U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Changes in SSL Device Efficiency and Optical Performance Under Accelerated Aging Conditions

U.S. Department of Energy—Solid-State Lighting Technology Area

June 2020

RTI Project Number
0215939.001.001

Changes in SSL Device Efficiency and Optical Performance Under Accelerated Aging Conditions

June 2020

Prepared for

U.S. Department of Energy

Through contract with
KeyLogic Systems, Inc.
3168 Collins Ferry Road
Morgantown, WV 26505

Prepared by

Lynn Davis, Kelley Rountree, Michelle McCombs, Karmann Mills, and Roger Pope
RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the National Energy Technology Laboratory (NETL) Mission Execution and Strategic Analysis (MESA) contract, award number DE-FE0025912.

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
°C	degree Celsius
α	decay rate constant in 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
λ_{max}	maximum emission wavelength
ac	alternating current
ANSI	American National Standards Institute
AST	accelerated stress test
B	initialization constant
CCT	correlated color temperature
CIE	International Commission on Illumination (*Commission Internationale de l'Éclairage*)
CRI	color rendering index
CSM	chromaticity shift mode
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
EMI	electromagnetic interference
hr, hrs	hour, hours

IC	integrated circuit
IES	Illuminating Engineering Society
I_f	forward current
in	inch
K	Kelvin
L_{70}	time required for the luminous flux to decay to 70% of the initial value
LAE	lighting application efficiency
LED	light-emitting diode
LFM	luminous flux maintenance
lm	lumen
lm/W	lumens per watt
mA	milliampere or milliamp
MESA	Mission Execution and Strategic Analysis
MOSFET	metal-oxide-semiconductor field-effect transistor
MP-LED	mid-power LED
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
nm	nanometer
PCB	printed circuit board
pc-LED	phosphor-converted LED
R_f	fidelity index in ANSI/IES TM-30-18
R_g	gamut index in ANSI/IES TM-30-18
RTOL	room temperature operational life
SKU	stock keeping unit
SPD	spectral power distribution
SSL	solid-state lighting
t	time
T_j	junction temperature
TLA	temporal light artifacts

TRIAC	triode for ac
u'	chromaticity coordinate in the CIE 1976 color space
V	volt
v'	chromaticity coordinate in the CIE 1976 color space
V_f	forward voltage
W	watt
W/nm	watts per nanometer

Executive Summary

Lighting application efficiency (LAE) describes the efficient delivery of light from the light source to the lighted task and is viewed as a new frontier—increasing energy savings with solid-state lighting (SSL) technologies. The framework for LAE that is proposed by the U.S. Department of Energy (DOE) consists of four major 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 a significant impact on light source efficiency and long-term optical delivery and spectral efficiencies.

This report focused on the changes in light source, optical delivery, and spectral efficiencies that occur during aging of SSL devices. An accelerated stress test (AST) regiment was developed for the devices under test (DUTs) examined in this report to provide insights into how the performance of SSL devices change with aging. The AST protocols demonstrate that the SSL products discussed in this report often reduce light source efficiency to achieve different spectral characteristics. In addition, aging of the optical components (e.g., lenses, solder masks) in SSL devices can produce increased light absorption, which negatively impacts optical delivery efficiency and light source efficiency.

The modified spectral outputs of the selected SSL products discussed in this report come in a variety of form factors and achieve enhanced optical performance by using a variety of methods. All of the products examined in this study use mid-power light-emitting diodes (MP-LEDs), although the number, configuration, phosphor content, and light-emitting diode (LED) pump of the MP-LEDs differ. Product MS-1 is a 60-watt (W) replacement A19 lamp with a hermetically sealed glass globe, which contains an embedded optical filter to absorb green and yellow emissions, thereby creating a “sunlike” modified spectrum. Product MS-2 is a 60-W replacement A19 lamp with 30 MP-LEDs, and it uses a violet LED pump, along with green and red phosphor emissions, to produce a “healthy” spectrum. This spectrum omits blue emissions in an effort to reduce melanopic lux. Product MS-3 is an LED module consisting of 21 MP-LEDs that use a violet LED pump, along with blue, green, and red phosphors, to produce a “sunlike” spectrum. Products MS-4 and MS-5 are both 6-inch (in) downlights that use a manual switching mechanism so that users can select application-specific correlated color temperatures before installation. Products MS-4 and MS-5 both contain two LED primaries (2,700 Kelvin [K] and 5,000 K) 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.

This report summarizes the overall findings from up to 8,000 hours (hrs) of AST on the lamp DUTs (Products MS-1 and MS-2); up to 5,000 hrs of AST on the LED light engine DUTs (Product MS-3); and up to 7,000 hrs of AST on the downlight DUTs (Products MS-4 and MS-5). The AST procedures used in this study included a room temperature operational life (RTOL) test, an operational life test conducted at 45 degrees Celsius (°C; 45OL) test, 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 Products MS-1 and 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-1, MS-2, MS-4, and MS-5; four DUTs in each population for Product MS-3) were subjected to power cycling of 1 hr on and 1 hr off.

The key findings from this study include the following:

- Enhanced optical performance came at the cost of reduced light source efficiency for the lamps and light engines examined in this study. The optical filter used to produce a “sunlike” spectrum for Product MS-1 reduced light source efficiency by 26%, from 113 lumens per watt (lm/W) to 85 lm/W. Products MS-2 and MS-3 that used a violet-pumped LED to achieve “healthy” and “sunlike” enhanced optical performance, respectively, suffered the largest reduction in initial light source

efficiency (49 lm/W for Product MS-2 and 68 lm/W for Products MS-3) perhaps because of the use of violet LED as the optical pump. Product MS-2 also had the poorest color fidelity because of undersaturation of blues and oversaturation of greens and yellows.

- Chromaticity maintenance of the products in this study was generally good, with parametric failure only occurring for one product at one AST condition (i.e., Product MS-3 at 7575). The chromaticity shift for Product MS-3 in 7575 test conditions resulted from reduced emissions of the broad green and red phosphors used to mimic sunlight in the 500–750 nanometer (nm) range. As a result of these phosphor emission losses, chromaticity shifted toward the more stable violet-pumped LED and blue phosphor.

- Although chromaticity maintenance was acceptable for most products tested, different chromaticity shift mechanisms were observed for temperature and humidity tests compared with temperature alone for Products MS-1, MS-2, and MS-3. For Product MS-1, a relative increase in green emissions was observed with humidity, which may indicate humidity-accelerated degradation of the optical filter at green wavelengths (optical delivery efficiency reduction) or degradation of the emitters in the red region (spectral efficiency reduction). The violet-pumped products (i.e., MS-2 and MS-3) exhibited different chromaticity shift behavior in the temperature-humidity environments, with Product MS-2 shifting generally yellow because of photo-induced oxidation of the plastic globe (i.e., a reduction of optical delivery efficiency) and Product MS-3 shifting toward violet and blue emitters because of faster loss of emission from green and red phosphors (i.e., a reduction in spectral efficiency).

- Because of an initial drop in power consumption, the light source efficiency of downlights (Products MS-4 and MS-5) increased at RTOL throughout the test duration. The light source efficiency initially increased during 75OL until a decay in luminous flux maintenance (LFM) dominated light source efficiency, whereas the light source efficiency decreased for the entire 7575 test duration. It was found that increasing the ambient environment of an SSL device from 25°C to 75°C decreases the LFM by 2.7 to 5.5, depending on design of the SSL device. Adding humidity to the system (75OL to 7575) was found to decrease LFM by another factor of approximately 3.0.

- A common location of failure was identified for the downlights (Products MS-4 and MS-5) operated in the 7575 environment. This failure abruptly occurred between 3,000 to 5,000 hrs of testing on the film capacitor of the electromagnetic interference (EMI) filter near the diode bridge for 11 of the 12 downlights. It is likely that this failure was caused by a combination of the high electrical voltage across the capacitor, the location of the capacitor near the heat sources (e.g., transformers, diode bridges, power resistors), and the high stress environment of 7575.

- Longer test times are needed to fully understand the LFM, luminous efficacy changes, and chromaticity shifts for some of the products.

Because of the high reliability, light source efficiency, and spectral tuning capabilities of LEDs, the expectations of LAE for SSL products are greatly increased over traditional lighting products. The data gathered in this report begin to provide an understanding of the tradeoffs that current SSL products undergo when optimizing the different efficiency elements of LAE. As discussed in this report, the findings from the tests conducted show that the optimization of spectral efficiency can come at the cost of initial light source efficiency. Furthermore, the introduction of violet LEDs can promote long-term optical delivery efficiency degradation, and the introduction of optical filters or new phosphors can lead to unwanted spectral efficiency changes because the ratio of phosphor emitters changes with aging. The data presented in this report also identified a common failure location in 6-in downlights. The results regarding long-term behavior of the modified spectra devices studied provide valuable information about changes to the light source, spectral, and optical delivery efficiencies as the devices age. This information can be used to improve future SSL designs.

Table of Contents

List of Figures

List of Tables

1 Introduction

The use of light-emitting diodes (LEDs) in solid-state lighting (SSL) products imparts new versatility to the lighting product that is not easily achieved with traditional lighting products. For instance, LEDs provide SSL technologies with high source efficacy, leading to better efficiency. However, some of the main improvements that LEDs offer SSL technologies are more than just great energy savings (i.e., reduction in energy use or energy avoidance). The design flexibility and diverse lighting spectra that can be obtained with LEDs permit their use in many different applications and make SSL technologies the preferred lighting products over traditional light sources.

Although many SSL products have been engineered to replace traditional lamps and luminaires, LEDs offer SSL products form factors that are not possible with traditional lighting sources. The properties of LEDs allow more compact designs, and the use of optical systems in the luminaire controls how light is delivered to a specific application. As such, LED products are not confined to traditional lighting form factors such as conventional bulbs, fixture size, or fixture location but rather can be used to target light to specific areas and increase lighting application efficiency (LAE). These unique design advantages introduced by LEDs impact building architectures and provide financial savings by way of lower materials cost and targeted application efficiency.

LAE characterizes the efficient delivery of light from the light source to the lighted task and is viewed as a new frontier in the goal of continuing to increase energy savings from SSL technologies [1]. The framework for LAE proposed by DOE 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. Modified spectral outputs are achieved in a variety of ways, including the following:

- Filtering light emissions
- Omitting emitters from the phosphor mixture
- Adding additional emitters to the phosphor mixture
- Using multiple LED primaries and a manual switching mechanism.

Each of these modification choices might be chosen by the manufacturer for different reasons, but they are all similar because these spectral modifications require little or no intervention by the end user to reach the desired application spectrum. In addition, specific spectral modifications may improve some aspects of LAE, but they may also have a negative impact on others. For example, the use of a notch optical filter to absorb light emissions is advantageous because it can reduce emissions at specific wavelengths while allowing other wavelengths to pass through unattenuated, an outcome that is difficult to achieve with a normal phosphor-converted LED (pc-LED) architecture. Filtering modification might be useful to applications that have light sensitivity at distinct wavelengths or to produce spectra that mimic natural sunlight (i.e., improve the spectral efficiency element of LAE) but the changes may not be as beneficial to other LAE elements. A key advantage of SSL technologies is that the spectrum can be controlled to a greater extent, thereby allowing a more precise study of the overall impacts of spectrum modification on LAE.

Rather than filtering undesired wavelengths of light, some manufacturers modify the spectra by completely omitting specific emitters. Example applications include horticulture lighting, which omits or greatly reduces green light, or light targeted for human well-being at night, which can omit the blue LED pump. In contrast, the addition of emitters also modifies spectra and is generally used to precisely control the spectrum, which is often needed for high color rendering index (CRI) applications. Finally, rather than filter, omit, or add emitters, some products simply use more than one LED primary to allow users to switch between spectra. Switchable products are advantageous because they can be marketed for more than one application. Because of this flexibility, these types of switchable lights are often used in commercial and residential spaces for everyday use. As a result, a single product stock keeping unit (SKU) can replace multiple SKUs with fixed correlated color temperature (CCT) values, simplifying inventory management.

Each of these methods to modify spectral output have their own impacts on device performance and LAE. When the spectrum is modified because of an optical filter, photons generated by the device are absorbed by the filter. The result is that the energy spent to produce those absorbed photons is wasted, leading to lower device efficiency and luminous efficacy. Similarly, the addition of emitters introduces more concerns with the effects of each of the emitters contributing to the device performance and efficiency with time. In some new products geared toward human well-being, the blue LED is omitted from emissions and replaced with a violet LED. This violet LED lowers luminous efficacy and has the potential to distort color rendering properties. Finally, the increased electronic complexity necessary to regulate current to individual LED primaries for manual spectral mixing has the potential to lower device efficiency and increase overall production costs.

Because the reliability of SSL devices is generally high, accelerated stress tests (ASTs) have become the recognized approach to study their long-term performance [2]. This report discusses the use of ASTs to investigate the long-term changes in SSL device performance affecting LAE, in particular changes in light source, optical delivery, and spectral efficiencies. Although the initial loss of light source efficiency or color rendering properties might be beneficial for the end user's initial spectral application needs, little is known about the long-term reliability effects of these spectral modifications. This report serves to benchmark SSL product performances that have modified spectral output in terms of the chromaticity maintenance, luminous efficacy, product reliability, and their potential impacts on LAE.

2 Experimental Methods and Analytics

2.1 Samples

The devices under test (DUTs) in this study are categorized into four groups. The groups are products that:

- Filter light emissions from pc-LEDs to achieve a targeted spectral output
- Use pc-LEDs, but intentionally do not emit blue light
- Use pc-LEDs modified to emit at most visible wavelengths from violet to red
- Use two different pc-LED primaries, and their lighting spectrum can be manually switched between two or more possibilities.

Table 2-1 summarizes the optical properties and **Table 2-2** the electrical properties of the products studied and as discussed in this report. The American National Standards Institute (ANSI)/Illuminating Engineering Society (IES) TM-30-18 analysis of these products when they are new is presented in **Appendix A** of this report. Additional details for each product are provided in the remainder of this subsection of the report.

Table 2-1. Optical Properties of the SSL Products Examined During This Study.

Label	Spectral Modification	Luminous Flux (lm)	Nominal CCT (K)	R_f	R_g
Product MS-1	Optical filtering	620	2,800	91	103
Product MS-2	No blue emissions	575	2,600	59	109
Product MS-3	Addition of 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: K = Kelvin; R_f = fidelity index in ANSI/IES TM-30-18; R_g = gamut index in ANSI/IES TM-30-18.

Table 2-2. Electrical Properties of the SSL Products Examined During This Study.

Label	ac Power (W)	Power Efficiency	V_f of LEDs (V)	I_f of LEDs (mA)
Product MS-1	7.4	0.88	2.83	48
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	220
Product MS-4 High CCT	9.1	0.85	2.91	220
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; I_f = forward current; mA = milliamp; V_f = forward voltage.

2.1.1 Product MS-1

Product MS-1 is a 60-watt (W) replacement A19 lamp that contains an LED module with 16 series-connected mid-power light-emitting diodes (MP-LEDs) (3030 package size) mounted on a metal-core printed circuit board (PCB) shaped like a rectangular prism with a square base and topped with a square pyramid as shown in **Figure 2-1**. A hermetically sealed glass globe containing a light diffuser and an optical filter incorporated into the glass is positioned around the LED module. The combination of the PCB shape and the structure of the light diffuser in the globe gives the emissions from the product an approximately omnidirectional appearance. The optical filter made into the glass of the globe also gives the product a purplish-blue appearance in the off state and a yellowish appearance when energized (see **Figure 2-1**).

To convert alternating current (ac) power to the direct current (dc) power needed to drive the LEDs, the lamp contains a small driver with a triode for ac (TRIAC) dimmable integrated circuit (IC) containing an integrated metal-oxide semiconductor field-effect transistor (MOSFET). Other components in the driver circuit included a diode bridge rectifier, with film capacitors and an inductor on the ac input line, and an electrolytic capacitor on the dc output side of the PCB (**Figure 2-2**). The entire driver is small enough to fit into the A19 base of the lamp. The dc power supplied to the serially connected LEDs was 136 volts (V) at 48 milliamps (mA). Taking the configuration of the LED module into account, each LED package is operated at 8.5 V and 48 mA. Assuming that there are three serial LED emitters in each package, the forward voltage (V_f) value of each LED emitter is 2.83 V, and the forward current (I_f) value is 48 mA as summarized in **Table 2-2**.

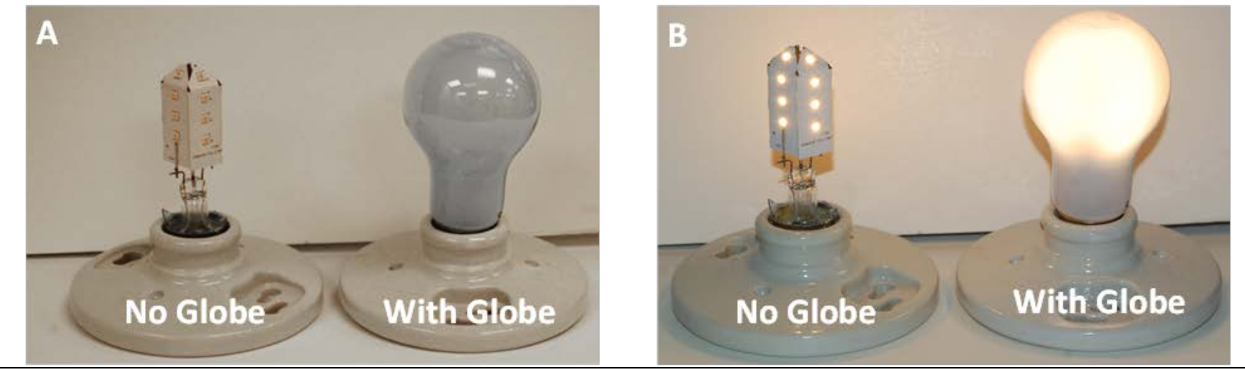

Figure 2-1. Product MS-1 without the globe and with the globe. (A) Lamps in unenergized state and (B) lamps energized with ac power.

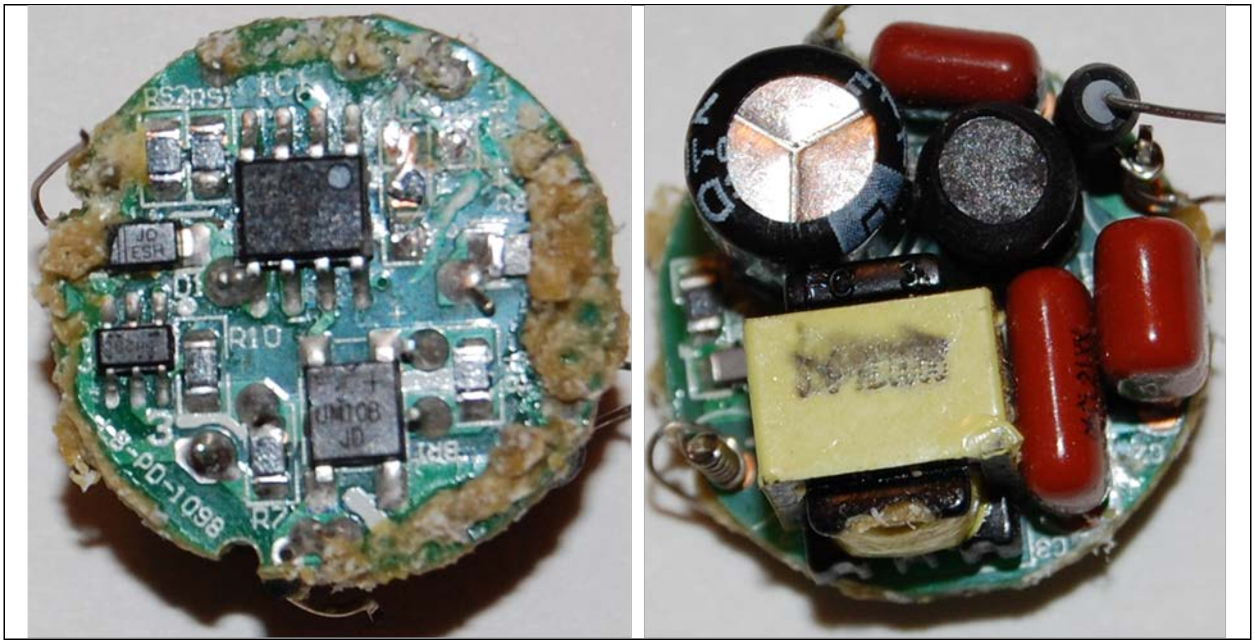

Figure 2-2: Front (on left) and back (on right) views of the driver used with Product MS-1.

Product MS-1 is rated by the lamp manufacturer for use in damp locations; however, the manufacturer does not provide any information about the maximum use temperature, only that the product is designed to start at temperatures greater than -20 degrees Celsius (°C). During our testing, the product housing reached 77°C during 6590 (i.e., life test performed at 65°C and 90% relative humidity) exposure.

The spectral power distributions (SPDs) of Product MS-1 without the globe and with the globe are presented in **Figure 2-3a**, and the chromaticity points of the product without the globe and with the globe are presented in **Figure 2-3b**. The pc-LEDs used in this device contain a blue LED pump combined with phosphors for emission at green, yellow, and red colors. The optical filter embedded in the glass globe had sharp absorption peaks at 585 and 575 nm, with weaker peaks at 518, 532, and 748 nm. The sharp absorption lines indicate the presence of a rare earth additive in the glass melt, which is consistent with the color change of the glass globe. The impact of these absorption peaks in the glass is to significantly reduce green and yellow emissions, but the absorption effect on blue and red emissions is minimal. The net results of adding the rare earth optical filter to the glass were a 20% reduction in radiant flux and a 26% reduction in luminous flux.

The light produced by the product exhibited excellent R_f (fidelity index in ANSI/IES TM-30-18) and R_g (gamut index in ANSI/IES TM-30-18) values. The initial color fidelity and R_f and R_g metrics were better for the device with the globe in place (**Figure A-1**, **Appendix A**) than without the globe (**Figure A-2, Appendix A**). In addition, the CCT value was approximately 81 Kelvin (K) higher with the globe than without it.

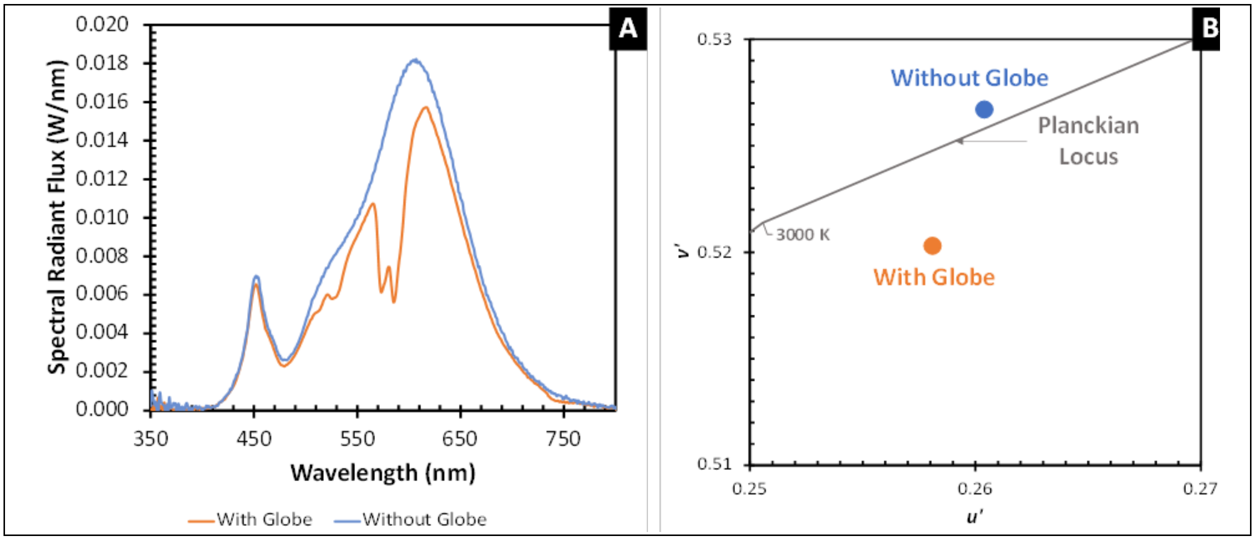

Figure 2-3: A comparison of light emission from Product MS-1 with and without the glass globe. (A) SPDs of Product MS-1 with the glass globe (orange trace) and without the globe (blue trace), and (B) chromaticity coordinates with the globe (orange) and without the globe (blue).

