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Initial Benchmarks and Long-Term Performance of Narrow-Band Red Emitters Used in SSL Devices

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Nomenclature or List of Acronyms

75OL	operational life test conducted at 75°C
7575	life test conducted at 75°C and 75% relative humidity
°C	degree Celsius
α	decay rate constant in IES TM-28-14 model
$\Delta u'$	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
Cd	Cadmium
CdSe	Cadmium selenide
Ce:YAG	Cerium-doped yttrium aluminum garnet
CIE	International Commission on Illumination (*Commission Internationale de l'Éclairage*)
CSM	chromaticity shift mode
dc	direct current
DOE	U.S. Department of Energy
DUT	device under test
EERE	Office of Energy Efficiency and Renewable Energy
EMC	epoxy molding compound
ft	foot
FWHM	full-width at half maximum
hr, hrs	hour, hours
IES	Illuminating Engineering Society

I_f	forward current
in	inch
IR	infrared
K	Kelvin
L_{70}	time required for the luminous flux to decay to 70% of the initial value
LED	light-emitting diode
LER	luminous efficacy of radiation
LFL	linear fluorescent lamp
LFM	luminous flux maintenance
lm	lumen
lm/W	lumens per watt
mA	milliampere or milliamp
MESA	Mission Execution and Strategic Analysis
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
QD	quantum dot
R_f	fidelity index in ANSI/IES TM-30-18
R_g	gamut index in ANSI/IES TM-30-18
RoHS	Restriction of Hazardous Substances Directive 2002/95/EC
RTOL	room temperature operational life
SPD	spectral power distribution
SSL	solid-state lighting
t	time
T_j	junction temperature
UL	Underwriter's Laboratory

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

Solid-state lighting (SSL) technologies that use light-emitting diodes (LEDs) provide increased energy savings compared to traditional lighting technologies like incandescent lamps. One of the primary factors leading to incandescent inefficiency is its spectral inefficiency. Most of the radiation produced by incandescent lamps is at wavelengths above 700 nm and since the human eye has very little response outside of the visible range (i.e., 380 nm to 720 nm), this radiation above 700 nm is lost as heat. SSL technologies that use traditional white LEDs provide an increase in spectral efficiency because most of the radiation they produce is in the visible range. However, conventional red phosphors used in phosphor-converted LEDs (pc-LEDs) have broad emission peaks (full-width at half maximum [FWHM] near 100 nm) that significantly spill over into the deep red and near-infrared (IR) regions (i.e., between 720 nm to 800 nm), where the human eye is not sensitive. By decreasing the FWHM of the red emitter (i.e., using a narrow-band red emitter) or shifting the red emission peak to lower wavelengths, a significant increase in luminous efficacy and spectral efficiency can be realized without sacrificing color rendering properties of the light source. This report focuses on a sampling of available SSL products that use narrow-band red emitters to provide a benchmark of these technologies.

In this report, initial assessments of the spectral efficiencies and color rendering properties of narrow-band red-emitting mid-power LEDs (MP-LEDs) are compared with a product that uses traditional, warm-white pc-LEDs (Product MS-4). An accelerated stress test (AST) regiment was developed for the devices under test (DUTs) in this study to observe and quantify long-term luminous flux and chromaticity changes. An analysis of the reliability of the narrow-band MP-LEDs relative to a traditional, warm-white pc-LED is provided.

The selected narrow-band red emitter products investigated in this report used different architectures to decrease deep red and near-IR emissions. The specific DUTs examined in this report include a 2-ft, Type A replacement, LED Tube (Product NB-1) and a light engine that contains two LED modules mounted to a heat sink (Product NB-2). Product NB-1 contains an LED module with 42 MP-LEDs encased in a glass tube. There are two different LED strings in parallel for Product NB-1, and both LED strings have 21 serially-connected MP-LEDs. Each string consists of two different types of MP-LEDs arranged sequentially. The first type of MP-LED has a broad (FWHM greater than 100 nm), orange peak centered at 595 nm while the second type of MP-LED contains the narrow-band red phosphor with peaks that are consistent with a PFS/KSF phosphor. The LED modules of Product NB-2 contain 21 MP-LEDs that use a hybrid red emitter with narrow-band red quantum dots (QDs) and a red phosphor (i.e., a QD-phosphor mixture).

This report summarizes the overall findings from up to 7,000 hours (hrs) of AST on the Product NB-1 DUTs and 5,000 hrs of AST on the Product NB-2 DUTs. The AST procedures used in this study included a room temperature operational life (RTOL) test, an operational life test conducted at 75°C (75OL), and a wet high-temperature operational life test performed at 75°C and 75% relative humidity (7575). During the ASTs described herein, separate populations of each product (three DUTs in each population for Product NB-1; four DUTs in each population for Product NB-2) were subjected to power cycling of 1 hr on and 1 hr off.

The key findings from this study include the following:

- The narrowing of the red emission bands for the products in this study led to significant gains in the luminous efficacy of radiation (LER) compared to the conventional warm-white pc-LED Product MS-4. The PFS/KSF phosphor used in Product NB-1 substantially decreased emissions above 700 nm, and LER was determined to be 329 lm/W. The phosphor-QD mixture used in Product NB-2 reduced some of the near-IR emissions relative to the all-phosphor Product MS-4, and LER for Product NB-2 was 294 lm/W. These LER correlate to 16.6% and 3.1% increases for Products NB-1 and NB-2, respectively, when compared to LER of 282 lm/W (3,500 K) 285 lm/W (2,700 K) for Product MS-4.

- The color rendering properties of Products NB-1 and NB-2 were excellent ($R_f = 92$, $R_g = 99$), supporting the finding that increases in spectral efficiency in the red region can be achieved in a manner such that color rendering is not adversely affected.

- The temperature stability of the products in this study was generally good. The luminous flux maintenances (LFMs) of both products remained above 0.98 in RTOL and 75OL over the duration of test (7,000 hrs for Product NB-1; 5,000 hrs for Product NB-2). In addition, the magnitude of chromaticity shift ($\Delta u'v'$) remained small for both products in the RTOL and 75OL test conditions ($\Delta u'v' < 0.001$).

- The products in this study were affected by the presence of humidity in the 7575 environment. LFM decreased drastically for both products and by 5,000 hrs LFM reached 0.83 and 0.85 for Products NB-1 and NB-2, respectively. Chromaticity shift also increased substantially for both products, with Product NB-1 (PFS/KSF phosphor) experiencing a shift in the blue direction ($\Delta u'v' = 0.005$) after 6,000 hrs and all DUTs of Product NB-2 (phosphor-QD mixture) failing parametrically due to excessive chromaticity shift ($\Delta u'v' > 0.007$) in the green direction by 3,000 hrs.

