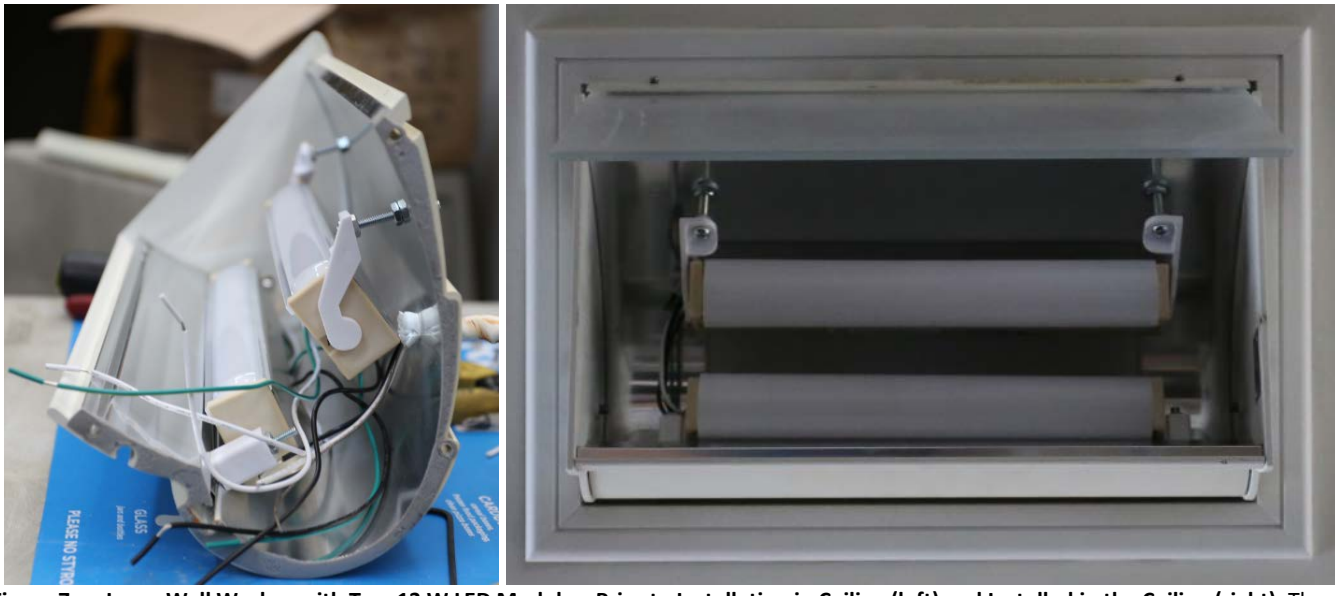

Figure 7. Large Wall Washer with Two 13 W LED Modules: Prior to Installation in Ceiling (left) and Installed in the Ceiling (right). The left photograph shows the modules without sleeves and the right photograph shows the modules with sleeves. The wall washer's glass lens was swung open and can be seen toward the top of the right photograph.

UMD Facilities Management found the mock-up process of the large and small wall washers to be worth the time and effort. Table 1 lists the pros and cons identified during the mock-up process for the incumbent halogen lamp, LED module, and LED wall washer.

Table 1. Pros and Cons of the Halogen Lamp, LED Module, and LED Wall Washer. The halogen lamp, LED module, and LED wall washer are compared based on cost, life, installation, and performance factors identified in the CSPAC mock-up process.

Source	Pros	Cons
Halogen lamp	• Lowest initial cost • Smooth dimming performance	• High maintenance cost (required frequent lamp replacement) • Short life (~2000 hr) • High energy consumption • Melting supply conductor insulation
LED module	• Low initial cost (one-third of the LED wall washer) • No ceiling modification costs • Long-rated lumen maintenance • Low energy consumption • Acceptable light distribution • Acceptable color performance • Low operating temperature • Acceptable dimming performance • Size and lumen output options	• Installation required electrical wiring work (licensed electricians) • Noticeable flicker (not considered an issue for application)
LED wall washer	• Long-rated lumen maintenance • Low energy consumption • Low operating temperature • Smooth dimming performance (to less than 10%)	• Initial cost (three times LED module) • Ceiling modification or custom trim plate costs • Installation required electrical wiring work (licensed electricians) and access above the ceiling • Narrow light distribution on wall (did not match halogen) • Glare

4 Illuminance and Color Measurement Results

Measurements were recorded before and after the retrofit from halogen to LED to capture any changes in the lighting quality, as well as long-term performance of the LED technology. Illuminance and color were measured on a portion of the wall and floor in a second floor hallway that is illuminated by small wall washers and in a third floor hallway that is illuminated by large wall washers. The areas are illustrated in Figure 8 and are referenced as 2782 (second floor) and 3797 (third floor) throughout the report—keeping with the University of Maryland (UMD) nomenclature for the Clarice Smith Performing Arts Center (CSPAC) spaces. Additional color measurements were recorded for 25 small wall washers: 16 in hallway 2782, 2 in area 2799, and 7 in hallway 2797. The small wall washer mock-ups took place in hallway 2797. Each fixture is labeled according to the area, followed by the count of the fixture relative to the front of the CSPAC, e.g., 2782-1 is the wall washer in hallway 2782 closest to the front entrance.