Note: *u'* = chromaticity coordinate in the International Commission on Illumination (*Commission Internationale de l'Éclairage* [CIE]) 1976 color space; *v'* = chromaticity coordinate in the CIE 1976 color space; W/nm = watts per nanometer.

2.1.2 Product MS-2

Product MS-2 is also a 60-W replacement A19 lamp, and it consists of 30 MP-LEDs (3030 package size). Each LED package contains two LED emitters connected in series, and the LED packages are mounted as a 10 serial string configuration on a metal-core PCB. Each of the 10 serial strings has three LED packages in parallel. The LED module is shown in **Figure 2-4**. The pc-LEDs in this product use a violet-pump LED (maximum emission wavelength (λ_{max}) approximately 416 nm) as the excitation source, and the phosphor mixture contains green (λ_{max} approximately 543 nm) and red emitters (λ_{max} approximately 641 nm), but has minimal emissions in the blue region (450 to 490 nm). The absence of blue emissions is intended to reduce melanopic lux, and the emitted spectrum is specifically designed to minimize melanopsin absorption by the human retina [3]. Product MS-2 also contains a plastic globe assumed to be made from polycarbonate, and the globe is attached to the heat sink base with a white silicone adhesive, so it is not sealed.

Product MS-2 is rated by the lamp manufacturer for use in damp locations. The manufacturer also states that the maximum temperature of the lamp base is 115°C. During our testing, the lamp base reached 87°C during 6590 exposure, well within the manufacturer's specifications.

The driver used with this product is encapsulated with a silicone thermal compound. The driver is housed in the middle of the heat sink, and its circuitry consists of an IC with integrated MOSFET, film capacitors on the ac input side, electrolytic capacitors on the dc output side, and inductors spanning both sides of the diode bridge. The ac power consumption of the driver was measured as 12 W, and dc output was measured as 10.8 W (62 V at 174 mA), for a driver power efficiency of 0.90. Taking the configuration of the LED module into account, each LED package is operated at 6.2 V and 58 mA. Because there are two serial LED emitters in each package, the V_f value of each LED emitter is 3.1 V and the I_f value is 58 mA as summarized in **Table 2-2**.

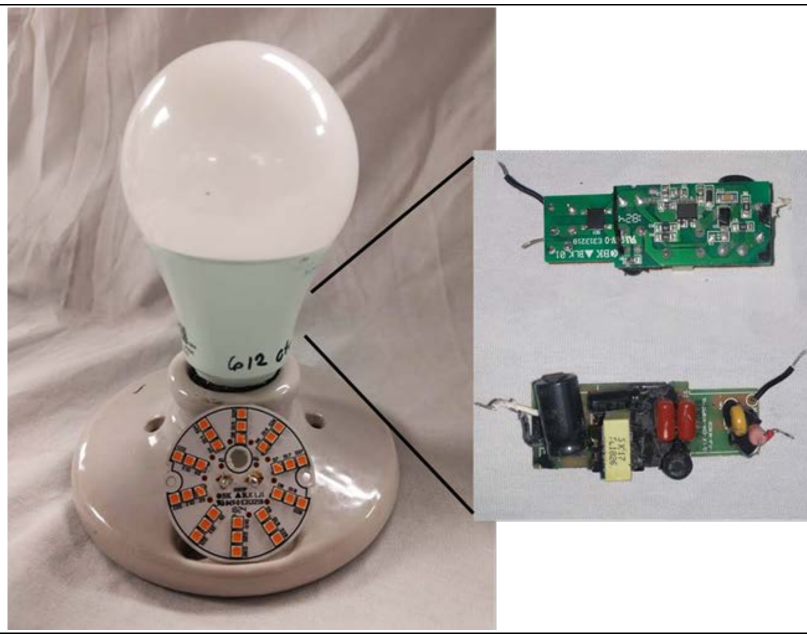

Figure 2-4: (On left) Product MS-2 with the globe, but in an unenergized state, along with the LED module. (On right) A close-up image of the driver used in Product MS-2.

Product MS-2 is promoted as a “healthy” LED source because the reduced melanopic lux could potentially avoid adverse circadian effects, especially when used at night or during times when blue-light exposure may advance or delay the circadian clock. However, the absence of blue emissions distorted the color rendering performance of the product as shown in **Figure A-3**. The light source is over-saturated at green to yellow wavelengths and is deficient at blue to cyan wavelengths. As a result, the R_f value was low, the R_g value was high, and there was wide variability in the color sample fidelity.

2.1.3 Product MS-3

Product MS-3 is an LED light engine consisting of two LED modules. Each LED module contains 21 MP-LEDs (3030 package size) arranged as three parallel strings of LEDs. In each LED string, there are seven serially connected LEDs and a resistor. For convenience, two LED modules are mounted on the same heat sink as shown in **Figure 2-5** to make a light engine. During testing, the two LED modules on a heat sink were connected in series to an LED driver that was placed outside the test chamber. The driver was operated at 22.5 W (50 V at 450 mA), indicating that the V_f supplied to each LED is 3.57 V and the I_f is 150 mA as summarized in **Table 2-2**. During photometric testing, the LED modules were operated individually at 25 V and 450 mA.

The manufacturer’s specification for the LEDs in this product are $I_f \leq 150$ mA, a maximum junction temperature (T_j) of 125°C, and a maximum operating ambient temperature of 85°C. During testing in 7575 (i.e., life test performed at 75°C and 75% relative humidity), the temperature of the LED light engine peaked at 87°C, slightly above the manufacturer’s specification, but I_f stayed within manufacturer’s specifications.

Figure 2-5: Product MS-3 LED light engine consisting of two LED modules mounted on a common heat sink.

Product MS-3 uses a violet LED (λ_{max} approximately 409 nm) and has phosphor emissions with major peaks in the blue (λ_{max} approximately 451 nm), green (λ_{max} approximately 532 nm), and red (λ_{max} approximately 626 nm) spectral regions as shown in **Figure A-4**. This spectral emission mimics that of sunlight at a CCT value of 5,000 K and produces much better color rendering properties than Product MS-2 (the other product with violet emissions), as shown in **Figure A-4.** The R_f value measured for this product was 94, and the measured R_g value was 103.

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, they are not reported here.

2.1.4 Product MS-4

Product MS-4 is a 6-inch (in) downlight with an integrated driver contained in an aluminum housing (**Figure 2-6**). The device contains two LED primaries, one with a nominal CCT value of 2,700 K and the other with a nominal CCT value of 5,000 K. Each LED primary consists of 12 serially connected MP-LEDs (2535 package size) mounted on a metal-core PCB with a single LED in each package. The device also contains a LED driver and a resistor bank that is set by using a manual switch during installation. 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. The maximum power delivered to an LED primary is approximately 7.7 W (35 V and 220 mA), which is distributed as a V_f of 2.91 V and an I_f of 220 mA for each LED at full power (see **Table 2-2**). The light emissions from Product MS-4 produced good color rendering as shown in **Figure A-5** (for CCT set to 2,700 K) and **Figure A-6** (for CCT set to 5,000 K).

Product MS-4 is rated by the lamp manufacturer for use in damp locations; however, the manufacturer did not provide a maximum operational temperature. During our testing, the product housing reached 86°C during 7575 exposure, which is within most expectations for this type of product.

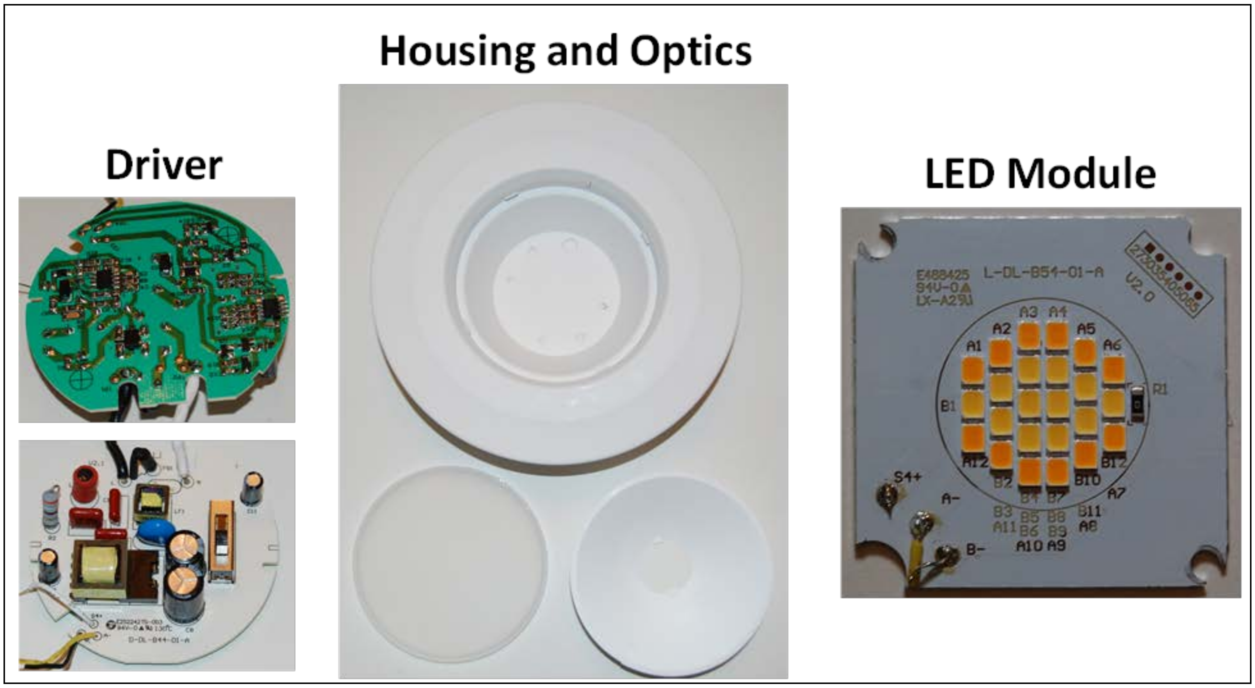

Figure 2-6: The components of Product MS-4.

2.1.5 Product MS-5

Product MS-5 is a 6-in downlight with an integrated driver contained in an aluminum housing (**Figure 2-7**). The device contains two LED primaries, one with a nominal CCT value of 2,700 K and the other with a nominal CCT value of 5,000 K. Each LED primary consists of 10 MP-LEDs (3030 package size), with two LEDs per package, mounted on a metal-core PCB. The LED driver 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. The maximum dc power delivered to an LED primary is 10.3 W (60.8 V and 169 mA [**Table 2-2]**). The light emissions from Product MS-5 produced good color rendering as shown in **Figure A-7** (for a setting of 2,700 K) and **Figure A-8** (for a setting of 5,000 K).

Product MS-5 is rated by the manufacturer for use in damp locations. The lamp manufacturer did not provide a maximum operational temperature. During our testing, the product housing reached 80°C during 7575 exposure, which is within most expectations for this type of product.

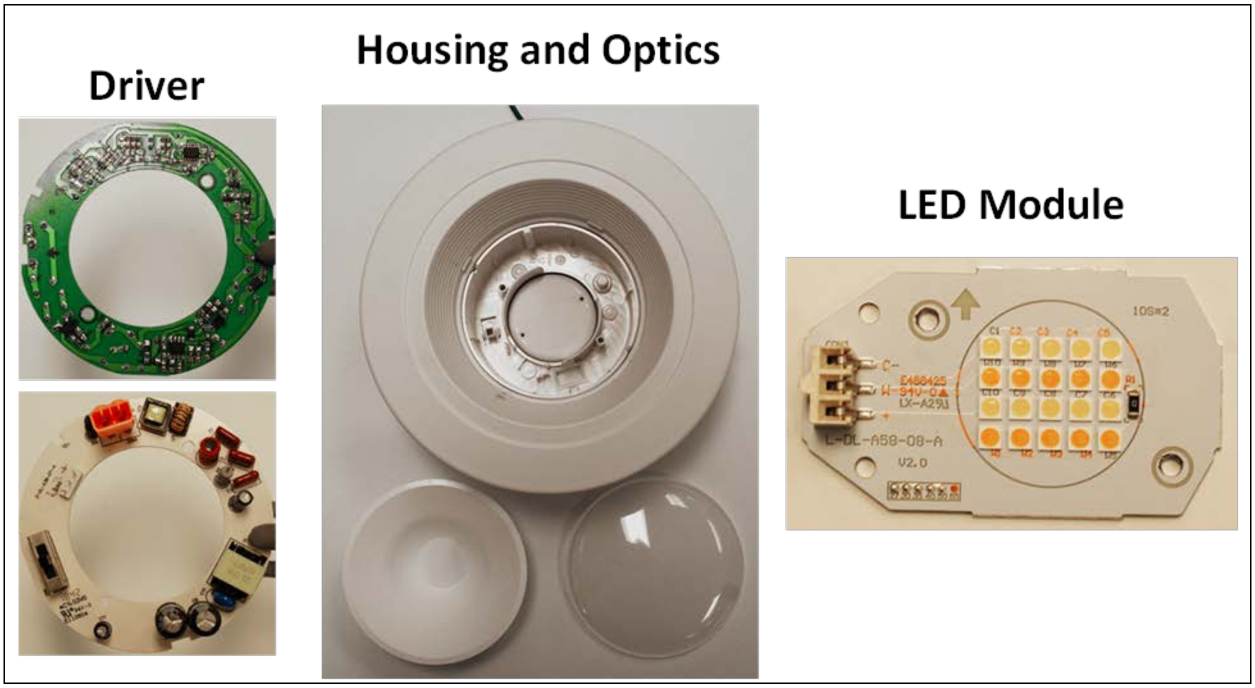

Figure 2-7: The components of Product MS-5.

2.2 Stress Testing Methods

The samples of each type of lamp or downlight 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. Because the LED modules were tested individually, the configuration provided four DUTs for each testing protocol. For the lamps (i.e., Product MS-1 and Product MS-2), each population was tested in one of three possible conditions: room temperature operational life (RTOL), an operational life test at an elevated ambient temperature of 45°C (45OL), and 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 7575. Either a temperature oven or a temperature-humidity environmental chamber was used for these tests. Humidity was not explicitly controlled in 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.

For this study, the lamps (i.e., Products MS-1 and MS-2) were mounted in porcelain lampholders and operated from ac mains in an upright configuration. A single aluminum heat sink was used to mount two LED modules (Product MS-3) as shown in **Figure 2-5**. The LED modules were connected in series to a driver that was placed outside the test chamber. Products MS-4 and MS-5 were used as supplied by the manufacturer without further modification.

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-in integrating sphere. Products MS-1, 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 [4]. When in the 4π configuration, the center post was used to supply power to Products MS-1, MS-2, and MS-3 during photometric testing. Products MS-1 and MS-2 were directly powered by line ac, whereas Product MS-3 was powered by an external driver. Products MS-4 and MS-5 were mounted external to the integrating sphere and powered by line ac.

3 Results

3.1 Product MS-1

3.1.1 Luminous Flux Maintenance

The luminous flux maintenance (LFM) of Product MS-1 was measured according to IES LM-84-14 with photometric testing after each 1,000 hrs of operational exposure in the RTOL, 45OL, and 6590 environments [5]. The results were analyzed by using IES TM-28-14 [6], and the findings are presented in **Figure 3-1**. The reduction in LFM at 4,000 hrs in the 6590 environment is the result of one DUT that experienced a large loss of luminous flux at that timepoint (LFM = 0.67). This DUT and another DUT failed at 5,000 hrs, so the LFM of the remaining device is shown at 5,000 and at 6,000 hrs. The remaining DUT was classified as a parametric failure (LFM = 0.32) in testing at 7,000 hrs, and no DUTs remained in the 6590 test population at that time. The loss of luminous flux is clearly impacted by temperature, as evidenced by the more than doubling of the decay rate constant (α) between RTOL and 45OL. The combination of temperature and humidity further accelerated luminous flux degradation, and the α value in 6590 was approximately 8 times higher than was observed during RTOL.

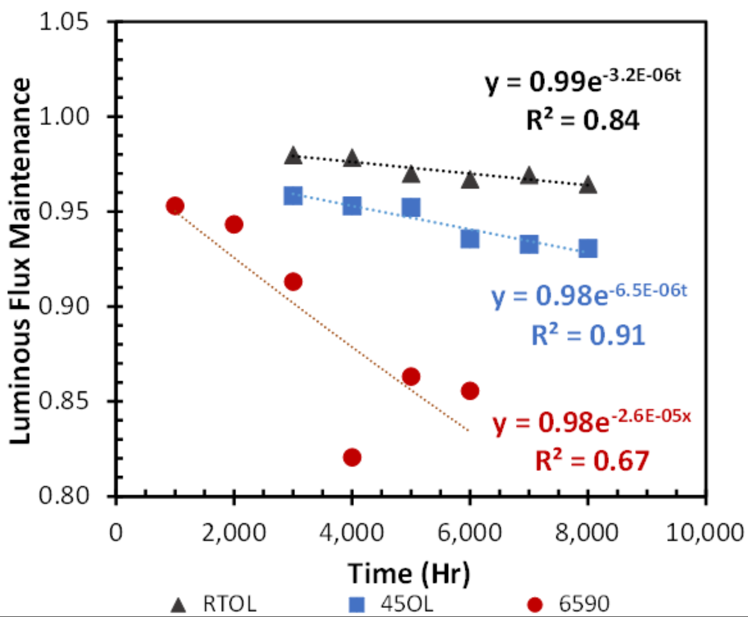

Figure 3-1: LFM of Product MS-1 during RTOL, 45OL, and 6590 according to IES LM-84-14 and IES TM-28-14.

3.1.2 Luminous Efficacy Maintenance

The luminous efficacy of Product MS-1 showed an exponential decay beginning at the start of AST and continuing for its duration, and the rate of exponential decay depended on temperature and humidity. The power consumption of the devices stayed relatively stable throughout testing. As a result, the luminous efficacy decreased at a similar rate as the luminous flux decay as shown in **Figure 3-2**.

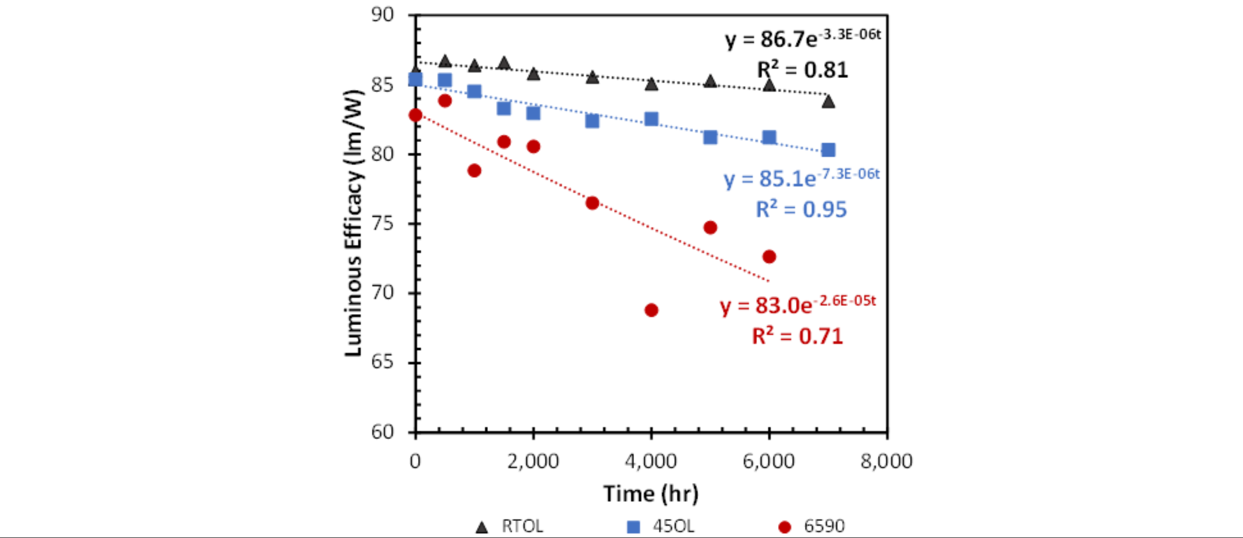

Figure 3-2: Luminous efficacy of Product MS-1 during RTOL, 45OL, and 6590.
Note: lm/W = lumens per watt.

3.1.3 Chromaticity Maintenance

The chromaticity behavior of Product MS-1 depended on the test environment with significant differences between the behavior observed in 45OL and 6590, as shown in **Figure 3-3**. During 45OL, the chromaticity of the test population shifted in the generally yellow direction (chromaticity shift mode [CSM]-3 mechanism) throughout the test exposure [7,8]. After, 8,000 hrs of exposure in 45OL, the total chromaticity shift was $\Delta u'v'$ = 0.002, with the shift occurring mainly along the $+\Delta v'$ (i.e., the change in the positive v' chromaticity coordinate) axis. An examination of the spectral changes occurring during 45OL concluded that a relative loss of blue emission was responsible for this shift.