- The phosphor-QD mixture was especially susceptible to the humid environment of 7575, and the emission peak of the mixture shifted by 7 nm toward a lower value by the end of the test in the 7575 conditions.

- Additional testing is needed to determine if the initial efficacy and LER gains will continue for long durations.

The results in this report serve to benchmark the reliability of narrow-band red emitters and direct future research. In this report, narrow-band red emitters are shown to provide significant gains in spectral efficiency without compromising color fidelity. The products studied had good stability in low-humidity environments but improvements can be made in high-humidity environments, particularly for the phosphor-QD mixture. The PSF/KSF phosphor showed better initial performance, but more research is needed to see if this trend will continue in the long term.

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1 Introduction

The use of light-emitting diodes (LEDs) in solid-state lighting (SSL) products significantly increases the efficiency of lighting devices compared to traditional incandescent lamps. SSL products are not only more efficient than incandescent lamps in converting electricity into radiation, they can also be designed to produce more light that is visible to humans (i.e., photopic light). As shown by the photopic sensitivity curve in **Figure 1-1,** the human eye has its maximum sensitivity for light at 555 nm. The light response of the human eye declines substantially around this wavelength such that there is very little response outside of the wavelengths between 380 nm and 720 nm (i.e., visible light). An incandescent light which has a correlated color temperature (CCT) of approximately 2,700 K produces most of its radiation at wavelengths above 700 nm, which is not visible to the human eye but can be readily observed as heat. The large amount of non-visible radiation produced by incandescent lamps is one of the factors in their poor efficiency. For an SSL device with an equivalent CCT value, the proper choice of the phosphor can minimize the production of radiation above 750 nm. However, red phosphors (e.g., nitride or oxynitride phosphors) typically used in SSL devices to provide good rendering of red hues have broad emission peaks that are approximately 100 nm full-width at half maximum (FWHM) resulting in significant spillover of light into the deeper red and near-infrared (near-IR) wavelength ranges where the human eye has minimal sensitivity. This behavior is a significant contributor to the spectral inefficiency of current phosphor-converted LEDs (pc-LEDs) [1].

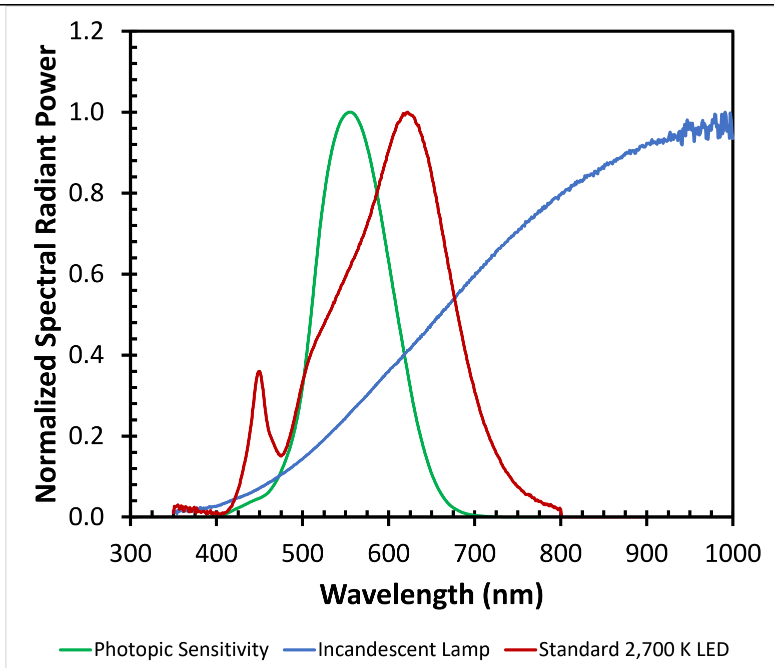

Figure 1-1: Comparison of the wavelength dependence of incandescent lamp emission, LED lamp emissions, and the photopic sensitivity curve. All spectra are normalized to a value of 1.0 for the maximum emission wavelength (λ_{max})

One of the first attempts with SSL products to reduce the spillover of emissions in the deep red and near-IR wavelengths was the use of hybrid LED architectures consisting of both pc-LED and direct-red emitters. As shown in **Figure 1-2**, this architecture has the advantage of producing light emissions closer to the photopic sensitivity curve with minimal emissions above 720 nm. While this lighting source design does produce excellent color rendering performance, there were issues with the different thermal stabilities of blue LEDs and red LEDs resulting in limitations in chromaticity stability and luminous flux maintenance [2]. While there are limits to the performance of the hybrid-LED architecture, the demonstrated ability to provide excellent color rendering and high luminous efficacy highlights the potential of narrow-band red emitters to improve the overall performance of SSL devices.

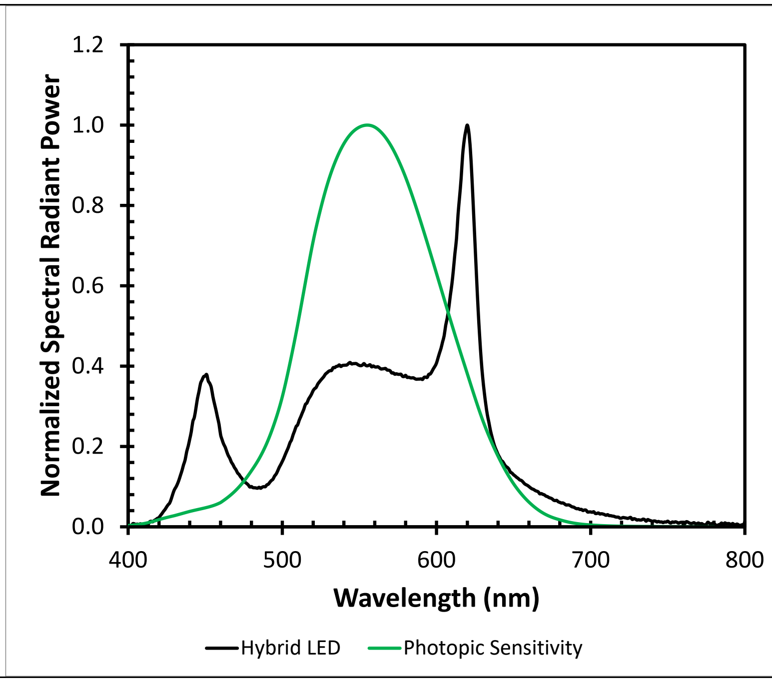

Figure 1-2: Comparison of the wavelength dependence of a typical hybrid-LED device with the photopic sensitivity curve. The spectral power distribution (SPD) is normalized to a value of 1.0 for λ_{max} [2].

