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Changes in SSL Device Efficiency and Optical Performance With Aging: Final Report

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Disclaimer

Nomenclature or List of Acronyms

45OL	operational life test conducted at 45°C
75OL	operational life test conducted at 75°C
6590	life test conducted at 65°C and 90% relative humidity
7575	life test conducted at 75°C and 75% relative humidity
α	decay rate constant in the IES TM-28-14 model
β	reciprocal of the time when the efficiency increases by 0.63γ
γ	maximum asymptotic increase relative to the starting value
$\Delta u'$	change in the u' coordinate of chromaticity
$\Delta u'v'$	chromaticity shift or the total change in chromaticity coordinates
$\Delta v'$	change in the v' coordinate of chromaticity
$\Phi(t)$	ratio of the luminous flux at any time
Φ_0	initial luminous flux
λ_c	centroid wavelength
°C	degree Celsius
ac	alternating current
ANSI	American National Standards Institute
AST	accelerated stress test
B	initialization constant or pre-exponential constant
CCT	correlated color temperature
CIE	International Commission on Illumination (*Commission Internationale de l'Éclairage*)
CSM-3	chromaticity shift mode-3
D2W	dim-to-warm
dc	direct current
DOE	U.S. Department of Energy
DUT	device under test
EERE	Office of Energy Efficiency and Renewable Energy
EML	equivalent melanopic lux

hr, hrs	hour, hours
IC	integrated circuit
IES	Illuminating Engineering Society
I_f	forward current
K	Kelvin
l	design-dependent factor for the lens as determined from a least squares fit of the simulation results
L_{70}	time required for the luminous flux to decay to 70% of the initial value
L(t)	Change in the normalized lens transmittance *[%T(t) / %T(t = 0)*] at time *t*
LAE	lighting application efficiency
LED	light-emitting diode
LE(t)	Luminaire efficiency at time *t*
LE(t = 0)	initial luminaire efficiency
LFM	luminous flux maintenance
lm	lumen
lm/W	lumens per watt
mA	milliampere
MESA	Mission Execution and Strategic Analysis
MP-LED	mid-power LED
MS	modified spectrum, modified spectra
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
nm	nanometer
PCB	printed circuit board
pc-LED	phosphor-converted LED
R	design-dependent factor for the reflector as determined from a least squares fit of the simulation results
R_f	fidelity index in ANSI/IES TM-30-18
R_g	gamut index in ANSI/IES TM-30-18
R(t)	change in the normalized reflector reflectance *[%R(t) / %R(t = 0)*] at time *t*

RTOL	room temperature operational life
SPD	spectral power distribution
SSL	solid-state lighting
t	time
TLA	temporal light artifacts
TM	technical memorandum
u'	chromaticity coordinate in the CIE 1976 color space
UV	ultraviolet
UV-C	ultraviolet Band C
UV-Vis-NIR	ultraviolet-visible-near infrared
V	volt
v'	chromaticity coordinate in the CIE 1976 color space
V_f	forward voltage
W	watt
W/nm	watts per nanometer

Executive Summary

The lighting application efficiency (LAE) framework proposed by the U.S. Department of Energy is a new frontier in thinking about the enormous potential of solid-state lighting (SSL) technologies. The LAE framework describes a method to evaluate the efficiency of light delivered to the task and consists of four major elements: light source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness. These four elements represent the targeted areas of improvement for research and development to increase energy savings in SSL devices while simultaneously providing new capabilities to the lighting system. This report builds on an initial report (Round 1)[1] that sampled SSL products with modified spectral output. The findings presented in the initial report showed that the method of spectral modification significantly impacted initial light source, optical delivery, and spectral efficiencies. This updated report will focus on the long-term changes in light source, optical delivery, and spectral efficiencies that occur during aging of SSL devices.

The products studied and presented in this report have different form factors and achieve enhanced optical performance by different methods, but they all broadly provide modified spectral outputs using mid-power light-emitting diodes (MP-LEDs). The specific devices under test (DUTs) examined in this report have been broadly categorized as those using violet-pumped light-emitting diodes (LEDs) and those that are switchable between preset correlated color temperature (CCT) values. The DUTs are four different products that provide modified spectra (MS). Product MS-2 uses a violet LED pump, along with green and red phosphor emissions, to produce white light that omits blue emissions. Product MS-2 is a standard 60-watt (W) replacement A19 lamp with 30 MP-LEDs, and its modified spectrum (i.e., blue-free lighting spectrum) is intended to reduce melanopic lux and promote biological benefits of blue-free light in the evening. Product MS-3 also uses a violet LED pump, along with blue, green, and red phosphors, to produce a spectrum that most naturally imitates sunlight. Product MS-3 is an LED module consisting of 21 MP-LEDs. Products MS-4 and MS-5 are both 6-inch downlights that use a manual switching mechanism so that users can select application-specific CCTs before installation. Products MS-4 and MS-5 both contain two blue LED pump primaries (warm white and cool white) for spectral tuning. Product MS-4 contains 12 MP-LEDs for each LED primary, and Product MS-5 contains 10 MP-LEDs for each LED primary. Product MS-1, which was discussed previously [1], is not covered in this report.

This report summarizes the overall findings from up to 14,000 hours (hrs) of accelerated stress test (AST) on the violet-pump LED DUTs (i.e., Products MS-2 and MS-3) and up to 12,000 hrs of AST on the downlight DUTs (i.e., Products MS-4 and MS-5). An AST regiment was developed and discussed in the initial report for the DUTs. These same AST procedures were used in this current study and included a room temperature operational life (RTOL) test, an operational life test conducted at 45 degrees Celsius (°C; 45OL), an operational life test conducted at 75°C (75OL), a wet high-temperature operational life test performed at 65°C and 90% relative humidity (6590), and a wet high-temperature operational life test performed at 75°C and 75% relative humidity (7575). The AST procedures used for Product MS-2 were RTOL, 45OL, and 6590. The AST procedures used for Products MS-3, MS-4, and MS-5 were RTOL, 75OL, and 7575. During the ASTs described herein, separate populations of each product (three DUTs in each population for Products MS-2, MS-4, and MS-5; four DUTs in each population for Product MS-3) were subjected to power cycling of 1 hour (hr) on and 1 hr off. Photometric measurements were taken after every 1,000 hrs of AST exposure.

The key findings from this study include the following:

- There is a strong time dependence to source efficiency, optical delivery efficiency, and spectral efficiency that changes significantly with product design and use conditions. Managing these time-dependent aging factors requires knowledge of the limitations of materials used in the lighting system. Accelerated stress testing can help provide that information in a reasonable time frame.

- High temperature tends to have the greatest impact on source efficiency, and some LED packages contain phosphors and other components that are more sensitivity to temperature than other packages. Design factors such as forward current and heat management impact the temperature stability of the LEDs in fielded products.

- Temperature-induced aging of lenses and other optical surfaces had a larger impact of luminous flux maintenance and chromaticity maintenance than LED degradation in the three products (i.e., MS-2, MS-4, and MS-5) with secondary optics. This finding demonstrates the importance of using heat-resistant optical materials in some environments.

- Humidity impacts source efficiency, optical deliver efficiency, and spectral efficiency. High temperature and high humidity caused significant chromaticity shifts and lumen depreciation that can impact product life.

- The luminous efficacy of the violet-pump LEDs examined during this study was generally lower than that excepted from typical blue-pump phosphor-converted LEDs (pcLEDs). Although the violet LEDs were found to be stable in the AST conditions, the stability of the phosphors used in the violet-pump LEDs varied greatly, resulting in significant changes in luminous flux and chromaticity in some conditions.

- Under specific conditions (e.g., switchable downlights in RTOL), source efficiency can actually increase during the first 10,000 hrs or so of operation. This finding suggests that long lifetime can be achieve in commercial products when the use conditions match the product design.

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1 Introduction

Solid-state lighting (SSL) technologies using light-emitting diode (LED) light sources continue to evolve and provide additional benefits over more traditional light sources. Although SSL technologies offer a significant advantage in device efficacy over older lighting technologies, SSL devices also provide a significant step forward in the ease of achieving spectral modification and spectral control. Spectral modification has emerged as an important capability of a new generation of SSL technologies and offer the possibility of tailoring light sources to meet both the visual and non-visual needs of human occupants [2]. Once understood, the ability of SSL devices to provide spectral modification may open a new frontier in energy-efficient, task optimized, lighting technologies [3].

RTI International has previously reported on the initial performance benchmarks of a group of SSL products with modified spectra [1], including those that achieve spectral modifications by:

- Filtering light emissions to achieve a targeted emission spectra
- Using violet-pump LEDs and omitting blue emitters from the phosphor mixture
- Using violet-pump LEDs and adding red, green, and blue emitters to the phosphor mixture
- Using multiple blue LED pump primaries and a manual switching mechanism to modify light color.

The initial report [1] also discussed the role of spectral efficiency as part of the overall lighting application efficiency (LAE) that can be used to characterize the efficient delivery of light from the light source to the lighted task [4]. The framework for LAE proposed by the U.S. Department of Energy (DOE) consists of four major efficiency elements: light source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness. The initial report examined the first three elements of LAE and demonstrated that not only are these initial values important, but the LAE performance of an SSL device changes over time.

It is well known that that light source efficiency of LEDs can degrade over time through various processes, thereby causing luminous flux decay and chromaticity shift [5]. Likewise, optical delivery efficiency can change over time as the materials used for lenses and reflector degrade and affect luminaire efficiency [6, 7]. The net result of such optical changes in SSL devices is a change in spectral emission properties of the light source over time, which can impact spectral efficiency. In addition, degradation in LEDs and power/control electronics can also impact spectral efficiency as devices age [7, 8].

To provide additional understanding of the effects of SSL device aging on long-term performance as evaluated through the LAE framework, this report builds on earlier findings [1] to provide measurements of modified-spectrum (MS) SSL devices that have been subjected to up to 14,000 hours (hrs) of accelerated stress tests (ASTs). This report focused on two broad classes of MS devices, those utilizing violet LEDs as optical pumps and those with blue LED optical pumps that are switchable between preset correlated color temperature (CCT) values. Products using a filtering optic are not included in this report but were discussed previously [1]. The results presented here show that MS devices continue to degrade over time and that temporal-dependent degradation has an impact on LAE. The findings presented in this report help to consolidate thinking regarding the temporal nature of time-based LAE degradation and provide insights on how to minimize these effects in future lighting designs.

2 Experimental Methods and Analytics

This report builds on our initial report that detailed changes in efficiency and optical performance of SSL devices with modified spectral output; many of the same AST protocols and measurement methods that were used during the study and discussed in this report were described previously [1]. This report focuses on the recent experimental findings and long-term trends of the devices under test (DUTs) with modified spectral content.

2.1 Samples

In this report, the DUTs have been categorized into two main groups: those that use phosphor-converted LEDs (pc-LEDs) with a violet LED pump to achieve a targeted, fixed output spectrum (Products MS-2 and MS-3) and those with two different pc-LED primaries (blue LED pumps) that have a lighting spectrum that can be manually switched between two or more possibilities (Products MS-4 and MS-5). These groups will be referred to as violet-pump LED products and switchable downlights, respectively, for the remainder of this report. **Figure 2-1** shows the violet-pump LED products, and **Figure 2-2** shows the switchable downlights.

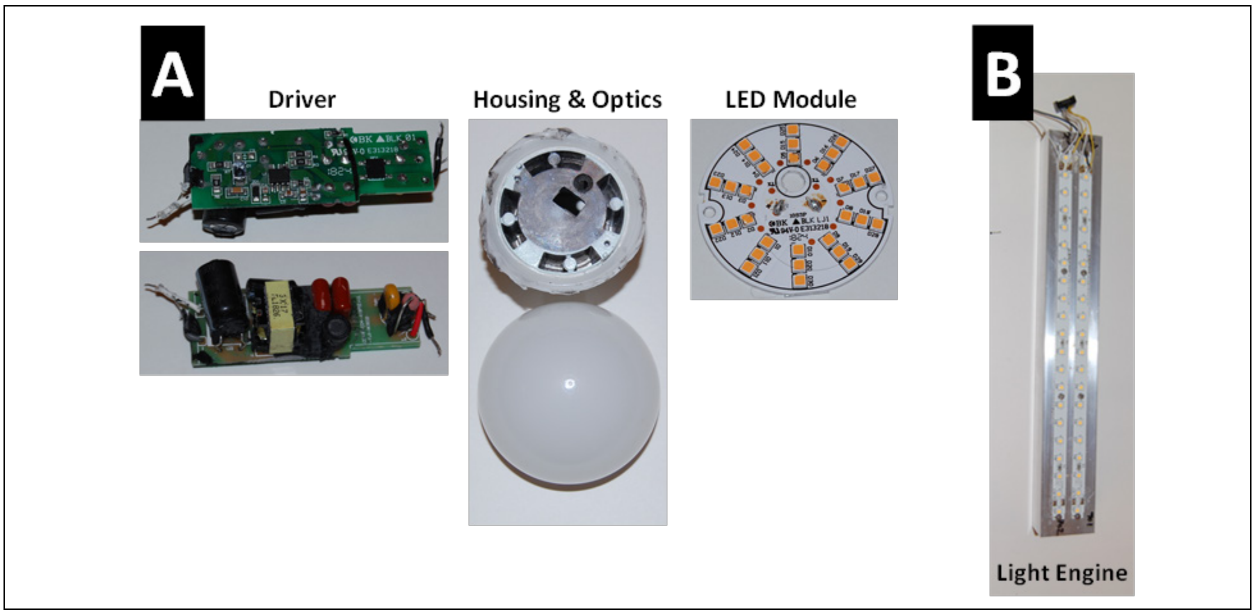

Figure 2-1: The violet-pump LEDs products: (A) MS-2 showing its LED module and electrical driver and (B) MS-3 light engine.

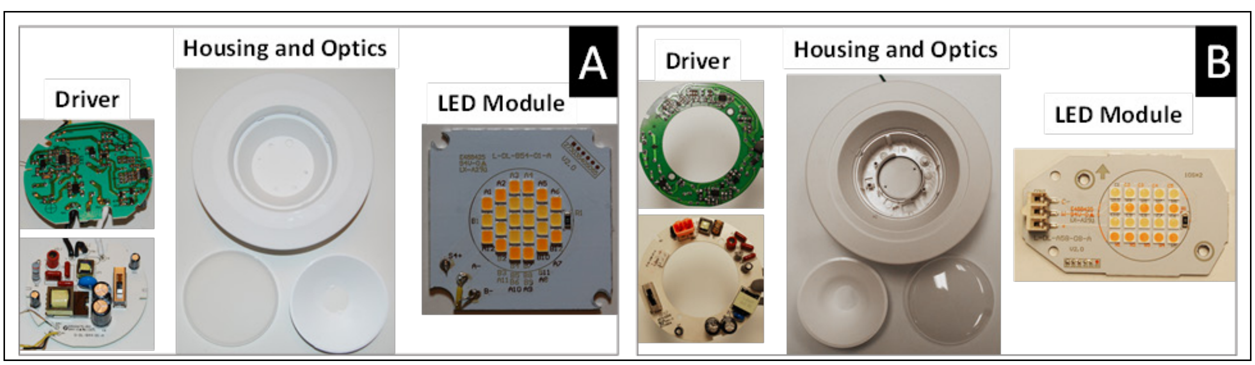

Figure 2-2: Switchable downlight products (A) MS-4 and (B) MS-5. The products are disassembled here to show their electrical drivers, housings and optics (i.e., optical lenses and reflectors), and LED modules.