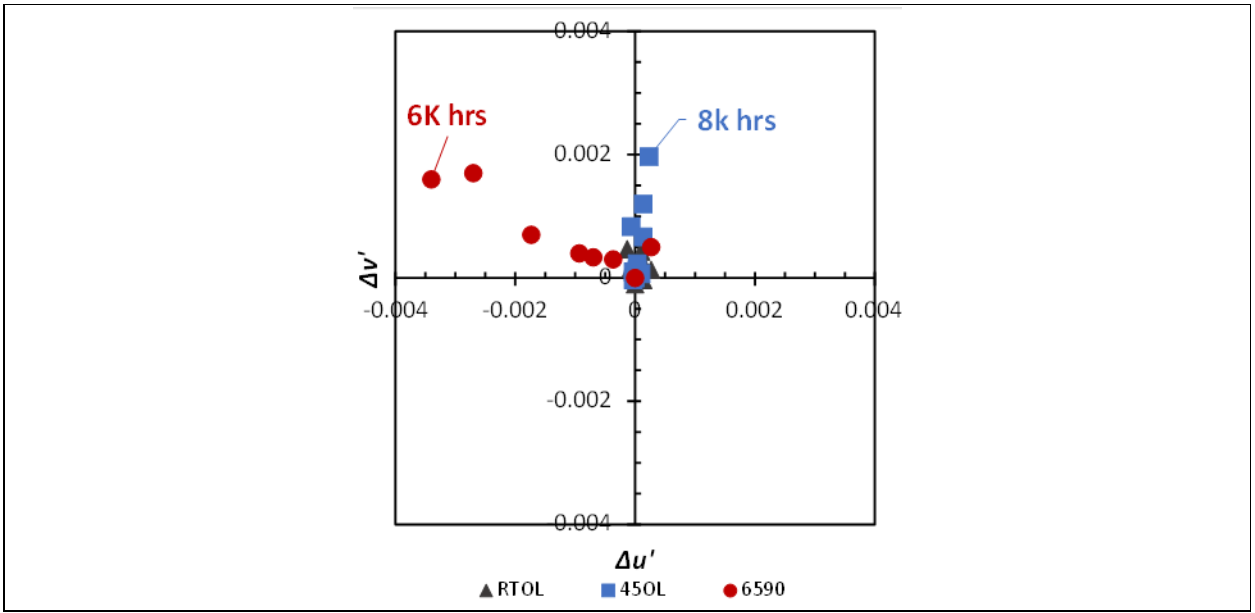

Figure 3-3: Chromaticity shift of Product MS-1 during RTOL, 45OL, and 6590.
Note: $\Delta u'$ = change in the u' coordinate of chromaticity and $\Delta v'$ = change in the v′ coordinate of chromaticity.

In contrast, the population of Product MS-1 during 6590 initially shifted in the yellow direction for the first 500 hrs of testing, and then began a steady shift in the green direction. This change appears to arise from a small decrease in the relative emissions at the blue and red wavelengths relative to the green and yellow wavelengths, which produces an increase in relative emissions between 500 and 625 nm as shown in **Figure 3-4**. For convenience, the SPD in **Figure 3-4** is normalized to the maximum intensity of the yellow emission at 565 nm.

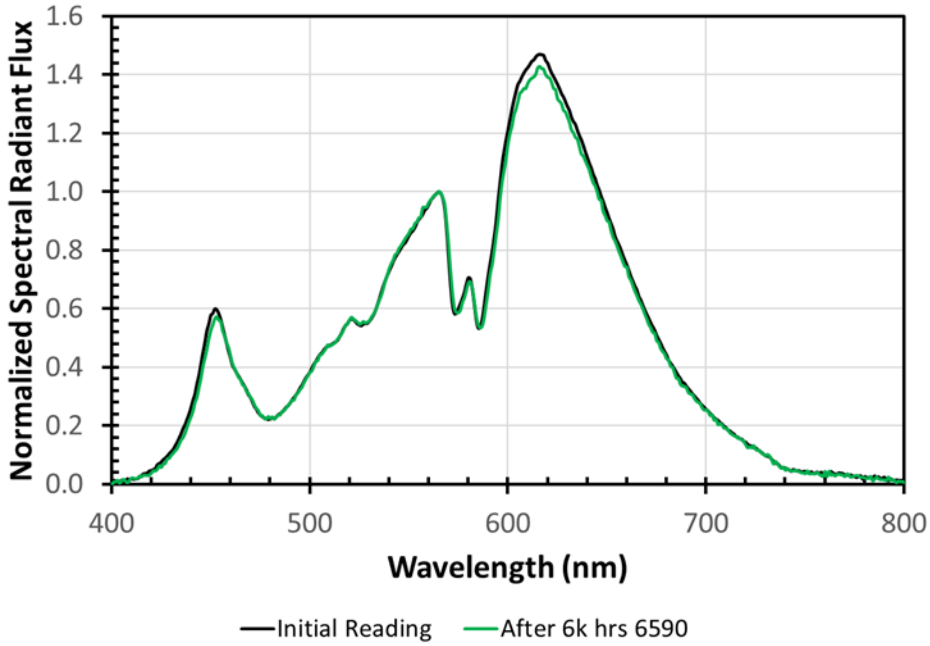

Figure 3-4: Normalized radiant flux for Product MS-1 at the beginning of testing and after 6,000 hrs of exposure during 6590. Spectra were normalized to the green emission peak at 565 nm.

3.1.4 Failure Analysis and Post-mortem Examination

All lamps tested during RTOL and 45OL survived 8,000 hrs of testing without any failures, as judged by either abrupt lights-out or parametric failure criteria. However, all three lamps during 6590 failed between 4,000 and 7,000 hrs of testing. One of the devices was an abrupt failure; the other two were parametric failures with reduced LFM values and excessive chromaticity shifts. For the two parametric failures, the ac power consumption and dc voltage delivered to the LEDs were unchanged after 7,000 hrs of 6590, indicating that the driver was functioning properly. However, the LEDs exhibited signs of discoloration from an unknown source, as shown in **Figure 3-5**. This discoloration on top of the die was the likely cause of the drastic changes in LFM and chromaticity maintenance observed during testing.

Figure 3-5: LED module from Product MS-1 after 7,000 hrs of 6590.

3.2 Product MS-2

3.2.1 Luminous Flux Maintenance

The LFM value of Product MS-2 was measured according to IES LM-84-14 with photometric testing after each 1,000 hrs of exposure to the RTOL, 45OL, and 6590 environments. The results were analyzed by using IES TM-28-14, and the findings are presented in **Figure 3-6**. There is little difference between the decay rate constants (α) in RTOL and 45OL, which suggests much less temperature sensitivity over the 25°C to 45°C range for Product MS-2 than for Product MS-1. However, the measured α values for Product MS-2 are higher than those measured for similar products such as dim-to-warm (D2W) lamps [9,10]. This finding is a little surprising because the forward current on each LED is only 58 mA (see **Section 2.1.2**).

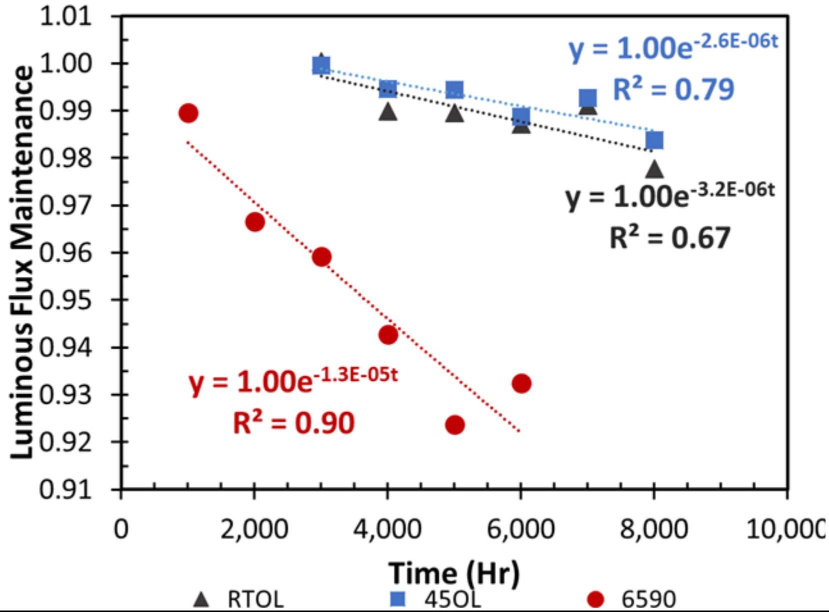

Figure 3-6: LFM of Product MS-2 during RTOL, 45OL, and 6590 according to IES LM-84-14 and IES TM-28-14.

3.2.2 Luminous Efficacy Maintenance

The luminous efficacy of Product MS-2 was approximately 50% lower than that of Product MS-1 (see **Figure** 3-7), but the measured values agreed with the manufacturer's specifications (550 lumens [lm] at 11.5 W). Luminous efficacy for Product MS-2 is a function of testing exposure times, with slower rates of exponential decline observed during milder tests (e.g., RTOL, 45OL) and a steeper exponential decline in more severe tests (e.g., 6590). This trend follows the same pattern observed for LFM, and the luminous efficacy was dominated by the change in luminous flux because the power consumption changed only slightly.

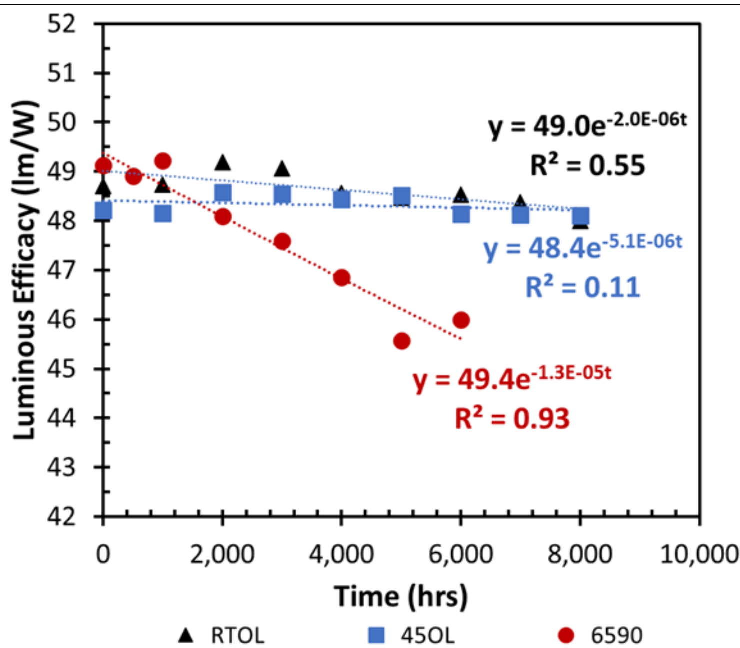

Figure 3-7: Luminous efficacy of Product MS-2 during RTOL, 45OL, and 6590.

3.2.3 Chromaticity Maintenance

Product MS-2 exhibited significant changes in chromaticity—even for the control sample, which was operated only for photometric testing. There are clearly two different CSMs that are active in Product MS-2, as shown in **Figure 3-8**. Initially, the chromaticity shifted in the -*Δv'* direction toward the violet emitter in a CSM-1 mechanism [7,8]. This mechanism was the only one observed for populations during RTOL and 45OL, and the magnitude of this shift, *Δu'v'*, was approximately 0.0036 after 8,000 hrs of 45OL test conditions. During 6590, a CSM-3 mechanism was observed in which the initial shift was in the direction of the violet emitter, and then the shift proceeded in a generally yellowish-red direction after 2,000 hrs of exposure.

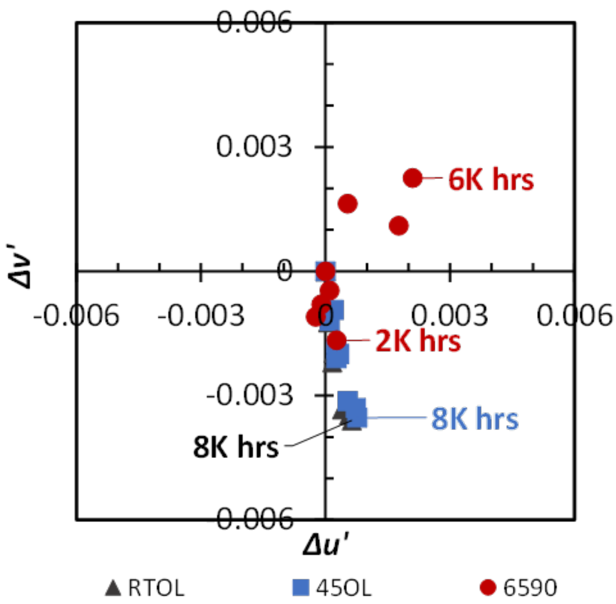

Figure 3-8: Chromaticity shift of Product MS-2 during RTOL, 45OL, and 6590.

An examination of the SPD changes during 6590 exposure explains the observed chromaticity shift. As shown in **Figure 3-9**, after 2,000 hrs of exposure to the 6590 environment, all spectra emissions were slightly reduced, but the reduction appeared to be greater for green and red emissions, accounting for the shift toward the violet chromaticity point. However, at 6,000 hrs, the violet emission had decreased markedly to the point where it was no longer the strongest emission from Product MS-2. The violet emission peak also changed slightly, and the emission maximum wavelength increased by 1 nm. In contrast, green and red emissions dropped only slightly, and the emission maxima appear to be unchanged. These behaviors suggest that photo-oxidation of the lens occurred, which would selectively absorb the violet emissions [11].

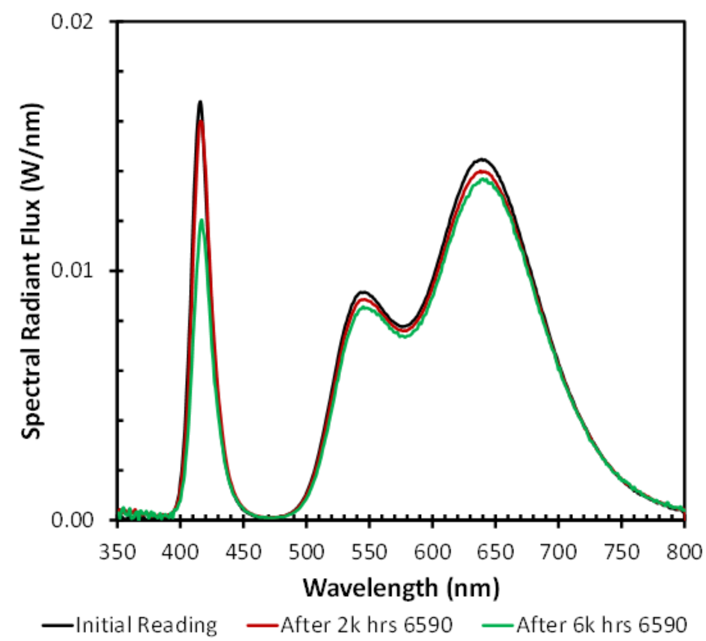

Figure 3-9: SPD of Product MS-2 as initially measured, after 2,000 hrs of 6590 exposure, and after 6,000 hrs of 6590 exposure.

To better under the measured SPDs from products exposed to the different AST environments, the spectra were deconvoluted into violet, green, and red components. The violet emission was fit with a single logistic power peak function, the green emission was fit with a single symmetric Gaussian peak, and the red emission was fit with two Gaussians, reflecting emissions from rare earth additives at two different lattice sites [12]. The resulting deconvolution is presented in **Figure 3-10**. This spectral deconvolution also enabled a determination of the chromaticity point of the violet, green, and red emitters (**Figure 3-11**), in which the chromaticity of the red emitter was the combination of the two red peaks in **Figure 3-10**.

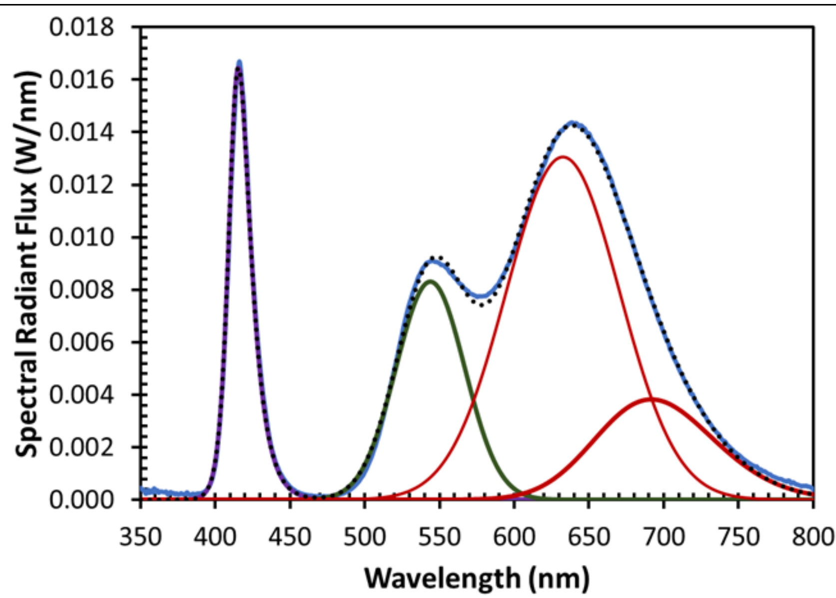

Figure 3-10: Spectral deconvolution of the initial emissions from Product MS-3.

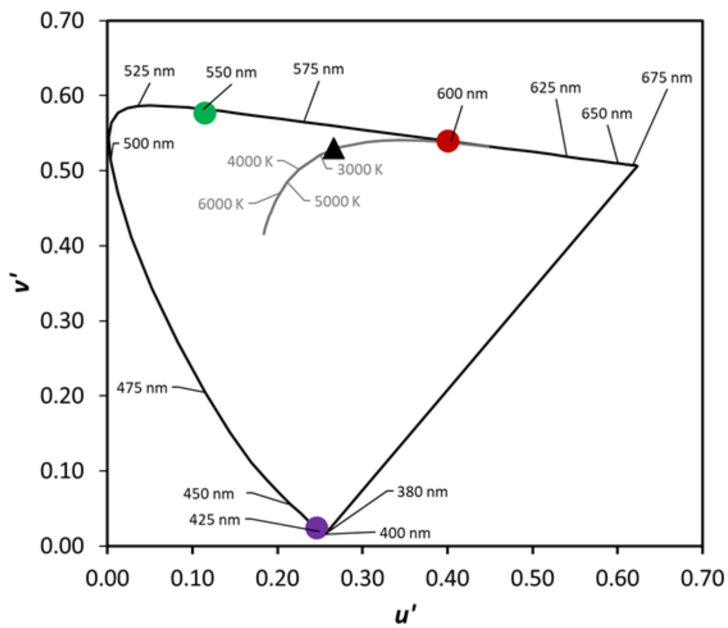

Figure 3-11: Chromaticity coordinates of the violet, green, and red emitters used in Product MS-2 plotted on the 1976 CIE chromaticity diagram. The black triangle is the chromaticity point of the white light produced by Product MS-2.

3.2.4 Failure Analysis and Post-mortem Examination

All lamps examined during RTOL and 45OL testing survived 8,000 hrs without experiencing either an abrupt lights-out failure or a parametric failure. However, during 6590, one of the three lamps began exhibiting excess temporal light artifacts (TLA) at approximately 5,225 hrs so it was classified as a failure. A disassembly of the failed DUT showed discoloration of the solder mask on the LED module and yellowing of the globe (**Figure** 3-12). In addition, the disassembled DUT had two LEDs that were not functioning, which may be tied to the occurrence of TLA, but the source of the TLA was not fully identified. However, the LEDs themselves were not discolored, in contrast to findings from Product MS-1. Both the discoloration of the solder mask and the yellowing of the globe likely caused increased absorption of blue light within this Product MS-2 DUT, which produced the observed yellow chromaticity shift.

Figure 3-12: Product MS-2 after 6,000 hrs of 6590 testing compared with a control sample.

3.3 Product MS-3

3.3.1 Luminous Flux Maintenance

Because the drivers used with the Product MS-3 test populations were external to the test chamber, measurement of luminous flux and chromaticity maintenance reflect only the changes in the LED modules. The LFM of Product MS-3 was measured after each 1,000 hrs of exposure to the RTOL, 75OL, and 7575 environments. Because of testing constraints, only 5,000 hrs of RTOL and 75OL testing were completed on Product MS-3, and only 4,000 hrs of 7575 testing were completed. However, as shown in **Figure 3-6**, the exponential decay model starting at 1,000 hrs was a good fit for the data; therefore, despite the testing limitations, the model is used here. As discussed in **Section 2.1.3** of this report, each MP-LED package in Product MS-3 was operated at 150 mA, which is the manufacturer's specified current limit for this product and the ambient temperature was within product specifications. The approximately 20-fold increase in the α values between RTOL and 75OL suggests that temperature has a significant impact on the emission properties of this product. In addition, the 2.5-times increase in α between 75OL and 7575 shows that humidity also has a major effect on the decay rate constant.

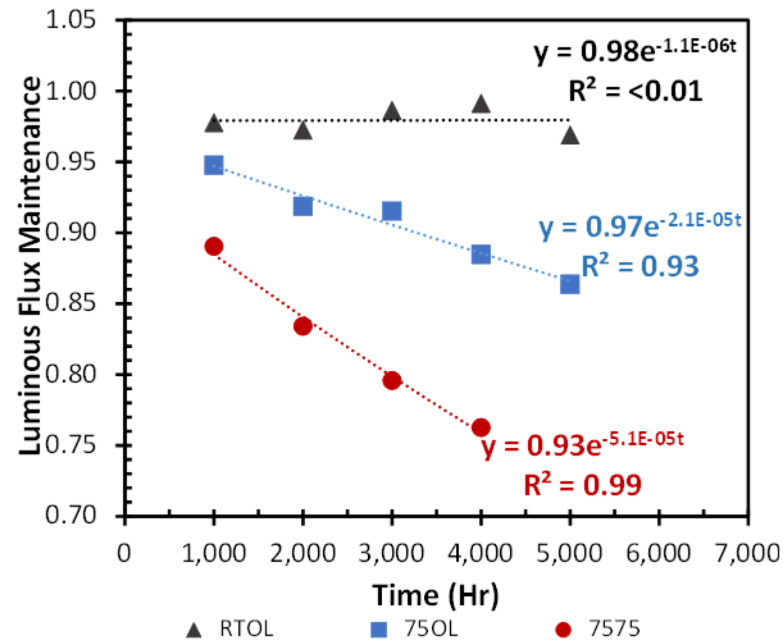

Figure 3-13: LFM for Product MS-3 during RTOL, 75OL, and 7575 according to IES LM-84-14 and IES TM-28-14.

3.3.2 Luminous Efficacy

The initial luminous efficacy of Product MS-3 was approximately 68 lm/W. Because the drivers used with the Product MS-3 test populations were external to the test chamber and because photometric and electrical measurements were made with a common control electrical driver, the measurement of luminous efficacy reflects only the changes in the LED modules. The luminous efficacy value decreased in an exponential manner beginning with the start of the AST, following a similar trend as the luminous flux decay as shown in **Figure 3-14**. There were no signs of discoloration of the LEDs during 6590 testing, although the solder mask on the LED modules did darken in color.