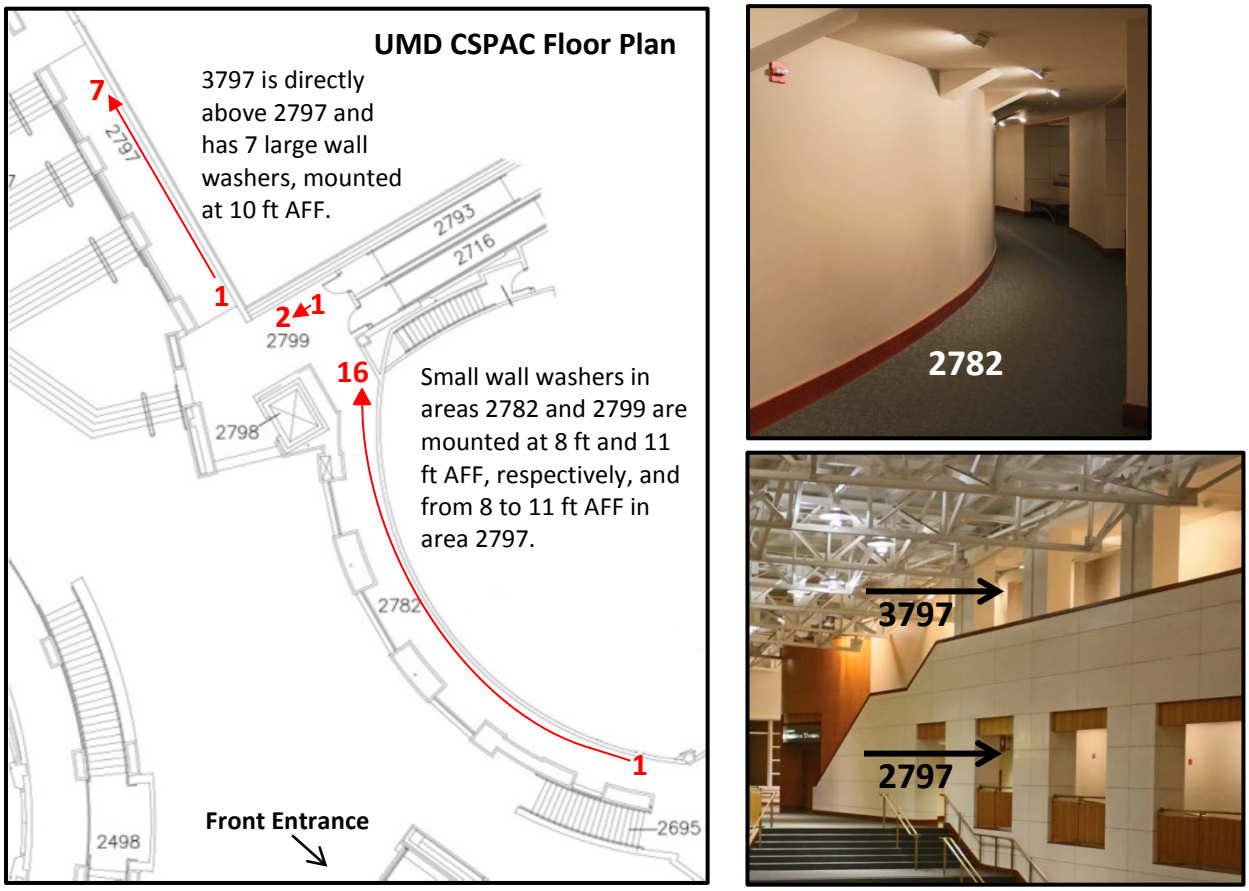

Figure 8. UMD CSPAC Interior – Partial Floor Plan of Second Floor Atrium and Adjacent Hallways (left), Photograph of Hallway 2782, and Photograph of Hallways 2797 and 3797 from Atrium. The red numbering indicates the wall washer labeling. Area 2782 has 16 small wall washers labeled 2782-1 to 2782-16, with the value following the dash representing the location of the wall washer relative to the front entrance of the building.

The equipment used to measure illuminance was the Konica Minolta Illuminance Meter T-10A (calibrated April 14, 2014) and the Konica Minolta Illuminance Spectrophotometer CL-500A.[2] The illuminance meters were always placed flat on the floor or on the wall when recording measurements. The timeline of the measurements is shown in Figure 9. The first set of field measurements was recorded in August 2014 when the 10 W LED modules were installed in the small wall washers and the second set of measurements was recorded in March 2015 when the 13 W LED modules were installed in the large wall washers. For a particular area of the CSPAC, illuminance measurements were always taken in the evening following the LED installation that occurred earlier in the day, and the halogen measurements occurred a night or two prior.

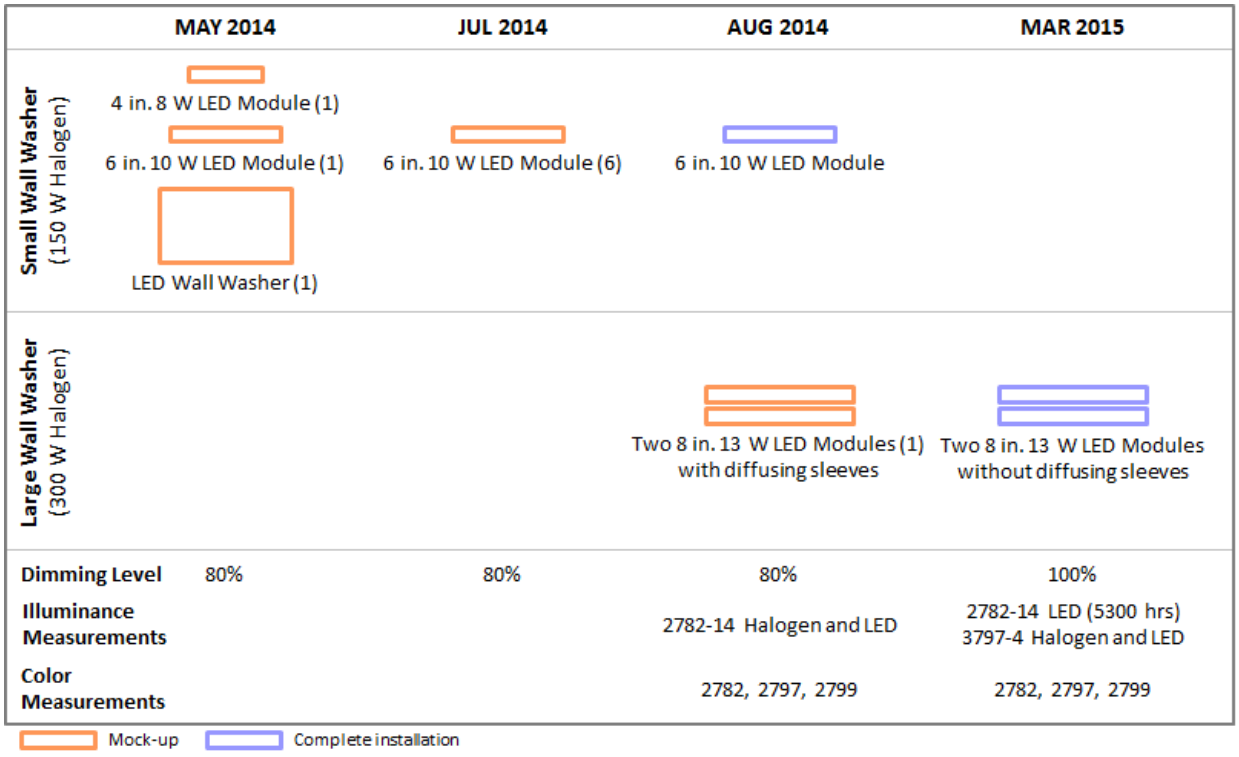

Figure 9. UMD CSPAC Wall Washer Retrofit Timeline: Mock-up, Installation, and Measurement. After potential alternatives to the incumbent halogen wall washers were assessed, the selected options were mocked-up in various stages, delineated above by the orange outline. The installation was completed for the small wall washers in August 2014 and for the large wall washers in March 2015, shown by the purple outline. The numbers in parentheses indicate how many of a given option were installed for the mock-up. The bottom third of the figure lists when and where the illuminance and color measurements were completed, and the dimming level at the time of measurement.