The SSL products examined in this study were first characterized in our initial report [1]. For convenience, initial electrical and optical properties are provided in **Appendix Table 1** and **Appendix Table 2** of the **Appendix**. The American National Standards Institute (ANSI)/Illuminating Engineering Society (IES) technical memorandum (TM)-30-18 analysis of these products when new was presented in our initial report [1]. Additional details about each product are provided in our initial report, and a brief summary is provided in this report.

2.1.1 Violet-Pump Light-Emitting Diode Products

Product MS-2 is a 60-watt (W) replacement A19 lamp with an LED module that consists of 30 mid-power light-emitting diodes (MP-LEDs; 3030 package size) mounted as a 10 serial string configuration on a metal-core printed circuit board (PCB; **Figure 2-1A**). Each LED package contains two LED emitters connected in series. The pc-LEDs in Product MS-2 use a violet-pump LED as the excitation source, and the phosphor mixture contains green and red emitters. The absence of blue emissions from Product MS-2 is intended to reduce melanopic lux, and the emitted spectrum is specifically designed to minimize melanopsin absorption by the human retina [9]. As discussed in our initial report, the absence of blue emissions also distorted the color rendering performance of the product [1]. The driver used with Product MS-2 is encapsulated with a silicone thermal compound and housed in the middle of the heat sink.

Product MS-3 is an LED module that contains 21 MP-LEDs (3030 package size). The MP-LEDs are arranged as three parallel strings of seven serially connected LEDs and a resistor. Product MS-3 uses a violet-pump LED and has phosphor emissions with major peaks in the blue, green, and red spectral regions to mimic natural sunlight (with a CCT value of 5,000 K). This produces much better color rendering properties than violet-pump LED Product MS-2 as shown in **Appendix Table 1.** For Product MS-3, two LED modules (i.e., DUTs) were mounted on the same heat sink and operated in series as shown in **Figure 2-1B** to make a light engine. During AST, power was supplied to the light engine by one LED driver that was placed outside the test chamber, delivering 25 volts (V) and 450 milliampere (mA) to the light engine. Because Product MS-3 was operated by a remote driver that was only used during testing, driver efficiency numbers will change with product configuration; therefore, the numbers are not reported here.

Another benefit of violet-pumped LEDs is that they have some capability for disinfecting exposed surfaces and air, albeit at much lower rates than ultraviolet Band C (UV-C) LEDs [10]. The disinfection potential of these violet-pumped sources was not examined in this study.

2.1.2 Switchable Downlight Products

Products MS-4 (**Figure 2-2A**) and MS-5 (**Figure 2-2B**) are 6-inch downlights with an integrated driver contained in an aluminum housing. Both products contain two sets LED primaries: one with a warm white CCT value and the other with a cool white CCT value. Both products have an LED driver that contains a resistor bank that is manually set during installation with an exterior switch. The switch setting determines the current distribution between the LED primaries and sets the color of the light emissions. Up to five different CCT values (i.e., 2,700 K; 3,000 K; 3,500 K; 4,000 K; and 5,000 K) can be accessed by changing the switch setting. For Product MS-4, the total current applied to the device was approximately 215 mA. The current distribution corresponding to the different CCT settings in presented in **Table 2-1**.

Table 2-1: Current distribution in the LED primaries at the different CCT setting of Product MS-4.

CCT Setting	Warm White Primary Current	Cool White Primary Current
2,700 K	211 mA	4 mA
3,000 K	168 mA	40 mA
3,500 K	115 mA	88 mA
4,000 K	66 mA	137 mA
5,000 K	3 mA	205 mA

For Product MS-5, the total current applied to the LEDs was 169 mA, and all of the current was applied to only one LED primary at the 2,700 K and 5,000 K settings. At the intermediate CCT settings, the current was distributed between the two LED primaries.

During AST, separate populations of lamps were used to represent the 2,700 K and 5,000 K settings, and the lamps were always set to only one CCT value during AST. For Products MS-4 and MS-5, the use of two different LED primaries to achieve the different CCT settings created a situation in which one LED primary was the *dominant* contributor and the other LED primary was a minor contributor to the light spectrum. The light emissions from Products MS-4 and MS-5 provided good color rendering as shown in **Appendix Table 1**. Full spectral power distributions (SPDs) and TM-30-18 analyses for Products MS-4 and MS-5 are provided in our initial report [1].

For Product MS-4, there are 12 serially connected MP-LEDs (2535 package size) for each pc-LED primary, and the pc-LEDs are mounted on a metal-core PCB with a single LED in each package. For Product MS-5, each pc-LED primary has 10 serially connected MP-LEDs (3030 package size), with two LEDs per package, mounted on a metal-core PCB. The maximum power delivered to each pc-LED primary is provided in **Appendix Table 2**.

2.2 Stress Testing Methods

For this study, Products MS-2, MS-4, and MS-5 were purchased either from online sources or local big box retailers and used as received. The DUTs of Product MS-2 were mounted in porcelain lamp holders and operated from alternating current (ac) mains in an upright configuration. In contrast, Products MS-4 and MS-5 were connected directly to ac mains, and operation was varied between upward facing and downward facing configurations. The LED packages of Product MS-3 were acquired from the manufacturer and built into light engines at RTI International's facility in Research Triangle Park, NC. The LED packages of Product MS-3 are shown in **Figure 2-1B** and described in **Section 2.1.1** of this report. The LED modules were connected in series to a driver that was placed outside the test chamber.

The samples of Products MS-2, MS-4, and MS-5 were separated into three populations, each consisting of three DUTs. For the light engine (Product MS-3), three test populations consisting of two light engines containing two LED modules each were tested. The test populations of Product MS-2 were tested in three possible conditions: room temperature operational life (RTOL), an operational life test at an elevated ambient temperature of 45 degrees Celsius (°C; 45OL), and an elevated ambient temperature of 65°C and relative humidity of 90% (6590). For Products MS-3, MS-4, and MS-5, each population was tested in one of three possible conditions: RTOL, an operational life test at an elevated ambient temperature of 75°C (75OL), or an elevated ambient temperature of 75°C and relative humidity of 75% (7575). Either a temperature oven or a temperature-humidity environmental chamber was used for these tests. Humidity was not explicitly controlled during RTOL, 45OL, or 75OL, and the ambient humidity was determined by the air handling system of the building. All DUTs were power cycled for 1 hour (hr) on and 1 hr off. Testing protocols and test durations that were used in our earlier report and also used in this report are provided in **Table 2-2**. No new data were added in this report for ASTs during which all the DUTs were reported as failures in our earlier report [1].

Table 2-2. Comparison of the testing procedures and test duration reported in previous studies and in this report.

Product	AST	DOE Report 1[2]	This Report
MS-1	RTOL	8,000 hrs	Not applicable
	45OL	8,000 hrs	Not applicable
	6590	6,000 hrs	Not applicable
MS-2	RTOL	8,000 hrs	14,000 hrs

	45OL	8,000 hrs	14,000 hrs
	6590	6,000 hrs	6,000 hrs
MS-3	RTOL	5,000 hrs	10,000 hrs
	75OL	5,000 hrs	10,000 hrs
	7575	4,000 hrs	7,000 hrs
MS-4	RTOL	7,000 hrs	12,000 hrs
	75OL	7,000 hrs	12,000 hrs
	7575	4,000 hrs	4,000 hrs
MS-5	RTOL	6,000 hrs	11,000 hrs
	75OL	6,000 hrs	11,000 hrs
	7575	5,000 hrs	4,000 hrs

The lamp manufacturers of Products MS-2, MS-4, and MS-5 rated their products as appropriate for use in damp locations. The maximum temperature reached by the DUTs remained well within manufacturer specifications (Product MS-2) or within expectations for the product type when a maximum temperature was not specified by the manufacturer (Products MS-4 and MS-5 reached maximum temperatures of 86°C and 80°C, respectively). During our testing, the temperature of the LED light engine peaked at 87°C, which is slightly above the manufacturer's specification of ambient temperature of 85°C. The forward current (I_f) stayed within manufacturer's specifications (I_f < 150 mA) at RTOL test conditions, but I_f was slightly above the derated manufacturer's specifications for ambient temperatures during 75OL and 7575.

2.3 Measurement Methods

2.3.1 Luminous Flux

The SPD, luminous flux, and chromaticity measurements of all samples were measured at room temperature in a calibrated 65-inch integrating sphere. Products MS-2 and MS-3 were mounted in the center of the sphere (4π geometry), and Products MS-4 and MS-5 were mounted on the exterior of the sphere facing inward (2π geometry).* Regular calibrations of the integrating sphere were performed by using a calibrated spectral flux standard (for 4π configuration) or a forward flux standard (for 2π configuration) that was traceable to standards from the National Institute of Standards and Technology (NIST). Background corrections were applied prior to calibration. Self-absorption corrections were made for all samples by using an auxiliary lamp mounted inside the sphere, which is in accordance with procedures in the joint ANSI and IES standard ANSI/IES LM-79-19 [11]. When in the 4π configuration, the center post was used to supply line ac to Product MS-2 and direct current (dc) from an external driver to Product MS-3 during photometric testing. Products MS-4 and MS-5 were mounted on an exterior port on the integrating sphere and powered by line ac.

2.3.2 Lens Transmittance

Diffuse transmittance of flat lenses was measured with a Cary 5000 ultraviolet-visible-near infrared (UV-Vis-NIR) spectrometer. The spectrometer was equipped with a monochromator and a diffuse transmittance and reflectance accessory. The lens was mounted on the incident port of the diffuse transmittance and reflectance accessory, and the transmittance spectrum was recorded. The instrument was calibrated for 100% transmittance by using no sample on the incident port and for 0% transmittance by blocking the monochromatic lighting from reaching the incident port.

* Because Products MS-4 and MS-5 were measured in the 2π configuration, they were placed in an open port on the exterior surface of the sphere and the surface area of the sphere accounted for by the port opening was only 0.2% of the total surface area of the sphere.

3 Results and Discussion

3.1 Violet-Pump Light-Emitting Diode Products

This section of the report provides updated data for Products MS-2 and MS-3. All data shown are the average of the population of DUTs at each AST environment (three DUTs for Product MS-2 and four DUTs for Product MS-3). Over the course of testing, five abrupt failures were observed for Product MS-2 and eight parametric failures were observed for Product MS-3. In this report, "parametric failures" are defined as samples that exhibited a luminous flux maintenance (LFM) value below 0.70 or exhibited a chromaticity shift of $\Delta u'v' \geq 0.007$. The test population (and data averaging) excluded lamps that failed abruptly or parametrically by the LFM parametric failure criteria from the failure time forward but did not exclude lamps that failed parametrically because of excess chromaticity shift, unless otherwise noted.

3.1.1 Luminous Flux Maintenance for Products MS-2 and MS-3

After each 1,000 hrs of exposure to the AST environments, the LFM values for Products MS-2 and MS-3 were measured according to IES LM-84-14 [12] (**Figure 3-1** and **Figure 3-2**) and analyzed by using IES TM-28-14 [13]. IES TM-28-14 is the established method for modeling and projecting the long-term LFM of LED lamps and luminaires [13]. TM-28-14 uses a single-exponential decay to describe the change in the luminous flux at any time ($\Phi(t)$) compared with the initial luminous flux (Φ_0) and can be expressed as shown in **Equation 3-1** as follows:

$$\Phi(t) / \Phi_0 = Be^{-\alpha t} \qquad \text{(Eq. 3-1)}$$

Where
B = Pre-exponential factor
α = Decay rate constant.
t = time

Comparisons of the α values of data derived from the measurements described in this report provide some relative measures of the light source decay. Higher values of α indicate more rapid LFM decay, whereas lower values of α indicate slower LFM decay.

For Product MS-2, the average population of RTOL DUTs experienced a slightly lower LFM compared with the 45OL test population. This result may be attributed to the intermittent failure of two RTOL DUTs. Between 9,000 and 10,000 hrs of RTOL exposure, two DUTs (613 and 614) started experiencing intermittent failure. One of these two intermittent DUTs exhibited abrupt failure by 11,000 hrs; the other failed abruptly by 12,000 hrs. Several thousand hours before abrupt failure, the LFM value of these DUTs began a slow decrease with an LFM decline of approximately 5% shortly before failure. In contrast, the RTOL DUT that did not exhibit abrupt failure maintained a consistent LFM value throughout. As a result, the RTOL data at 11,000 hrs was the average of two DUTs and from 12,000 hrs onward, the LFM data only reflect one DUT. Removing these two DUTs from the average gives rise to the sharp increase in average LFM observed at 12,000 hrs. For the IES TM-28-14 analysis, only the data from 5,000 hrs through 10,000 hrs were used for the RTOL condition to ensure that three DUTs were part of the model. The intermittency of the failed DUTs may suggest a manufacturing or material flaw.

More consistent behavior was observed for the DUTs in 45OL and 6590. The DUTs operated at 45OL experienced a gradual decrease in LFM through 13,000 hrs with no failures. For the 6590 population, one DUT failed abruptly between 5,000 and 6,000 hrs as previously reported [1], and the remaining two DUTs were removed from testing after 6,000 hours because of space limitations in the environmental chamber. The more aggressive conditions of the 6590 AST relative to 45OL led to almost a 20 times increase in α values.

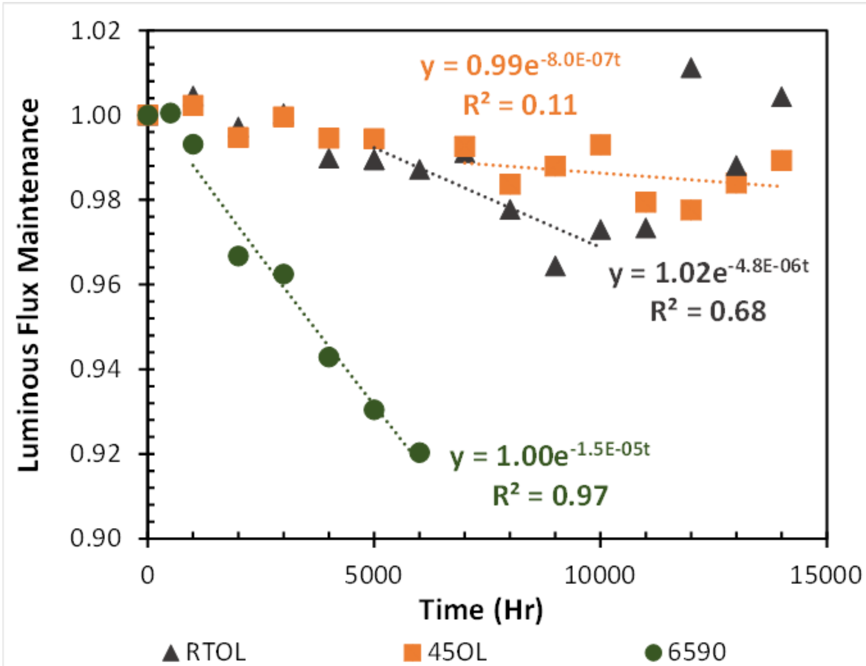

Figure 3-1: LFM of Product MS-2 during RTOL, 45OL, and 6590 according to IES LM-84-14. The dashed lines and least square fit parameters correspond to IES TM-28-14 models calculated as described in the text.