One of the first approaches to make a true narrow-band red phosphor was the host:activator concept in which an insulating host material having a wide bandgap (e.g., K_2SiF_6) is doped with a few molecular percent of an optically active cation (e.g., Mn^{4+}) [3]. The resulting phosphor enables absorption of blue light and luminescence of visible light [4]. This phosphor, termed a PFS/KSF phosphor, has five main emissions over the range 609–648 nm, the FWHM of each emission is less than 2 nm. The color of the phosphor is yellow under normal light, but light emissions from the phosphor are red when pumped with a blue light source. Because the red emission bands of the PFS/KSF phosphor are so narrow and cover much of the red portion of the spectrum, devices incorporating this material can have excellent color rendering and a wide color gamut, with minimal spillage into the near-IR region that is not visible to the human eye. The PFS/KSF phosphor has been reported to have no thermal quenching up to 150°C and can be implemented on LED chips and in LED packages. In addition, the PFS/KSF phosphor is compliant with the Regulation of Hazardous Substances Directive (RoHS 2002/95/EC) meaning that the level of potentially hazardous materials is below the limits allowed by the European Union. Devices known to include the PFS/KSF phosphor include linear fluorescent lamps and specification grade downlights.

Another option for narrow-band red emitters is quantum dots (QDs), a form of nanocrystalline material where the small size (typically less than 5 nm) produces unique quantum states that have λ_{max} values that depend on the size of the QD. Early research on this topic showed that QDs could be combined with a traditional SSL phosphor (e.g., silicate phosphors, cerium-doped yttrium aluminum garnet, Ce:YAG) to produce a spectrum similar to that of a hybrid-LED device (**Figure 1-3**) [5]. The early SSL products that used QDs typically utilized cadmium selenium (CdSe) cores surrounded by protective layers to reduce environmental oxidation. Cadmium (Cd) is a restricted substance according to the RoHS Directive, so the amount of Cd-based QDs that can be used in electronic devices may be subject to regulation. In addition, the absorption and emission bands of the early QDs were close together (i.e., small Stokes shift) resulting in significant photon self-absorption and loss of efficiency. As a result, these early QD devices were not as efficient as hybrid LEDs [5].

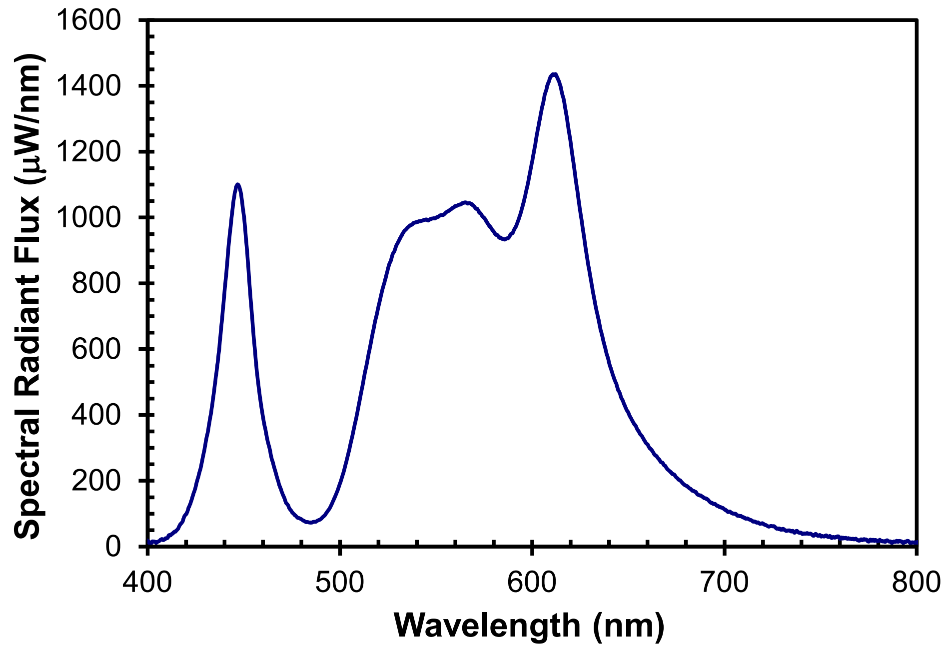

Figure 1-3: Emission spectrum of a photoluminescent nanofiber device containing a blue LED, a Ce:YAG phosphor, and red QDs [5]

However, QDs with greater Stokes shifts and increased thermal stability have recently become available and have been incorporated into MP-LED devices [6]. Like traditional QDs, these new materials have an emission spectrum that varies with size, and the emission wavelength is adjustable across the visible spectrum. In contrast to traditional QDs, these new materials have an extremely low self-absorption which should increase device efficiency while also providing excellent color rendering performance. These materials also employ a new encapsulation technology that provides greater protection for the QDs at high temperature, allowing QDs to be incorporated near the LED die and operated for extended periods. However, these LEDs are still subject to the RoHS requirements, which limits the amount of Cd-containing QDs that can be incorporated into an LED package [6]. Consequently, the QDs must be blended with a traditional broadband phosphor to provide a large color gamut across the visible spectrum. The use of red QDs in association with a phosphor can allow the width of the phosphor emission peak to be reduced providing for less radiation in the near-IR portion of the spectrum. Mid-power LED (MP-LED) packages incorporating these QDs were found to provide a luminous efficacy of 174 lumens per watt (lm/W) with a color rendering index of 93 and a Munsell R9 value of 55 in a RoHS compliant device that has less than 100 parts per million of Cd in the silicone encapsulant.

This report provides initial performance data on two SSL products that incorporate narrow-band red emitters. One product utilizes the PFS/KSF phosphor in a LED tube that is intended to replace linear fluorescent lamps. The other product is a MP-LED module that combines a small amount of red QDs with a phosphor to create a phosphor-QD mixture that provides high color rendering with reduced emissions in the near-IR. Separate populations of these devices were tested in different accelerated stress tests (ASTs) to examine the impact of temperature, humidity, and operational time on luminous flux and chromaticity maintenance. The results are compared to that of a LED downlight with a more conventional phosphor configuration to evaluate the long-term benefits of narrow-band red emitters compared to conventional LED technologies.