The measurements always occurred at night so that daylight would not affect the measurements. Ambient illumination from the HID luminaires in the atrium contributed to the measurements. It was impractical to separately measure this contribution, but it is relatively small compared to the wall washers. Since only measurements taken in the same areas were compared, the small contribution of light from the HID luminaires was assumed to be constant and thus did not affect the interpretation of the data.

[2] The Konica Minolta Illuminance Spectrophotometer was factory calibrated when purchased in November 2013 and was within calibration when tested by a National Voluntary Laboratory Accreditation Program accredited testing lab in June 2015.

4.1 Small Wall Washer Field Measurements: Illuminance

Hallway 2782 has a total of 16 small wall washers, mounted 2.5 ft away from the wall and 8 ft above the floor. This hallway was selected for the field measurements because the floor does not slope and the wall is smooth and continuous, making documentation of the measurements easier and more consistent. The 16 wall washers are spaced about 6 ft apart on center, so although the measurements were centered on one wall washer, the measurements captured the contributions of multiple wall washers. The measurements were taken from the center of wall washer 2782-14 to the center of the adjacent wall washer on both sides (2782-13 and 2782-15) on a 1 ft by 1 ft grid, as shown in Figure 10. The dimming level was 80% at the time of the field measurements and was not altered during the measurements. Re-lamping was not tracked, so the life of the halogen lamps at the time of the measurement was unknown.

ILLUMINANCE MEASUREMENTS (LUX)													
	HAL 2782-15						HAL 2782-14						HAL 2782-13
ft	6	5	4	3	2	1	0	1	2	3	4	5	6
1	303	299	213	160	175	254	318	293	211	160	209	290	311
2	227	238	203	172	181	223	258	254	219	181	196	196	239
3	173	184	174	162	160	178	197	207	200	174	177	177	183
4	124	135	138	134	126	123	131	146	152	143	134	134	125
5	90	98	105	107	103	98	104	114	121	115	107	107	90
6	70	74	79	81	81	78	80	86	89	90	86	86	73
0.5	123	130	141	149	160	168	178	185	195	196	189	189	161
1.5	100	105	112	119	128	134	139	146	152	152	150	150	128
2.5	77	79	81	85	88	89	92	94	96	95	95	95	83
3.5	61	62	64	65	66	66	67	67	65	65	62	62	56

	Max	Min	Avg	Avg/Min	Max/Min
Wall	318	70	160	2.3	4.6
Floor	196	56	113	2.0	3.5

Figure 10. 2782-14 Illuminance Measurements (lux): Halogen. The operating hours for the halogen lamps at the time of measurement was unknown. The dimming level was at 80%. The measurements were taken on a 1 ft by 1 ft grid on the wall and the floor, with the wall illuminance measurements at the top of the figure, the floor illuminance measurements in the middle, and the summary statistics at the bottom. The distance of the measurement point from the ceiling or wall is listed in the far left column, and the top row indicates the source, fixture label, and distance of the measurement point from the center of the center fixture on the wall. Orange = highest illuminance; yellow = mid-point illuminance; white = lowest illuminance.

Two sets of measurements in hallway 2782 were recorded after the retrofit using the same method as the previous illuminance measurements. The first set was recorded in August 2014 after the retrofit of the 150 W halogen lamps with 10 W LED modules in the small wall washers, shown in Figure 11. During the field measurements, flicker was noticed when taking illuminance measurements on the wall. The dimming level was set at 80% for the first set of measurements.

ILLUMINANCE MEASUREMENTS (LUX)													
	LED-initial 2782-15						LED-initial 2782-14						LED-initial 2782-13
ft	6	5	4	3	2	1	0	1	2	3	4	5	6
1	120	105	68	51	64	102	128	101	65	53	60	106	123
2	82	77	59	48	53	67	76	69	55	50	60	78	85
3	54	51	44	39	41	47	50	47	42	41	46	53	55
4	36	35	32	30	31	32	33	32	31	31	33	36	37
5	26	25	25	24	24	25	25	25	24	25	26	27	27
6	20	19	19	19	19	19	19	20	19	20	20	20	20
0.5	34	35	36	37	38	38	39	39	39	39	40	39	39
1.5	36	36	37	38	40	41	41	42	41	41	41	41	41
2.5	35	35	36	38	39	41	42	42	41	40	41	41	41
3.5	32	32	33	35	36	37	38	38	38	37	37	36	37

	Max	Min	Avg	Avg/Min	Max/Min
Wall	128	19	46	2.5	6.9
Floor	42	32	38	1.2	1.3

Figure 11. 2782-14 Illuminance Measurements (lux): LED Initial. The dimming level was at 80%. The measurements were taken on a 1 ft by 1 ft grid on the wall and the floor. The wall illuminance measurements are at the top of the figure, the floor illuminance measurements are in the middle, and the summary statistics are at the bottom. The distance of the measurement point from the ceiling or wall is listed in the far left column, and the top row indicates the source, fixture label, and distance of the measurement point from the center of the center fixture on the wall. Orange = highest illuminance; yellow = mid-point illuminance; white = lowest illuminance.

Shortly after the 10 W LED module retrofit, in September 2014, the dimming system was adjusted so that the wall washers operated at 100% output every day (except for the four hours they were off at night), and the voltage delivered was changed from 115 V to 120 V to mitigate the flicker. The second set of measurements was recorded in March 2015 after the 10 W LED modules had been operating for 4600 hours, shown in Figure

12. The dimming level was 100% at the time of the field measurements, and there was still noticeable flicker. Flicker was not measured in the field or laboratory. As of the writing of this report, there have been no complaints about flicker.