The LFM of Product MS-3 showed substantial differences between the RTOL, 75OL, and 7575 test populations (**Figure 3-2**). The RTOL DUTs experienced a gradual decrease in LFM over the entire test duration (10,000 hrs). The 75OL DUTs experienced two regions of luminous flux decay: an initial period of fast decay until 5,000 hrs, and then slower decay from 5,000 through 10,000 hrs. This finding may suggest that multiple mechanisms that lower emissions are at work in the Product MS-3 DUTs. The first mechanism is greatly accelerated by temperature, whereas the long-term mechanism is less impacted by temperature. The IES-28-14 model for this test condition only covers the long-term mechanism because it extends from 5,000 hrs to 10,000 hrs. At the most aggressive AST environment (7575), the LFM of all three DUTs fell below 0.70 by 7,000 hrs. The α value for the 7575 test condition was approximately 5.3 times greater than the α value for 75OL, suggesting that humidity also impacts the LFM decline.

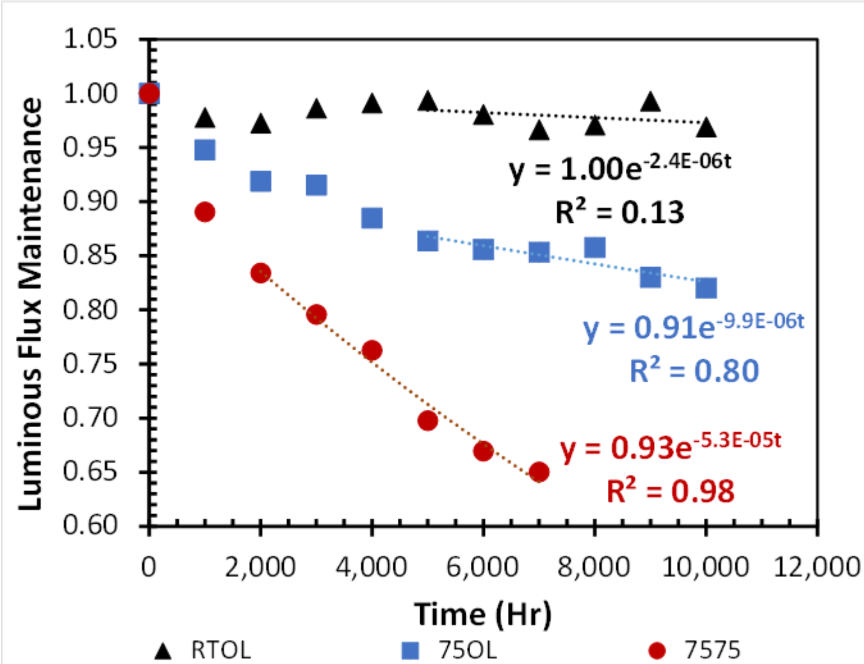

Figure 3-2: LFM for Product MS-3 during RTOL, 75OL, and 7575 according to IES LM-84-14. The dashed lines and least square fit parameters correspond to IES TM-28-14 models calculated as described in the text.

Care should be exercised when comparing the results of Product MS-2 with Product MS-3. First, Product MS-2 was subjected to less aggressive ASTs to try to prolong electrical component life. Second, although both products have violet-pump LEDs, Product MS-2 is a lamp with optics and an integrated power supply, whereas Product MS-3 is solely an LED module. Therefore, the LFM of Product MS-2 is subject to changes in electrical components, optics, the LED module, and the LED packages, whereas Product MS-3 is subject to changes in only the LED module and LED packages. As previously reported and shown in **Appendix Table 2**, the forward current of the LEDs was 58 mA for Product MS-2 and 150 mA for Product MS-3. Finally, the manufacturer's recommended maximum currents for the LEDs used in Product MS-2 and MS-3 are 165 mA and 150 mA, respectively. The LEDs in Product MS-2 were only operated at 35% of their rated maximum value, whereas those for Product MS-3 were operated at 100% of the rate maximum value. As a result, the higher degradation levels observed for Product MS-3 can be attributed, at least in part, to the higher driver currents and the more aggressive test conditions.

3.1.2 Luminous Efficacy Maintenance for Products MS-2 and MS-3

The use of the violet-pump LED and omission of blue emissions led to lower initial luminous efficacy for Product MS-2 relative to a standard LED product with a CCT of approximately 2,600 K [8]. As AST progressed, the luminous efficacy of Product MS-2 continued to be dominated by the change in luminous flux because change in power consumption was negligible (see **Figure 3-3**). As such, the luminous efficacy for Product MS-2 is a function of the AST exposure times. For example, the most aggressive test condition (6590) had a rate of luminous efficacy exponential decline (1.3×10^{-5}) was similar to the α value for LFM (1.5×10^{-5}) determined by IES TM-28-14. Because of the abrupt failure of two DUTs in the RTOL test (failure times of 11,000 hrs and 12,000 hrs), the luminous efficacy was only modeled through 10,000 hrs for the RTOL population. The rate of exponential decline for the luminous efficacy of the RTOL population was larger than the rate of luminous efficacy decline for the 45OL population. The behavior further supports that luminous efficacy maintenance was dominated by luminous flux.

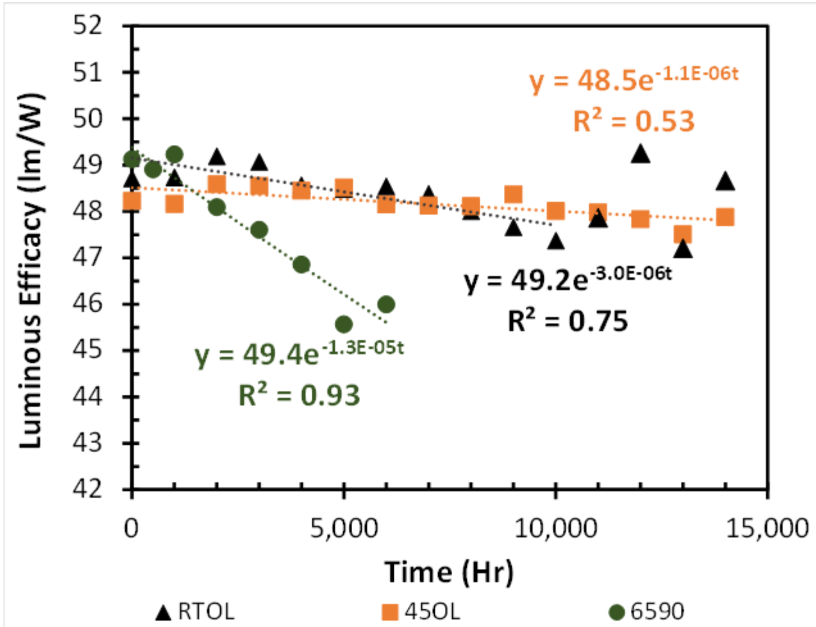

Figure 3-3: Luminous efficacy of Product MS-2 during RTOL, 45OL, and 6590 and least square models and fit parameters for an exponential decay model for each test condition.

For Product MS-3, the luminous efficacy value also decreased in an exponential manner over the course of AST as shown in **Figure 3-4**. The rates of decline were similar to the α values determined from the LFM models (**Figure 3-2**). Because Product MS-3 is a light engine and the electrical drivers were operated outside the test chamber, the change in luminous efficacy only reflects the change in the LED modules. The solder mask on the LED modules did darken, but the large area of the integrating sphere relative to the LED module makes any loss from solder mask darkening negligible [14]. By the end of test, there were no signs of discoloration on the LEDs.

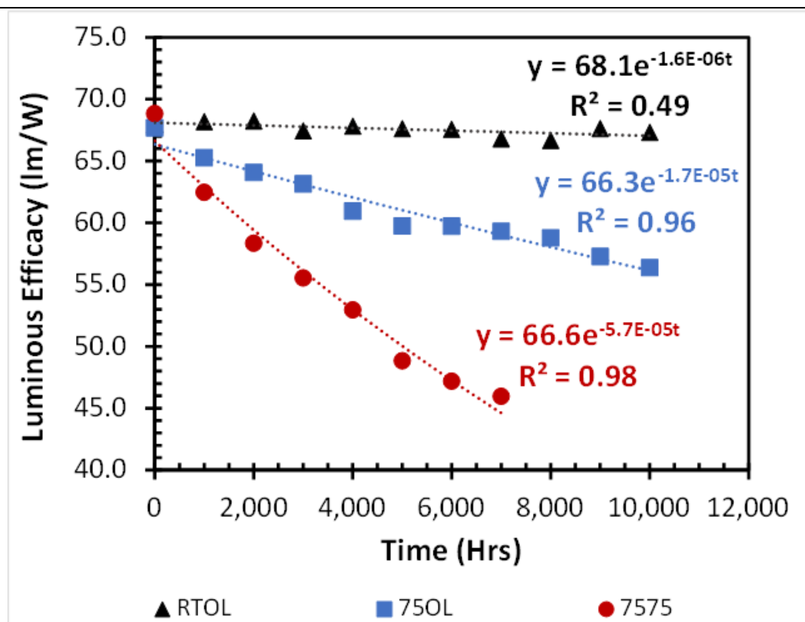

Figure 3-4: Luminous efficacy of Product MS-3 during RTOL, 75OL, and 7575 and least square models exponential decay model and model parameters for each test condition.

3.1.3 Chromaticity Maintenance for Products MS-2 and MS-3

For all products that are tested, we maintained a control lamp that did not undergo AST but was measured every time that product was tested. In almost every case, the control lamp maintained steady LFM and chromaticity values. However, as mentioned in our initial report [1], the control lamp for Product MS-2 experienced a significant chromaticity shift in the direction of the violet emitter. The control lamp for Product MS-2 was only operated during photometric testing and always stored at room temperature in its original packaging when it was not operated. From May 2019 to January 2021, the control lamp for Product MS-2 was photometrically tested 21 times. During this time, the luminous flux averaged 579 ± 4 lumens (lm), but the chromaticity changed significantly ($\Delta u'v'$ = 0.0044), and most of the chromaticity shift was in the -$\Delta v'$ direction (i.e., toward the violet emitter). This shift was because of a relative increase in the strength of violet emissions at the expense of green and red emissions. A similar shift occurred in the control sample and those used during RTOL and 45OL. A different chromaticity shift behavior was observed for the DUTs in the 6590 environment because of the more aggressive nature of this test. Chromaticity results reported here are corrected for the shift in the control in order to separate general drift in the chromaticity of the product from that caused by the AST conditions.

Our initial results showed minimal chromaticity changes for the Product MS-2 DUTs during RTOL and 45OL after correcting for the shift of the control. In contrast, there were substantially significant changes in chromaticity for the 6590 test populations, and the magnitude of the chromaticity shift ($\Delta u'v'$) was approximately 0.0055 in the yellow-red direction for the 6590 population. This behavior has been categorized as a chromaticity shift mode-3 (CSM-3). As testing continued through 14,000 hrs, very little change was observed for the chromaticity coordinates of the RTOL and 45OL test populations as shown in **Figure 3-5**. The chromaticity shift behavior observed for the MS-2 products suggests a significant change in the chromaticity shift mechanism between the 45OL and 6590 test environments.

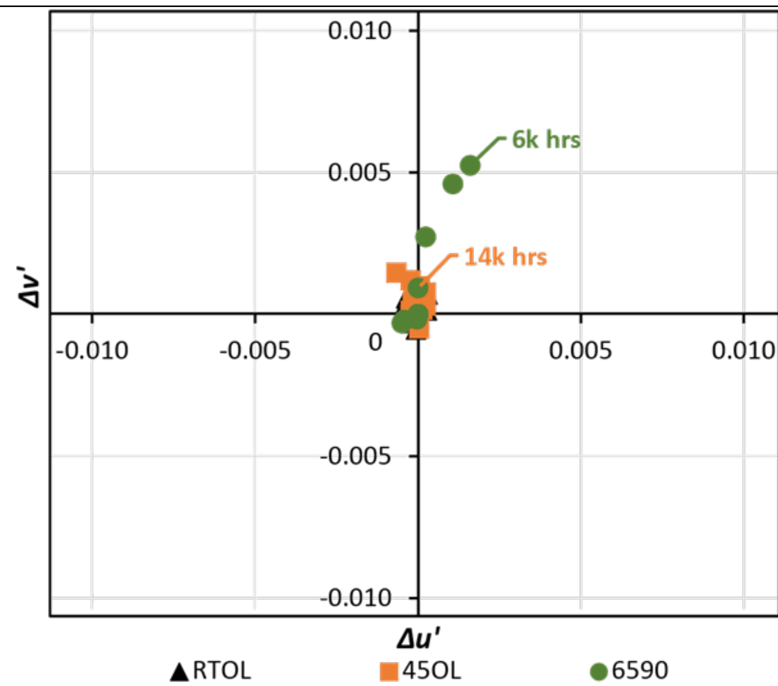

Figure 3-5: Chromaticity shift of Product MS-2 during RTOL, 45OL, and 6590.

Because Product MS-3 does not have any optical lenses or reflectors and the electrical drivers were kept outside the test chamber, any observed chromaticity shift reflects a change in the LED module or LED package. In our initial report, which included chromaticity shifts through 5,000 hrs (RTOL and 75OL) and 4,000 hrs (7575), chromaticity shift was minimal ($\Delta u'v'$ < 0.001) for RTOL and significant for 75OL ($\Delta u'v'$

approximately 0.005), and the average 7575 test population underwent parametric failure by 2,000 hrs [1]. The previously reported chromaticity shift trends continued during further testing for Product MS-3 DUTs as shown in **Figure 3-6**. Through 10,000 hrs, the chromaticity shift for the RTOL DUTs remained minimal ($\Delta u'v'$ < 0.001). For the 75OL tests, the direction of chromaticity shift continued mainly along the -$\Delta v'$ axis, though there was some slight shifting toward the -$\Delta u'$ axis, which suggests that the chromaticity point is shifting mainly toward the violet LED emitter. The slight shift along the -$\Delta u'$ axis suggests that the relative emissions from the green and red phosphors are changing and that the green phosphor has a greater long-term stability than the red phosphor in the 75OL conditions. The greater stability of the green phosphor was supported by the temporal SPDs of a representative 75OL DUT shown in **Figure 3-7**. The red emitter initially had higher flux, but by 10,000 hrs, its emission was slightly lower than that of the green emitter. Furthermore, between 5,000 hrs (our initial report) and 10,000 hrs, the intensities of the blue and violet emitters remained almost the same, but both red and green emitters had lower intensity. These data explain the predominant chromaticity shift in the violet/blue direction. The magnitude of the chromaticity shift in 75OL ($\Delta u'v'$ = 0.0075) led to parametric failure of all four DUTs by 10,000 hrs (one DUT failed at 7,000 hrs, two failed at 9,000 hrs, and the last DUT failed at 10,000 hrs). As previously mentioned at the beginning of this section of the report, parametric chromaticity shift failures were not excluded from data averaging.

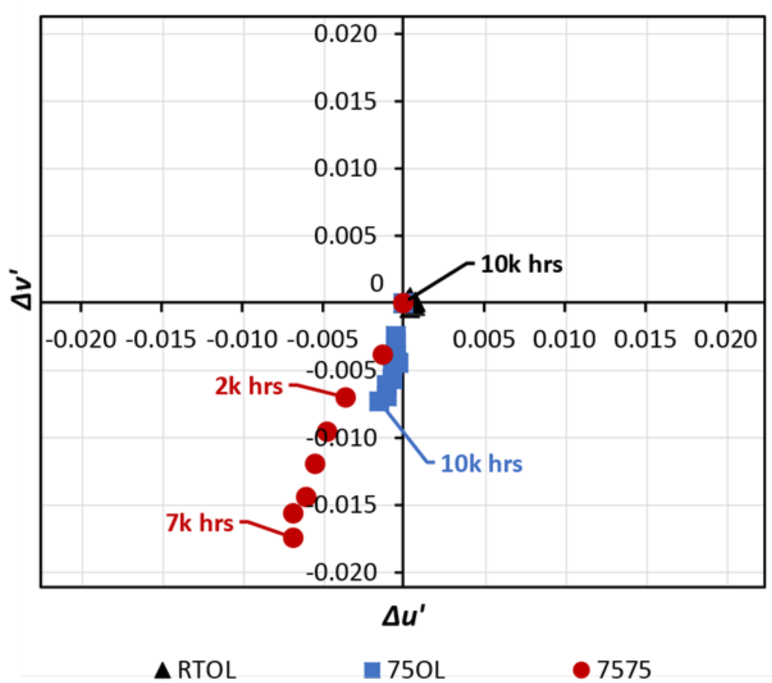

Figure 3-6: Chromaticity shift diagram for Product MS-3 in RTOL, 75OL, and 7575.