2 Experimental and Analytical Methods

2.1 Samples

The devices under test (DUTs)—Products NB-1 and NB-2—in this study use different approaches to achieve narrow-band red emission. Both Product NB-1 and Product NB-2 utilize pc-LEDs, but Product NB-1 adds a set of pc-LEDs that contain PFS/KSF phosphor, whereas Product NB-2 adds QDs to the phosphor mix. The Product MS-4 DUTs were previously evaluated by RTI and are presented as a comparison spectrum to the narrow-band products [7]. Product MS-4 is a standard warm-white LED with a blue LED pump and an all-phosphor secondary emitter to produce high color fidelity (R_f) and high color gamut (R_g). Product MS-4 also has a switchable CCT value of 2,700 K, 3,000 K, 3,500 K, 4,000 K, and 5,000 K, allowing one lamp to represent many standard SSL products. **Table 2-1** summarizes the optical properties and **Table 2-2** the electrical properties of these devices. Throughout this report, Product NB-1 is compared to Product MS-4 set to 3,500 K and Product NB-2 is compared to Product MS-4 set to 2,700 K because of the similarity in CCT at these settings. 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 section of the report.

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

Label	Narrow band Emitter	Luminous Flux (lm)	Nominal CCT (K)	R_f	R_g
Product NB-1	PFS/PKS Phosphor	1,325	3,500	92	99
Product NB-2	QD	1,208	2,700	92	99
Product MS-4 (2,700 K)	NA	795	2,800	92	100
Product MS-4 (3,500 K)	NA	855	3,500	93	100

Note: 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)	Luminous Efficacy (lm/W)	V_f of LEDs (V)	I_f of LEDs (mA)
Product NB-1	12.0	110	2.88	94
Product NB-2	13.3	91	3.30	148
Product MS-4 (2,700 K)	9.4	85	2.91	220
Product MS-4 (3,500 K)	9.4	91	-[a]	-[a]

Note: ac = alternating current; I_f = forward current; V_f = forward voltage.

[a] Product MS-4 has two LED primaries. These LED primaries operate at different V_f and I_f. The power consumption of the LED primaries at an intermediate setting is similar to that of the warm white primary at the 2,700 K setting.

2.1.1 Product NB-1

Product NB-1 is an Underwriter's Laboratory (UL) Type A 2-ft replacement LED tube for traditional linear fluorescent lighting (LFL) as shown in **Figure 2-1**. Product NB-1 contains an LED module encased in a glass tube that mixes the light from the LEDs and provides a 270° light distribution. The LED module contains 42 MP-LEDs (3030 package size) mounted on a rectangular metal-core printed circuit board (PCB) as shown in **Figure 2-2**. The LED module contains two different types of pc-LED packages—one with a yellow-colored phosphor and one with an orange-colored phosphor. The pc-LEDs have a yellow appearance or an orange appearance in white light suggesting a difference in phosphor composition and likely CCT values. There are 21 MP-LEDs of each pc-LED type. The different types of pc-LEDs are arranged in an alternating fashion on the PCB, with the first 21 MP-LEDs connected in series regardless of CCT. These first 21 serially connected MP-LEDs are connected in parallel to a set of capacitors and the rest of the MP-LEDs (i.e., the second set of 21 serially connected MP-LEDs). The second set of MP-LEDs are also connected serially regardless of CCT. The arrangement of the pc-LEDs ensures that both colored pc-LEDs receive equal drive current with little additional electronic circuitry. The PCB contains identical electronic circuitry at both ends of the LED module to enable the LED tubes to operate with traditional LFL ballasts (plug-and-play), offering quick and low-cost installation (depending on LFL ballast compatibility). The electronic circuitry includes four capacitors, two resistors, two diodes, and two fuses on each end.

Figure 2-1: Product NB-1 in a traditional fluorescent lighting fixture.

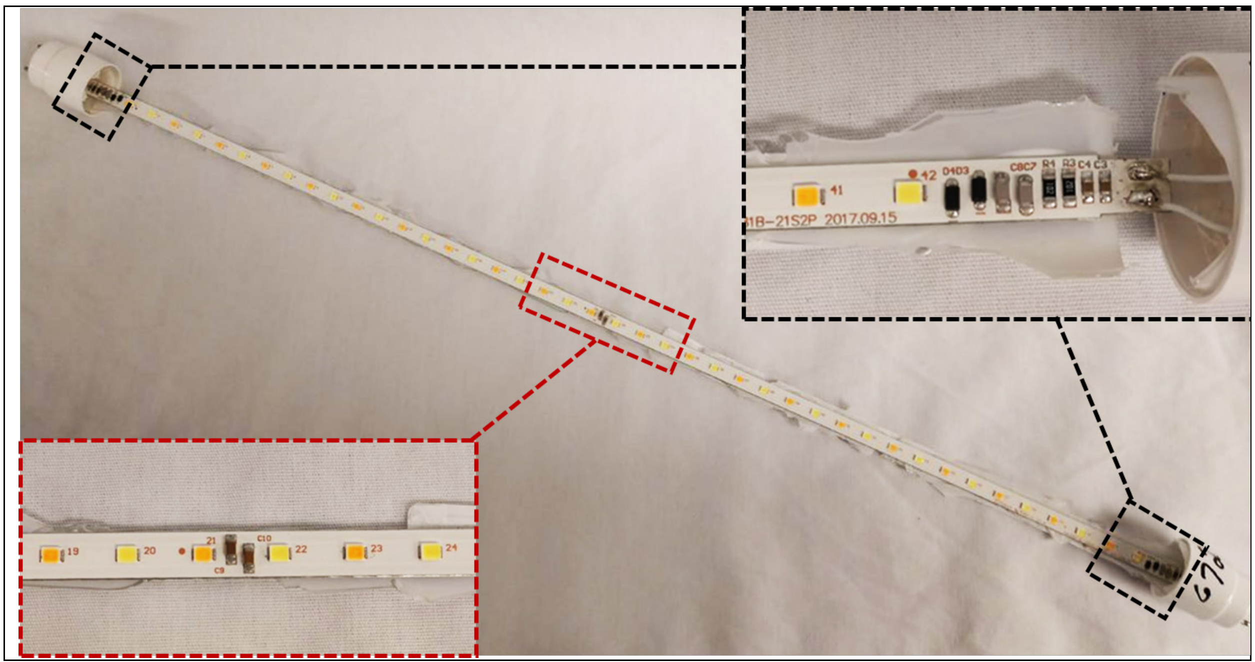

Figure 2-2: Product NB-1 with the glass globe removed. The black dotted inset shows the electronic circuitry on the PCB while the red dotted inset shows the arrangement of the LEDs and capacitors in the center of the LED module.

Only one of the LED packages (i.e., the LED package with the yellow-colored phosphor) used in Product NB-1 contains the PFS/KSF narrow-band red phosphor as shown by the absolute irradiance data in **Figure 2-3** (black trace). The PFS/KSF narrow-band red phosphor is combined with phosphors that emit broadly in the green and yellow wavelengths (500 nm to 600 nm). The narrow-band red phosphor has sharp emission peaks at 614 nm, 631 nm, and 636 nm, with weaker peaks at 609 nm and 648 nm consistent with expectations for a PFS phosphor [3]. The LED packages with an orange-colored phosphor contain a broad emission peak at approximately 595 nm (FWHM approximately 110 nm) and a smaller green/yellow phosphor emission peak.