ILLUMINANCE MEASUREMENTS (LUX)													
	LED-4600 2782-15						LED-4600 2782-14						LED-4600 2782-13
ft	6	5	4	3	2	1	0	1	2	3	4	5	6
1	123	110	69	44	46	70	87	69	47	43	60	95	112
2	89	81	59	43	42	50	56	51	42	41	53	72	80
3	55	52	42	35	33	35	36	35	32	34	40	49	52
4	37	35	31	27	26	26	26	26	25	27	30	33	35
5	25	24	23	22	20	20	20	20	20	21	23	24	25
6	19	18	18	17	16	16	16	16	16	17	18	19	19
0.5	32	32	31	31	30	30	30	31	31	32	34	35	36
1.5	33	33	33	32	32	32	32	33	33	34	35	36	37
2.5	32	32	32	32	32	32	33	33	33	34	34	36	36
3.5	30	30	30	30	30	31	31	31	31	32	32	33	33

	Max	Min	Avg	Avg/Min	Max/Min
Wall	123	16	40	2.6	7.8
Floor	37	30	32	1.1	1.2

Figure 12. 2782-14 Illuminance Measurements (lux): LED 4600 Hours. Voltage was increased from 115 V to 120 V along with dimming level (from 80% to 100%) to mitigate flicker between the initial and 4600 hour measurements. The measurements were taken on a 1 ft by 1 ft grid on the wall and the floor. The wall illuminance measurements are at the top of the figure, the floor illuminance measurements are in the middle, and the summary statistics are at the bottom. The distance of the measurement point from the ceiling or wall is listed in the far left column, and the top row indicates the source, fixture label, and distance of the measurement point from the center of the center fixture on the wall. Orange = highest illuminance; yellow = mid-point illuminance; white = lowest illuminance.

4.2 Small Wall Washer Field Measurements: Color

In August 2014 and March 2015, color properties were documented by measuring the spectral power distribution (SPD) of the light exiting 25 wall washers: 16 wall washers in hallway 2782, 2 wall washers in area 2799, and 7 wall washers in hallway 2797. The measurements were taken 1 ft below the ceiling, with the meter flat against the wall, directly in front of the wall washers. For each SPD measurement, the CL-500A software calculated several metrics that are commonly used to characterize color appearance of light, including the

coordinates in the International Commission on Illumination (CIE) 1976 uniform-chromaticity scale (UCS) chromaticity diagram (u',v'), which are plotted in Figure 13. Each plot of the (u',v') chromaticity coordinates is an average of two or three SPD measurements of a given wall washer.

In August 2014, 18 LED modules in hallway 2782 and area 2799 were installed. In hallway 2797 six LED modules had already been operating for 700 hours, and one had been operating for 1600 hours. These differences in operating hours were due to the mock-ups that occurred in May and July 2014. When the second set of SPD measurements were recorded in March 2015, the wall washers had been operating an additional 4600 hours since the August 2014 measurements.[3,4]

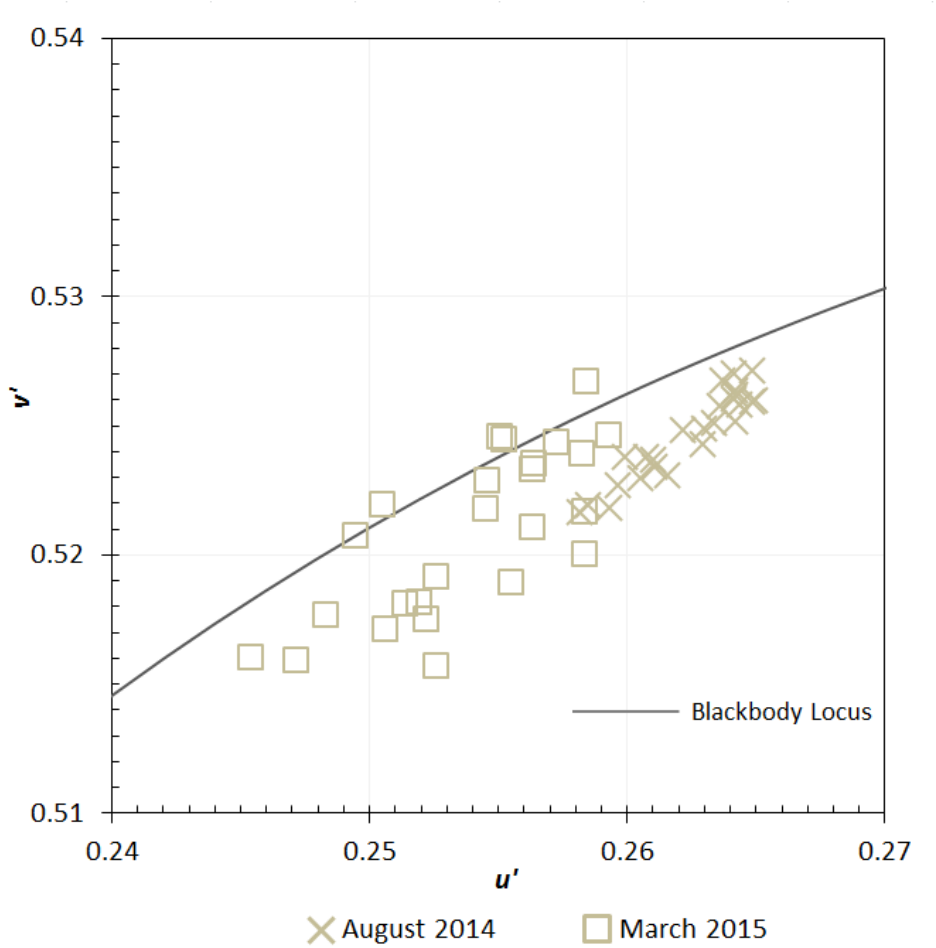

Figure 13. Small Wall Washer Chromaticity Coordinates Plotted on 1976 CIE UCS (u',v') Chromaticity Diagram. The diagram shows the chromaticity coordinates of the light exiting 25 wall washers in three different areas on the second floor, measured in both August 2014 and March 2015. In August 2014, 18 of the modules had just been installed, 6 had been operating for 700 hours, and 1 had been operating for 1600 hours—the differences due to mock-ups prior to the full retrofit of the small wall washers. In March 2015, the wall washers had been operating an additional 4600 hours since the August 2014 measurements. Three of the 50 plotted points are based only on one recorded measurement, and the remaining points are an average of two to three SPD measurements per wall washer.