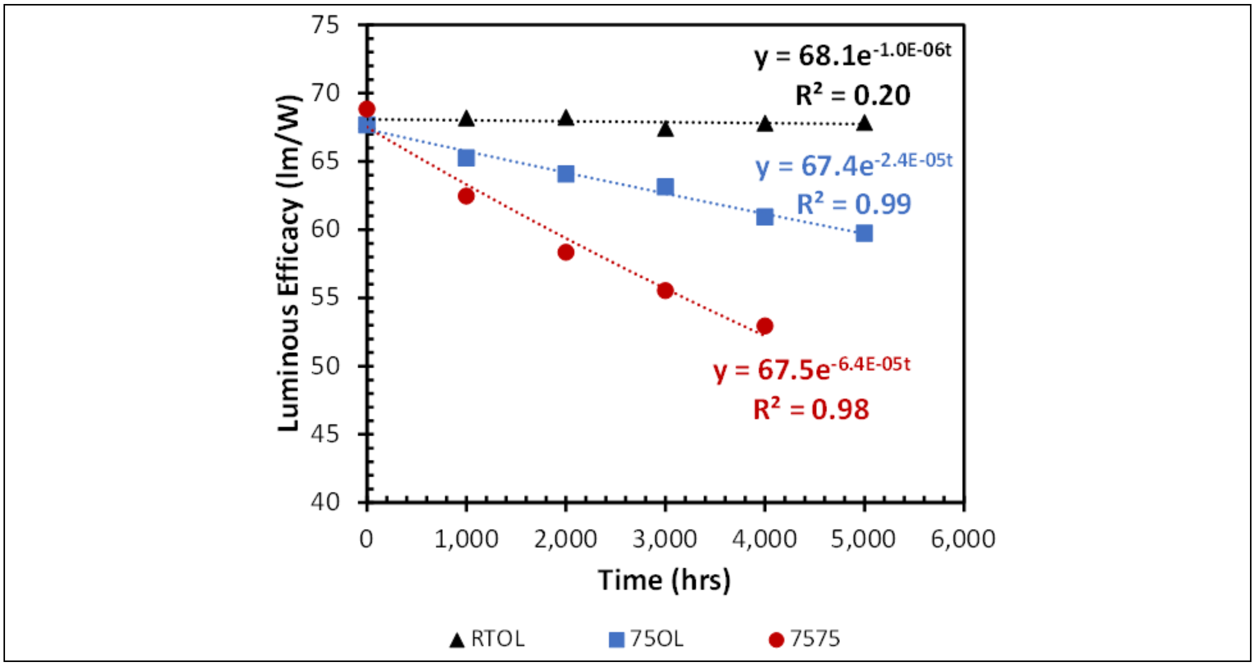

Figure 3-14: Luminous efficacy of Product MS-3 during RTOL, 75OL, and 7575.

3.3.3 Chromaticity Maintenance

Slight differences were observed regarding the chromaticity shift direction between the 75OL and 7575 tests, as shown in **Figure 3-15**. During 75OL, the direction of the chromaticity shift was mainly along the -$\Delta v'$ axis, which suggests that the chromaticity point is shifting toward the violet LED emitter. The magnitude of this shift, $\Delta u'v'$, is nearly 0.005 after 5,000 hrs of 75OL exposure, which is a significant shift but below the parametric limit. In contrast, the chromaticity shift during RTOL was minimal ($\Delta u'v' < 0.001$) through 5,000 hrs of testing. An examination of the SPD time series change during 75OL (**Figure 3-16**) reveals that the phosphor emissions were decreasing during 75OL exposure, but the violet emission intensity stayed relatively constant. This finding was consistent with a shift toward the chromaticity point of the violet LED.

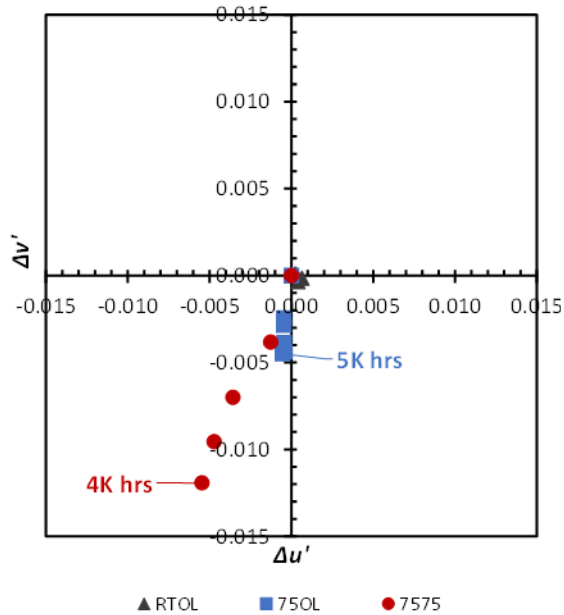

Figure 3-15: Chromaticity shift diagram for Product MS-3 in RTOL, 75OL, and 7575.

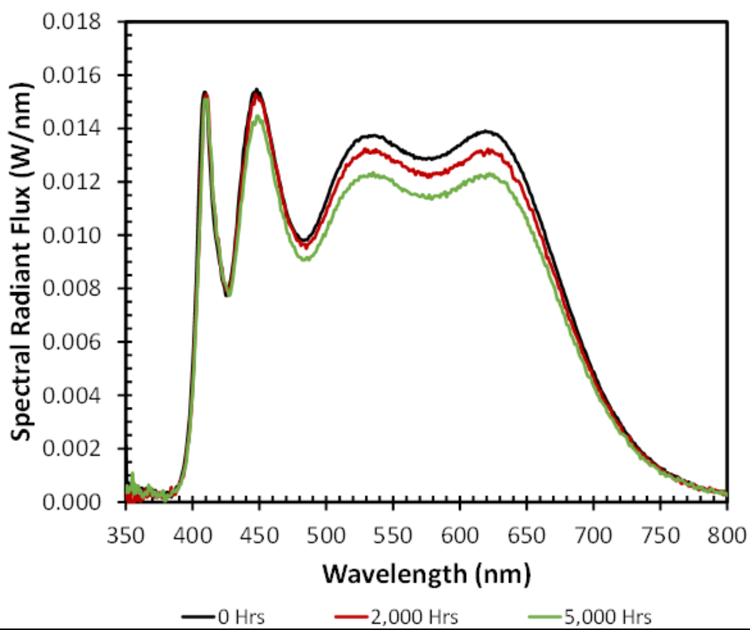

Figure 3-16: SPDs for Product MS-3 operated during 75OL for various times.

During 7575, the chromaticity shift was still predominantly in the -*Δv'* direction, but there was also more change in the -*Δu'* direction than in 75OL. The magnitudes of these changes are greatly accelerated compared with those during 75OL, and the total chromaticity shift (*Δu'v'*) was 0.013 after 4,000 hrs of testing, which is large enough to be considered a parametric failure. This chromaticity shift magnitude is also approximately 3 times the change observed during 75OL. During 7575, the main shift toward the violet LED chromaticity point indicates that the violet emission was increasing relative to those of the phosphor, and an examination of the SPD from 7575 testing showed a sharp drop in phosphor emissions (**Figure 3-17**) relative to the violet LED. The small shift in the -*Δu'* direction suggests that the ratio of green and orange-red emissions was changing

[7,8]. An examination of **Figure 3-17** shows that the orange-red and green emission maxima were approximately equal during initial testing of Product MS-3. However, after 4,000 hrs of testing during 7575, the green emission maximum is clearly larger than the orange-red peak maximum, consistent with a change in the green to orange-red emissions ratio.

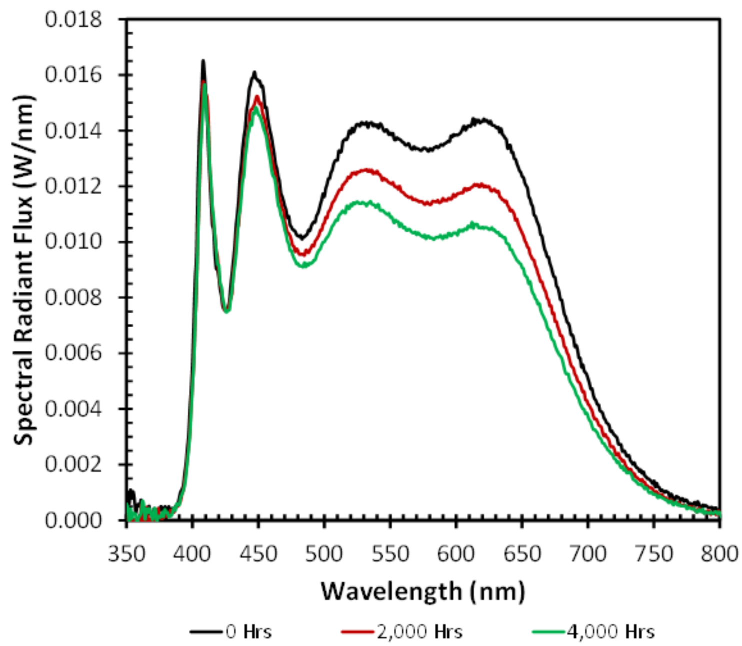

Figure 3-17: SPDs for Product MS-3 operated during 7575 at various times.

To better under the measured SPDs from Product MS-3 DUTs exposed to the different AST environments and to verify changes in the green to orange-red emissions ratio, the spectra were deconvoluted into violet, blue, green, and red components. The violet emission was fit with a single logistic power peak function, and the blue, green, and orange-red emitters were fit with two Gaussians, reflecting emissions from rare earth additives at two different lattice sites [12]. Because of the substantial overlap of the emissions from the green and orange-red phosphors, an estimation of the spectrum of the orange-red phosphor was derived from a “sunlike” product with a warmer CCT, which allowed for better isolation of the orange-red emitter, that was manufactured by the same company as Product MS-3. The spectrum of the green emitter was then deduced by subtracting the blue and orange-red emissions. The resulting deconvolution is presented in **Figure 3-18**. This spectral deconvolution also enabled the chromaticity points of the violet, blue, green, and orange-red emitters to be determined (**Figure 3-19**).

From the temporal radiant power plots generated from the spectral deconvolution, α values were calculated for each of the emitters by using an exponential decay model and are shown in **Table 3-1**. From these α values, a more quantitative understanding of the stability of the phosphors can be gained. In the 75OL environment, the decay rates of green and orange-red emissions were very similar and approximately twice that of the blue emitter; however, the violet LED emission loss was minimal. These relative rates account for the chromaticity shift observed directly along the $-\Delta v'$ axis toward the violet emitter. With the additional humidity in the 7575 environment, the α value of the green emitter nearly doubled, whereas the α value of the orange-red emitter almost tripled. The humidity did not affect the α value of the blue emitter, and the decay of the violet emitter was still minimal. The instability of the green and orange-red emitters in the 7575 environment accounted for the three-fold increase in chromaticity shift and movement toward $-\Delta u'$.

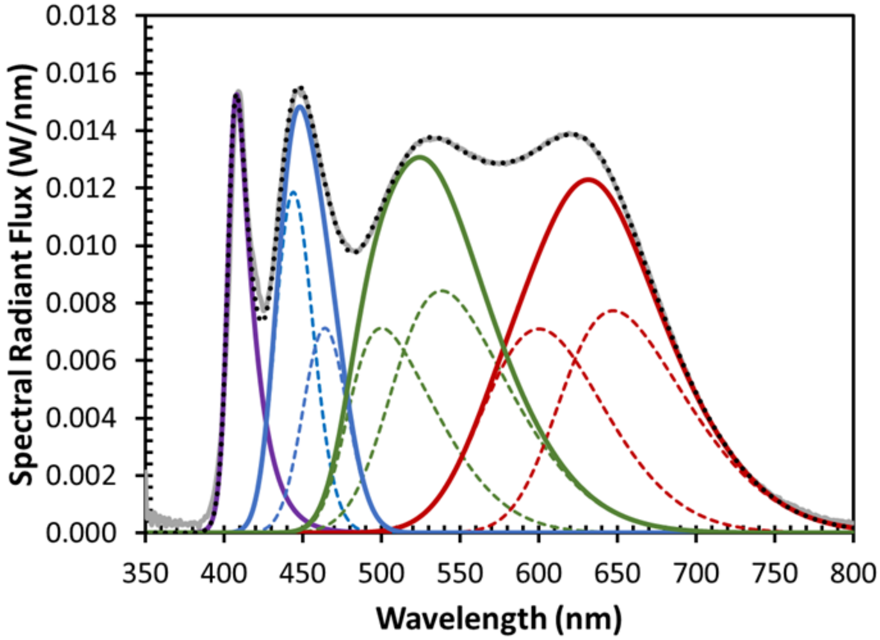

Figure 3-18: Spectral deconvolution of the initial emissions from Product MS-3.

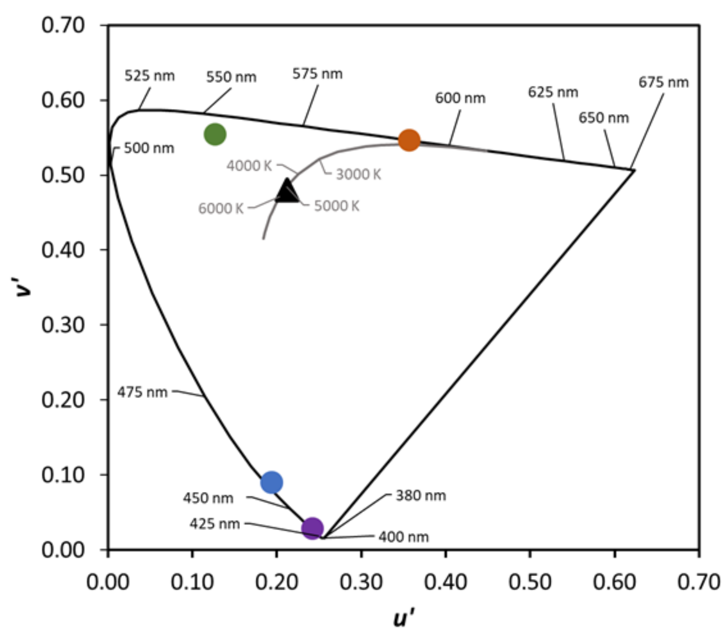

Figure 3-19: Chromaticity coordinates of the violet, blue, green, and orange-red emitters used in Product MS-3 are plotted on the 1976 CIE chromaticity diagram. The black triangle is the chromaticity point of the white light produced by Product MS-3.

Table 3-1: The α Values Calculated for the Emitters of Product MS-3 at Different AST Conditions.

Emitter	AST	
	75OL	7575
Violet LED	-2.06×10^{-6}	2.57×10^{-6}
Blue phosphor	1.13×10^{-5}	1.11×10^{-5}
Green phosphor	2.29×10^{-5}	4.36×10^{-5}
Orange-red phosphor	2.52×10^{-5}	7.17×10^{-5}

3.3.4 Failure Analysis and Post-mortem Examination

To date, no failures have been observed with Product MS-3 during testing.

3.4 Product MS-4

3.4.1 Luminous Flux Maintenance

The LFM of Product MS-4 was measured according to IES LM-84-14. Photometric testing was performed after every 1,000 hrs of exposure to the RTOL, 75OL, and 7575 environments. The results were analyzed by using IES TM-28-14, and the findings are in **Figure 3-20** for the 2,700 K LED primary and **Figure 3-21** for the 5,000 K primary. The DUTs were divided into two groups of three samples for each AST. Group 1 was only operated at 2,700 K during the AST, and Group 2 was only operated at 5,000 K. After every 3,000 hrs of testing, the unused primary for each group was tested, and the CCT value was returned to the original setting.

For a specific test condition, the α values for the 2,700 K primaries were similar to those of the 5,000 K primaries. However, there was nearly a three-fold difference between the α values in RTOL and 75OL, which indicates a temperature sensitivity of the light emissions. There was also an approximately three-fold difference in the α values of 7575 and 75OL, which indicates a moisture susceptibility for the product. All Product MS-4 DUTs in 7575 failed between 3,000 and 5,000 hrs, so data are not presented past 4,000 hrs for this test.

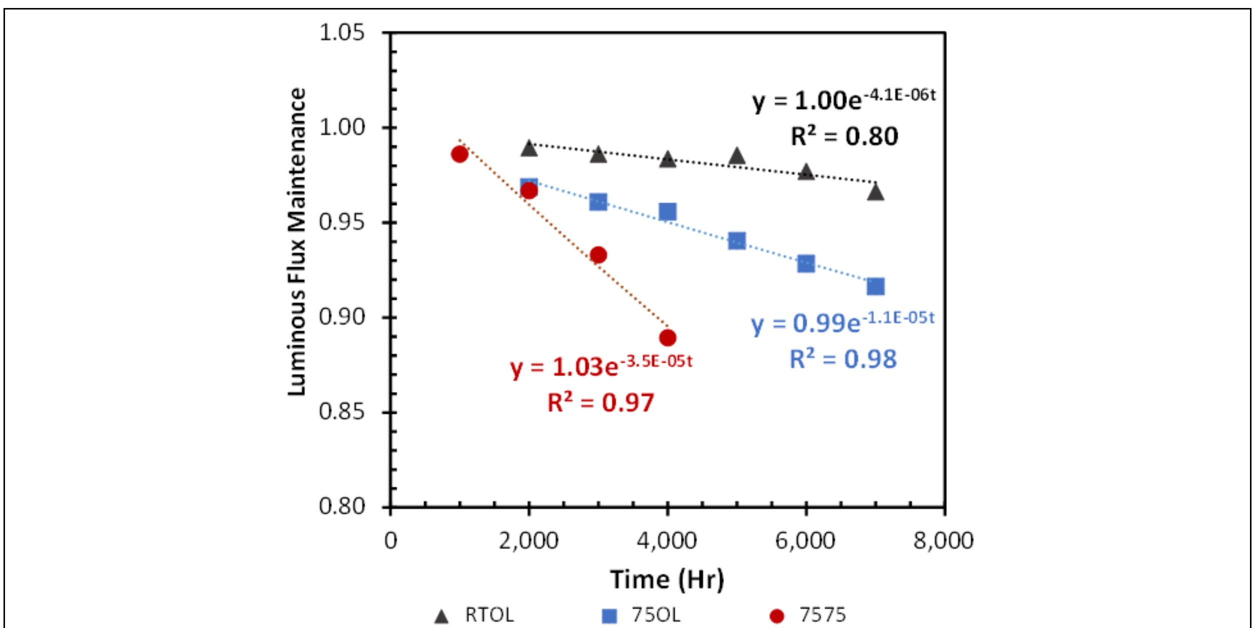

Figure 3-20: LFM of the Product MS-4 test populations operated with the 2,700 K primary. Testing was performed during RTOL, 75OL, and 7575.

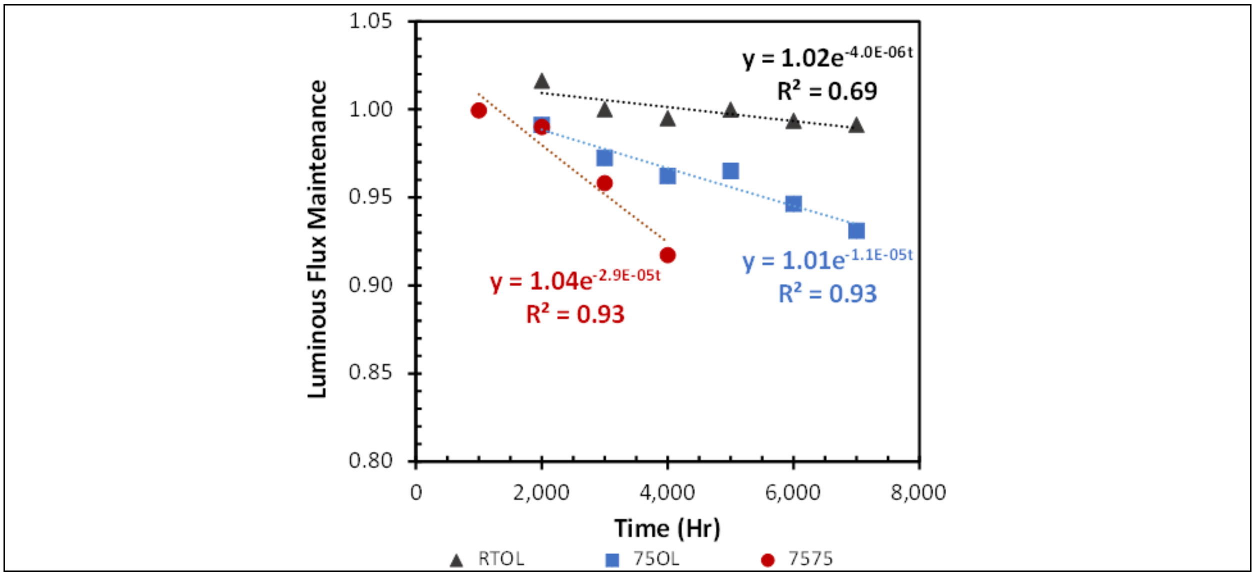

Figure 3-21: LFM of the Product MS-4 test populations operated with the 5,000 K primary. Testing was performed in RTOL, 75OL, and 7575.

3.4.2 Luminous Efficacy

The luminous efficacy for Product MS-4 initially increased with use (**Figure 3-22**) because of a small (3–4%) drop in power consumption that occurred during the first 1,000 hrs of operation. As a result, the luminous efficacy increased throughout the 7,000-hr test period for both LED primaries during RTOL testing. For the 75OL DUTs, there was also a small initial increase in luminous efficacy for both LED primaries, followed by a prolonged decrease. For 7575, the luminous efficacy decreased at most measurement times, and the rate of decrease seemed to stabilize for both primaries after 500 hrs of testing.

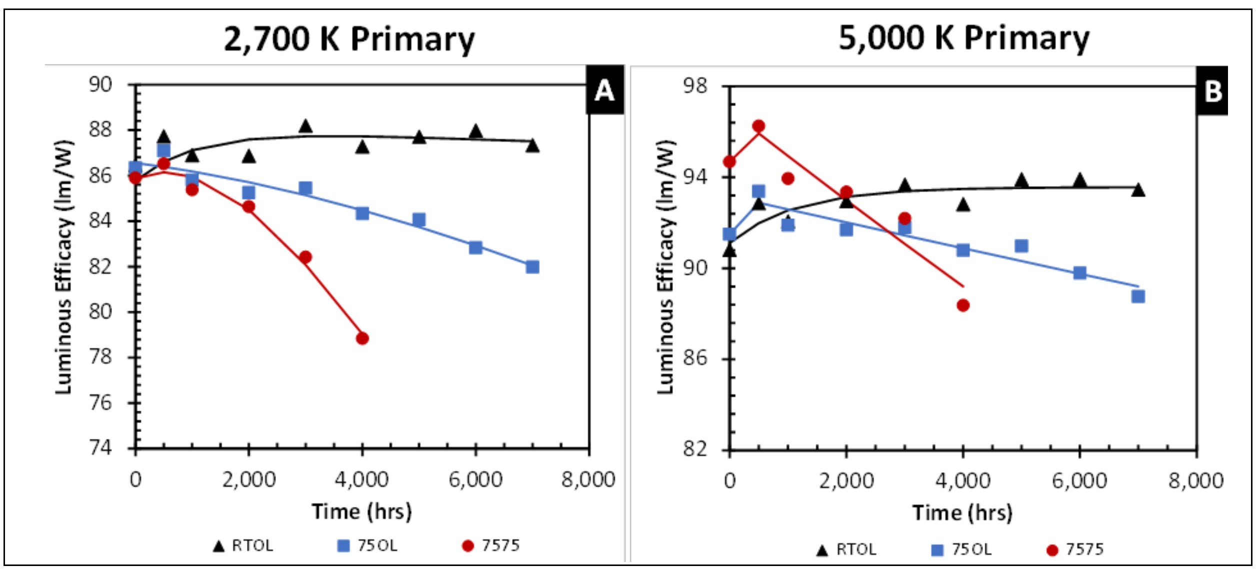

Figure 3-22: Temporal change in luminous efficacy for Product MS-4: (A) for the 2,700 K primary and (B) for the 5,000 primary.

We previously reported in a publication 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 ($Be^{-\alpha t}$) [13]. The combined function is shown in Equation 1 as follows:

$$Luminous\ Efficacy = e^{-\alpha t}\left[B + \gamma\left(1 - e^{-\beta t}\right)\right] \qquad \text{Equation 1}$$

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 large, Equation 1 reduces to an exponential decay function. However, Equation 1 can also be used to model the initial increase in luminous efficacy when t is small. A recursive algorithm was performed on the measured data for luminous efficacy by using Equation 1 to model the observed behavior. The recursive algorithm minimized the $(\text{error})^2$ value by changing α, B, γ, and β.[1] The best-fit parameters for each LED primary are presented in **Table 3-2**. For 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 primaries in 75OL and 7575.