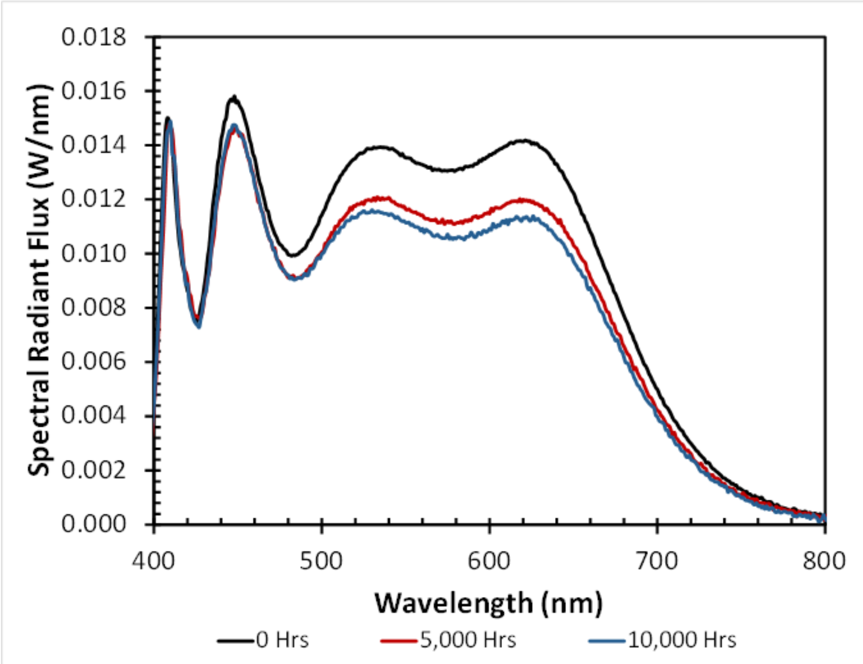

Figure 3-7: SPDs for Product MS-3 operated during 75OL for various times.

For the 7575 DUTs, all DUTs underwent parametric chromaticity shift failure by 3,000 hrs. At 3,000 hrs, the LFM for the 7575 Product MS-3 DUTs was approximately 0.83. The 7575 DUTs were put back into test to study long-term chromaticity shift trends until all four DUTs had an LFM below 0.70, which occurred at 7,000 hrs. At 7,000 hrs, the chromaticity shift was large and continued in the predominantly $-\Delta v'$ direction (toward the violet emitter), but with a more significant change in the $-\Delta u'$ direction than during 75OL. The magnitudes of these changes were greatly accelerated compared with those during 75OL, and the total chromaticity shift ($\Delta u'v'$) was 0.019. Temporal SPDs from a representative 7575 DUT showed a sharp drop in phosphor emissions (**Figure 3-8**) relative to the violet LED. A closer examination of the green and orange-red emitters showed that the green emission maximum goes from equal intensity to clearly larger intensity than the orange-red peak maximum, consistent with a change in the green to orange-red emissions ratio.

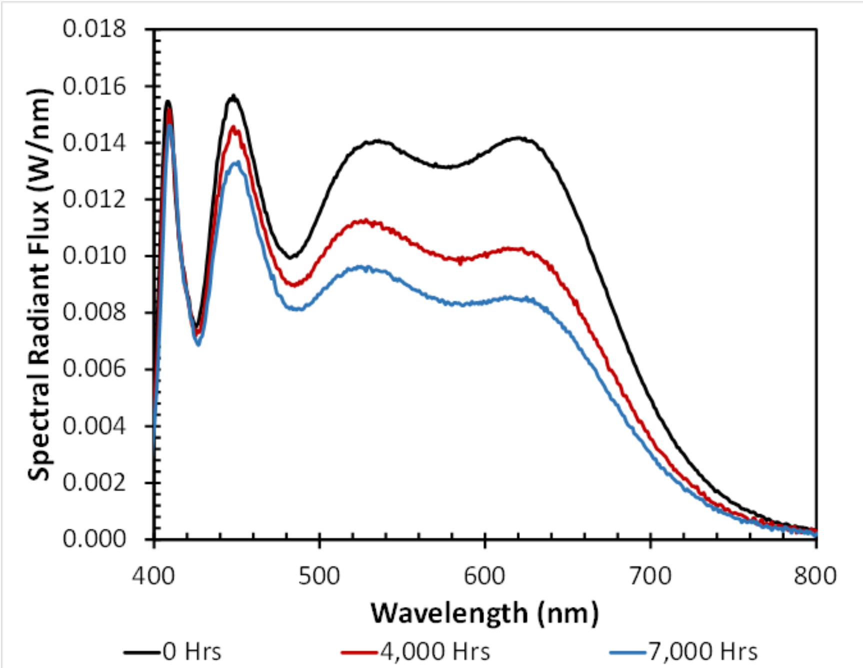

Figure 3-8: SPDs for Product MS-3 operated during 7575 at various times.

3.1.4 Failure Analysis and Post-mortem Examination for Products MS-2 and MS-3

By the end of the testing period discussed in this report, a total of three DUTs failed for Product MS-2 (two DUTs during RTOL and one DUT during 6590) and eight DUTs failed for Product MS-3 (four DUTs during 75OL and four DUTs during 7575). A list of the failed DUTs and their failure descriptions for Products MS-2 and MS-3 is provided in **Table 3-1**.

For Product MS-2, we previously reported that one of the 6590 DUTs began exhibiting excess temporal light artifacts (TLA) at approximately 5,225 hrs so it was classified as a failure [1]. A disassembly of the failed DUT showed discoloration of the solder mask on the LED module, yellowing of the globe, and two non-functioning LEDs. The failed LEDs were hypothesized to be tied to the occurrence of TLA, but the source of the TLA was traced to a solder joint failure on a through-hole connected to the flyback transformer in the driver. All lamps subjected to 45OL testing survived 14,000 hrs without experiencing either an abrupt lights-out failure or a parametric failure. However, during RTOL, two out of the three DUTs started experiencing intermittent failures between 9,000 and 10,000 hrs, with both DUTs experiencing abrupt failures by 12,000 hrs (**Table 3-1**). The power characteristics of the two failed RTOL DUTs are provided in **Table 3-2**. After failure, there was no light emission from DUT 613, but the DUT was still pulling power from the ac mains line, albeit the power was minimal, and the electrical driver was not providing any voltage or current to the LED module. This failure was eventually traced to two film capacitors in the electromagnetic interference filter. When DUT 614 was removed from testing, it would not produce light. However, when DUT 614 underwent failure analysis, it turned on after the globe was removed and did not shut back off for the remainder of multiple analysis steps. The electrical characteristics for DUT 614 after 14,000 hrs were similar to its initial electrical characteristics, and an assignment of the cause of failure could not be made.

Table 3-1. Failure Descriptions for Products MS-2 and MS-3.

Product	DUT	AST	Failure Type	Time to Failure (hr)
MS-2	613	RTOL	Abrupt—filter capacitors	11,000
MS-2	614	RTOL	Abrupt—cause not found	12,000
MS-2	619	6590	Parametric (LFM < 0.70, excessive TLA)—solder joint failure	6,000
MS-3	703	75OL	Parametric (chromaticity shift)	7,000
MS-3	704	75OL	Parametric (chromaticity shift)	10,000
MS-3	705	75OL	Parametric (chromaticity shift)	9,000
MS-3	706	75OL	Parametric (chromaticity shift)	9,000
MS-3	707	7575	Parametric (chromaticity shift) Parametric (LFM < 0.70)	2,000 5,000
MS-3	708	7575	Parametric (chromaticity shift) Parametric (LFM < 0.70)	2,000 5,000
MS-3	709	7575	Parametric (chromaticity shift) Parametric (LFM < 0.70)	3,000 7,000
MS-3	710	7575	Parametric (chromaticity shift) Parametric (LFM < 0.70)	2,000 7,000

Table 3-2. Electrical Properties for the Failed RTOL Product MS-2 DUTs.

DUT	Power Factor	Current (mA)	ac Power (W)	dc Voltage (V)	Volt Amperes (W)
613	0.47	0.6	0.035	0	0.068
614	0.89	118	12.95	63.7	14.4

Product MS-3 experienced high reliability through 10,000 hrs during the RTOL test (the LFM was approximately 0.97 and $\Delta u'v' < 0.001$). However, parametric failures were observed at the aggressive testing conditions of 75OL and 7575 (**Table 3-1**). The maximum forward current for the Product MS-3 LEDs is rated at 150 mA but above an ambient temperature of 65°C, the maximum forward current is derated to slightly greater than 100 mA until the ambient temperature reaches 85°C, which is the maximum ambient temperature for operation (see **Figure 3-9**). At an ambient temperature of 75°C, the maximum forward current is limited to approximately 130 mA. During our testing, the current supplied to all DUTs was 150 mA, regardless of ambient temperature, in an effort to maximally stress the DUTs. As noted in **Section 2.1.1** of this report, the maximum ambient temperature of the 7575 DUTs peaked at 87°C, which is above the manufacturer's rating of 85°C. All DUTs in the 75OL and 7575 tests underwent parametric failure by chromaticity shift at the end of test in these extreme conditions. The chromaticity shifted in the violet and blue direction by an unacceptable magnitude ($\Delta u'v' > 0.007$) by 2,000 to 3,000 hrs during 7575 and by 7,000 to 10,000 hrs during 75OL. These results suggest greater stability of the violet LED and blue phosphor relative to the red and green phosphors used in this product at high temperature and also show that the degradation pathways are promoted by temperature and moisture. Even under the harsh conditions of 75OL and 7575, the LFM remained acceptable through 10,000 hrs for the 75OL DUTs and at least through 5,000 hrs for all 7575 DUTs. By 7,000 hrs, all DUTs in the 7575 test experienced parametric failures for the LFM below 0.70.

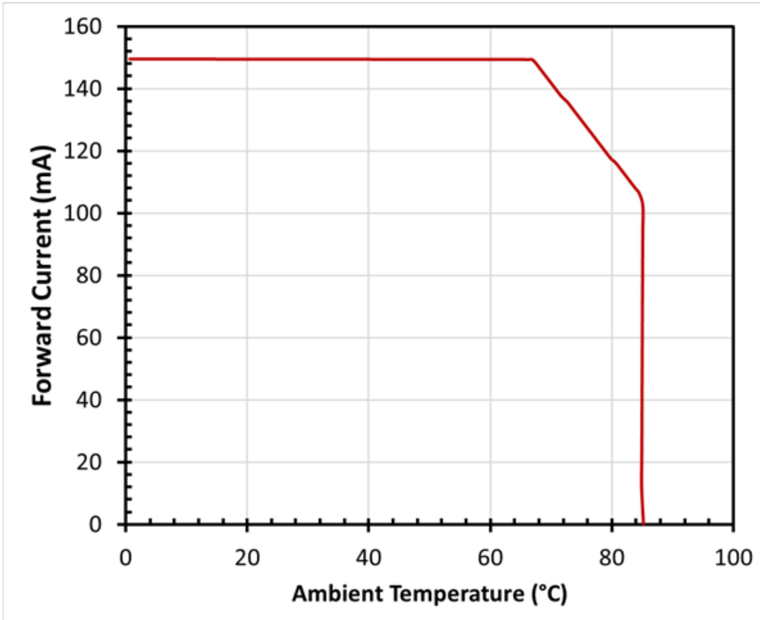

Figure 3-9: Maximum forward current as a function of ambient temperature for LEDs used in Product MS-3.

3.2 Switchable Downlight Products

This section of the report provides updated data for Products MS-4 and MS-5. All data shown are the average of the population of DUTs at each AST environment (three DUTs for each test). Over the course of testing, three abrupt failures were observed in 7575 for each product, and no parametric failures were observed. Failure analysis of the abrupt failures in 7575 has been discussed previously in our initial report [1].

3.2.1 Luminous Flux Maintenance for Product MS-4

The switchable downlight products have two LED primaries that combine to produce CCT values between 2,700 K and 5,000 K, depending on the setting of a switch (see **Table 2-1**). During AST, the CCT setting determined which LED primary was dominant and which was a minor contributor to the total light flux. Photometric testing was performed on the CCT setting used during the ASTs after every 1,000 hrs of exposure to the RTOL, 75OL, and 7575 environments by using the procedures described in IES LM-84-14 [12]. The complete test results are presented in **Figure 3-10a** for the 2,700 K setting and **Figure 3-10b** for the 5,000 K setting. The results were modeled by using IES TM-28-14, and the findings of this analysis are presented in **Figure 3-11a** for the 2,700 K setting and **Figure 3-11b** for the 5,000 K setting. Ambient temperature had a significant impact on the decay rate constant (α) and the value increased by 14.6 times between RTOL and 75OL for the 2,700 K setting. A similar increase of 13.3 times was measured for the 5,000 K setting. When comparing the α values of 75OL and 7575, the addition of humidity was observed to increase the rate of luminous flux decay by 2.3 times for the 2,700 K setting and 1.6 times for the 5,000 K setting.

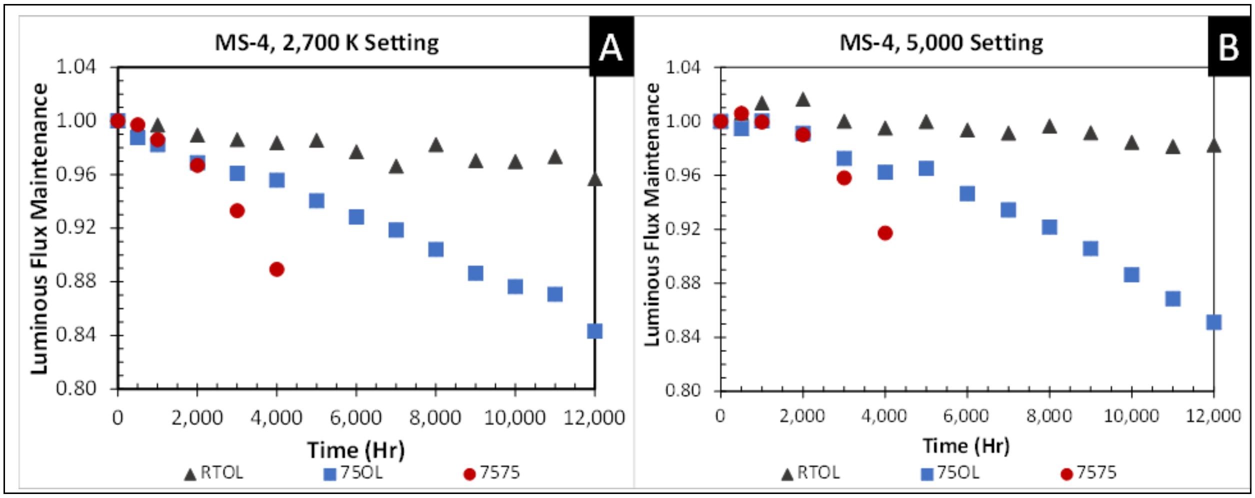

Figure 3-10: The LFM of the Product MS-4 test populations operated with (A) 2,700 K setting during AST or (B) 5,000 K setting during AST. Testing was performed following RTOL, 75OL, or 7575 environments.