[3] For further information download the *LED Color Characteristics* Technology Fact Sheet developed by the DOE SSL Program: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-color-characteristics-factsheet.pdf.

[4] For further information download the *Color Maintenance of LEDs in Laboratory and Field Applications* GATEWAY report developed by the DOE SSL Program: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_color-maintenance.pdf.

4.3 Small Wall Washer Laboratory Measurements

UMD Facilities Management provided a spare 10 W LED module for photometric testing to understand how the diffusing lens affected the lumen output of the module. The photometric testing was completed at a National Voluntary Laboratory Accreditation Program accredited laboratory according to the Illuminating Engineering Society (IES) LM-79-08 test procedure. The lumen output of the 2700 K 6 in. LED module without the diffusing lens was 536 lumens (lm) and with the diffusing lens was 443 lm, resulting in a calculated transmittance of 83%. There was no shift in color.

4.4 Large Wall Washer Field Measurements

In hallway 3797, there are a total of seven large wallwashers, mounted 3 ft from the wall and 10 ft above the floor. This hallway was selected because the wall washers are close to the wall, the wall is smooth and plain, the floor is flat, and it is the shortest mounting height of all the large wall washers. The other large wall washers are all mounted in areas where measurements would be very difficult, including over stairs, at ceiling heights greater than 18 ft, and in large spaces with multiple sources of light. Illuminance measurements in area 3797 were recorded in March 2015 to capture the performance of the large wall washers, each of which was converted from a single 300 W halogen lamp to two 13 W LED modules. Measurements were recorded on a 1 ft by 1 ft grid from the center of 3797-4 to the center of the adjacent wall washer on both sides (3797-3 and 3797-5), listed in Figure 15. The halogen lamps in the adjacent wall washers were both new, and the operating time of the lamp in the center wall washer at the time of measurement was unknown.

The day following the halogen measurements, the retrofit of the 300 W halogen lamp to two 13 W LED modules was completed for the large wall washers in area 3797, shown in Figure 14, and in the evening measurements were recorded following the same method used the prior evening. The measurements are detailed in Figure 16.

Figure 14. Hallway 3797 Photograph: LED Initial. The photograph shows the seven large wall washers in the foreground, with additional large wall washers over the stairs, illuminating the background. Wall washer 3797-1 was installed in August 2014, and the remaining wall washers in 3797 were installed in March 2015. Illuminance measurements were recorded for the wall and floor areas near 3797-4.

ILLUMINANCE MEASUREMENTS (LUX)															
	HAL 3797-5							HAL 3797-4							HAL 3797-3
ft	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7
0.5	457	440	303	229	224	294	383	429	398	291	195	174	225	341	467
1.5	525	488	372	292	278	345	453	494	470	371	262	230	280	402	526
2.5	461	434	362	306	297	337	401	425	400	339	277	255	296	374	455
3.5	354	338	310	285	277	297	318	328	315	288	255	248	273	316	342
4.5	228	275	272	260	257	259	263	264	261	251	236	233	246	266	271
5.5	223	222	239	239	240	230	219	214	217	220	215	213	218	216	200
6.5	173	180	195	203	202	190	177	174	177	180	181	181	174	166	152
7.5	142	148	163	173	171	162	149	145	143	148	153	151	145	135	126
8.5	123	126	136	143	143	137	132	130	131	132	136	133	128	117	110
0.5	267	281	305	322	326	324	323	323	322	322	318	308	292	275	256
1.5	236	246	258	270	276	275	276	276	274	274	271	263	252	238	227
2.3	176	185	194	201	204	203	203	202	201	201	198	195	188	183	177
3.5	140	146	149	153	155	156	155	155	155	153	152	150	146	143	140

	Max	Min	Avg	Avg/Min	Max/Min
Wall	526	110	257	2.3	4.8
Floor	326	140	227	1.6	2.3

Figure 15. 3797-4 Illuminance Measurements (lux): Halogen. Wall washers 3797-3 and 3797-5 were re-lamped prior to the measurements and the operating hours of the halogen lamp in wall washer 3797-4 was unknown. The dimming level was 100%. The measurements were taken on a 1 ft by 1 ft grid on the wall and the floor. The wall illuminance measurements are at the top of the figure, the floor illuminance measurements are in the middle, and the summary statistics are at the bottom. The distance of the measurement point from the ceiling or wall is listed in the far left column, and the top row indicates the source, fixture label, and distance of the measurement point from the center of the center fixture. Orange = highest illuminance; yellow = mid-point illuminance; white = lowest illuminance.

ILLUMINANCE MEASUREMENTS (LUX)															
	LED-initial 3797-5							LED-initial 3797-4							LED-initial 3797-3
ft	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7
0.5	404	346	231	161	159	232	353	420	360	236	149	133	163	264	394
1.5	449	422	276	209	213	286	397	461	408	298	203	171	206	315	443
2.5	392	328	259	215	218	269	336	372	343	270	205	181	201	270	355
3.5	261	227	196	176	176	200	231	245	229	195	163	152	163	193	233
4.5	176	158	148	139	141	150	164	168	160	146	131	124	129	141	162
5.5	131	120	116	112	112	116	119	121	117	112	104	100	101	106	117
6.5	101	98	96	95	95	95	98	99	97	93	89	86	86	87	90
7.5	81	80	79	79	79	79	79	77	76	73	74	71	69	68	73
8.5	67	67	65	65	66	65	66	64	65	63	63	62	58	58	61
0.5	143	143	144	144	144	144	144	144	144	143	143	142	142	142	142
1.5	144	145	146	147	148	149	150	149	149	148	147	146	145	146	145
2.3	133	135	137	139	141	142	142	143	142	140	139	137	135	134	132
3.5	118	120	121	122	123	123	123	123	123	121	118	116	115	114	113

	Max	Min	Avg	Avg/Min	Max/Min
Wall	461	58	174	3.0	7.9
Floor	150	113	137	1.2	1.3

Figure 16. 3797-4 Illuminance Measurements (lux): LED Initial. The dimming level was 100%. The measurements were taken on a 1 ft by 1 ft grid on the wall and the floor. The wall illuminance measurements are at the top of the figure, the floor illuminance measurements are in the middle, and the summary statistics are at the bottom. The distance of the measurement point from the ceiling or wall is listed in the far left column, and the top row indicates the source, fixture label, and distance of the measurement point from the center of the center fixture on the wall. Orange = highest illuminance; yellow = mid-point illuminance; white = lowest illuminance.