Table 3-2: Parametric Fits for the Luminous Efficacy Model of the LED Primaries in Product MS-5.

Parameters	2,700 K Primary			5,000 K Primary		
	RTOL	75OL	7575	RTOL	75OL	7575
α	1.1×10^{-6}	2.0×10^{-5}	6.0×10^{-5}	0	6.2×10^{-6}	2.08×10^{-5}
B	85.8	86.6	85.9	91.1	91.5	94.7
γ	2.4	20.0	20.8	2.5	1.7	2.2
β	0.001	<0.001	<0.001	0.001	0.031	0.025
Error^2	2.87	1.14	0.65	1.95	1.61	3.15

3.4.3 Chromaticity Maintenance

The chromaticity maintenance of Product MS-4 was similar for the 2,700 K and 5,000 K primaries over the test duration considered in this report (**Figure 3-23)**. The temporal changes in chromaticity shift are presented in **Figure A-9** for the 2,700 K primary and in **Figure A-10** for the 5,000 K primary. For both LED primaries, the chromaticity shift was in the generally yellow direction (i.e., the change was bigger along the $+\Delta v'$ axis). The direction of the two shift vectors was slightly different, which can be attributed to the position of the white point for each CCT value relative to the chromaticity of the blue emitter. The magnitude of the chromaticity shift was slightly larger for the 5,000 K primary than for the 2,700 K primary. In addition, the 2,700 K primary started to exhibit a component of a green shift (i.e., a change in the $-\Delta u'$ direction) after 2,000 hrs of testing. The behavior has been attributed to photo-oxidation of the phosphor [6,7].

[1] "Error" is defined as the difference between the measured value and the value predicted by the model.

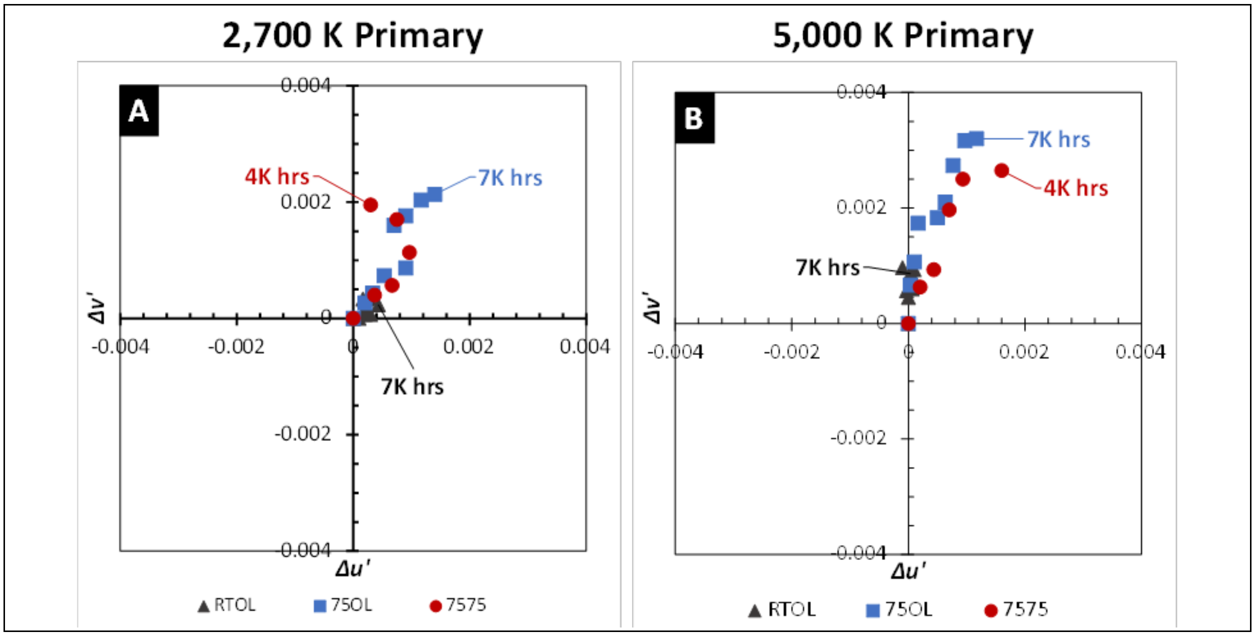

Figure 3-23: Chromaticity shift for Product MS-4: (A) for the 2,700 K primary and (B) for the 5,000 K primary.

3.4.4 Failure Analysis and Post-mortem Examination

All of the Product MS-4 DUTs during 7575 testing failed abruptly between 3,000 and 5,000 hrs. A tear-down of these failed DUTs revealed the same result for the failure site—a film capacitor located beside a transformer (**Figure 3-24**). It is speculated that the thermal mass of the transformer combined with the placement of the film capacitor in the electromagnetic interference (EMI) filter raised the stress level on this component such that it was the failure site in all cases. During testing, it was recorded that all failed Product MS-4 parts had an open fuse and, in some cases, other components (e.g., film capacitors, power resistors) near this capacitor were discolored or had failed.

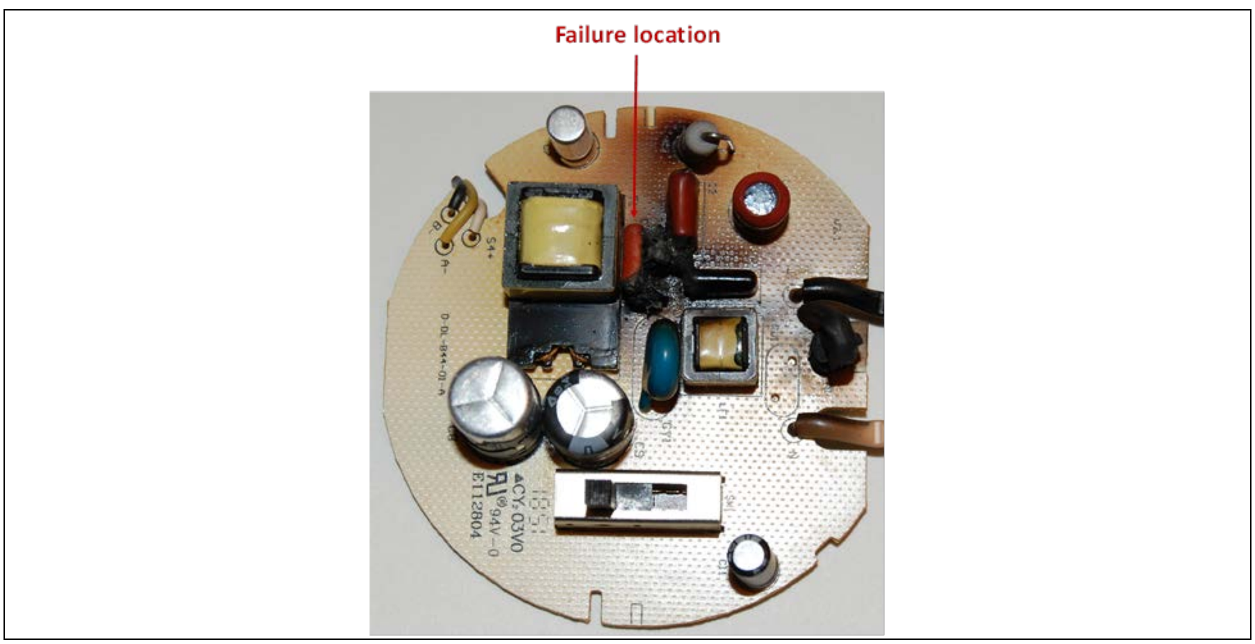

Figure 3-24: Failed driver from Product MS-4 after 5,000 hrs of 7575.

Disassembly of the failed Product MS-4 DUTs also showed moderate discoloration of the solder mask on the LED modules and yellowing of the lenses, but the LED-facing side of the reflectors remained relatively unchanged and the LEDs were not discolored. Transmittance measurements of the lenses operated during 7575 test conditions after 5,000 hrs revealed that the lenses used in the 2,700 K LED primary DUTs underwent a greater amount of change than the lenses used in DUTs set to operate the 5,000 K LED primary (**Figure 3-25**). The changes were greatest at lower energy wavelengths (less than 550 nm) and reflect greater lens yellowing for the 2,700 K LED primary than for the 5,000 K LED primary. Photo-oxidation of lenses is typically promoted by blue wavelengths, and the radiant power of blue emissions was higher in the 5,000 K LED primary, which suggests that yellowing of the lenses on the 5,000 K product is expected to be greater. Because there is a difference between the expected outcome and experimental findings, more investigation is needed to understand the cause of greater lens yellowing in the 2,700 K LED primary DUTs.

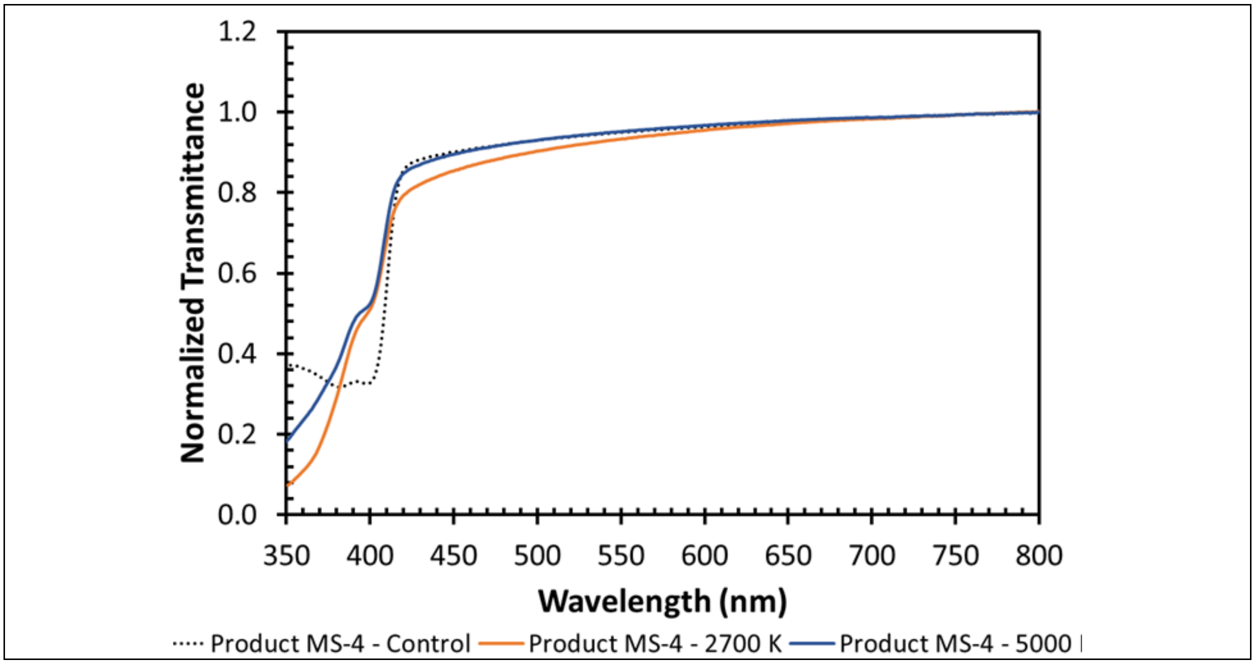

Figure 3-25: Transmittance data (normalized at 800 nm) for Product MS-4 lenses show less transmittance at high energy wavelengths after AST.

3.5 Product MS-5

3.5.1 Luminous Flux Maintenance

The LFM of Product MS-5 was measured according to IES LM-84-14, and photometric testing was performed after every 1,000 hrs of exposure to the RTOL, 75OL, and 7575 environments. The results were analyzed by using IES TM-28-14, and the findings are presented in **Figure 3-26** for the 2,700 K primary and **Figure 3-27** for the 5,000 K primary. The DUTs were divided into two groups of three samples for each AST. Group 1 was operated at 2,700 K in AST, and Group 2 was only operated at 5,000 K. After every 3,000 hrs of testing, the unused LED primary for each group was tested, and then the CCT value was returned to the original setting.

For a specific test condition, the α values for the 2,700 K primaries were lower than those of the 5,000 K LED primaries. There was also a large difference between the α values for both LED primaries in RTOL and the corresponding α in 75OL, which suggests a temperature sensitivity of the light emissions. There was an approximately three-fold increase in the α values of both LED primaries for 7575 over 75OL, which indicates a moisture susceptibility for Product MS-5. Although no parametric failures were observed during the test interval, five out of the six Product MS-5 DUTs in 7575 failed abruptly between 4,000 and 5,000 hrs; therefore, data are not presented for this test past the time when devices of a set CCT value failed.

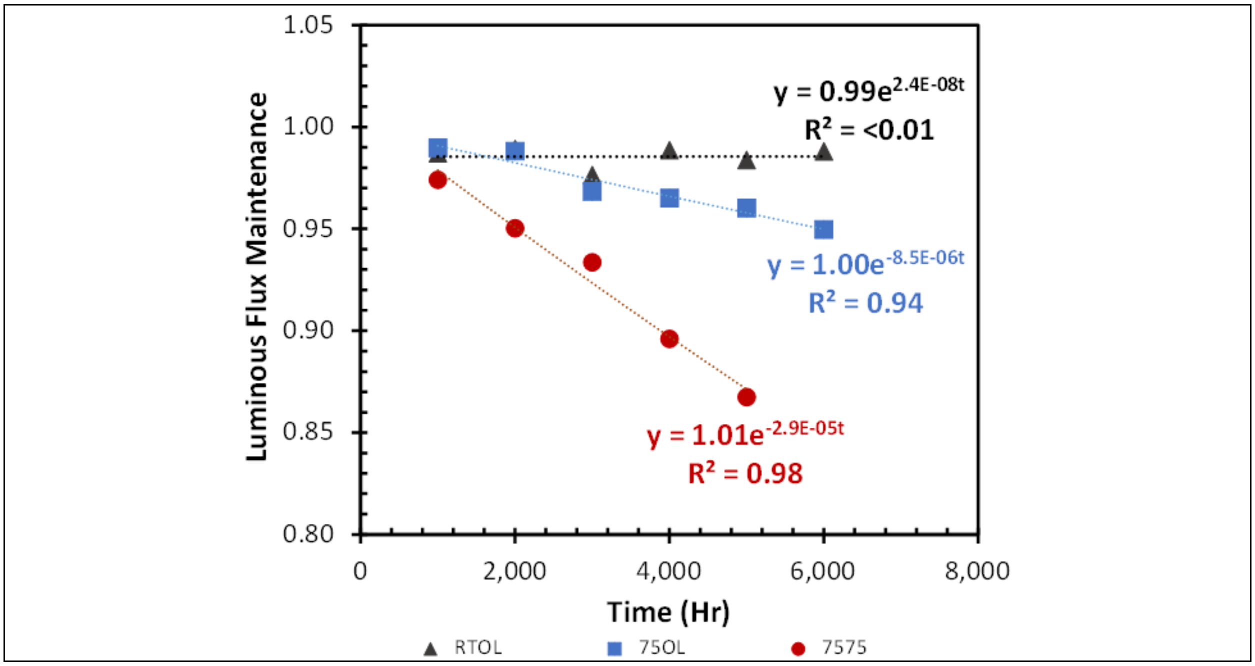

Figure 3-26: LFM of the 2,700 K primary for Product MS-5 in different AST protocols.

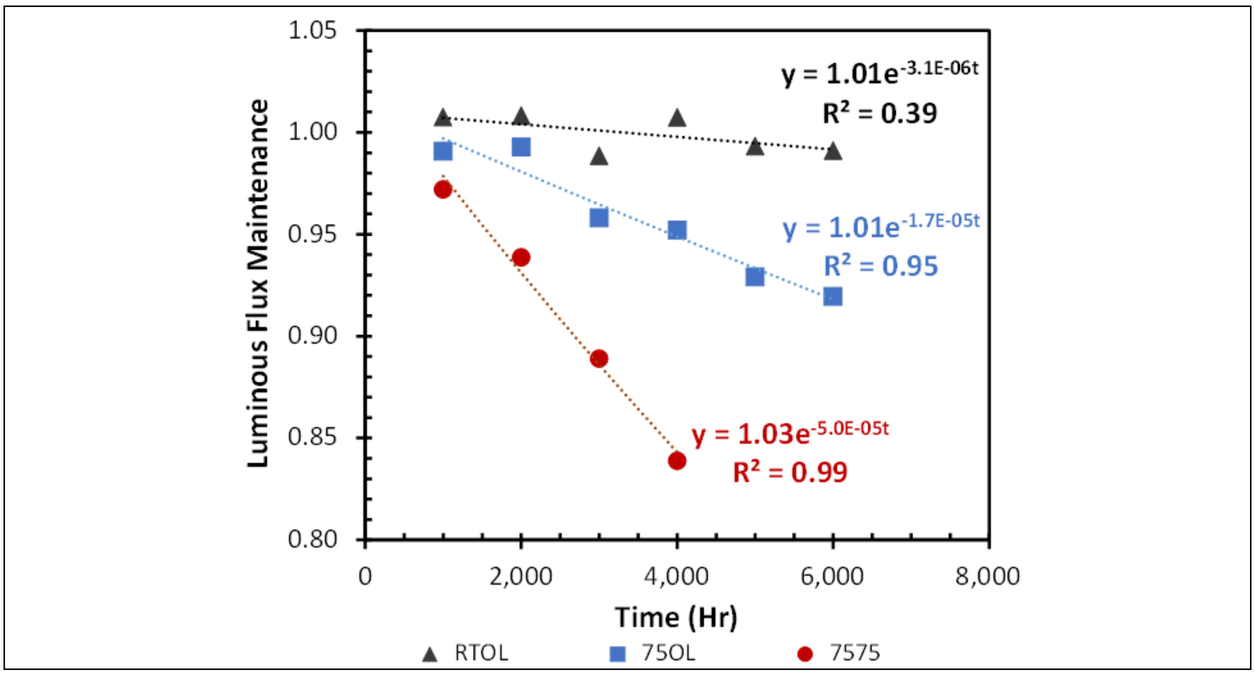

Figure 3-27: LFM of the 5,000 K primary for Product MS-5 in different AST protocols.

3.5.2 Luminous Efficacy

The luminous efficacy for Product MS-5 initially increased with use (**Figure 3-28**) during mild AST conditions because of the minimal change in LFM and a small (3–4%) drop in power consumption. The luminous efficacy increased throughout the 6,000-hr test period for both LED primaries in RTOL testing. For the 75OL DUTs, there was a small, initial increase in luminous efficacy for both LED primaries, followed by a prolonged decrease that tracked the reduction of luminous flux. For 7575, the luminous efficacy decreased at every measurement time, and the rate of decrease seemed to stabilize after 500 hrs of testing, possibly indicating an initially slower rate of decline.

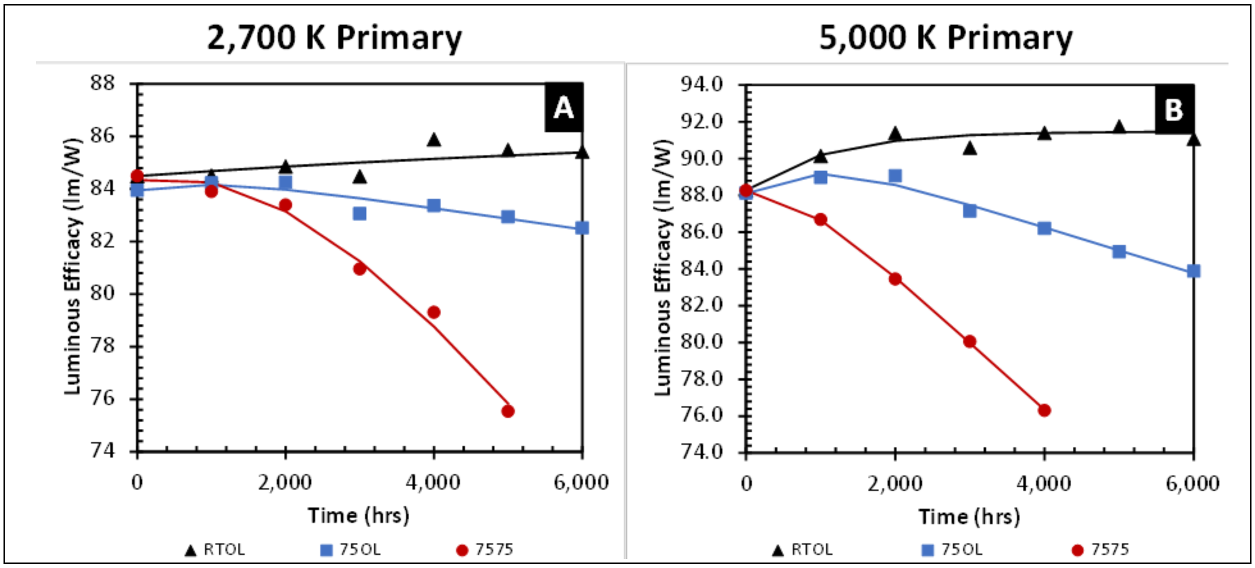

Figure 3-28: Temporal change in luminous efficacy for Product MS-5: (A) for the 2,700 K primary and (B) for the 5,000 primary.

Equation 1 was used to model the initial increase in luminous efficacy reported in **Figure 3-28**. A recursive algorithm was used to minimized the $(\text{error})^2$ value by changing α, B, γ, and β. The best-fit parameters for each LED primary in RTOL, 75OL, and 7575 are presented in **Table 3-3**. For 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 primaries in 75OL and 7575. A comparison of **Table 3-3**, **Figure 3-26**, and **Figure 3-27** shows that the α values for exponential decay of luminous efficiency are similar to those for LFM. A notable exception is the 2,700 K LED primary in 75OL, in which the luminous efficacy α value was approximately half of that for luminous flux, possibly because of the measured initial efficiency increase. With prolonged operation in 75OL, it is anticipated that the α values for 75OL and 7575 would converge.

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

Parameters	2,700 K Primary			5,000 K Primary		
	RTOL	75OL	7575	RTOL	75OL	7575
α	0	4.9×10^{-6}	9.9×10^{-5}	0	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	229	3.2	3.4	4.2
β	0.001	0.001	<0.001	0.001	0.001	<0.001
Error^2	0.89	0.44	0.67	0.89	0.42	0.02

3.5.3 Chromaticity Maintenance

The chromaticity maintenance of Product MS-5 was similar for the 2,700 K and 5,000 K primaries as shown in **Figure 3-29**. The temporal changes in chromaticity shift are given in **Figure A-11** for the 2,700 K primary and in **Figure A-12** for the 5,000 K primary. For both LED primaries, the chromaticity shift was in the generally yellow direction (i.e., the change was mainly along the $+\Delta v'$ axis). The direction of the two shift vectors was slightly different, which can be attributed to the position of the initial chromaticity point at each CCT to the chromaticity value of the blue emitter. The magnitude of the chromaticity shift during 7575 was slightly larger for the 5,000 K primary than for the 2,700 K primary. In addition, the initial chromaticity shift for the 2,700 K primary 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 has also been observed in other LEDs and likely represent 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) [7,8,14].