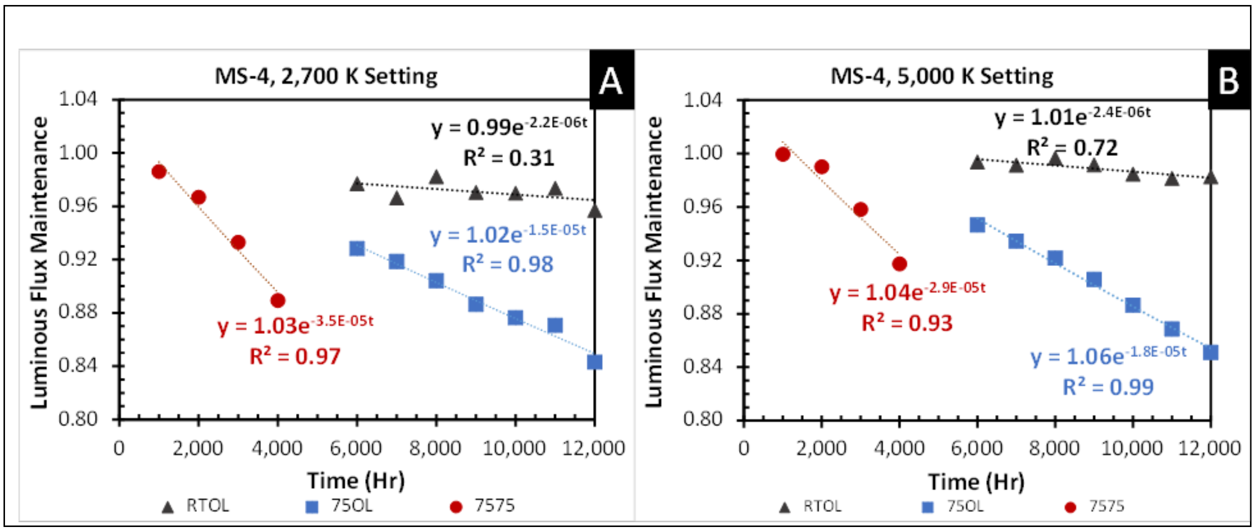

Figure 3-11: LM-28-14 models of the LFM for Product MS-4 test populations operated with (A) the 2,700 K setting during AST or (B) the 5,000 K setting during AST. Testing was performed in either RTOL, 75OL, or 7575 environments.

Based on the values determined during the TM-28-14 analysis, the L_{70} value for the 2,700 K primary operated in the 75°C ambient environment was projected to be 25,100 hrs, whereas the L_{70} value for the 5,000 K primary operated in the 75°C ambient environment was projected to be 23,100 hrs.

In performing these tests, the DUTs were divided into two groups of three samples for each AST. Group 1 DUTs were placed in the 2,700 K setting during the AST, and the 5,000 K setting was not used during AST. Group 2 DUTs were placed in the 5,000 K setting during AST, and the 2,700 K LED primary was not used during these tests. After every 3,000 hrs of testing, photometric measurements were taken on the unused CCT setting. Afterwards, the CCT control switch on the downlight was returned to the original setting prior to the next AST cycle.

The photometric properties for the unused CCT settings were measured periodically (see **Figure 3-12**), and the LFM data demonstrate that light emissions from the minor LED primary degraded at a significant rate during 75OL and 7575 even though the LEDs were hardly used during the AST. After 12,000 hrs of 75OL, the LFM values of the unused CCT settings were 0.89 (2,700 K setting) and 0.87 (5,000 K setting), respectively. These values were slightly larger than those measured for the active settings after 12,000 hrs of 75OL, which are 0.84 (2,700 K setting) and 0.85 (5,000 K setting). Because the LEDs for the unused CCT setting experience minimal electrical current during AST, they would not be expected to degrade during AST. However, the findings shown in **Figure 3-12** suggests that factors other than light source efficiency degradation is contributing to the observed rapid LFM decline.

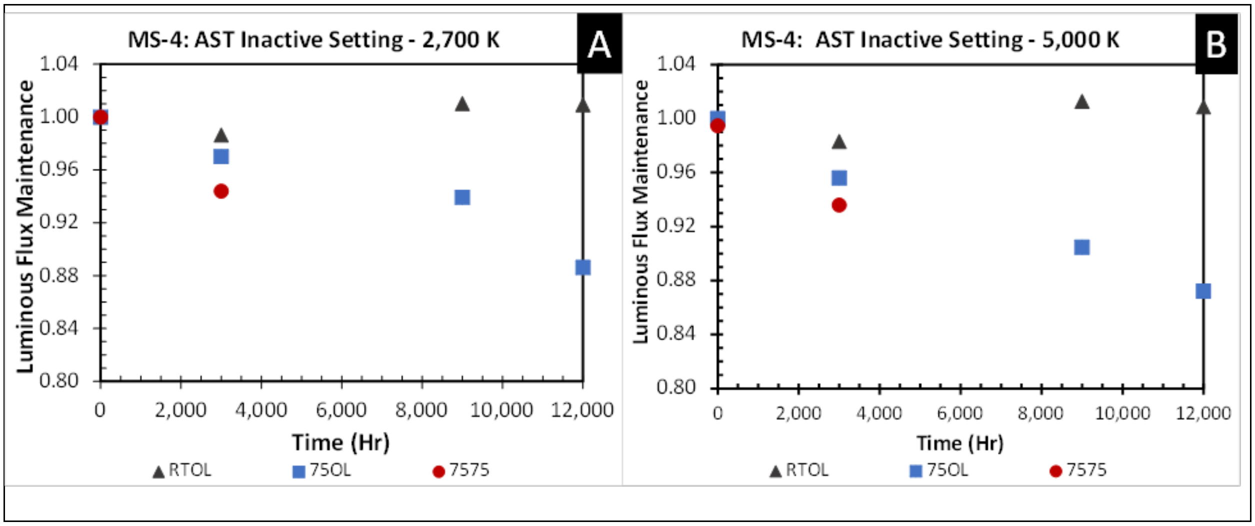

Figure 3-12: The LFM of the Product MS-4 test populations operated with (A) 2,700 K setting on during photometric testing but not used during AST or (B) 5,000 K setting on during photometric testing but not used during AST. Testing was performed following RTOL, 75OL, or 7575 environments.

For samples in the RTOL environment for 12,000 hrs, the LFM of the unused CCT setting was measured as 1.01 for both the 2,700 K and 5,000 K settings. For the active CCT settings under these conditions, the LFM of the 2,700 K setting was 0.96, and the LFM of the 5,000 K setting was 0.98, demonstrating only a minor amount of light source degradation in this condition.

3.2.2 Luminous Efficacy for Product MS-4

The luminous efficacies for Product MS-4 DUTs when the 2,700 K and 5,000 K settings were used during AST are shown in **Figure 3-13a** and **Figure 3-13b**, respectively. During RTOL, luminous efficacy initially increased with use during RTOL because of a small (3% to 4%) drop in power consumption that occurred during the first 1,000 hrs of operation. As a result, the luminous efficacy for both CCT settings was higher after 12,000 hrs of use than the initial luminous efficacy, and this value reaches a limiting value after approximately 3,000 hrs to 6,000 hrs of use. For the 75OL DUTs, there was also a small initial increase in luminous efficacy for both CCT settings, followed by a slow decrease. For DUTs in the 7575 environment, the luminous efficacy initially increased slightly or remained constant, but then decreased rapidly after 500 hrs of exposure because of the loss of luminous flux.

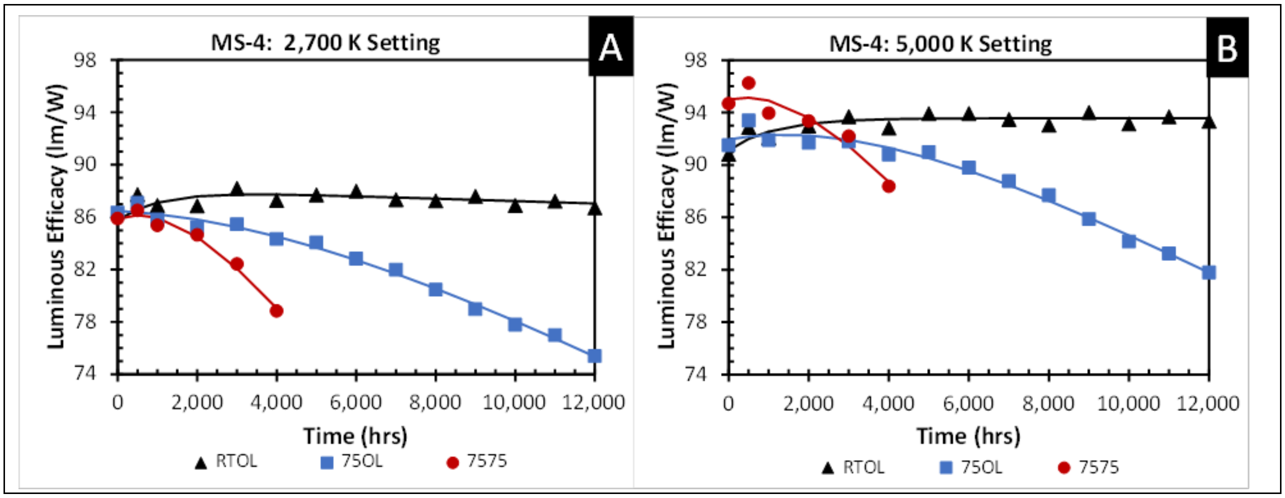

Figure 3-13: The temporal change in luminous efficacy for Product MS-4: (A) for samples with the 2,700 K setting in use during AST and (B) for samples with the 5,000 K setting in use during AST. Testing was performed in the RTOL, 75OL, and 7575 environments.

We previously reported [15] that such behavior in LEDs can be modeled by using an efficiency function formed as the product of a bounded exponential equation $\gamma(1 - e^{-\beta t})e^{-\alpha t}$ and an exponential decay equation ($Be^{-\alpha t}$) [3, 15]. The combined function is shown in **Equation 3-2** as follows:

$$Luminous\ efficacy = e^{-\alpha t}\left[B + \gamma\left(1 - e^{-\beta t}\right)\right] \quad \text{(Eq. 3-2)}$$

Where

α = Decay rate constant

B = Initialization constant

γ = Maximum asymptotic increase relative to the starting value

β = Reciprocal of the time when the efficiency increases by 0.63γ

t = Time.

When t is very large, **Equation 3-2** reduces to an exponential decay function used for luminous efficacy models in **Section 3.1.2**. At small values of t (relative to total lifetime), the bounded exponential term $(1 - e^{-\beta t})$ is non-zero, and **Equation 2** can also be used to model the initial increase in luminous efficacy. The estimated luminous efficacy was estimated by using **Equation 3-2** and changing α, B, γ, and β. This value was compared with the measure luminous efficacy and the estimated value recalculated until the $(\text{error})^2$ value was minimized. The best-fit parameters for each CCT setting exposed to the RTOL, 75OL, and 7575 environments are presented in **Table 3-3**. For RTOL DUTs in which the 5,000 K setting was used during AST, the exponential decay part of the model could not be calculated because there was no reduction in luminous efficacy during the 12,000-hr test period. However, all parameters could be calculated for both CCT settings during 75OL and 7575 and for the 2,700 K setting during RTOL.

Table 3-3: Parametric Fits for the Luminous Efficacy Model of the LED Primaries in Product MS-4.

Parameters	2,700 K Setting in AST			5,000 K Setting in AST		
	RTOL	75OL	7575	RTOL	75OL	7575
α	1.1×10^{-6}	3.4×10^{-5}	6.0×10^{-5}	Not applicable	2.2×10^{-5}	5.5×10^{-5}
B	85.8	86.5	85.9	91.1	91.9	95.0
γ	2.4	76.0	20.8	2.5	16.6	26.2
β	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
$Error^2$	3.21	1.64	0.65	2.68	3.21	3.01

3.2.3 Chromaticity Maintenance for Product MS-4

The chromaticity of Product MS-4 DUTs when the 2,700 K and 5,000 K settings were used during AST shifted in the generally yellow-red direction as shown in **Figure 3-14**. This shift follows CSM-3 behavior. The temporal changes in chromaticity shift are presented in **Appendix Figure 1** for DUTs in which the 2,700 setting was used during AST and in **Appendix Figure 2** for DUTs when the 5,000 K setting was used in AST. For both settings, the chromaticity shift was in the generally yellow-red direction (i.e., the change was larger along the $+\Delta v'$ axis than along the $+\Delta u'$ axis). After 12,000 hrs of exposure, the $\Delta v'$ values for both LED primaries were similar ($\Delta v'$ approximately +0.0035), but the shift in $\Delta u'$ was slightly larger for the 2,700 LED primary. The shifts for RTOL, 75OL, and to a point 7575 are in the same general direction, suggesting that the same chromaticity shift mechanism was active in all three test environments. For DUTs set to 2,700 K in 7575, there was an indication of a chromaticity shift in the green direction (i.e., $\Delta u'$ begins to decrease) after approximately 2,000 hrs of exposure. This behavior has been attributed to photo-oxidation of the phosphor [16].

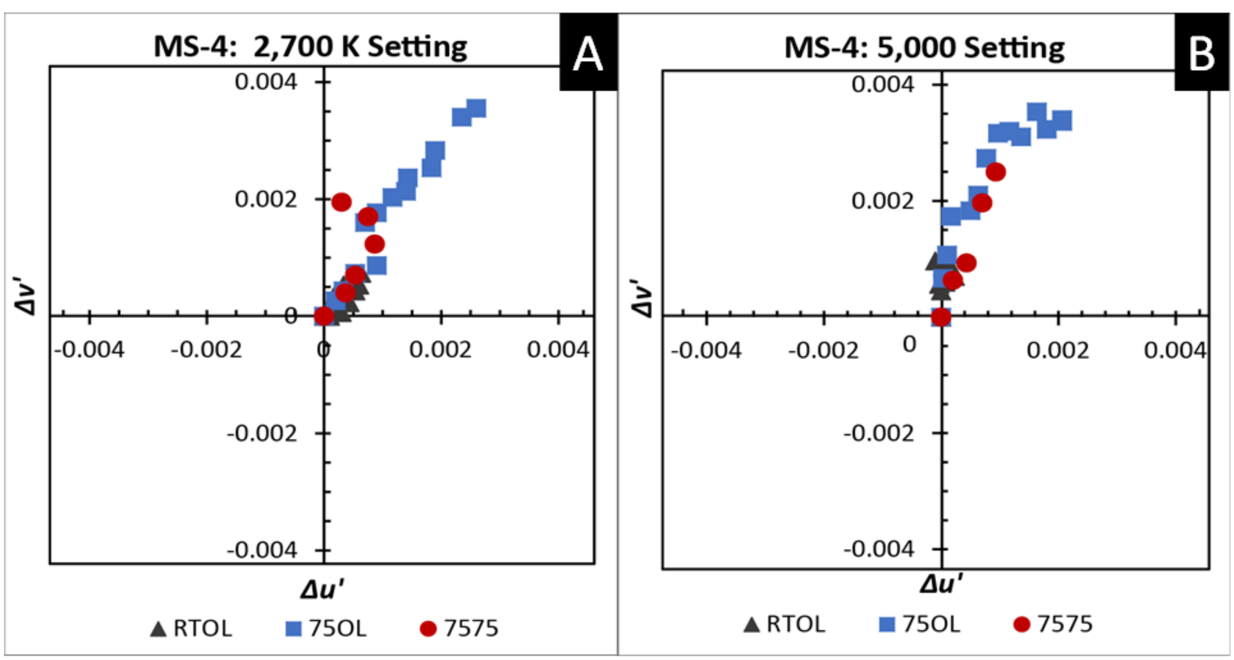

Figure 3-14: The chromaticity shift for Product MS-4: (A) for the 2,700 K setting that was used during AST and (B) for the 5,000 K setting that was used during AST. Chromaticity was measured after exposure to the RTOL, 75OL, and 7575 environments.