5 Discussion

The University of Maryland (UMD) Clarice Smith Performing Arts Center (CSPAC) wall washer retrofit project was driven by the need to reduce the maintenance burden on UMD Facilities Management, with a low-cost solution that delivers the same quality of light. Even though the reduction in energy consumption is high for this particular project, it was viewed as a secondary benefit. In this particular application there were some minor visual changes, but these changes were considered acceptable by UMD Facilities Management and key CSPAC staff. The visual differences of the most concern for this project were distribution, wall brightness, and color.

5.1 Illuminance Measurements

One of the changes after the retrofit was the amount of light reaching the walls and the floor; however, the distribution was visually similar. The illuminance measurements support similarities in distribution. Despite the reduced illuminance levels, the illuminance levels in the hallways still met IES recommendations. While the LED modules provided less light, these modules still delivered enough luminous flux to serve the original purposes of illuminating the floor so students can safely transition between classes and spaces and adding visual interest to the CSPAC atrium at night.

5.1.1 2782-14 Measurements

The illuminance level produced by the LED modules is considerably different than that of the halogen; however, the majority of the time walking is the only task that occurs in hallway 2782-14. According to the IES 10th Edition Lighting Handbook,[5] public transition spaces that are independent passageways (not encompassed by surrounding task areas) are recommended to have an illuminance of 25 lux (lx) on horizontal surfaces and 15 lx on vertical surfaces, when the majority of occupants are under the age of 25. This is appropriate for the hallways because these 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 measured illuminance levels in hallway 2782 are listed in Table 2 along with the IES recommendations. The average illuminance of the initial LED measurements still exceeded the IES recommendations by 15 lx or more after 4600 hours of operation.

Illuminance levels decreased after 4600 operating hours, even with the dimming level set at 100% instead of 80%. 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. Another confounding factor is that the lumen output of LEDs decreases as temperature rises. If the temperature increased when the dimming level was raised from 80% to 100% output, then the lumen output at 100% may not have increased as much as expected. A decrease in lumen output over the life of the product is also expected, which is likely contributing to the measured decrease in illuminance.

The measured illuminance at a given point on the walls ranged between 20% and 40% as much illuminance with the LED modules as with the halogen, and on the floor 20% to 67% as much illuminance, as shown in Figure 17. Overall, while not exact, the distribution remains similar, with a considerable decrease in illuminance.

[5] DiLaura et al., IES 10th Edition Lighting Handbook, pp.10.26-10.27.

Table 2. **2782-14 Illuminance Measurements and IES Recommendations.** The dimming level was at 80% at the time of the initial measurements and was at 100% at the time of the 4600 hour measurements. The IES recommendations are from the 10th Edition IES Handbook. The vertical illuminance recommendations are specified for 5 ft above finished floor (AFF). Measurements were recorded at 4.75 ft AFF on the wall (3 ft from the top of the wall), so the illuminance measurements in this row were used for the comparisons.

Source	Area	Max	Min	Avg.	Avg/Min	Max/Min
LED Initial (Dim at 80%)	Wall	128	19	46	2.5	6.9
	Floor	42	32	38	1.2	1.3
	5 ft AFF	---	---	47	1.2	---
LED 4600 hr (Dim at 100%)	Wall	123	16	40	2.6	7.8
	Floor	37	30	32	1.1	1.2
	5 ft AFF	---	---	41	1.3	---
HAL (Dim at 80%)	Wall	318	70	160	2.3	4.6
	Floor	196	56	113	2.0	3.5
	5 ft AFF	---	---	181	1.1	---
IES Recomm. Passageway	Horz.	---	---	25	2.0	---
	Vert. (5 ft AFF)	---	---	15	2.0	---

RELATIVE ILLUMINANCE													
	LED-initial/HAL 2782-15					LED-initial/HAL 2782-14				LED-initial/HAL 2782-13			
ft	6	5	4	3	2	1	0	1	2	3	4	5	6
1	40%	35%	32%	32%	36%	40%	40%	34%	31%	33%	29%	36%	39%
2	36%	32%	29%	28%	29%	30%	30%	27%	25%	28%	30%	40%	36%
3	31%	28%	25%	24%	26%	26%	25%	23%	21%	23%	26%	30%	30%
4	29%	26%	23%	23%	24%	26%	25%	22%	20%	22%	25%	27%	30%
5	29%	26%	23%	22%	23%	25%	24%	22%	20%	21%	24%	25%	30%
6	28%	26%	24%	23%	23%	24%	24%	23%	22%	22%	23%	24%	28%
0.5	28%	27%	26%	25%	23%	22%	22%	21%	20%	20%	21%	21%	25%
1.5	36%	35%	33%	32%	31%	30%	29%	28%	27%	27%	27%	27%	32%
2.5	45%	45%	45%	45%	45%	45%	45%	44%	43%	42%	43%	43%	49%
3.5	51%	52%	52%	53%	54%	56%	56%	56%	58%	57%	59%	58%	67%

Figure 17. **2782-14 Relative Illuminance: Percentage of LED Illuminance Compared to Halogen.** The percent of measured LED illuminance compared to measured halogen illuminance at a given point is shown. The dimming level was 80%. The measurements were taken on a 1 ft by 1 ft grid on the wall and the floor. The wall illuminance measurements are at the top of the figure, the floor illuminance measurements are at the bottom. The distance of the measurement point from the ceiling or wall is listed in the far left column, and the top row indicates the wall washer labels, the ratio, and the distance of the measurement point from the center fixture. Blue = highest percentage; green = lowest percentage.