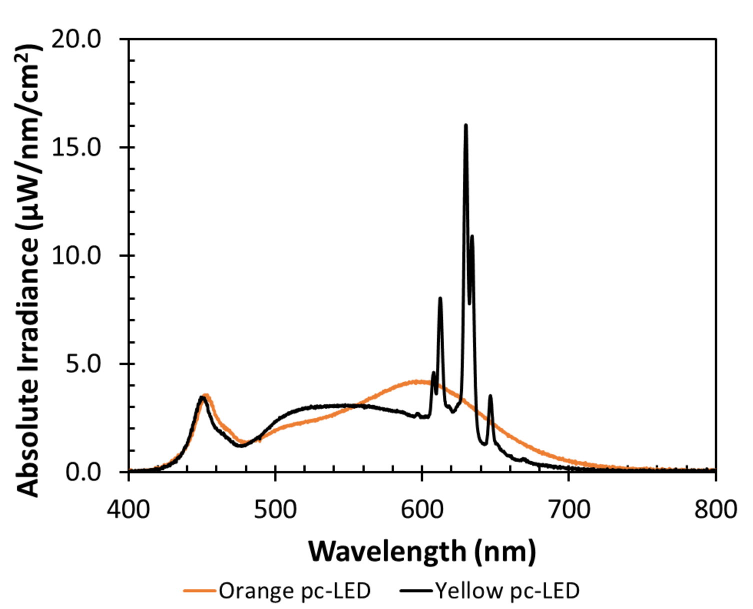

Figure 2-3: The absolute irradiance spectra of the pc-LEDs used in Product NB-1.

The SPD of Product NB-1 is compared to the SPD of Product MS-4 set to 3,500 K in **Figure 2-4**. While the IR emissions of both products are low, the narrow-band PFS/KSF phosphor of Product NB-1 lowers the long-wavelength emissions from this product and increases the percentage of radiation that is visible light. Product NB-1 exhibited excellent R_f (fidelity index in ANSI/IES TM-30-18) and R_g (gamut index in ANSI/IES TM-30-18) values (**Figure A-1**, **Appendix A**).

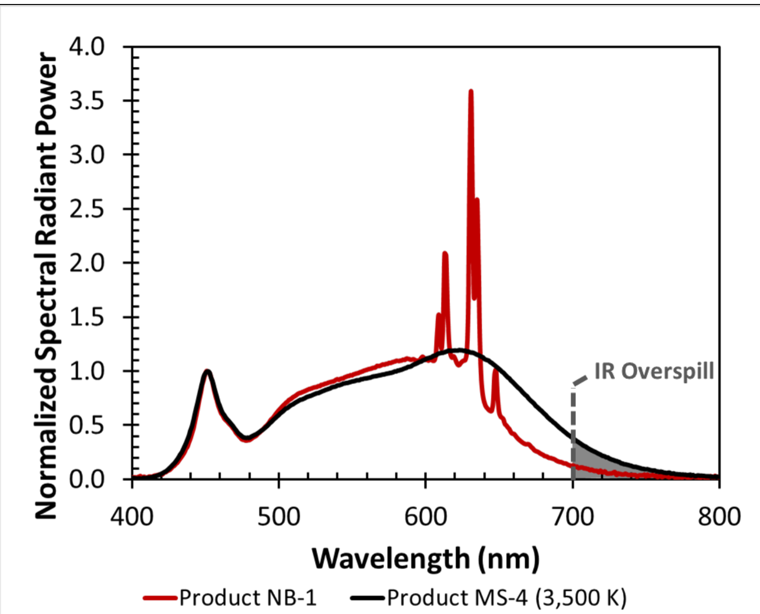

Figure 2-4: The SPD of Product NB-1 shows reduced IR emissions compared to Product MS-4. Emissions are normalized to the blue peak.

A compatible LFL ballast suggested by the manufacturer of Product NB-1 was purchased to operate this product, and the dc power supplied to each LED string was 60.4 volts (V) at 94 milliamps (mA). Taking the configuration of the LED module into account, each LED package is operated at an average 2.88 V and 94 mA as summarized in **Table 2-2**.

Product NB-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. During our testing, the product housing reached a maximum temperature of 80°C during 7575 (i.e., life test performed at 75°C and 75% relative humidity) exposure.

2.1.2 Product NB-2

Product NB-2 is an LED light engine consisting of two LED modules that were analyzed separately and without any secondary optics. Each LED module contains 21 MP-LEDs (3030 package size) arranged as three parallel strings of LEDs with seven serially connected LEDs and a resistor in each string. The MP-LEDs utilize an epoxy molding compound (EMC) as the base polymer for the LED package. For convenience, two LED modules are mounted on the same heat sink as shown in **Figure 2-5.** The LEDs in Product NB-2 are operated at higher currents than those in Product NB-1, so the visible light generated by the 21 LEDs in each DUT for Product NB-2 is similar to that of the 42 LEDs in Product NB-1. However, there are no secondary optics used with Product NB-2, and each LED module could be operated independently if desired. During AST, the two LED modules on a heat sink were connected in series to an LED driver that was placed outside the test chamber. In this configuration, the driver was operated at 20.4 W (46.2 V at 443 mA), indicating that the V_f supplied to each individual LED is 3.30 V and the I_f is 148 mA as summarized in Table 2-2. During photometric testing, the LED modules were operated individually at 23.1 V and 443 mA which also produced a V_f value of 3.30 V and I_f value of 148 mA across each LED package.

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

Product NB-2 uses a blue LED pump, phosphor emissions in the green/yellow spectral region, and a hybrid red phosphor with narrow-band red QDs (λ_{max} of the phosphor-QD mixture is approximately 622 nm) as shown in **Figure A-2**. Due to the use of the QDs, the spectral emission from Product NB-2 reduces IR overspill and increases emission in the red region compared to traditional red phosphors, as shown in **Figure 2-6**. Because the total amount of QDs introduced into the phosphor-QD mix is limited by RoHS, a separate emission peak from the QDs is not found in the spectrum. The emissions from the QDs blend into the phosphor emission peak to create a continuous spectrum with reduced emissions at red wavelengths (e.g., 650–720 nm) where photopic sensitivity is lower. The light produced by the product exhibited excellent R_f and R_g values (92 and 100, respectively as shown in **Figure A-2**).