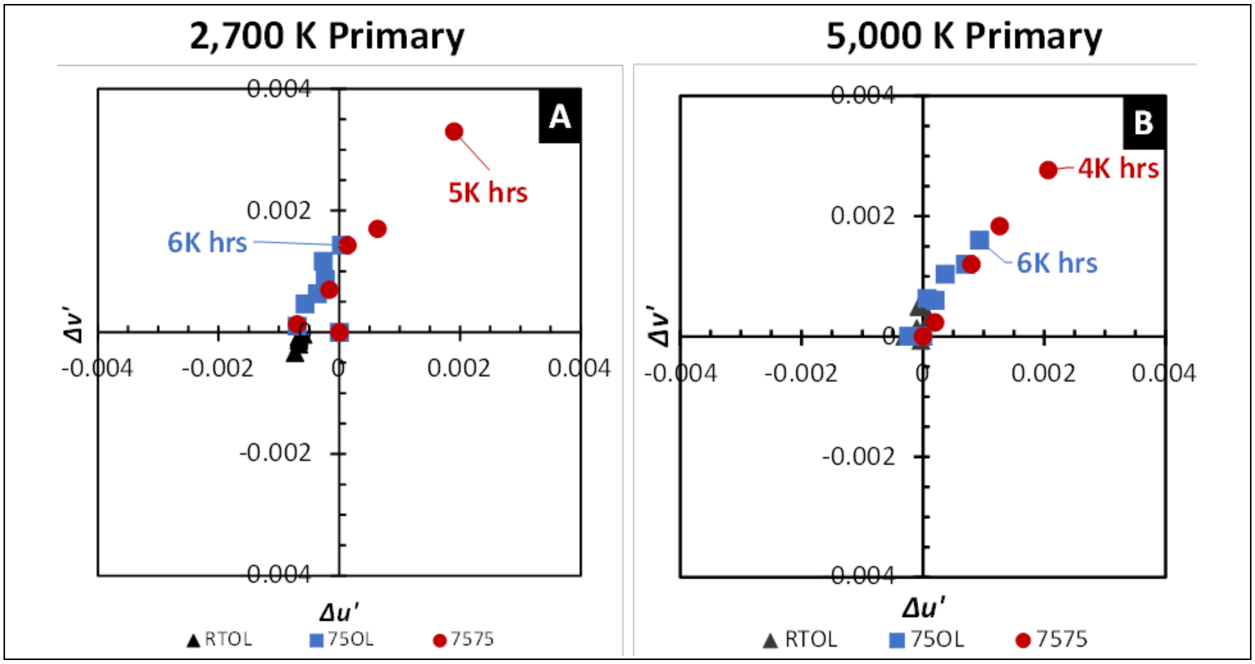

Figure 3-29: Chromaticity shift for Product MS-5: (A) for the 2,700 K primary and (B) for the 5,000 primary.

3.5.4 Failure Analysis and Post-mortem Examination

Five out of the six Product MS-5 DUTs that were exposed to the 7575 test failed abruptly between 4,000 and 5,000 hrs. A tear-down of all Product MS-5 failures revealed the same result for the failure site—a film capacitor located immediately after the diode bridge (**Figure 3-30**). This failure also caused the fuse to fail and resulted in significant discoloration of the driver PCB and nearby components. Other nearby components, including a film capacitor and a power resistor, were still operational but highly discolored from the malfunction of the film capacitor. We speculate that the electrical stress combined with the thermal environment caused by the neighboring power resistor and diode bridge rectifier were responsible for the failure of this capacitor in the DUTs subjected to 7575 testing.

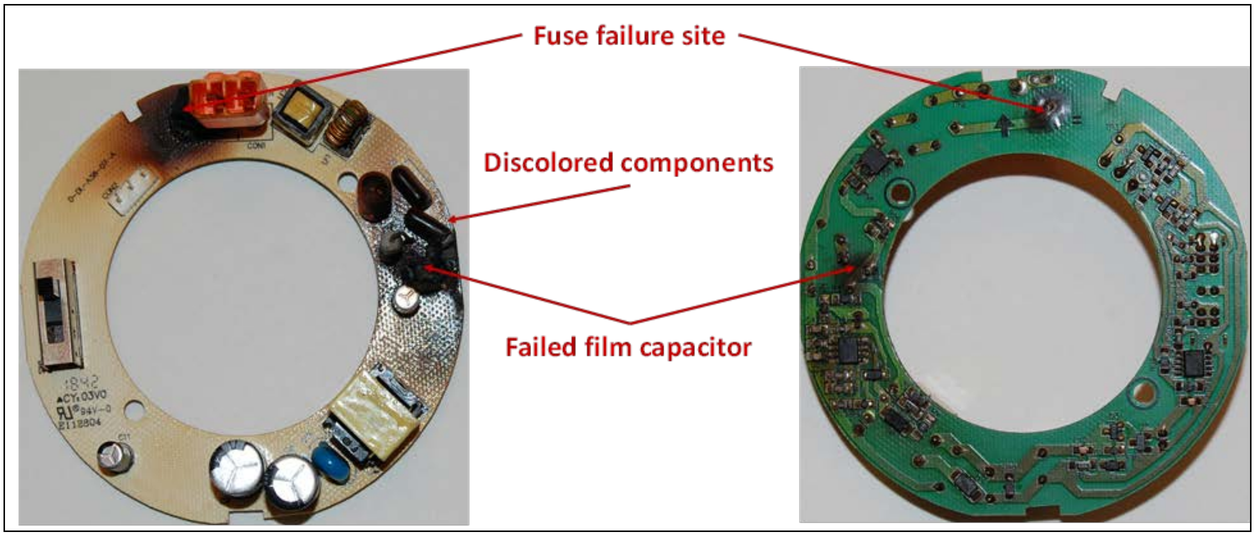

Figure 3-30: Failed driver from Product MS-5 after 5,000 hrs of 7575.

Disassembly of the failed Product MS-5 DUTs also showed significant discoloration of the solder mask on the LED modules; however, the solder mask discoloration did not occur in the area around the LEDs. The reflector appears to prevent the solder mask around the LEDs from discoloring, suggesting that solder mask discoloration may be tied to failure of the film capacitor. Indeed, there were black marks on the backside of the reflector near where the failed film capacitor was located. The LED-facing side of the reflectors remained relatively unchanged. Transmittance measurements of the lenses operated during 7575 test conditions after 5,000 hrs revealed that the lenses used in the 5,000 K LED primary DUTs underwent greater change than the lenses used in the 2,700 K LED primary DUTs (**Figure 3-31**). The changes were greatest at lower energy wavelengths (less than 550 nm) and reflect greater lens yellowing for the 5,000 K LED primary, which is typical of photo-oxidation promoted by blue wavelengths [11].

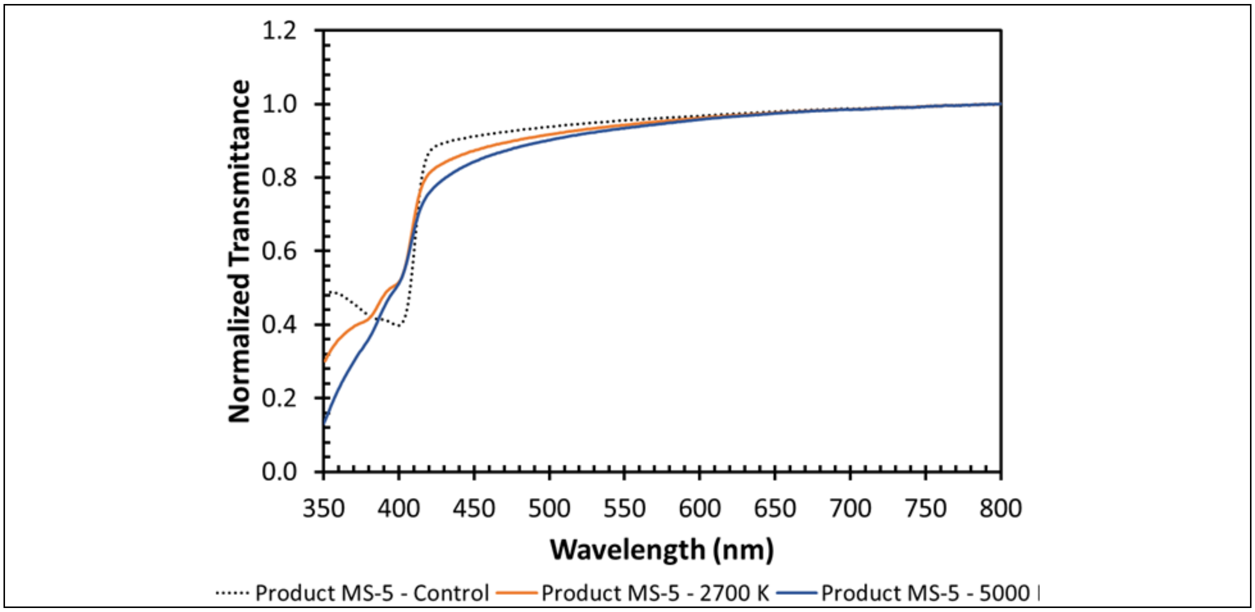

Figure 3-31: Transmittance data (normalized at 800 nm) for Product MS-5 lenses show less transmittance at high energy wavelengths after AST.

4 Discussion

The report demonstrates that LED lighting products offer a range of capabilities; 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 [15]. 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 [16].

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 luminous flux maintenance 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 ($\Delta u'v'$) exceed 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 D2W lamps and demonstrated that under mild conditions, the LFM is high enough for L_{70} to reach the projection limit. However, under more severe conditions such as temperature and humidity, the L_{70} value is often below the projection limit [9]. 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 (i.e., 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 maintenance. 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 chromaticity maintenance.

In general, the long-term luminous efficacy of SSL devices is determined by the LFM. As previously discussed, 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, in other devices, there is a definite trend toward exponential decay of the luminous efficacy of SSL devices 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 Lamps

The two lamps examined during this study achieved modified spectral output for the purpose of producing a particular lighting spectrum in two different ways. Product MS-1 incorporates an optical filter in the glass globe surrounding the LEDs. The optical filter absorbed some green and yellow emissions, resulting in a chromaticity shift in a blueish-green direction by $\Delta u'v'$ = 0.007 and an increase in CCT value by 81 K. Product MS-2 uses a special phosphor mixed with a violet-pump LED to eliminate nearly all blue emissions. This product is touted as being a "healthy" SSL device because the elimination of blue would reduce the melanopic flux and could potentially provide a circadian benefit.

A comparison of the LFM for Products MS-1 and MS-2 with those previously measured for D2W lamps (e.g., D2W-Product A and D2W-Product B) shows that the α values of Products MS-1 and MS-2 are generally higher than those measured for the D2W lamps [9], indicating a faster decline in light source efficiency. This finding is somewhat surprising because the I_f value of these devices (i.e., 48 mA for Product MS-1 and 58 mA for Product MS-2) are lower than those for the D2W products, and lower I_f values typical extend LED lifetimes [17].[2]

These α values were used to project L_{70} values for Products MS-1 and MS-2, and the findings are presented in **Table 4-1** For both products, the projected L_{70} times were the allowed projection limit for most AST conditions. This finding suggests that longer testing times are needed to fully understand the LFM changes and their impacts on LAE. The only exception was Product MS-1 during 6590, which exhibited a rapid decline in LFM (and luminous efficacy) from the onset of testing.

Table 4-1: Calculated L_{70} Values for Products MS-1 and MS-2 During Different AST Conditions.

Product	RTOL	45OL	6590
MS-1	>24,000 hrs[a]	>24,000 hrs[a]	13,000 hrs
MS-2	>24,000 hrs[a]	>24,000 hrs[a]	>24,000 hrs[a]

[a] Projected values are limited by the sample size and test duration.

The chromaticity shift of Products MS-1 and MS-2 remained within the parametric limits throughout the test period. Product MS-1 exhibited virtually no chromaticity shift following 8,000 hrs during RTOL and only a small shift in the generally yellow direction ($\Delta u'v'$ approximately is 0.002) after 8,000 hrs during 45OL. Product MS-2 exhibited the same shift behavior during RTOL and 45OL, with chromaticity shifting toward the violet emitter, and the magnitude of this shift was approximately 0.0035 after 8,000 hrs during both tests.

[2] For example, the I_f for each LED in D2W-Product A was 100 mA [9].

Although the magnitudes of the chromaticity shifts were within parametric limits during the test durations, different chromaticity shift mechanisms appeared over time during temperature and humidity tests compared with only temperature tests. During 6590, Product MS-1 initially shifted in the yellow direction (as did the DUTs during RTOL and 45OL), but the shift proceeded in a generally green direction beginning with 1,000 hrs of exposure. A close examination of the SPD (**Figure 3-4**) shows that peak positions are not changing, but the light emission is becoming slightly enriched in green as 6590 exposure proceeds. Because peak positions are not changing, the rise in green emissions is likely due to either (1) a decrease in green absorption by the optical filter in the glass because of moisture sensitivity or (2) a change in the phosphor that increases green emissions over time. Whatever the cause, this temporal change represents a possible shift in spectral efficiency. In a similar manner, Product MS-2 initially shifted toward the violet emitter through 2,000 hrs of 6590 exposure, and then the chromaticity shift reversed direction and began to change in the red-yellow direction. An examination of the SPD (**Figure 3-9**) shows that the violet emitter is being attenuated more rapidly after 2,000 hrs of 6590. We believe that this change is because of photo-induced oxidation of the polymer globe around the LEDs, which increases absorption of short wavelengths [11]. This is an example of an adverse change in the optical delivery efficiency component of LAE, and this change can have potentially sizable negative impacts on overall performance.

Based on the analysis, the enhanced optical performance that was achieved through spectra modification in Products MS-1 and MS-2 came at a cost of reduced light source efficiency from the beginning of use and potentially reduced optical delivery efficiency and changes in spectral efficiency with long-term use. The additional use of a glass globe with an optical filter reduced the overall emissions of the LEDs in Product MS-1 from 836 lm to 614 lm (26%). This light absorption dropped the luminous efficacy of the device from 113 lm/W to the observed 85 lm/W (25%). Although this is still a respectable value for luminous efficacy, especially compared with incandescent lamps, it illustrates the light source efficiency penalty of spectral modification by absorption.

A different tactic was used for spectral modification for Product MS-2, but this approach also demonstrates the efficiency penalty that comes with spectral modification. Although the elimination of blue emissions by omitting a blue phosphor may reduce the melanopic lux produced by the lamp, this approach also resulted in poor color fidelity (**Figure A-3**) with under-saturation of blues and over-saturation of greens and yellows. Product MS-2 also exhibited the lowest luminous efficacy of the devices studied and presented in this report, 49 lm/W, presumably due to the use of a violet-pumped LED. The luminous efficacy value of Product MS-2 was approximately 60% of Product MS-1 and was also lower than observed for A19 replacement lamps in the D2W study [9].

4.2 LED Light Engine

The only LED light engine that was examined during this study was Product MS-3, a violet-pumped pc-LED device that has a spectral output intended to mimic sunlight ("sunlike") at a CCT value of 5,000 K. As shown in **Figure A-4**, the light emissions from Product MS-3 resemble the solar spectrum from 400 to 750 nm, although there are some deviations especially over the 400- to 520-nm range. The performance of this product is achieved by using a violet-pump LED and phosphors for blue, green, and red emissions. The net result was excellent initial color fidelity and color gamut; however, there were several trade-offs with using this approach.

First, the initial luminous efficacy of Product MS-3 was only 68 lm/W because of the use of the violet LED. This value was the second lowest initial luminous efficacy measured in this study, with the violet-pump Product MS-2 being the lowest. It should be noted that this product was only measured as a light engine with no optics, so additional losses may occur when adding the LED module to a luminaire or lamp. The luminous efficacy of Product MS-3 remained stable during RTOL but dropped rapidly once exposure to 75OL or 7575 began. Therefore, a finding from this study was that the initial light source efficiency was well below the state of the art, and the product was sensitive to temperature and humidity, which can also impact long-term spectral efficiency.

Second, reinforcing the temperature and humidity sensitivity of this product, the luminous flux decay of Product MS-3 in 75OL and 7575 was among the highest measured in this study (see **Figure 3-13**). It should also be mentioned that Product MS-3 was the only product examined during this test without a lens. Therefore, no judgments could be made about changes in optical delivery efficiency. The luminous flux degradation was driven primarily by reduced emissions from the phosphors (**Figure 3-15** and **Figure 3-16**), which suggests that a thermal and moisture quenching process has occurred in the phosphors. Because all photometric testing is performed at room temperature, the quenching processes must have occurred during 75OL and 7575, and the damage to the phosphor remained during room temperature testing. The sizable reduction in phosphor emissions produced large chromaticity shifts, especially in the 7575 DUTs and to a lesser extent in the 75OL DUTs. Through 4,000 hrs of testing during 7575, the chromaticity shift magnitude, $\Delta u'v'$, was greater than 0.012, which greatly exceeds the parametric threshold. The chromaticity shift is mainly toward the violet chromaticity point, which is consistent with the SPD containing proportionately greater violet content, and there is also a small shift in the green direction, which suggests a larger temperature and humidity degradation of the red phosphor compared with the green phosphor. This conclusion is supported by the temporal change of the SPD from devices during 7575 (see **Figure 3-15**).

4.3 LED Downlights

Both LED downlights examined in this study achieved spectral modification by setting a switch to a predetermined CCT value. This spectral modification method is a single-use tuning mechanism in which the lighting color is adjusted to a desired setting prior to fixture installation. Changing the light to another CCT value requires removal of the lamp and adjusting the switching appropriately. This spectral tuning method contrasts with fully tunable lighting methods in which the fixture CCT value can be adjusted remotely and at anytime. Despite the different tuning methods, the switching downlights 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 separate transistor switches for each LED primary [17].

The ratio of the α values for 75OL to RTOL indicates the acceleration factor of temperature alone for Products MS-4 and MS-5. Likewise, a comparison of the α values for 75OL and 7575 provides a measure of the acceleration factor of high humidity in the presence of high heat for these products. These values are compiled in **Table 4-1: Calculated L70 Values for Products MS-1 and** MS-2 During Different AST Conditions..

Table 4-2: Comparison of the α Values and α Ratios for the LED Downlights Under Different Stress Conditions.

Product	CCT	RTOL	75OL	7575[a]	75OL/RTOL Acceleration Factor	7575/75OL Acceleration Factor
MS-4	2,700 K	4.1×10^{-6}	1.1×10^{-5}	3.5×10^{-5}	2.7	3.2
MS-4	5,000 K	4.0×10^{-6}	1.1×10^{-5}	2.9×10^{-5}	2.8	2.6
MS-5	2,700 K	2.4×10^{-6}	8.5×10^{-6}	2.7×10^{-5}	3.5	3.2
MS-5	5,000 K	3.1×10^{-6}	1.7×10^{-5}	5.0×10^{-5}	5.5	2.9

[a] The α values in 7575 represent exponential fits to the LFM data over the period from 1,000 to 4,000 hrs because the devices experienced abrupt failure at approximately 4,000 hrs.

For these products, ambient temperatures of 75°C reduce LFM by a factor of 2.7 to 5.5, relative to RTOL. Stated differently, the acceleration factor of 75OL is 2.7 to 5.5, relative to RTOL. The LED primaries at both CCT settings in Product MS-4 had an acceleration factor of 2.7 to 2.8, whereas the 75OL acceleration factor was slightly higher for the 2,700 K setting of Product MS-5. For unknown reasons, 75OL caused a greater decline in LFM at the 5,000 K setting of Product MS-5, relative to the RTOL results, as shown in **Table 4-2**.

When comparing the α values of 7575 with 75OL, adding high humidity at 75°C decreases LFM by an additional factor of approximately 3.0. If the acceleration factor is calculated relative to RTOL, then the value varies between 7.5 and 15, with the variation being determined mainly by the impact of temperature.

The light source efficiency, as measured by the luminous efficacy of the downlights reported here, varied depending upon the AST conditions. Both primaries of Products MS-4 and MS-5 exhibited an increase in luminous efficacy throughout the RTOL test interval, resulting mainly from a drop in power consumption. During 75OL, there was also an initial increase in luminous efficacy that typically lasted less than 1,000 hrs. Then, the luminous efficacy decreased primarily due to the decay in LFM. DUTs tested during 7575 only exhibited exponential decreases in luminous efficacy throughout the test period. An examination of **Figure** 3-22 **and Figure 3-28** shows that there was an acceleration in luminous efficacy decay when proceeding from RTOL to 75OL and then to 7575. Unfortunately, the RTOL samples for both Products MS-4 and MS-5 have not entered the phase during which luminous efficacy decreases in an exponential decay manner, so acceleration factors, relative to RTOL, require additional testing before they can be determined. As a first estimate, it can be assumed that the acceleration factor for luminous efficacy follows that of LFM.

When calculating accelerating factors for chromaticity shift, it is important to be able to identify the emergence phase of chromaticity shift. The “emergence phase” is defined in ANSI/IES TM-35-19 as the final phase of chromaticity shift during which $\Delta u'v'$ increases as an approximately linear function of time until the chromaticity threshold is reached [18]. Although the measured chromaticity shifts for Products MS-4 and MS-5 remained below the parametric failure threshold (i.e., $\Delta u'v'$ = 0.007), the two LED primaries on both products exhibited a potential emergence phase during 75OL and 7575 by 1,000 hrs of testing (see **Figure A-9**, **Figure** A-10, **Figure A-11**, **Figure A-12**). Although the timing of the appearance of the emergence phase was similar during 75OL and 7575, the rate was generally higher during 7575. It is important to note that the emergence phase was not visible yet for any of the RTOL trials for Products MS-4 and MS-5, which is an indication that longer test times are needed for RTOL.

Although the accelerated conditions did not produce parametric failures in downlights according to our definitions, the 7575 test condition did produce abrupt failures between 3,000 and 5,000 hrs of testing for 11 out of the 12 downlights examined during this study. In all cases, the root cause of the abrupt failures was a film capacitor on the EMI filter near the diode bridge. It is highly likely that this location was the failure site in the driver circuits for both Products MS-4 and MS-5 for two reasons. The first reason is because the electrical voltage across the terminals of the capacitor is the highest in the circuit (close to the root mean square value of the line voltage). The second reason is because these capacitors are near heat sources (e.g., transformers, diode bridges, power resistors). These factors, combined with the high humidity of the 7575 environment, degraded the film capacitor in the EMI filter and ultimately resulted in an abrupt failure of the device. This outcome provides additional evidence that the long-term performance of LED devices is dependent upon the entire lighting device, including LEDs, optics, and electronics.

5 Conclusions

LAE describes the efficient delivery of light from the light source to the lighted task and is viewed as a new frontier in increasing energy savings with SSL technologies. The framework for LAE proposed by DOE 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.

Another focus of this report is the changes in light source, optical delivery, and spectral efficiencies that occur during aging of SSL devices. We have instituted an accelerated testing regiment for the DUTs examined in this report, and these protocols provide additional insights into how the performance of SSL devices change with aging. The AST protocols demonstrate that the SSL products examined during the study and discussed in this report often reduce source efficiency to achieve different spectral characteristics. In addition, aging of the optical components (e.g., lenses, solder masks) in SSL devices can produce increased light absorption, which negatively impacts optical delivery efficiency and possibly source efficiency. Finally, the design of SSL drivers was found to have a significant impact on long-term performance. Drivers in temperature-humidity environments tended to abruptly fail because of excessive thermal and electrical stress on a film capacitor in the EMI suppression circuit. Better thermal management capabilities in the SSL device may help to reduce the likelihood of this failure mode.