5.1.2 3797-4 Measurements

Measurements were recorded on a 1 ft by 1 ft grid spacing for wall washer 3797-4, located in the middle of area 3797, after the large wall washer retrofit was completed in hallway 3797 in March 2015. The measurements are summarized in Table 3. The average illuminance on the wall and on the floor far exceeds IES recommendations for both the 300 W halogen lamp and the two 13 W LED modules in the 3797 large wall washers. There were no diffusing sleeves on the 13 W LED modules (as of the writing of this report, there were no plans to remove the sleeves from the 10 W LED modules, but removal may be considered in the future).

Table 3. 3797-4 Illuminance Measurement Summary. The dimming level was 100% at the time of the measurements. The IES recommendations are from the 10th Edition IES Handbook. The vertical illuminance recommendations are specified for 5 ft AFF. Measurements were recorded at 4.5 and 5.5 ft AFF on the wall (4.5 and 5.5 ft from the top of the 10 ft wall), so the illuminance measurements in these rows were used for the comparisons.

Source	Area	Max	Min	Avg.	Avg/Min	Max/Min
LED Initial (Dim at 100 %)	Wall	461	58	174	3.0	7.9
	Floor	150	113	137	1.2	1.3
	5 ft AFF	---	---	131	1.3	---
HAL	Wall	526	110	257	2.3	4.8
	Floor	326	140	227	1.6	2.3
	5 ft AFF	---	---	239	1.2	---
IES Recomm. Passageway	Horz.	---	---	25	2.0	---
	Vert. (5 ft AFF)	---	---	15	2.0	---

The measured illuminance at a given point on the walls ranged between nearly equal (98%) to a little less than half (45%) as much illuminance with the LED modules as with the halogen, and on the floor from as high as 84% to as low as 44% as much illuminance, as shown in Figure 18. Overall, the distribution remains similar, although the LED modules delivered less light near the bottom of the wall.

RELATIVE ILLUMINANCE															
	LED-initial/HAL 3797-5						LED-initial/HAL 3797-4						LED-initial/HAL 3797-3		
ft	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7
0.5	0.88	0.79	0.76	0.70	0.71	0.79	0.92	0.98	0.90	0.81	0.77	0.76	0.72	0.78	0.84
1.5	0.86	0.86	0.74	0.72	0.77	0.83	0.88	0.93	0.87	0.80	0.78	0.74	0.74	0.78	0.84
2.5	0.85	0.76	0.72	0.70	0.73	0.80	0.84	0.88	0.86	0.80	0.74	0.71	0.68	0.72	0.78
3.5	0.74	0.67	0.63	0.62	0.64	0.68	0.73	0.75	0.73	0.68	0.64	0.61	0.60	0.61	0.68
4.5	0.77	0.58	0.54	0.53	0.55	0.58	0.62	0.64	0.62	0.58	0.55	0.53	0.52	0.53	0.60
5.5	0.59	0.54	0.49	0.47	0.47	0.50	0.55	0.56	0.54	0.51	0.48	0.47	0.46	0.49	0.58
6.5	0.58	0.55	0.49	0.47	0.47	0.50	0.55	0.57	0.55	0.52	0.49	0.48	0.50	0.52	0.59
7.5	0.57	0.54	0.49	0.45	0.46	0.49	0.53	0.53	0.53	0.49	0.48	0.47	0.48	0.51	0.58
8.5	0.54	0.53	0.48	0.45	0.46	0.47	0.50	0.49	0.50	0.48	0.46	0.47	0.45	0.50	0.55
0.5	0.53	0.51	0.47	0.45	0.44	0.44	0.45	0.45	0.45	0.44	0.45	0.46	0.48	0.52	0.55
1.5	0.61	0.59	0.56	0.54	0.54	0.54	0.54	0.54	0.55	0.54	0.54	0.56	0.58	0.61	0.64
2.3	0.76	0.73	0.71	0.69	0.69	0.70	0.70	0.71	0.71	0.70	0.70	0.70	0.71	0.73	0.75
3.5	0.84	0.82	0.81	0.79	0.79	0.79	0.80	0.79	0.79	0.79	0.78	0.77	0.78	0.80	0.81

Figure 18. 3797-4 Relative Illuminance: Percentage of LED Illuminance Compared to Halogen. The percent of measured LED illuminance compared to measured halogen illuminance at a given point is shown. The dimming level was 100%. The measurements were taken on a 1 ft by 1 ft grid on the wall and the floor. The wall illuminance measurements are at the top of the figure, the floor illuminance measurements are at the bottom. The distance of the measurement point from the ceiling or wall is listed in the far left column, and the top row indicates the wall washer labels, the ratio, and the distance of the measurement point from the center fixture. Blue = highest percentage; green = lowest percentage.

5.2 Color Measurements

Further analysis of the chromaticity coordinates of the light exiting the 16 wall washers reveals a trend that is dependent on the area of CSPAC, shown in Figure 19. Wall washers in areas 2782 and 2799 are generally shifting toward blue, while wall washers in area 2797 remain relatively stable. Further investigation of the installed LED modules in these areas revealed that although the 6 in. LED module labels installed in these wall washers had the same product specification, the dates on the labels were different. The LED modules installed in wall washers 2797 in May and July 2014 are dated 2013, and the modules installed in wall washers 2782 and 2799 in August 2014 are dated 2012.