The manufacturer's specification for the LED packages used in this product are $I_f \leq 180$ mA, a maximum junction temperature (T_j) of 125°C, and a maximum operating ambient temperature of 100°C. During testing in 7575, the temperature of the LED light engine peaked at 83°C and $I_f = 148$ mA , well within the manufacture's specifications.

Because Product NB-2 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.

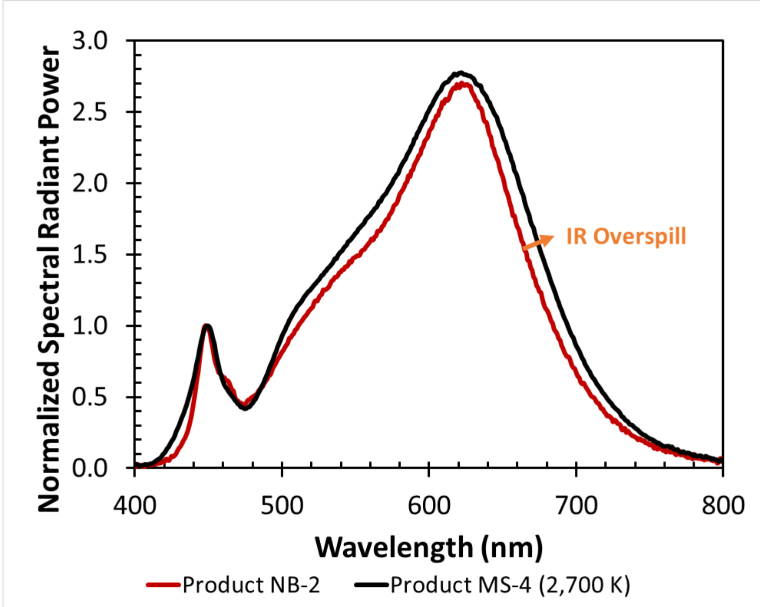

Figure 2-6: The SPD of Product NB-2 compared with a conventional all-phosphor reference (Product MS-4 at 2,700 K) shows reduced IR overspill. The SPD was normalized to blue emissions.

2.1.3 Product MS-4

Product MS-4 is a 6-inch 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. By changing a switch on the back of the product, the current distribution between the two LED primaries can be changed, and the CCT value of light produced by the lamp changed in discrete steps. This analysis will only compare the narrow-band phosphors to the 2,7000 K and 3,500 K settings of this product, which are similar to the CCT values of Product NB-2 and Product NB-1, respectively. Further device details about Product MS-4 and its full evaluation can be found in our previous report [7]. The maximum power delivered to the 2,700 K LED primary was 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-3** (for CCT set to 2,700 K) and **Figure A-4** (for a CCT value set to 3,500 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.

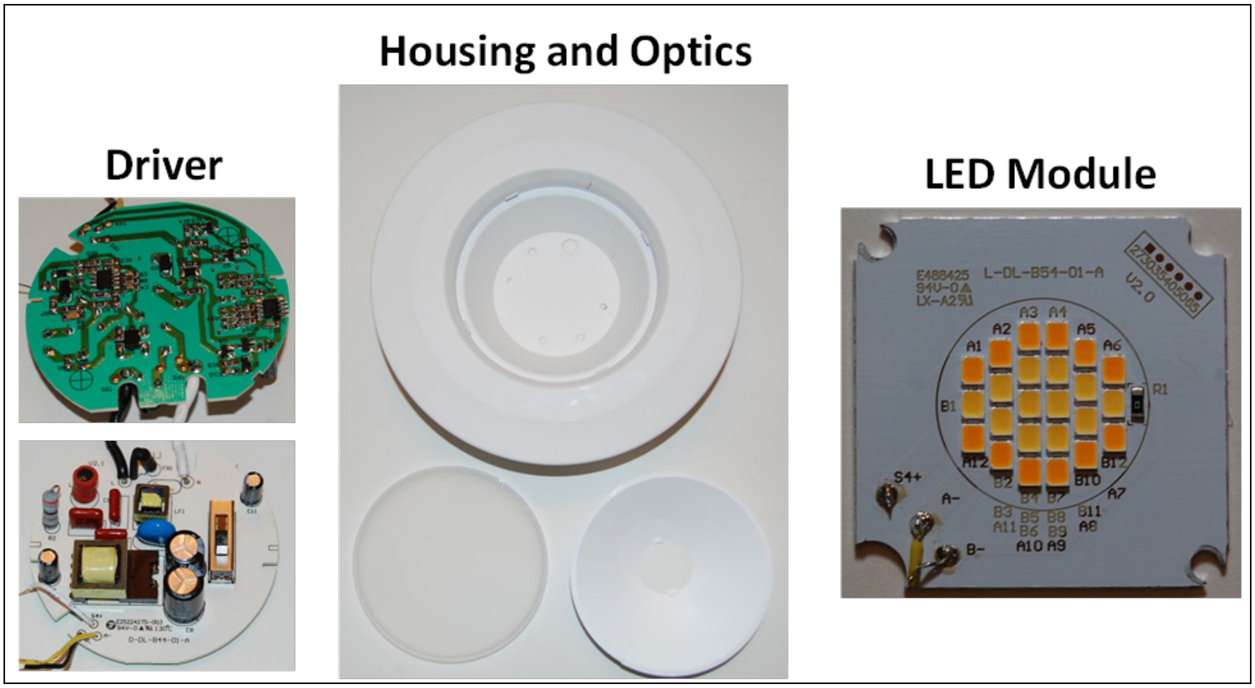

Figure 2-7: The components of Product MS-4.

2.2 Stress Testing Methods

The samples of each product were separated into three populations, and 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 75°C (75OL), or 7575. Either a temperature oven or a temperature-humidity environmental chamber was used for these tests, but humidity was not explicitly controlled in RTOL or 75OL (ambient humidity was determined by the air handling system of the building). For the LED tubes (Product NB-1), the population test size for each of the conditions was set to three DUTs. For the light engine (Product NB-2), two light engines containing two LED modules each were tested, giving four DUTs for each testing protocol. All DUTs were power cycled for 1 hour (hr) on and 1 hr off.

For this study, Product NB-1 was mounted to a traditional 2-ft T8 LFL fixture, and the DUTs were operated with a traditional LFL ballast recommended by the lamp manufacturer. The LFL ballast was stored within the LFL fixture and therefore experienced the AST protocol with the Product NB-1 DUTs. Product NB-2 used a single aluminum heat sink to mount two LED modules as shown in **Figure 2-5**. The LED modules were connected in series to a driver that was placed outside the test chamber.