3.2.4 Lens Transmittance Changes for Product MS-4

The changes in the LFM of the LEDs that were minor contributors to the light emitted during AST demonstrate that aging of the SSL devices impacts more than the LEDs—it also impacts the optical system. Aging of the optical system has been shown to reduce lens transmittance and the reflectance of surfaces used to shape the light beam [6, 7]. The net result of these aging processes was an increase in light absorption inside the SSL device and a reduction in luminaire efficiency[†], which produced a drop in luminous flux. In downlights, degradation of both lenses and reflective surfaces has been shown to contribute to these changes, but the impact of lens dominates for devices with an optical cavity less than 3 inches in height [7]. For Product MS-4, the optical cavity is only 1-inch deep, so it is expected that degradation of these lenses would account for the drop in the LFM from the inactive primary.

Measurements of the transmittance of the Product MS-4 lenses from samples in the various AST environments confirm greater degradation in the lens samples from the 7575 and 75OL environments than from the RTOL environment (see **Figure 3-15**). The net result was a significant attenuation of light emitted from the LED module at the base of the optical cavity. This attenuation affected the entire LED board, including both the LEDs that are operated at high currents during AST (see **Figure 3-11**) and those that are operated at minimal currents (see **Figure 3-12**).

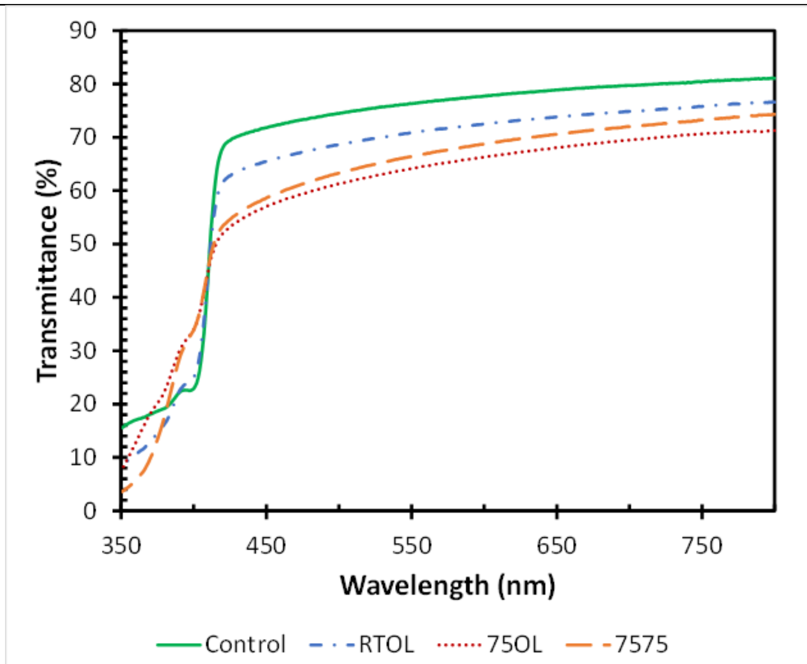

Figure 3-15: Spectral transmittance measurements for Product MS-4 lenses subjected to the various AST environments.

3.2.5 Luminous Flux Maintenance for Product MS-5

The LFM measurements of Product MS-5 were collected on the active CCT setting after every 1,000 hrs of exposure to RTOL, 75OL, and 7575 environments by using the procedures described in IES LM-84-14 [12]. The complete test results are provided in **Figure 3-16a** for the 2,700 setting and **Figure 3-16b** for the 5,000 K setting. The results were analyzed by using IES TM-28-14 to determine the LFM, and the findings are shown in **Figure 3-17a** for the 2,700 K setting and **Figure 3-17b** for the 5,000 K setting. A very slow change in LFM

[†] "Luminaire efficiency" is the luminous flux emitted by a luminaire divided by the luminous flux emitted by the sources.

($\alpha = 4.2 \times 10^{-7}$) was measured for the 2,700 K setting after 12,000 hrs of RTOL, and a larger decline in LFM ($\alpha = 4.0 \times 10^{-6}$) was measured for the 5,000 K setting during the same test. Temperature accelerated the decrease in the LFM with α values increasing to 1.0×10^{-5} for the 2,700 K setting and 1.9×10^{-5} for the 5,000 K setting. The addition of humidity further accelerated the decline in the LFM, and the ratio of α values for 7575 to 75OL was approximately 2.7 for both LED primaries.

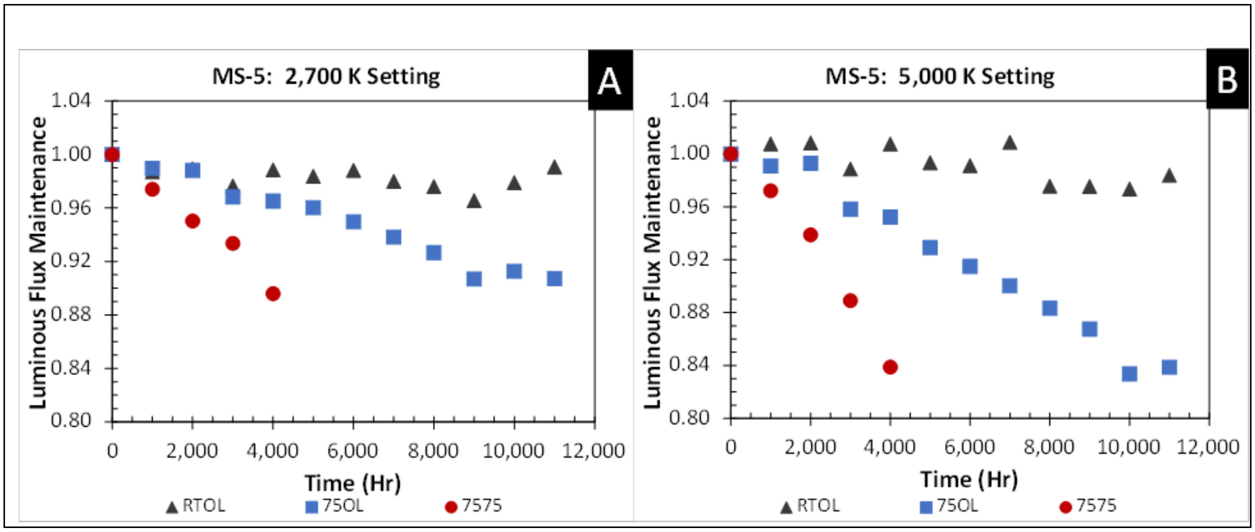

Figure 3-16: The LFM of the Product MS-5 test populations operated with (A) the 2,700 K setting that was used during AST or (B) the 5,000 K setting that was used during AST. Testing was performed following RTOL, 75OL, or 7575 environments.

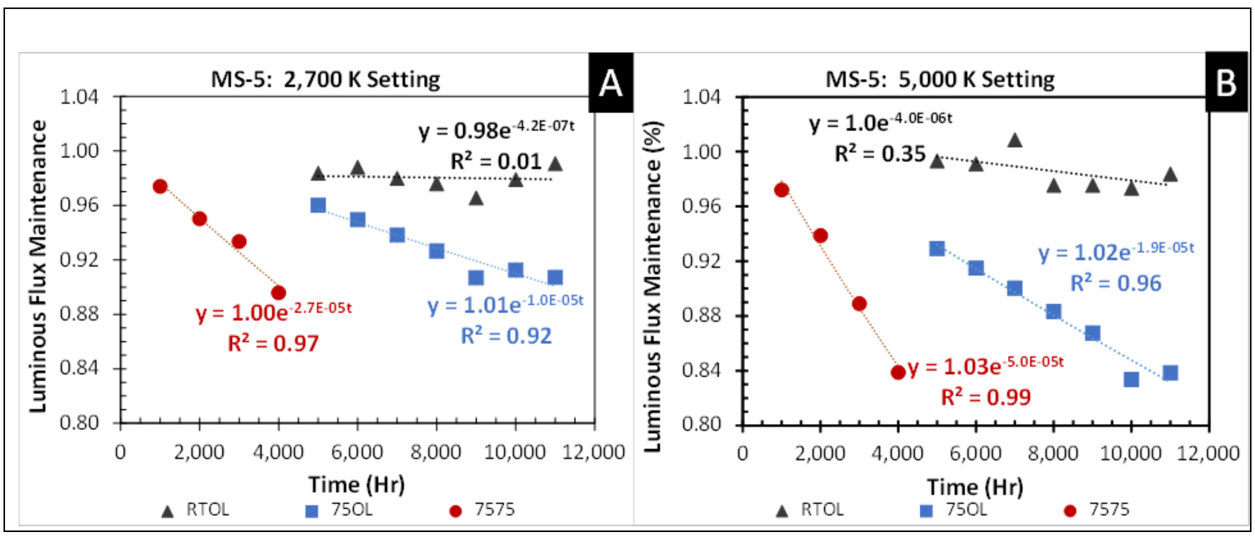

Figure 3-17: The TM-28-14 models of the LFM for Product MS-5 test populations operated with (A) the 2,700 K setting that was used during AST or (B) the 5,000 K setting that was used during AST. Testing was performed in either RTOL, 75OL, or 7575 environments.

Based on the values determined during the TM-28-14 analysis for the MS-5 DUTs, the L_{70} value for the 2,700 K setting in the 75°C ambient environment was projected to be 36,700 hrs, and the L_{70} value for the 5,000 K setting in the 75°C ambient environment was projected to be 19,800 hrs.

The photometric properties for the CCT setting that was not used during AST was still measured periodically, and the LFM data, which are provided in **Figure 3-18**, demonstrate that light emissions from the LEDs not used during AST still degraded at a significant rate during 75OL and 7575. After 11,000 hrs of 75OL, the LFM for the unused CCT settings were 0.77 for the 2,700 K setting and 0.78 for the 5,000 K setting. Even though the LEDs used to produce these CCT values were inactive during 75OL, the LFM values were smaller than those measured for the active LEDs after 11,000 hrs of 75OL, which are 0.91 for the 2,700 K setting and 0.84 for the 5,000 K setting. Since the LEDs of the CCT setting that was not used during AST, this degradation cannot be attributed to the degradation caused by electrical current flowing through the LEDs during AST. Instead, other factors likely associated with the optical systems of the downlights, are primarily responsible for this light loss as discussed in **Section 3.2.8**.

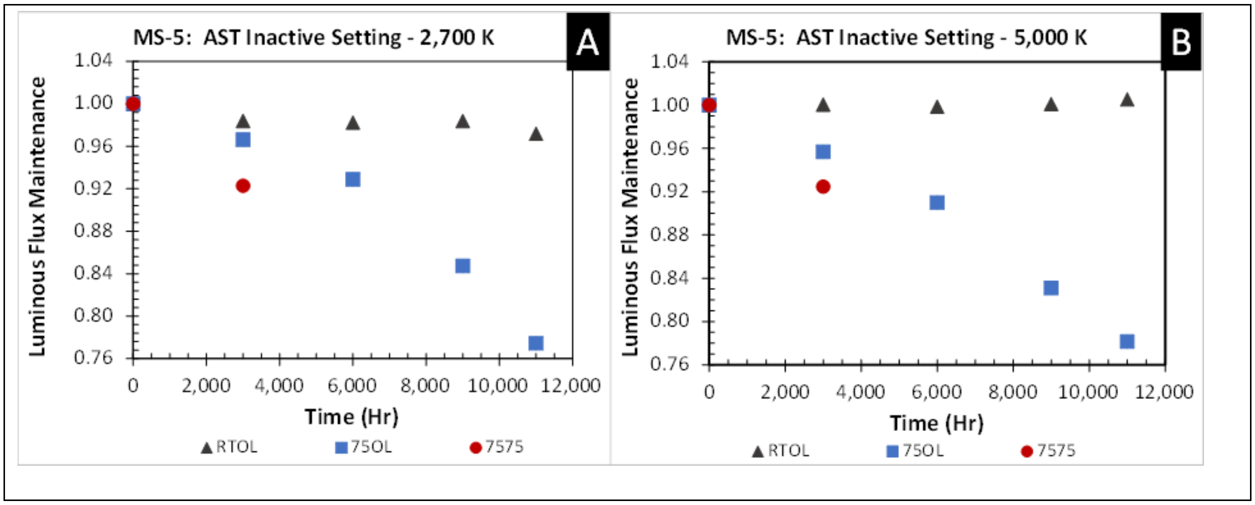

Figure 3-18: The LFM of the Product MS-5 test populations operated with (A) the 2,700 K setting on during photometric testing but inactive during AST or (B) the 5,000 K setting on during photometric testing but inactive during AST. Testing was performed following RTOL, 75OL, or 7575 environments.

3.2.6 Luminous Efficacy for Product MS-5

The luminous efficacy for Product MS-5 initially increased with use during RTOL because of the minimal change in the LFM and a small (3% to 4%) drop in power consumption. For the 75OL DUTs, there was a small, initial increase in luminous efficacy for both CCT settings for the first 2,000 hrs of testing, followed by a prolonged decrease that tracked the reduction of luminous flux. For the 7575 environment, the luminous efficacy decreased at every measurement time.

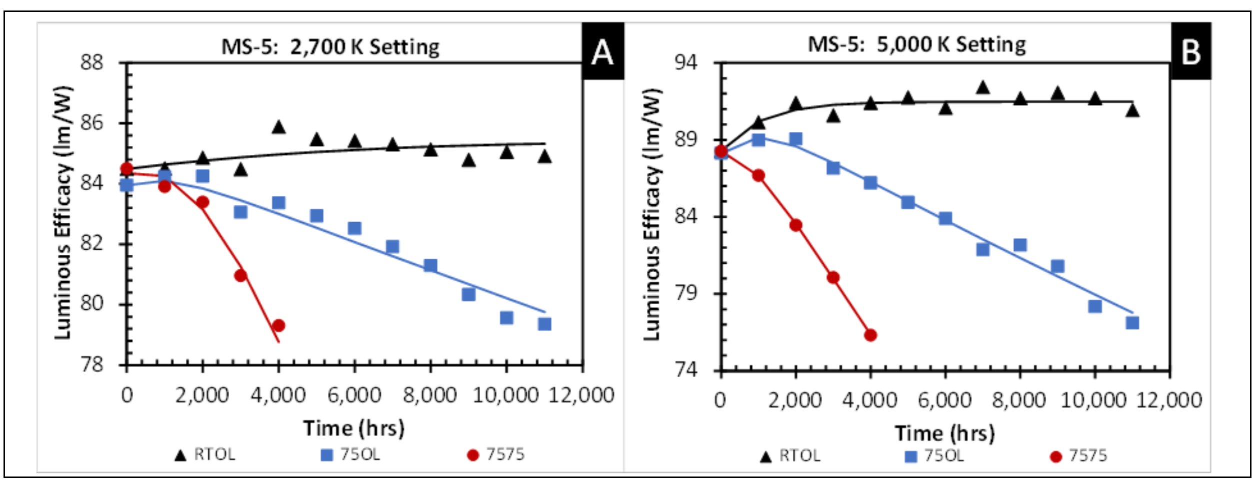

Figure 3-19: The temporal change in luminous efficacy for Product MS-5 (A) for the 2,700 K setting and (B) for the 5,000 setting. Testing was performed on different populations in RTOL, 75OL, and 7575 environments.