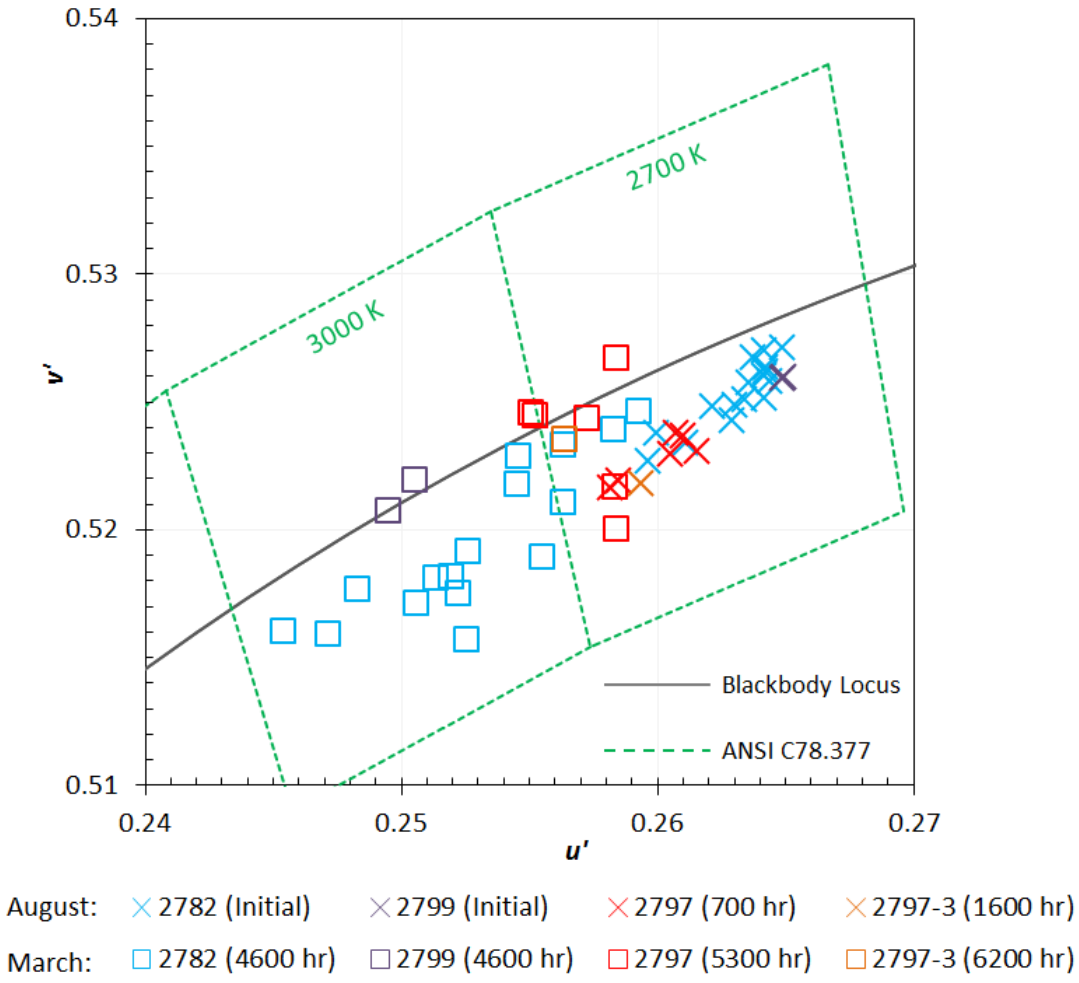

Figure 19. Small Wall Washer Chromaticity Coordinates Plotted on 1976 CIE UCS (*u*',*v*') Chromaticity Diagram: Measurements shown by CSPAC Area. The diagram shows the chromaticity coordinates of the light exiting 25 wall washers in three different areas on the second floor, measured in both August 2014 and March 2015. In August 2014, 18 of the wall washers had just been installed, 6 had been operating for 700 hours, and one had been operating for 1600 hours—the differences due to mock-ups prior to the full retrofit of the small wall washers. In March 2015, the wall washers had been operating an additional 4600 hours since the August 2014 measurements. The ANSI-defined areas for LED products rated at 3000 K and 2700 K are also shown.

For comparison, ENERGY STAR requires that the change in chromaticity ($\Delta u',v'$) is less than 0.007 over the 6,000 hour test period. Only 2 of the 18 LED modules in areas 2782 and 2799 shifted less than 0.007 (0.006 and 0.005), while all 7 of the LED modules in area 2797 shifted less than 0.007. The LED module manufacturer made no claims about color consistency over time, and the product was not ENERGY STAR qualified. The color shift was not expected by the LED module manufacturer or the chip manufacturer, and is not consistent with LM-80 test data. The manufacturers are investigating the causes for the unexpected results in some of the products.

When initially investigating potential reasons for the color shift, several wall washers in hallway 2782 and area 2799 were examined. For the majority of the installed LED modules that were examined, the thermal pads were installed incorrectly. Some of the thermal pads were installed on the wall washer reflector behind the module, on the plastic side of the module, or on the back of the module. If the thermal pad was correctly installed on the side with the aluminum heat sink and was installed with this side touching the wall washer housing, the module was not hot to the touch, even though the thermal pad itself was not in full contact with the luminaire housing (due to the curvature of the housing). The differences in the installation of the thermal pads occurred in all

three areas, unlike the measured differences in (u',v') chromaticity coordinates which seem to be dependent on area, so it is unlikely that installation of the thermal pads was a major contributor to the measured color shift.

The reasons for the differences in the installation of the thermal pads are that the LED modules were installed by several electricians within a given hallway and the manufacturer's instructions that were shipped with the modules were unclear, so even a single electrician may have installed the thermal pad differently for different wall washers. The installation instructions required interpretation by the electricians, who are not always familiar with LED technology and may not understand the thermal properties of LEDs. The installation instructions provided on the manufacturer's website are clearer than those included with the products, but it is unreasonable to assume that the electricians would use anything except the instructions provided with the LED modules.

6 Conclusions

The need to reduce maintenance was a primary motivation for the early adoption of LED technology, which first occurred in outdoor lighting applications where maintenance costs are often high. Although adoption of LED technology is now common for a variety of reasons including energy savings, the motivation that led to the initial adoption of LED technology was the same motivation for the University of Maryland (UMD) Clarice Smith Performing Arts Center (CSPAC) wall washer retrofit project. The UMD CSPAC wall washer retrofit project was driven by the need to reduce maintenance; the resulting energy savings was a secondary benefit.

As the efficacy and lifetime of LED technology continues to improve, more demands are being placed on the visual appearance of the light. The visual appearance is a concern for many retrofits, even when maintenance or energy efficiency is the primary concern, because often facilities personnel do not want to go through the process of getting approvals for any appearance changes. If a new luminaire can deliver a quality of light similar to the incumbent product, the retrofit process can often move more quickly.

The LED module selected by UMD Facilities Management is a low-cost solution that provides an acceptable quality of light, which was initially verified with mock-ups. In this particular application there were some visual changes after the retrofit, the largest being the amount of light reaching the walls and the floor, with some smaller changes in distribution. Flicker was noticeable and considered acceptable for this application, but may not be acceptable for other applications. There were also some changes in the color appearance of the light, which was a reminder of the care that must be taken when ordering and receiving products.

All installed LED modules were operational and required no maintenance as of the writing of this report, so the benefits of the LED module wall washer retrofit are already being realized. UMD Facilities Management is pleased with the results of this retrofit, and continues to initiate LED retrofit projects across the UMD campus.