2.3 Measurement Methods

2.3.1 Luminous Flux

The SPD, luminous flux, and chromaticity measurements of all samples were taken at room temperature in a calibrated 65-in integrating sphere. Products NB-1 and NB-2 were mounted in the center of the sphere (4π geometry), and Product MS-4 was mounted on the exterior of the sphere facing inward (2π geometry). During photometric testing in the 4π geometry, the center post supplied ac power to the 2-ft T8 LFL fixture and accompanying ballast for Product NB-1. The center post provided dc power (from the external driver) to Product NB-2. A control electrical driver (not exposed to test conditions) was reserved for photometric tests for Products NB-1 and NB-2 so that electrical losses due to the driver were eliminated. Product MS-4 was mounted external to the integrating sphere and powered by line ac. 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 ANSI/IES LM-79-19 [8].

2.3.2 Power Measurements

The electrical characteristics of the DUTs examined in this study were measured when needed with a Xitron 2802 two-channel power analyzer. An unexposed driver of the same product was used as a control and measured concurrently. In obtaining the power characteristics, the driver and LED loads were configured as for the AST experiments except that output power connections supplied by the LFL ballast (Product NB-1) or external driver (Product NB-2) were made to the power analyzer to measure the output ac power (Product NB-1) and output dc power (Product NB-2) supplied by the driver to each product. To measure the direct current (dc) across the pc-LEDs of Product NB-1, one of the pc-LEDs was removed and replaced with electrical wire to pass into the ammeter of the power analyzer.

2.3.3 Absolute Irradiance Measurements

The absolute irradiances of the Product NB-1 LED primaries were measured using an Ocean Optics USB4000 UV-Vis spectrometer fitted with a cosine corrector. The spectrometer was calibrated with a tungsten halogen light source traceable to NIST standards. The glass globe of a Product NB-1 DUT was removed to expose the individual LED packages on the LED module. The tip of the cosine corrector for the spectrometer was then pointed directly between one LED package with a yellow appearance and one LED package with an orange appearance at a distance of 2.75 inches (in) as shown in **Figure 2-8**. Prior to taking an absolute irradiance measurement, all LED packages except the LED package to be measured were covered with electrical tape to block light emissions.

Figure 2-8: Absolute irradiance measurement setup for Product NB-1 pc-LEDs.

3 Results

The luminous flux maintenance (LFM) and chromaticity maintenance of the DUTs of Products NB-1 and NB-2 are reported in this section. The test populations of Product NB-1 and Product NB-2 underwent 7,000 and 5,000 hrs, respectively, of operational exposure in RTOL, 75OL, and 7575 environments. Product NB-1 had two failures occur in the 7575 environment. One of the failures occurred prior to 1,000 hrs while the other occurred at 7,000 hrs. At 1,000 hrs, a new Product NB-1 DUT was added to the test matrix to keep the total number of DUTs at three during testing (i.e., the DUT was started 1,000 hrs after the other two DUTs in 7575, and it only completed 6,000 hrs of testing in 7575 for this report while the other two DUTs completed 7,000 hrs). Data for Product NB-1 in the 7575 environment are shown through 6,000 hrs where proper data averaging can occur

3.1 Product NB-1

3.1.1 Luminous Flux Maintenance

The LFM of Product NB-1 was measured according to IES LM-84-14 with photometric testing after each 1,000 hrs of operational exposure in the RTOL, 75OL, and 7575 environments [9]. The results were analyzed by using IES TM-28-14 [10], and the findings are presented in **Figure 3-1**. After 7,000 hrs of operation, the LFM for DUTs operated in the RTOL and 75OL test environments (LFM = 1.00 ± 0.01) increased slightly. The stability in LFM in both RTOL and 75OL environments suggests that the emitters in Product NB-1 are not greatly impacted by temperature in the 25°C to 75°C range over the length of test duration in this report. Further, the increase in LFM during the first 7,000 hrs of testing is likely at least partially due to the relatively low forward current supplied to each LED (see **Table 2-2**). For the DUTs operated in the 7575 environment, the luminous flux decayed substantially over the same period (LFM = 0.82 after 6,000 hrs). Using the decay rate constant (α), the projected time to L70 for the Product NB-1 DUTs operated in the 7575 environment is 10,480 hrs. The increase in luminous flux degradation from 75OL to 7575 suggests that humidity is primarily responsible for the accelerated luminous flux degradation.

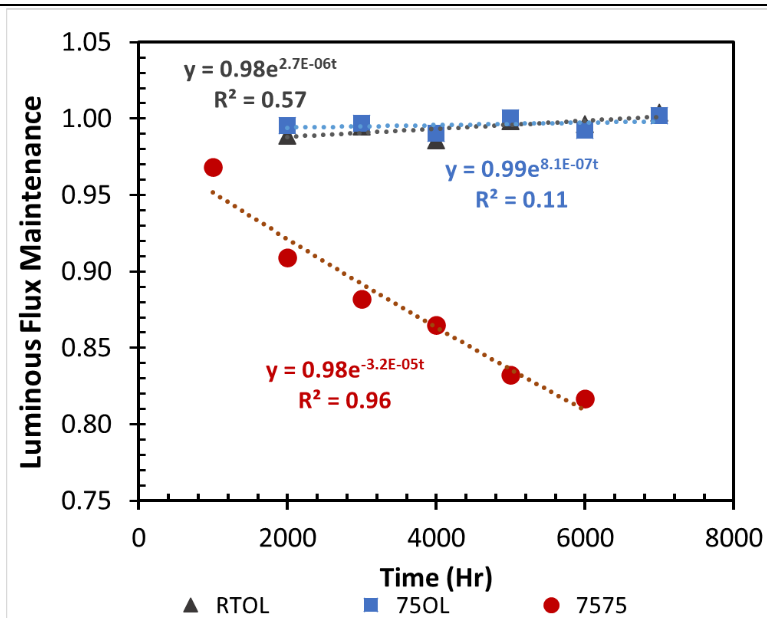

Figure 3-1: LFM of Product NB-1 during RTOL, 75OL, and 7575 according to IES LM-84-14 and IES TM-28-14.