Equation 2 was used to model the initial increase in luminous efficacy reported in **Figure 3-19**. The estimated luminous efficacy is calculated by using **Equation 2** by changing α, B, γ, and β. This value was compared with the measure luminous efficacy and the estimated value recalculated until the $(\text{error})^2$ value was minimized. The best-fit parameters for each CCT setting exposed to the RTOL, 75OL, and 7575 environments are presented in **Figure 3-19**. For DUTs set to 5,000 K in RTOL, the exponential decay part of the model could not be calculated because there was no reduction in luminous efficacy during the test period. However, all parameters could be calculated for both CCT settings during 75OL and 7575 and for the 2,700 setting during RTOL.

Table 3-4: Parametric Fits for the Luminous Efficacy Model of the LED Primaries in Product MS-5.

Parameters	2,700 K Setting			5,000 K Setting		
	RTOL	75OL	7575	RTOL	75OL	7575
α	5.3×10^{-7}	5.7×10^{-6}	1.1×10^{-4}	Not applicable	1.5×10^{-5}	4.8×10^{-5}
B	84.5	83.9	84.3	88.3	88.1	88.3
γ	2.0	1.0	648	3.2	3.5	4.4
β	< 0.001	0.001	< 0.001	< 0.001	0.001	< 0.001
Error^2	1.77	1.65	0.67	2.56	3.04	0.02

3.2.7 Chromaticity Maintenance for Product MS-5

During the different AST environments, the chromaticity maintenance of Product MS-5 was similar for the 2,700 K and 5,000 K settings as shown in **Figure 3-20**. The temporal changes in chromaticity shift are provided in **Appendix Figure 3** for the 2,700 K setting and in **Appendix Figure 4** for the 5,000 K setting. For both, the chromaticity shift was in the generally yellow-red direction (i.e., the change was mainly along the $+\Delta v'$ axis, with the change along the $+\Delta u'$ axis being smaller) and displays CSM-3 behavior. The magnitude of the chromaticity shift during 7575 was larger for the 5,000 K setting than for the 2,700 K setting. In addition, the initial chromaticity shift for the 2,700 K setting was in the generally green direction for all test conditions, and then the shift proceeded more toward a yellowish-red chromaticity. The initial green shift of the MP-LEDs was also observed in other LEDs and likely represented a short-term chromaticity change in the phosphors (i.e., the initial green shift) followed by the observed continuous long-term change (i.e., the yellow-red shift) [16, 17].

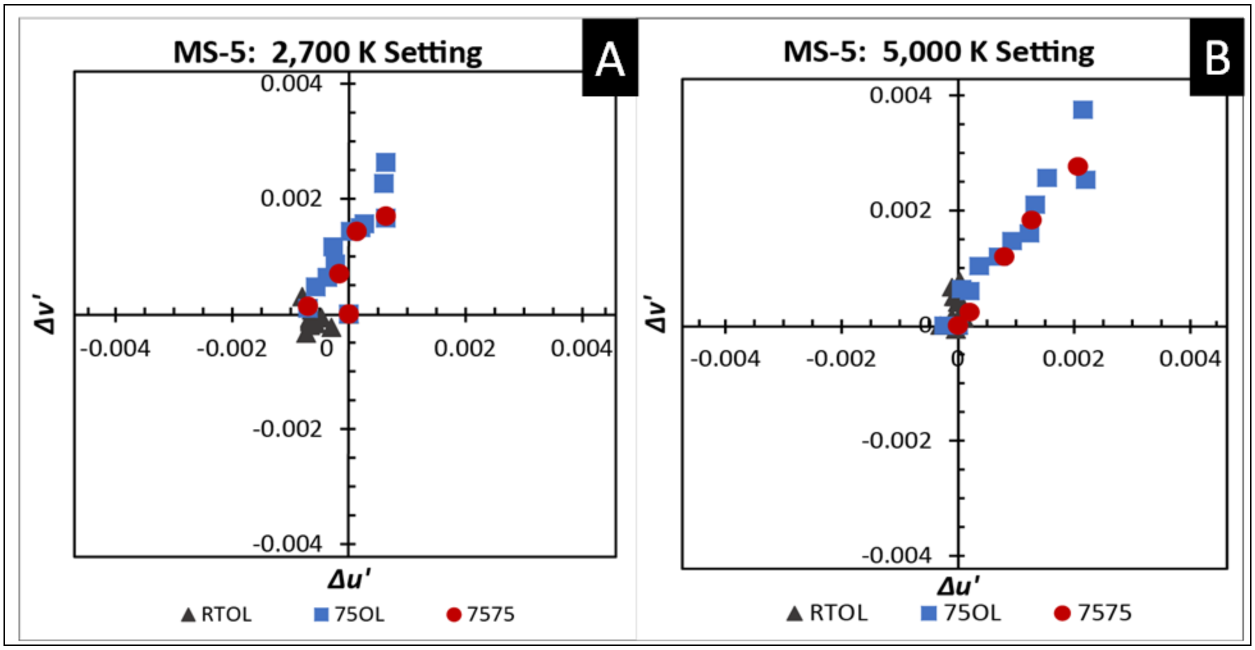

Figure 3-20: The chromaticity shift for Product MS-5 (A) for the 2,700 K setting and (B) for the 5,000 setting in the RTOL, 75OL, and 7575 environments.

3.2.8 Lens Transmittance for Product MS-5

The appearance of the lenses and reflectors used on the MS-5 products were noticeably discolored after exposure to the 75OL and 7575 environments. Unfortunately, the curved shape of the lens made it difficult to obtain an accurate measurement of transmittance. Likewise, the complex shape of the reflector (see **Figure 2-2**) prevented an accurate measurement of its reflectance. Given the attenuation that was observed for the device settings that were not in use during AST, it is reasonable to assume that the degradation of the lens and reflector also played a significant role in the lumen depreciation.

4 Discussion

The report demonstrates that LED lighting products offer a range of capabilities beyond energy efficient lighting; however, some products require a trade-off in the different elements of LAE (e.g., light source efficiency, optical delivery efficiency, spectral efficiency, and intensity efficiency) to achieve their modified performance. The balance of these trade-offs continues to change during long-term use of the products as shown by the results presented here. For example, achieving a higher spectral efficiency through a modified spectral output may come at the cost of initial luminous efficacy or long-term chromaticity stability as observed for Products MS-1, MS-2, and MS-3.

Because of the long lifetimes of most SSL products, it is difficult to assess the long-term performance and temporal nature of the LAE changes for lighting products on a laboratory timescale. Fortunately, AST methods have emerged as the recommended approach in studying the long-term robustness and reliability of LED products [18]. There are two broad classification of failures in LED products that typically occur when using AST methods: (1) abrupt failures, in which the device suddenly stops providing the expected light levels; and (2) parametric failures, in which the device gradually falls out of specification in a key performance area. Typically, abrupt failures are easy to recognize because they are instances when either the device no longer provides light at all (i.e., "lights-out" failures), when the light level has dropped precipitously (e.g., typically less than 50% of the original value), or when the level of TLA has increased to the point where the light source is unusable. Abrupt failures are typically linked to the light source efficiency component of LAE because some devices consume electricity even when no light is produced [19].

Parametric failures are defined by a change in a key performance parameter (e.g., luminous flux, chromaticity, luminous efficacy, temporal lighting artifacts) that exceeds a predefined limit termed the “failure threshold.” As such, parametric failures can affect any of the four elements of LAE. The limits for parametric failure vary depending upon the application, but in this work, the following definitions were used for the failure thresholds:

- **LFM**—Parametric failure occurs when the luminous flux value falls below 70% of the initial luminous flux, which is referred to as the LFM life, L_{70}. Changes in LFM mainly affect light source efficiency but can also be caused by changes in optical delivery efficiency of the device.
- **Chromaticity maintenance**—Parametric failure occurs when the chromaticity shift *(Δu'v')* exceeds 0.007. Changes in chromaticity maintenance may impact spectral efficiency and could also be the result of changes in optical delivery efficiency of the device.
- **Luminous efficacy**—Parametric failure occurs when the luminous efficacy falls below 70% of the initial value. This value is typically viewed as the fundamental measurement of light source efficiency.

When determining L_{70}, a standard test procedure (IES LM-84-14) combined with a luminous flux projection method (IES TM-28-14) is used to estimate long-term LFM. When three DUTs are used when testing LED lamps, light engines, and luminaires, the maximum projection time allowed by IES TM-28-14 is 3 times the test duration. We have previously used this method with dim-to-warm (D2W) lamps and demonstrated that under mild conditions, the LFM is high enough for L_{70} to reach the maximum allowed projection value. However, under more severe conditions such as temperature and humidity, the L_{70} value is often below the maximum allowed value [8]. The relative LFM decay of a device evaluated during different ASTs can be used to estimate the acceleration factor of the exposure method for lumen depreciation.

Currently, no equivalent to IES TM-28-14 exists for projecting chromaticity shift in LED lamps, light engines, and luminaires. Fortunately, AST methods can often accelerate chromaticity shifts in SSL devices and reduce the time required for changes in LED components (e.g., phosphors) or system optical elements (e.g., lenses). Therefore, in this study, we used the relative chromaticity maintenance performance of the DUTs in AST as an indication of potential long-term trends in chromaticity caused by changes in the materials used in the light source LEDs and the luminaire optics. In the absence of a quantitative model of chromaticity shift components, only qualitative information can be determined regarding the impacts of different AST environments on materials and the corresponding effect on chromaticity maintenance.

In general, the long-term luminous efficacy of SSL devices is determined by the LFM. As discussed in **Section 3.2**, there can be improved efficiencies in power consumption of SSL devices during initial use that can extend the time when luminous efficacy remains above the parametric failure threshold. However, as shown in **Section 3.1**, there is a definite trend in other devices toward exponential decay of the luminous efficacy under all test conditions. Consequently, we would expect the acceleration factors for luminous efficacy loss in the different AST environments to closely follow the behavior measured for LFM.

4.1 Time-Dependence Changes in Light Source Efficiency

Light source efficiency is best measured on individual LEDs or LED modules without secondary optics in order to eliminate effects arising from optical degradation. During the current study, only Product MS-3 allowed direct measurement of the light source efficiency. The initial luminous efficacy of Product MS-3 was only 68 lumens per watt (lm/W) because of the use of violet LEDs as the optical pump. This value is well below that typically measured for LEDs that use blue pumps, which can exceed 150 lm/W [4]. Although the source efficiency of the violet-pump LEDs may not be near the upper limit of that available with other SSL technologies, the change in the source efficiency does provide insights regarding aging of the devices over time.

For Product MS-3, the radiant power of violet emissions from the LEDs remained higher regardless of the test environment. In contrast, the emissions from the phosphors used for Product MS-3 changed significantly, resulting in not only reductions in luminous flux (see **Figure 3-2**) and luminous efficacy (see **Figure 3-4**), but also a large chromaticity shift toward the violet emitter (see **Figure 3-6**). The phosphors used in Product MS-3 had temperature stabilities that decreased in the order blue phosphor > green phosphor > red phosphor. As a result, the light emissions become depleted in red emissions over time as evidenced by the chromaticity shift. Although the composition of the phosphors used in this product is not known, there is clearly a sensitivity to moisture and temperature, especially for the longer wavelength emissions.

The LFM and chromaticity maintenance measured for Product MS-3 demonstrate the importance of knowing the long-term characteristics of the materials used in the light source. As demonstrated for Product MS-3, differential aging of the phosphors used in the source LEDs can have undesired effects on chromaticity maintenance and loss of luminous flux. The degradation of light emissions from Product MS-3 were undoubtedly accelerated by the high temperature and high electrical current used in this testing. The LEDs were operated at 111% of the manufacturer's derated current limit for 75°C operation. However, many other LEDs are able to operate at 75°C without any significant derating, suggesting that there is a known sensitivity at these use conditions with Product MS-3. Although many blue-pump MP-LEDs are able to operate for extended times in these environments [19], the phosphor mix used in this violet-pump LED product was not able to withstand the test conditions. Ironically, the performance of the violet LED changed little through 10,000 hrs of 75OL or 7,000 hrs of 7575.

For most blue-pump LED devices, the luminous efficacy will likely be higher than the value that was observed during these tests for Product MS-3. Two typical examples are Products MS-4 and MS-5 which both exhibited initial luminous efficacies of approximately 90 lm/W, even after taking the optical losses into account. The cerium-doped yttrium aluminum garnet phosphor commonly used in blue-pump LEDs in known to be very stable to temperature, although some nitride phosphors used to impart a warm white color are less stable [17]. Because of their different long-term characteristics, the choice between products using violet-pump LEDs and blue-pump LEDs should be made with knowledge of the impact of the expected use environment of the long-term performance of the device.

4.2 Time-Dependent Changes in Optical Delivery Efficiency

Both LED downlights examined during this study achieved spectral modification by setting a switch to a predetermined CCT value. This method of spectral modification was a single-use tuning mechanism in which the CCT value was adjusted to a desired setting prior to fixture installation. Changing the light to another CCT value required removal of the lamp and adjusting the switching appropriately. In between these extremes, the current was distributed between the two LED primaries in a pre-determined manner (e.g., see **Table 2-1**). This spectral tuning method contrasts with fully tunable lighting methods in which the fixture CCT value can be adjusted remotely and at any time. Despite the different tuning methods, the downlights products tested here have many common features with fully tunable white lighting systems, including two LED primaries, two LED control channels, and the use of a two-stage driver with a separate transistor switch for each LED primary [19].

Although a lot of attention has been paid to the impact of LED degradation on the LFM, chromaticity shift, and luminous efficacy, other factors of the lighting system can have a significant impact on lifetime that may exceed that of the LEDs [18]. During AST, the switchable downlight DUTs were set to either a warm white or cool white CCT value, meaning that one of the two LED primaries was set to either a zero current (e.g., Product MS-5) or a minimal value (Product MS-4), and the other LED primary was set to a maximum value. However, the luminous flux degradation of the two LED primaries was pretty much the same regardless of which one was the dominant one during AST. Clearly, the LED primary that was operated at a minimal current level (≤ 3 mA, as shown in **Table 2-1**) would be expected to have a better LFM value than one that was operated at a maximum current value. Therefore, factors beyond LED degradation must be controlled to maximize the LFM for these products.

Physical inspections of both Products MS-4 and MS-5 DUTs showed that there was a yellowing of both the main secondary lens and the white reflector surfaces. A previous examination of the impact of changes in SSL device optical efficiency (i.e., lens transmittance, reflector reflectance) for 6-inch downlights showed that **Equation 4-1** can be used to model the change in device performance [7, 20].

$$LE(t) = LE(t = 0)[L(t)]^{l}[R(t)]^{r} \qquad \text{(Eq. } 4\text{-}1\text{)}$$

Where

$LE(t)$ = Luminaire efficiency at time t

$LE(t = 0)$ = Initial luminaire efficiency

$L(t)$ = Change in the normalized lens transmittance $[\%T(t) / \%T(t = 0)]$ at time t

l = Design-dependent factor for the lens as determined from a least squares fit of the simulation results

$R(t)$ = Change in the normalized reflector reflectance $[\%R(t) / \%R(t = 0)]$ at time t

R = Design-dependent factor for the reflector as determined from a least squares fit of the simulation results.