LEDs have imparted significant new capabilities to lighting devices that include improved source efficiencies, high reliability, and the ability to modify the output spectrum to a desired application. These capabilities allow exploration of the trade-offs between source efficiency and other aspects of LAE such as optical delivery and spectral efficiencies. The data and information presented in this report shows that when evaluating the LAE performance of SSL products, it is important to consider both the initial performance and the long-term behavior. Because of the high reliability of SSL devices, consideration of the long-term performance of SSL devices can only be made through appropriate ASTs such as those described in this report. Without results from such ASTs, an understanding of the lifetime device efficiency and optical performance of SSL devices is incomplete.

References

1. DOE (U.S. Department of Energy) BTO (Building Technologies Office) Lighting R&D (Research and Development) Program. (2020, January). *2019 Lighting R&D opportunities.* DOE, Washington, DC. Available at https://www.energy.gov/sites/prod/files/2020/01/f70/ssl-rd-opportunities2-jan2020.pdf

2. Next Generation Lighting Industry Alliance and the LED (Light-Emitting Diodes) Systems Reliability Consortium. (2014, September). *LED luminaire lifetime: Recommendations for testing and reporting*. Third edition. Available at https://www.nglia.org/pdfs/led_luminaire_lifetime_guide_sept2014.pdf

3. Lucas, R. J., Pierson, S., Berson, D. M., Brown, T. M., Cooper, H. M., Czeizler, C. A., …, Brainard, G. C. (2014). Measuring and using light in the melanopsin age. *Trends in Neurosciences*, 37(1), 1–9.

4. ANSI (American National Standards Institute) and IES (Illuminating Engineering Society) (2019). *ANSI/IES LM-79-19: Approved Method: Optical and Electrical Measurements of Solid-State Lighting Products*. New York, NY: IES.

5. IES (Illuminating Engineering Society). (2014). *IES LM-84-14: Measuring Luminous Flux and Color Maintenance of LED Lamps, Light Engines, and Luminaires.* New York, NY: IES.

6. IES (Illuminating Engineering Society). (2014). *IES TM-28-14: Projecting Long-Term Luminous Flux Maintenance of LED Lamps and Luminaires*. New York, NY: IES.

7. Next Generation Lighting Industry Alliance and the LED (Light-Emitting Diodes) Systems Reliability Consortium. (2017, April). *LED luminaire reliability: Impact of color shift*. Available at https://www.nglia.org/pdfs/lsrc_colorshift_apr2017r.pdf

8. Davis, J. L., Mills, K., Yaga, R., Johnson, C., Hansen, M., & Royer, M. (2018). Chromaticity maintenance in LED devices. In *Solid State Lighting Reliability Part 2: Components to Systems*. Van Driel, W., Fan, X., & Zhang, G. (eds.). New York, NY: Springer.

9. Rountree, K., Davis, L., McCombs, M., Pope, R., Kim, J., Mills, K., & Hansen, M. (2020, January). *Dim-to-warm LED lighting: Stress testing results for select products*. U.S. Department of Energy, Washington, DC. Available at https://www.energy.gov/sites/prod/files/2020/04/f73/ssl-d2w-led-stress-testing-2020.pdf

10. Next Generation Lighting Industry Alliance and the LED (Light-Emitting Diodes) Systems Reliability Consortium. (2019, July). *Dim-to-warm LED lighting: Initial benchmarks*. Available at https://www.nglia.org/documents/LSRC_Dim-to-Warm_Paper_final_073019r.pdf

11. Mehr, Y., Bahrami, A., van Driel, W. D., Fan, X. J., Davis, J. L., & Zhang, G.Q. (2020). Degradation of optical materials in solid-state lighting systems. *International Materials Reviews*, 65(2), 102–128.

12. Yamamoto, H., Li, Y. Q., Hirosaki, N., & Xie, R. (2011). *Nitride Phosphors and Solid-State Lighting*. United States: Taylor & Francis.

13. Bobashev, G., Baldasaro, N., Mills, K., & Davis, J. L. (2016). An efficiency-decay model for lumen maintenance. *IEEE Transactions on Device and Materials Reliability*, 16(3), 277–281.

14. Davis, J. L., & Hansen, M. (2020, March). *Lumen and chromaticity maintenance behavior of light-emitting diode (LED) packages based on LM-80 data*. U.S. Department of Energy, Washington, DC. Available at https://www.energy.gov/sites/prod/files/2020/03/f73/rti_lm-80-white-leds_mar2020.pdf

15. Next Generation Lighting Industry Alliance and the LED (Light-Emitting Diodes) Systems Reliability Consortium. (2014, September). *LED luminaire lifetime: Recommendations for testing and reporting*. Available at https://www.nglia.org/pdfs/led_luminaire_lifetime_guide_sept2014.pdf

16. Davis, J. L., & Rountree, K. (2019, February). *Accelerated stress testing results on single-channel and multichannel drivers: Final repor*t. U.S. Department of Energy, Washington, DC. Available at https://www.energy.gov/sites/prod/files/2019/08/f65/ssl_rti_single-multi-channel_driver_final_0.pdf

17. Davis, L., Rountree, K., McCombs, M., & Mills, K. (2019, July). *Accelerated stress testing of multi-Source LED products: Round 2*. U.S. Department of Energy, Washington, DC. Available at: https://www.energy.gov/sites/prod/files/2019/09/f66/ssl_rnd2-multi-source-led-products_jul2019.pdf

18. ANSI (American National Standards Institute) and IES (Illuminating Engineering Society). (2019). ANSI/IES TM-35-19: Technical memorandum: Projecting long-term chromaticity coordinate shift of LED packages, arrays, and modules. New York.

Appendix A

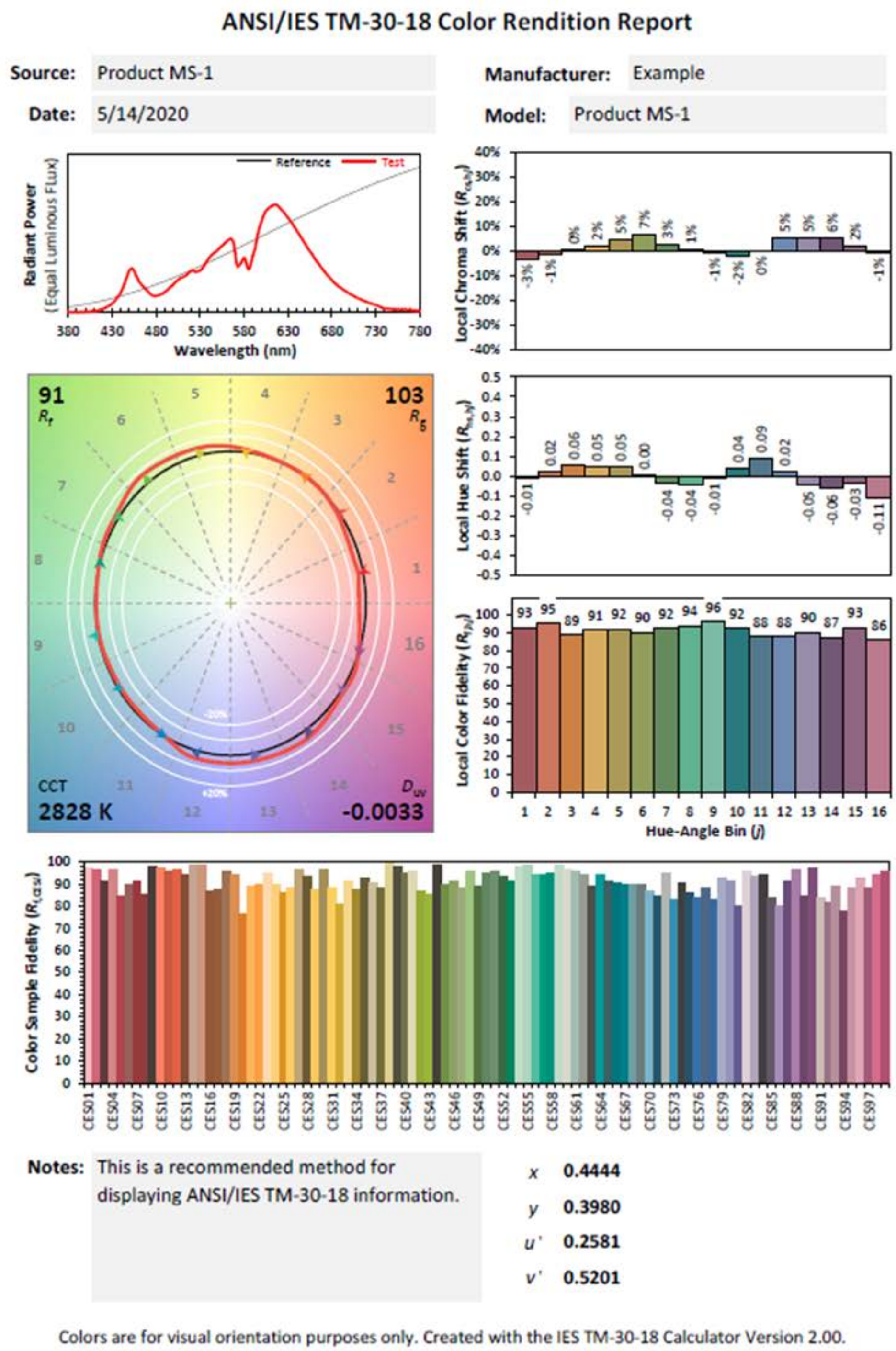

Figure A-1. ANSI/IES TM-30-18 analysis for Product MS-1 with the glass globe.

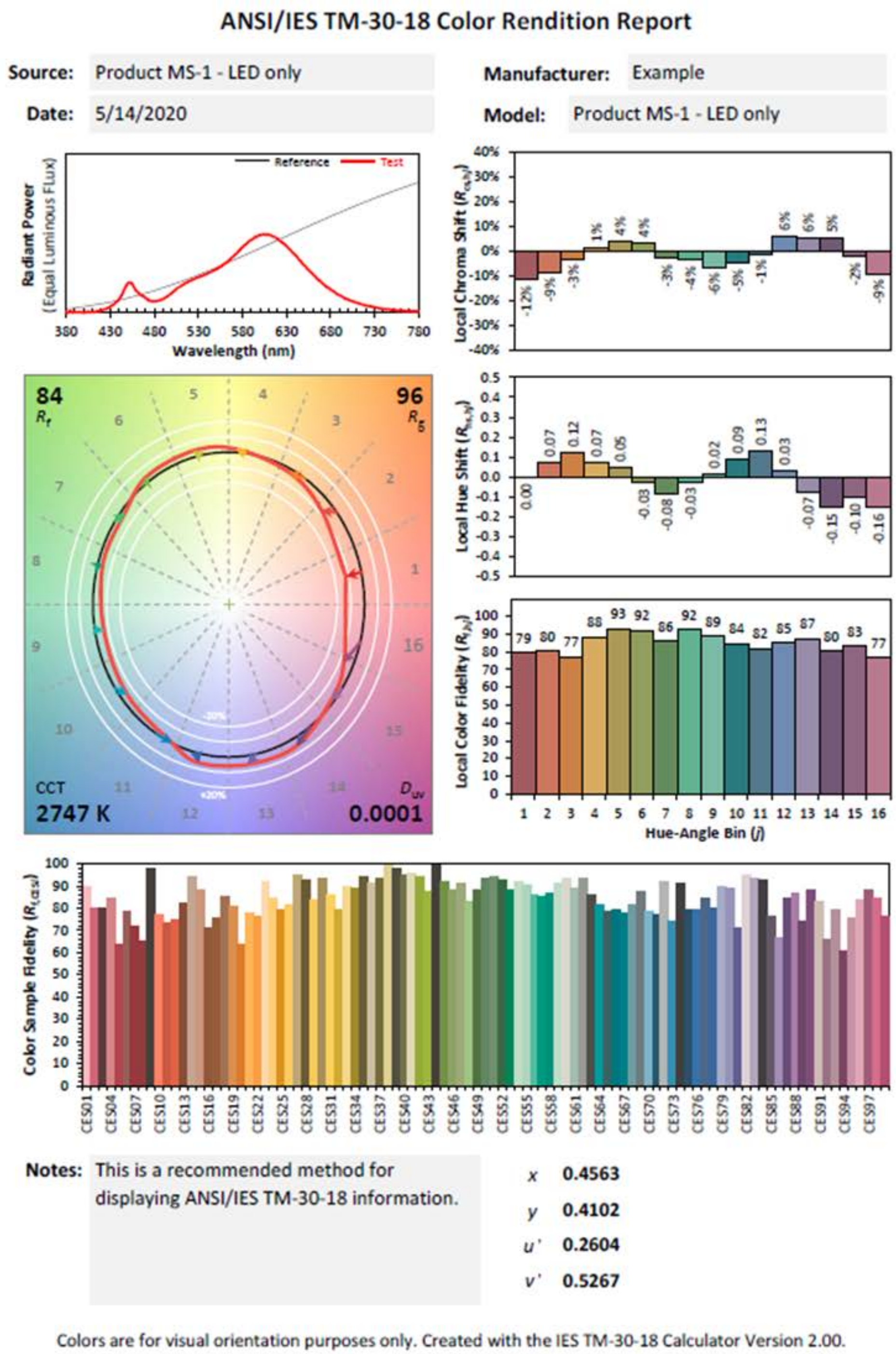

Figure A-2: ANSI/IES TM-30-18 analysis for LEDs from Product MS-1 without the glass globe.

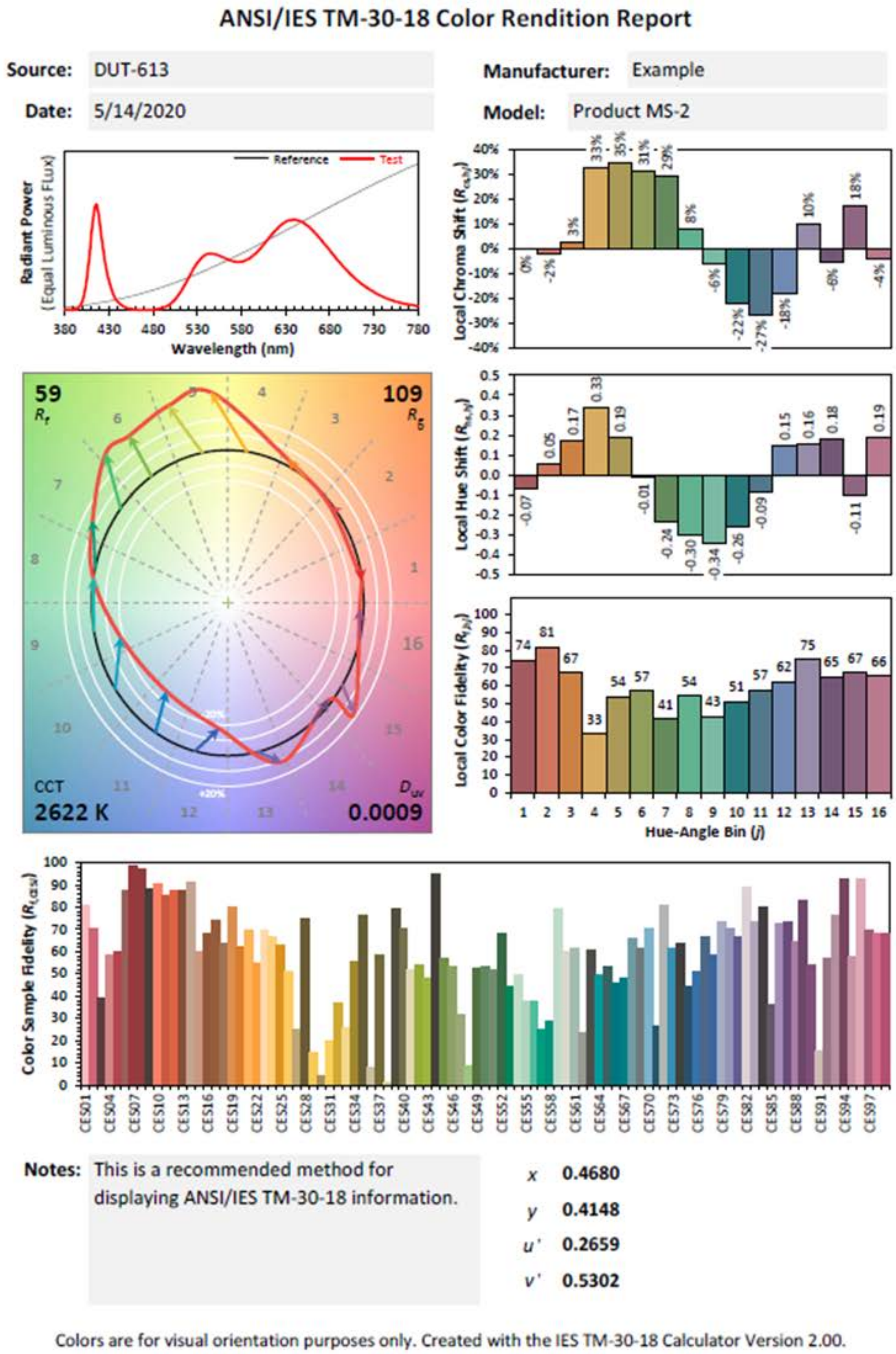

Figure A-3 ANSI/IES TM-30-18 analysis for Product MS-2.

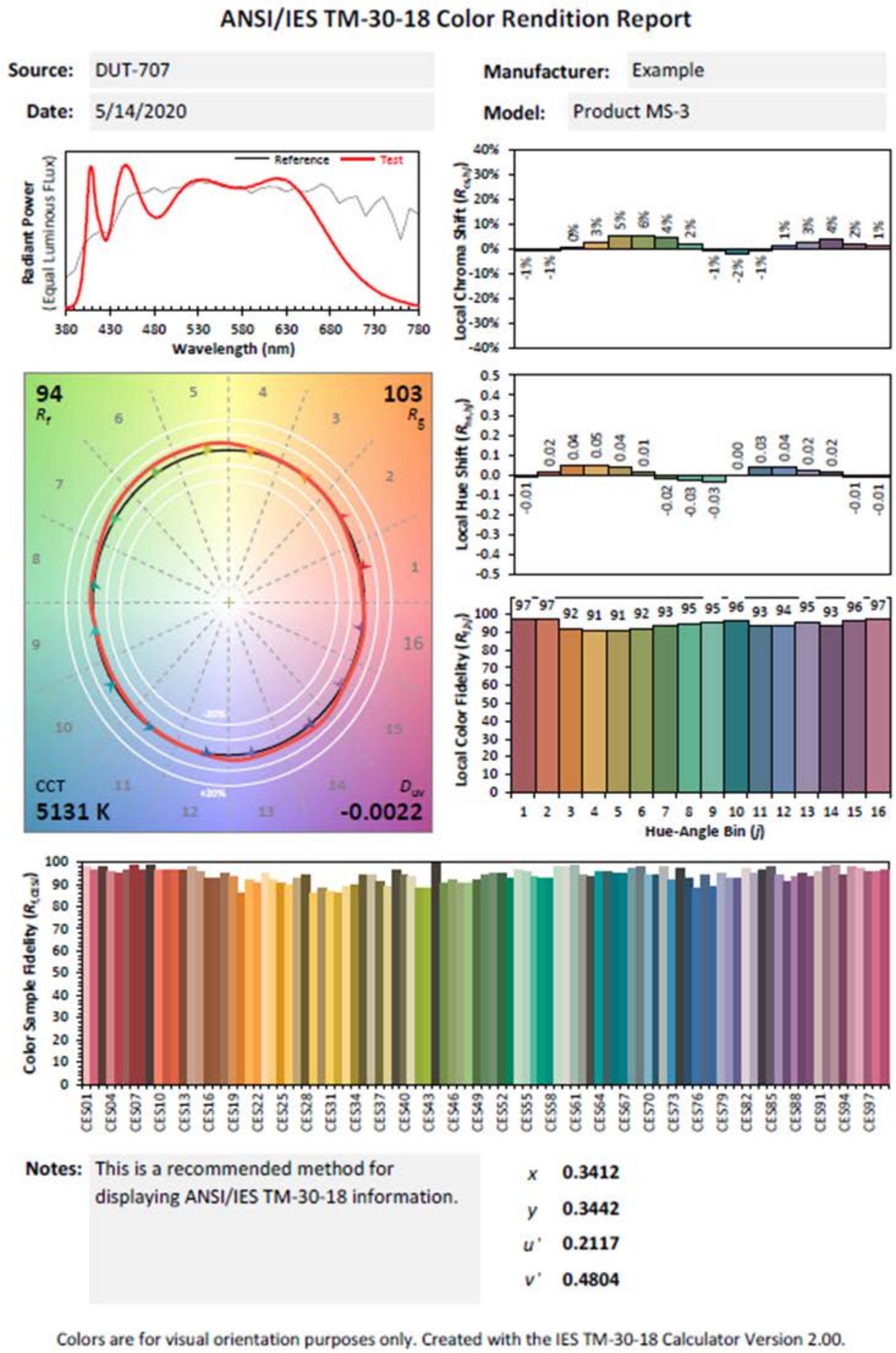

Figure A-4: ANSI/IES TM-30-18 analysis for Product MS-3.

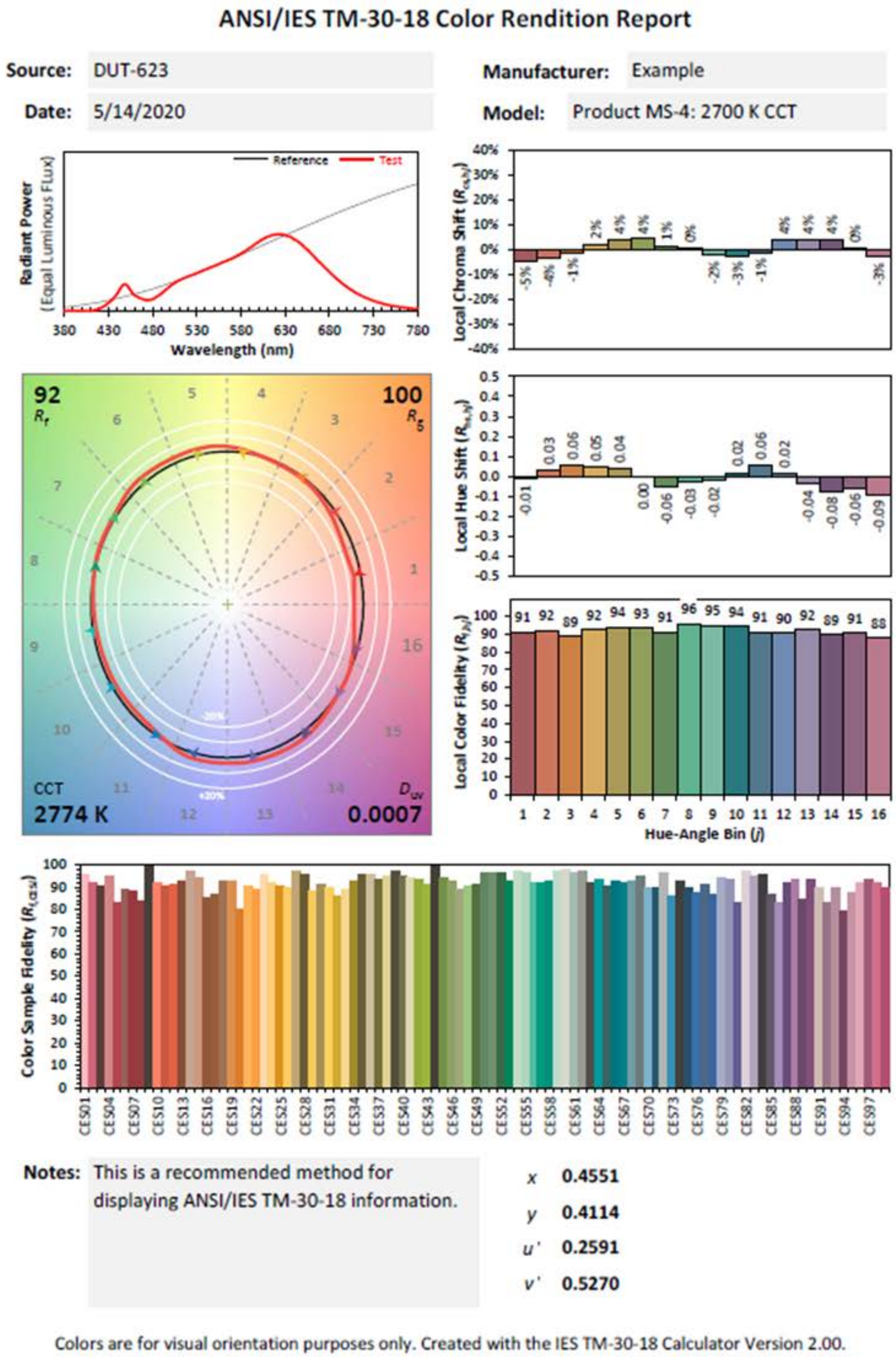

Figure A-5: ANSI/IES TM-30-18 analysis for Product MS-4 set to a CCT value of 2,700 K.