For a 6-inch downlight with a 1-inch optical cavity with tapered walls, $l = 1.05$ and $r = 0.55$ meaning that the degradation of the lens has a much bigger impact on longer term optical performance than changes in the reflector. A similar argument can be made for other geometries (e.g., Product MS-2), even though the relative contribution of the lens and reflector surfaces, which are dependent on geometry, will be different. For Product MS-2, changes in the transmittance of the secondary lens would be expected to have a dominant impact on optical delivery efficiency because the devices do not have much in the way of reflectors or other optical surfaces (see **Figure 2-1A**).

Figure 3-15 demonstrates that transmittance of the lens on Product MS-4 changed significantly during the AST, resulting in increased light absorption and a reduction in luminaire efficiency, yielding a lower luminous flux value. In addition, because the increase in absorbance was greatest at low wavelengths, this part of the spectrum was filtered from the light with greater prevalence, resulting in a shift in the yellow-red direction in agreement with the findings presented in **Figure 3-14**. A similar assignment of the mechanism for luminous flux depreciation and chromaticity shift can also be made for Product MS-5 DUTs.

This finding provides another example of the importance of knowing the long-term behavior of the entire luminaire system when assessing product reliability. During RTOL, virtually no change in the LFM was observed at 12,000 hrs of testing. However, after 12,000 hrs during 75OL, a significant drop in the LFM was measured for both the Product MS-4 and MS-5 DUTs. It is clear that the degradation of the lenses in Products MS-4 and MS-5 DUTs is responsible for this loss of luminous flux and not changes in the LEDs. Therefore, the use of better materials for lenses would likely extend the lifetime of the switchable downlight products or similar products when used in the field and promote greater efficiency in light delivery over the lifetime of the products.

4.3 Time-Dependent Changes in Spectral Efficiency

"Spectral efficiency" refers to providing the proper light for the task, regardless of whether it is a spectrum that is specially tailored to provide a desired equivalent melanopic lux (EML) level, high color rendering, monochromatic colors, or other desired light. For example, Product MS-2 was specifically designed to provide a low EML value to prevent disruption of circadian rhythms by blue light in the evening. Product MS-3 was designed to provide a spectrum that has some of the characteristics of sunlight. Products MS-4 and MS-5 were designed to provide switchable spectra to match the light color with the space to achieve a desired appearance in the area that is being lit.

Although the initial spectral efficiency of an SSL device depends upon the properties of the chosen light source, the long-term spectral efficiency can change significantly as the device ages. All of the products examined in this study underwent significant changes in their emission spectra during the simulated aging that occurred in the AST environments. The net result was a shift in the generally yellow-red direction for products where the optical efficiency changed significant during aging (e.g., Products MS-2, MS-4, and MS-5) and a shift in the blue-violet direction for the product where source efficiency dropped. The yellow-red shift was because of selective filtering of blue emissions by the lenses as the optical system in the SSL device ages. The blue-violet shift found in Product MS-3 can be attributed to the relative stability of the violet LED pump used in this product and the relative instability of the phosphors, particularly the red and green phosphors, that are also used to produce white light. Although these changes impacted source efficiency and optical delivery efficiency, they also changed the light emission spectrum in demonstrable ways. Consequentially, if the goal of the light source is to achieve a particular spectrum over a long period of time, it is essential to know how the light source spectrum will change with time to ensure that the desired spectrum is delivered throughout the product's intended life.

5 Conclusions

LAE describes the efficient delivery of light from the light source to the task and is viewed as a new frontier in increasing the energy savings that are possible with SSL technologies. The framework for LAE consists of four major efficiency elements: light source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness. This report focuses on a sampling of the available SSL products that can be broadly defined as having modified spectral output because the method of spectra modification has significant impacts on light source efficiency and long-term optical and spectral efficiencies. The DUTs examined during this test can be broadly classified as pcLEDs that either contain a violet LED pump or a blue LED pump. The tested violet LED pump devices were either an A19 lamp (Product MS-2) or a light engine (Product MS-3), whereas the blue LED pump devices were switchable downlights (Products MS-4 and MS-5).

A focus on this study was to build on the earlier benchmarks of these types of products [1] to study the effects of long-term aging on source efficiency, optical delivery efficiency, and spectral efficiency. The results demonstrated that understanding the properties of the materials used in the SSL system is essential to providing products with long-term performance in a variety of different use environments. For source efficiency, initial luminous efficacy values are important. In addition, temperature and moisture stability of critical LED components (e.g., red and green emissions) should be controlled to maintain performance during the product's lifetime. Likewise, optical delivery efficiency can change significantly during the use of an SSL device because of aging of the lenses in the device and, to a lesser extent, aging of reflective surfaces. Ignoring these materials limitations when choosing or designing an SSL device can result in low LFM performance and significant chromaticity shifts during the product's lifetime. However, matching the SSL materials and product designs with the use environment can result in long-term performance at high efficacy and optimal spectrum output for the lifetime of the product.

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Appendix

Appendix Table 1. Optical Properties of the Solid-State Lighting Products Examined During This Study.

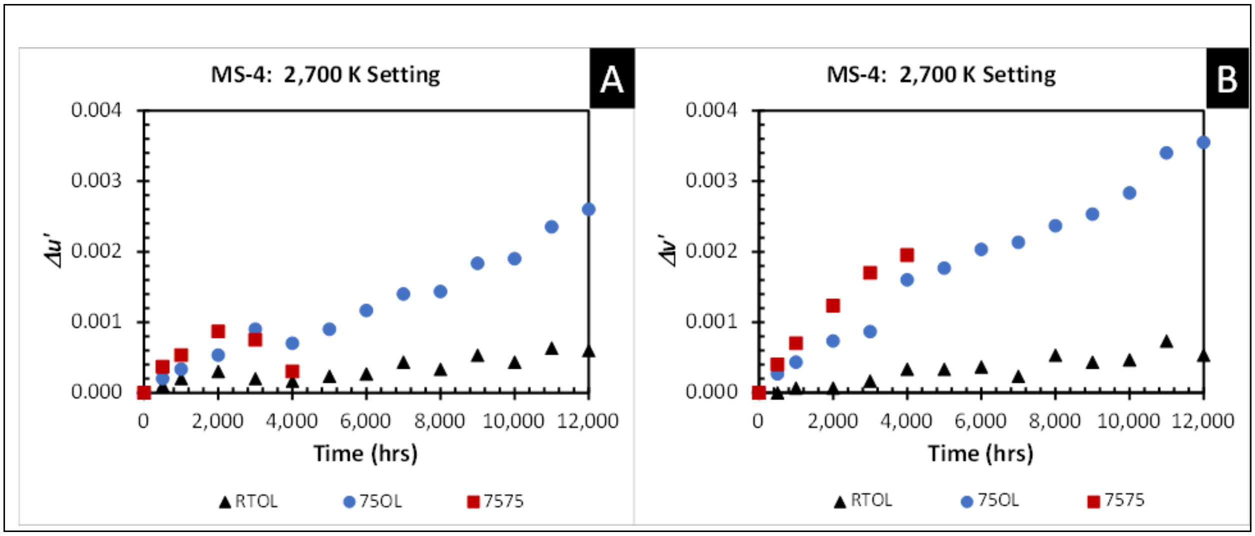
Label	Spectral Modification	Luminous Flux (lm)	Nominal CCT (K)	R_f	R_g
Product MS-2	Violet-pump LED with no blue emissions	575	2,600	59	109
Product MS-3	Violet-pump LED with additional emitters	984	5,200	94	103
Product MS-4 Low CCT	Switchable CCT	795	2,800	92	100
Product MS-4 High CCT	Switchable CCT	858	5,000	93	101
Product MS-5 Low CCT	Switchable CCT	1,019	2,700	91	97
Product MS-5 High CCT	Switchable CCT	1,107	4,900	89	96

Note: CCT = correlated color temperature; K = Kelvin; LED = light-emitting diode; lm = lumen; R_f = fidelity index in American National Standards Institute/Illuminating Engineering Society (ANSI/IES) technical memorandum (TM)-30-18; R_g = gamut index in ANSI/IES TM-30-18.

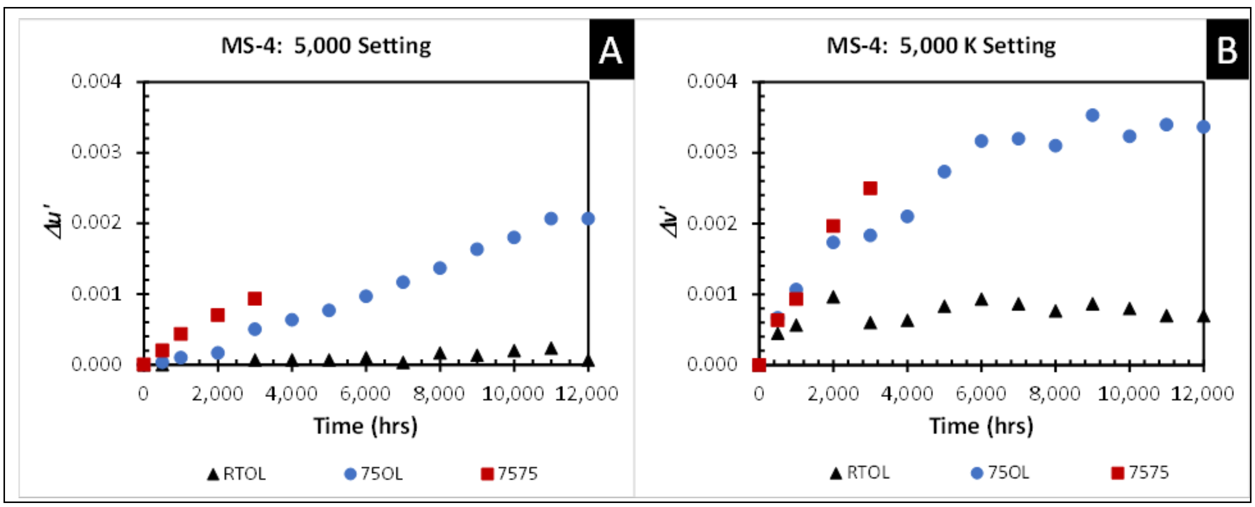
Appendix Table 2. Electrical Properties of the Solid-State Lighting Products Examined During This Study.

Label	ac Power (W)	Power Efficiency	V_f of LEDs (V)	I_f of LEDs (mA)
Product MS-2	12.0	0.90	3.1	58
Product MS-3	14.3	Not applicable	3.57	150
Product MS-4 Low CCT	9.1	0.85	2.91	215
Product MS-4 High CCT	9.1	0.85	2.91	215
Product MS-5 Low CCT	11.8	0.86	3.01	169
Product MS-5 High CCT	12.1	0.85	3.04	169

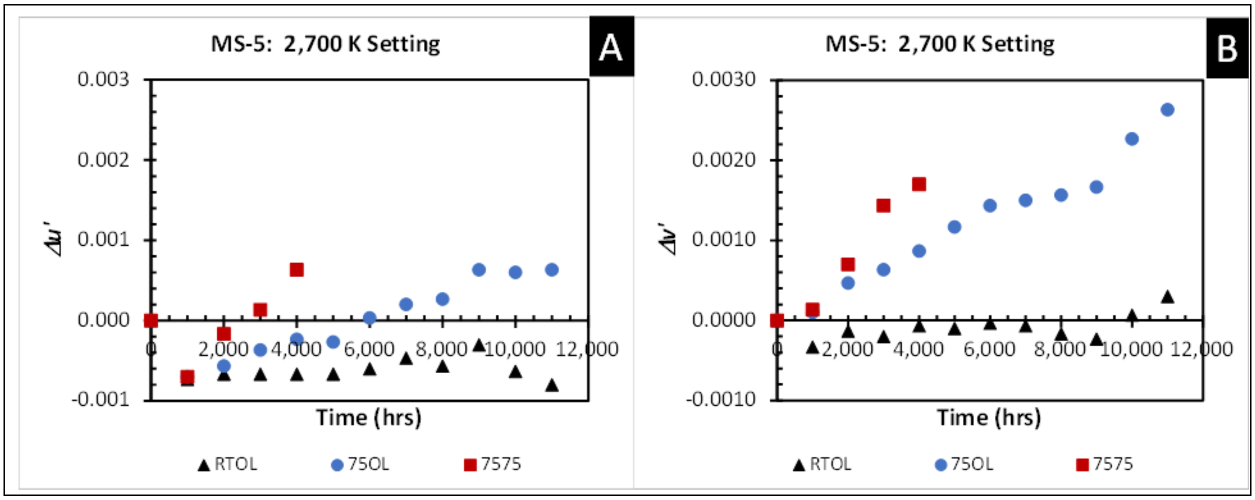
Note: ac = alternating current; CCT = correlated color temperature; I_f = forward current; LED = light-emitting diode; mA = milliampere; V_f = forward voltage; W = watt.



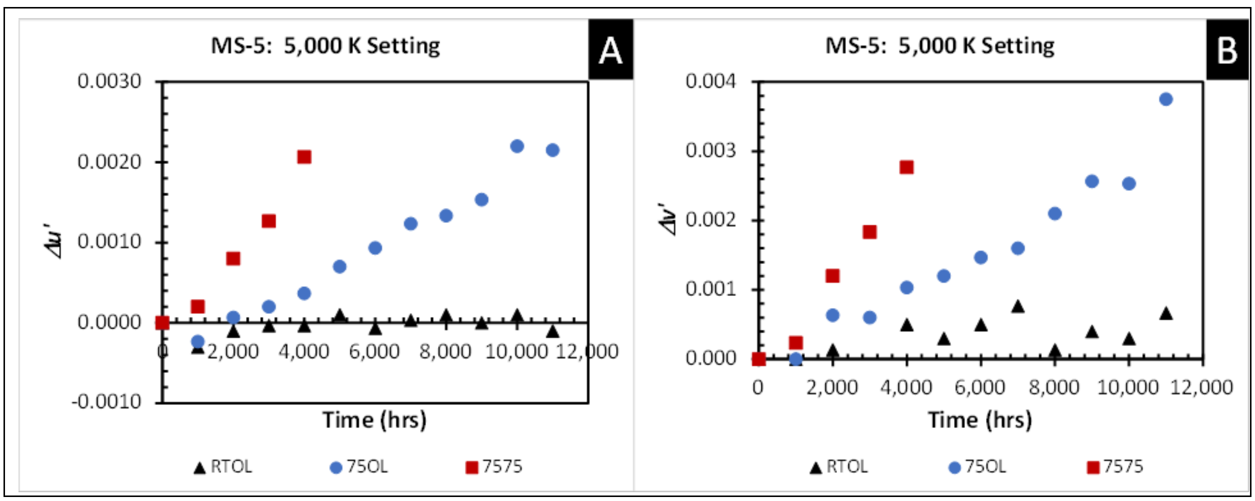
Appendix Figure 1: Temporal change in the chromaticity of the MS-4 DUTs when the 2,700 K primary was active in the different AST environments. The values for $\Delta u'$ are given in (A), and the values for $\Delta v'$ are given in (B).



Appendix Figure 2: Temporal change in the chromaticity of the MS-4 DUTs when the 5,000 K primary was active in the different AST environments. The values for $\Delta u'$ are given in (A), and the values for $\Delta v'$ are given in (B).



Appendix Figure 3: Temporal change in the chromaticity of the MS-5 DUTs when the 2,700 K primary was active in the different AST environments. The values for *Δu′* are given in (A), and the values for *Δv′* are given in (B).



Appendix Figure 4: Temporal change in the chromaticity of the MS-5 DUTs when the 2,700 K primary was active in the different AST environments. The values for *Δu′* are given in (A), and the values for *Δv′* are given in (B).

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