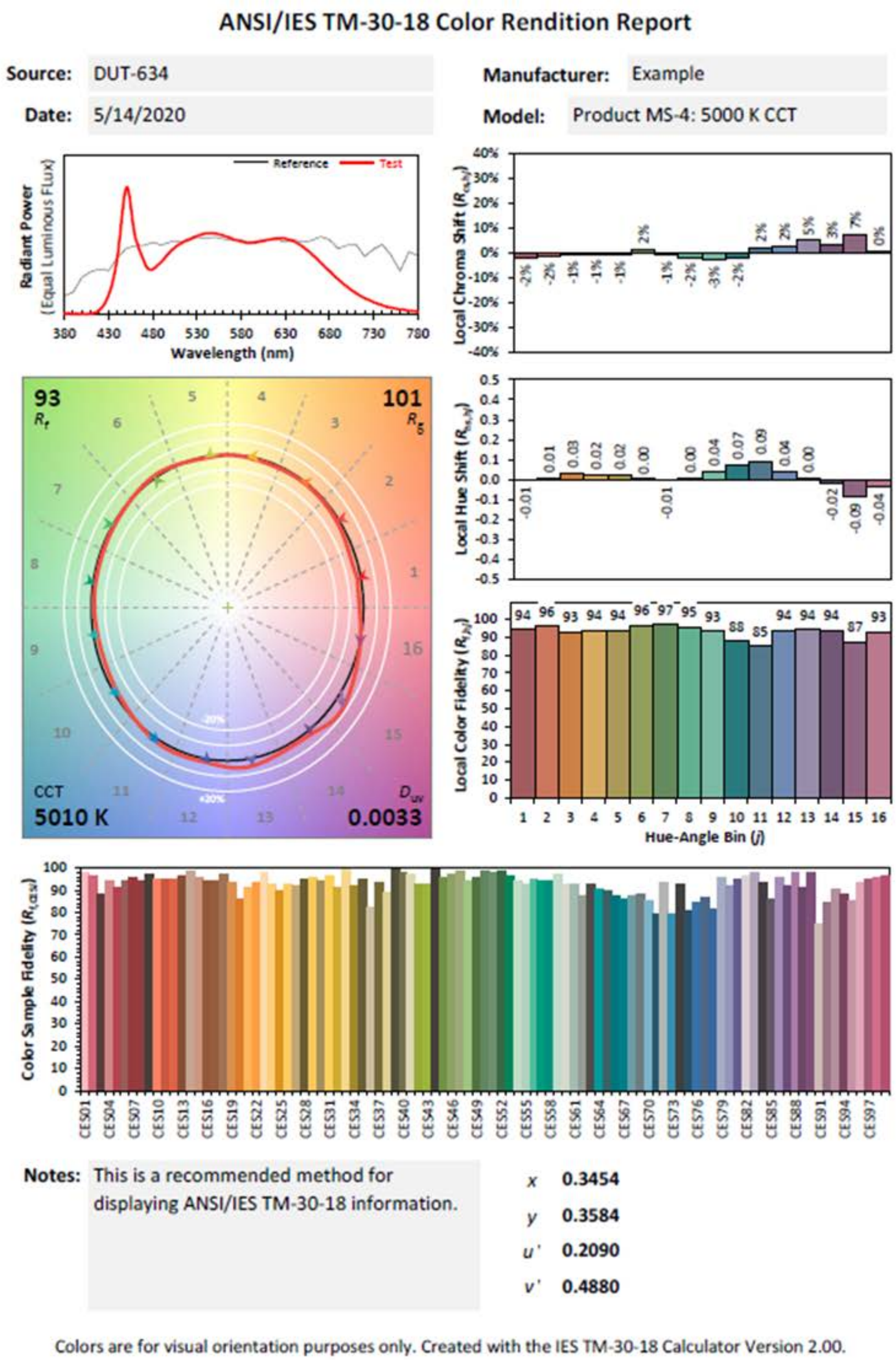

Figure A-6: ANSI/IES TM-30-18 analysis for Product MS-4 set to a CCT value of 5,000 K.

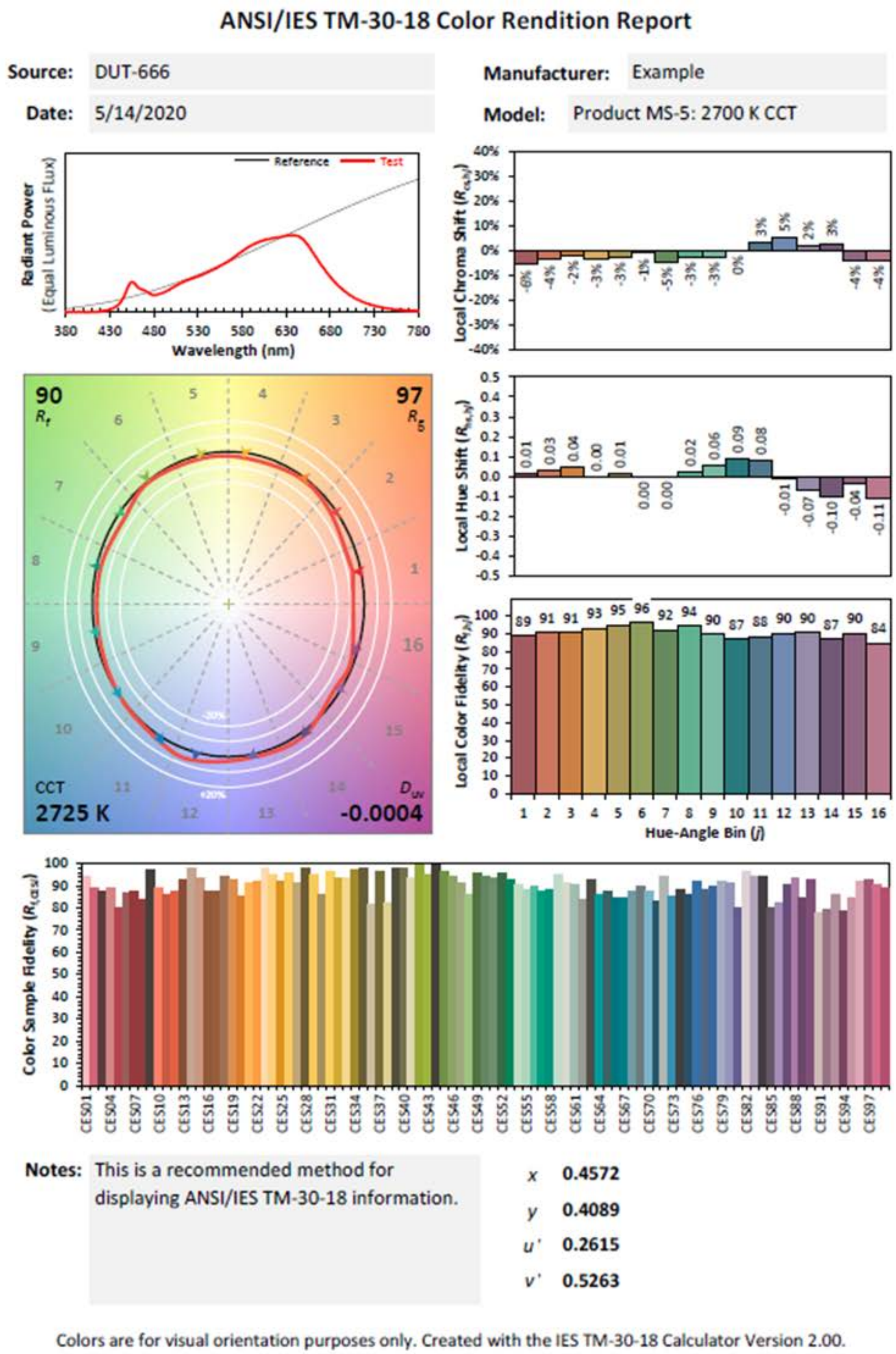

Figure A-7: ANSI/IES TM-30-18 analysis for Product MS-5 set to a CCT value of 2,700 K.

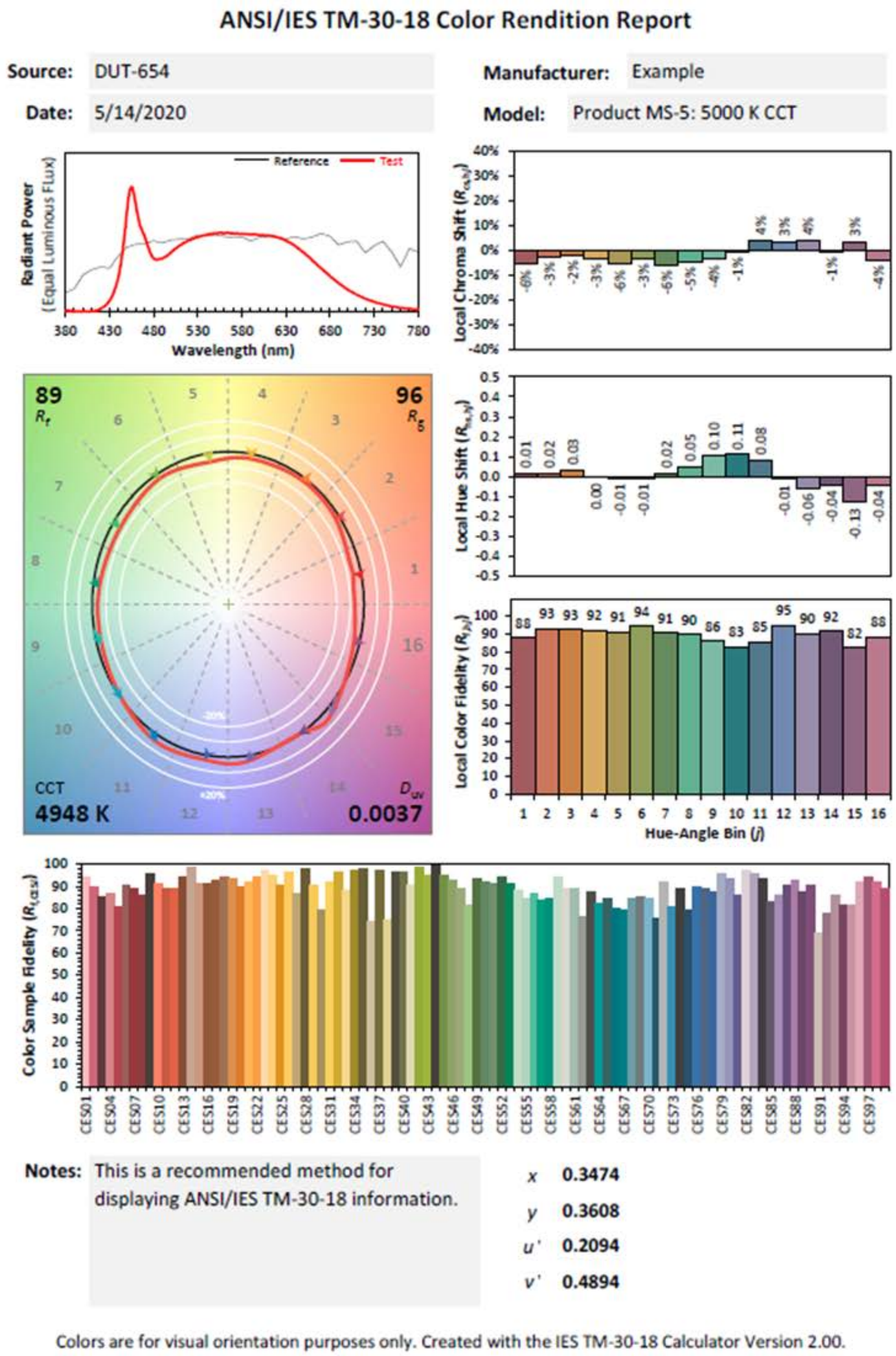

Figure A-8: ANSI/IES TM-30-18 analysis for Product MS-5 set to a CCT value of 5,000 K.

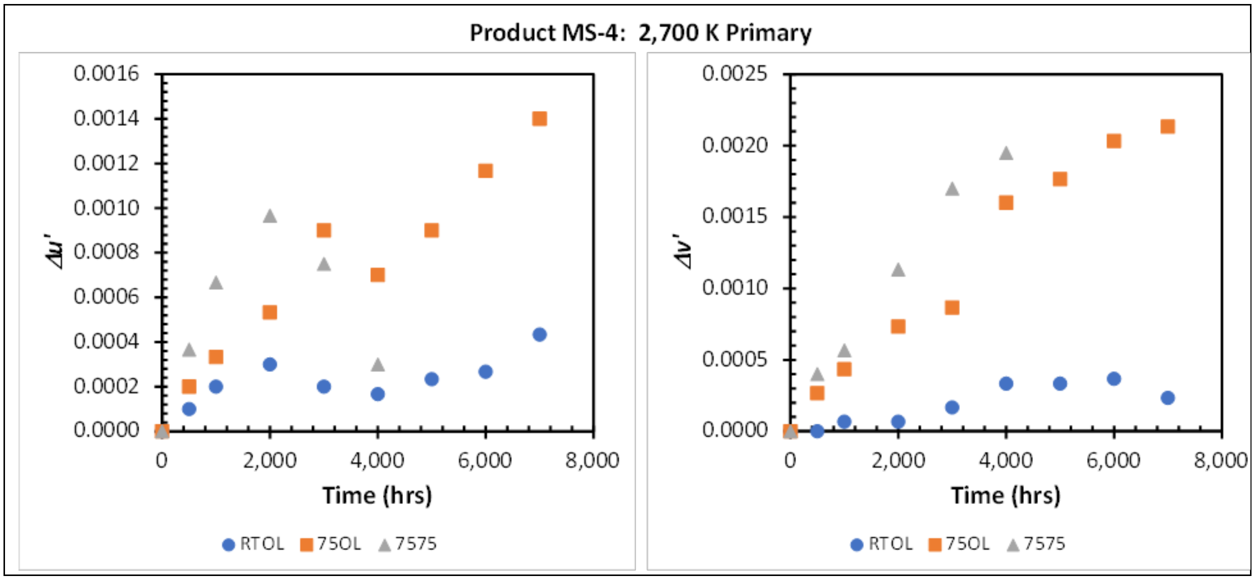

Figure A-9: Temporal change in $\Delta u'$ and $\Delta v'$ from the 2,700 K primary of Product MS-4 in different AST environments.

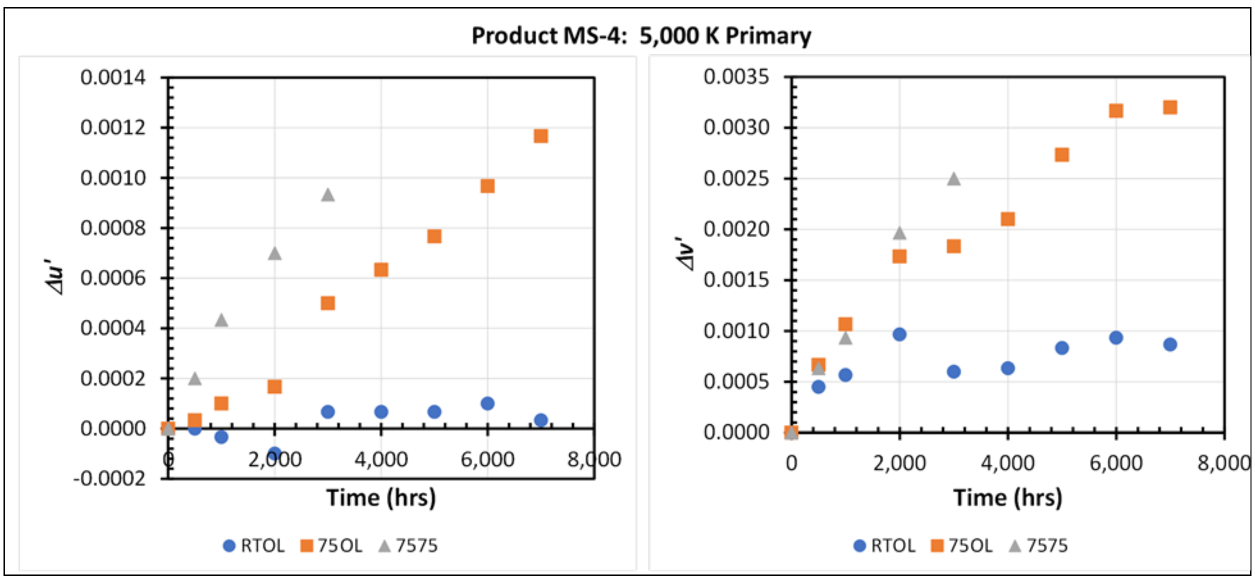

Figure A-10: Temporal change in $\Delta u'$ and $\Delta v'$ from the 5,000 K primary of Product MS-4 in different AST environments.

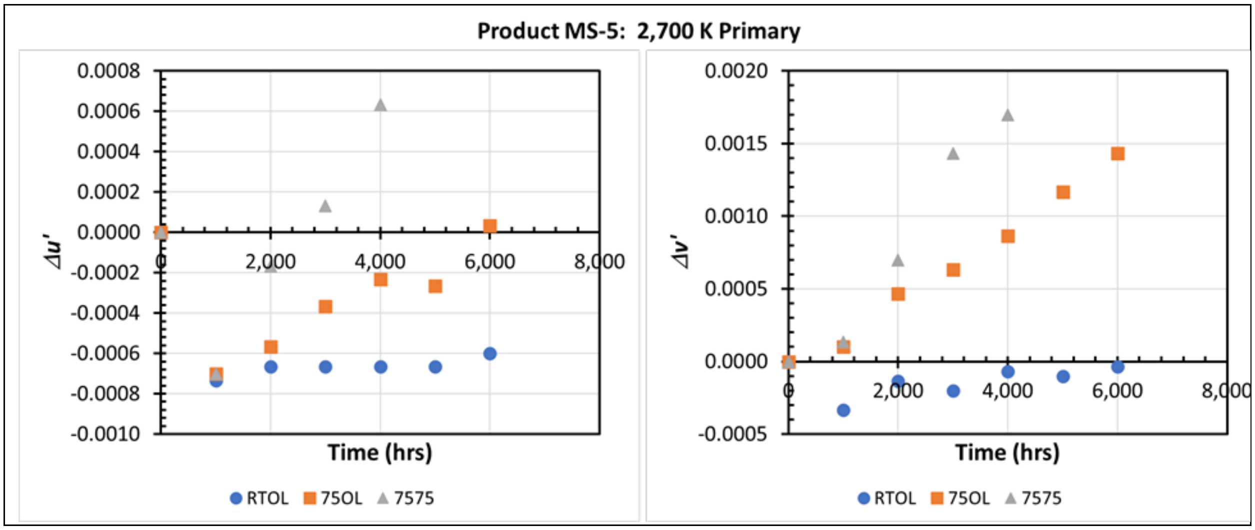

Figure A-11: Temporal change in $\Delta u'$ and $\Delta v'$ from the 2,700 K primary of Product MS-5 in different AST environments.

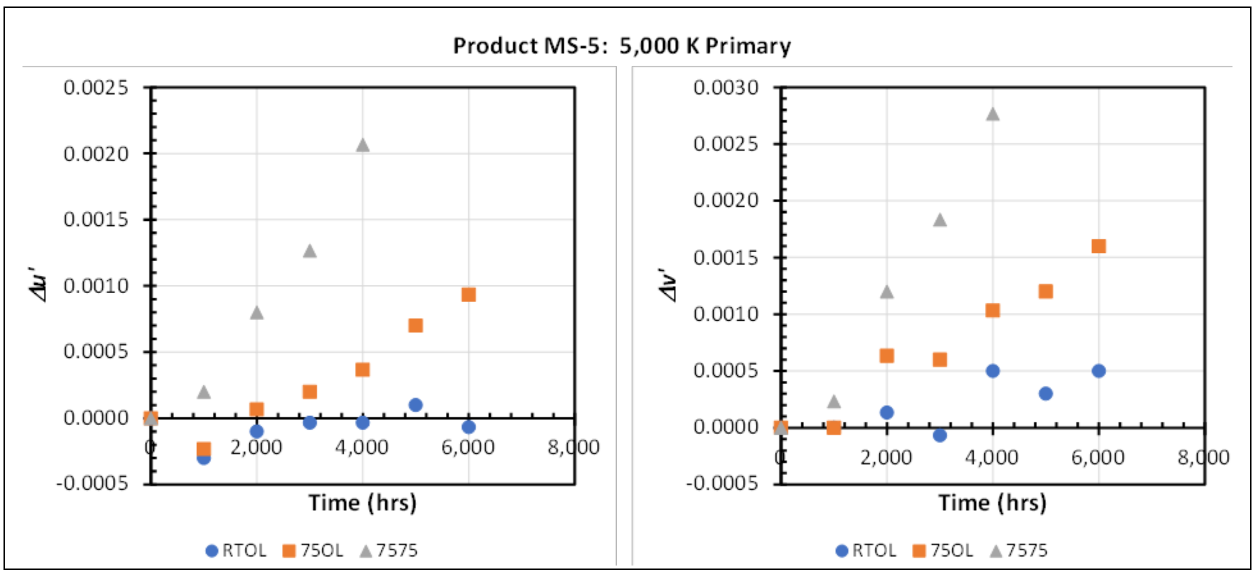

Figure A-12: Temporal change in $\Delta u'$ and $\Delta v'$ from the 5,000 K primary of Product MS-5 in different AST environments.

(This page intentionally left blank)

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

For more information, visit:
energy.gov/eere/ssl

DOE/EE-2078 • June 2020