3.1.2 Chromaticity Maintenance

The chromaticity behavior of Product NB-1 was impacted by the test environment as shown in **Figure 3-2**. At ambient and elevated temperatures (i.e., RTOL and 75OL), Product NB-1 DUTs exhibited a small chromaticity shift in the initial blue direction ($-\Delta v'$), followed by a slight shift in the green direction ($-\Delta u'$) around 5,000 hrs. The overall magnitude of these shifts was small ($\Delta u'v' < 0.001$), showing that the DUTs operated at RTOL and 75OL had good chromaticity maintenance over the entire test duration. The addition of humidity had a large impact on the chromaticity behavior of Product NB-1 DUTs. During 7575, the chromaticity of the test population initially shifted in the green direction, but this shift was short-lived (500 hrs). For the duration of the test (from 1,000 to 6,000 hrs), the chromaticity of the 7575 test population shifted in the generally blue direction (chromaticity shift mode [CSM]-1 mechanism) [11,12]. An examination of the spectral changes occurring during 7575 concluded that the phosphor emissions from green to red wavelengths (500 to 700 nm) declined significantly, leading to a relative rise in blue emissions (see **Figure 3-3**), which is consistent with a chromaticity shift in a generally blue direction. The decline in phosphor emissions was accelerated by humidity as indicated by the difference in behavior between 75OL and 7575 suggesting that humidity may affect the long-term quantum efficiency of the phosphors. The average magnitude of chromaticity shift for the 7575 DUTs after 6,000 hrs was *Δu'v'* = 0.0050, whereas it was only 0.0005 in 75OL.

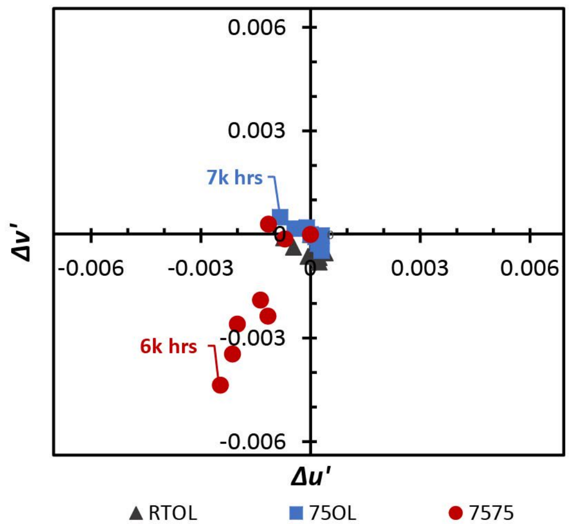

Figure 3-2: Chromaticity shift of Product NB-1 during RTOL, 75OL, and 7575.

Note: *Δu'* = change in the *u'* coordinate of chromaticity and *Δv'* = change in the v' coordinate of chromaticity.

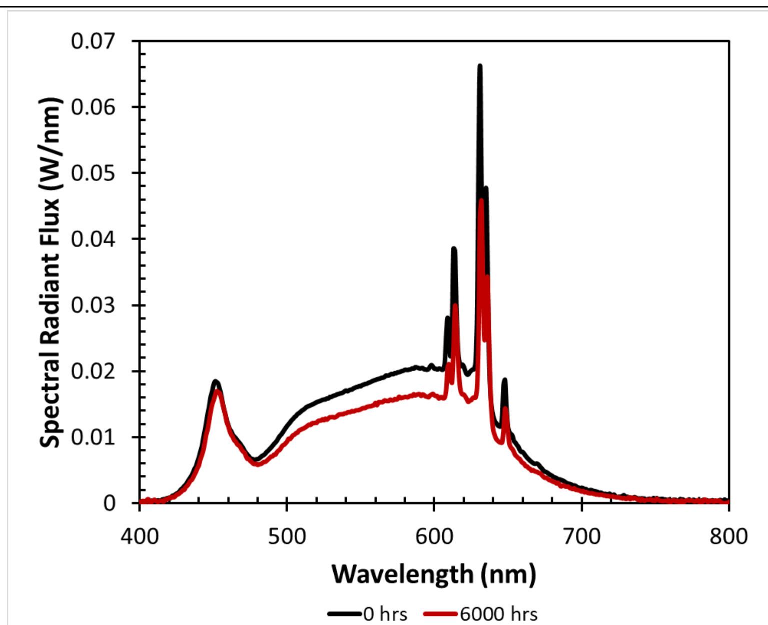

Figure 3-3: Spectral radiant flux for Product NB-1 at the beginning of testing and after 6,000 hrs of exposure during 7575.

3.1.3 Failure Analysis and Post-mortem Examination

All DUTs tested in the RTOL and 75OL environments survived 7,000 hrs of testing without any failures, as judged by either abrupt lights-out or parametric failure criteria. However, one DUT failed prior to 1,000 hrs and one DUT failed at 7,000 hrs of operation in the 7575 environment. The LFL ballast of the DUT that failed at 1,000 hrs in 7575 AST was found to be damaged at 500 hrs. The LFL ballast was replaced, and the new ballast failed prior to 1,000 hrs of operation. The Product NB-1 DUT was still operational (with LFM = 0.97 and minimal chromaticity shift) when connected to the control LFL ballast. The LFL ballasts were recommended by the manufacturer as a compatible ballast for this product, so it was determined that there must be an electrical issue on the DUT itself that caused damage to the LFL ballasts. The exact cause of the failure could not be determined.

The second of these failed Product NB-1 DUTs failed at 7,000 hrs when the product was being photometrically tested. The base of Product NB-1 is composed of plastic, and the plastic material of this DUT became brittle and cracked when it was removed from the LFL fixture for photometric testing as shown in **Figure 3-4**. The damage was severe enough that the lamp could not be operated safely in the fixture again, and the photometric test at 7,000 hrs could not be performed. An examination of the LED packages of the failed device showed some discoloration and darkening near the LED die for both pc-LEDs (though the discoloration was more visible for the orange colored pc-LED, see **Figure 3-5**).

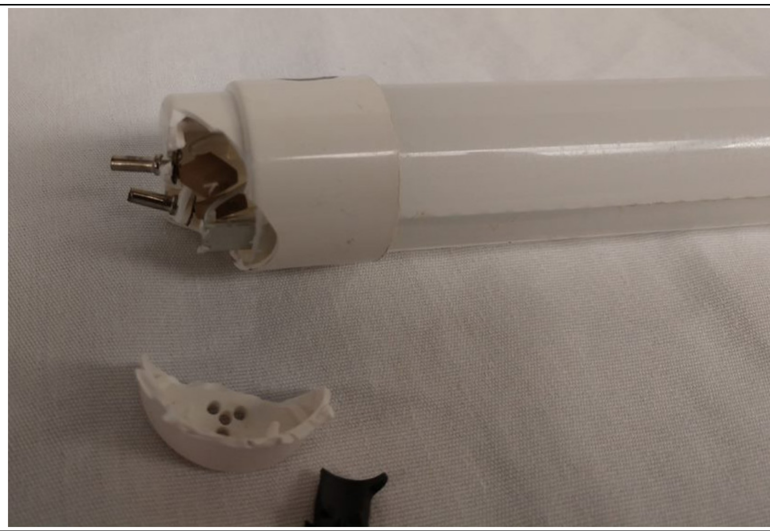

Figure 3-4: The base of a Product NB-1 DUT cracked and broke open during photometric testing after 7,000 hrs of 7575.

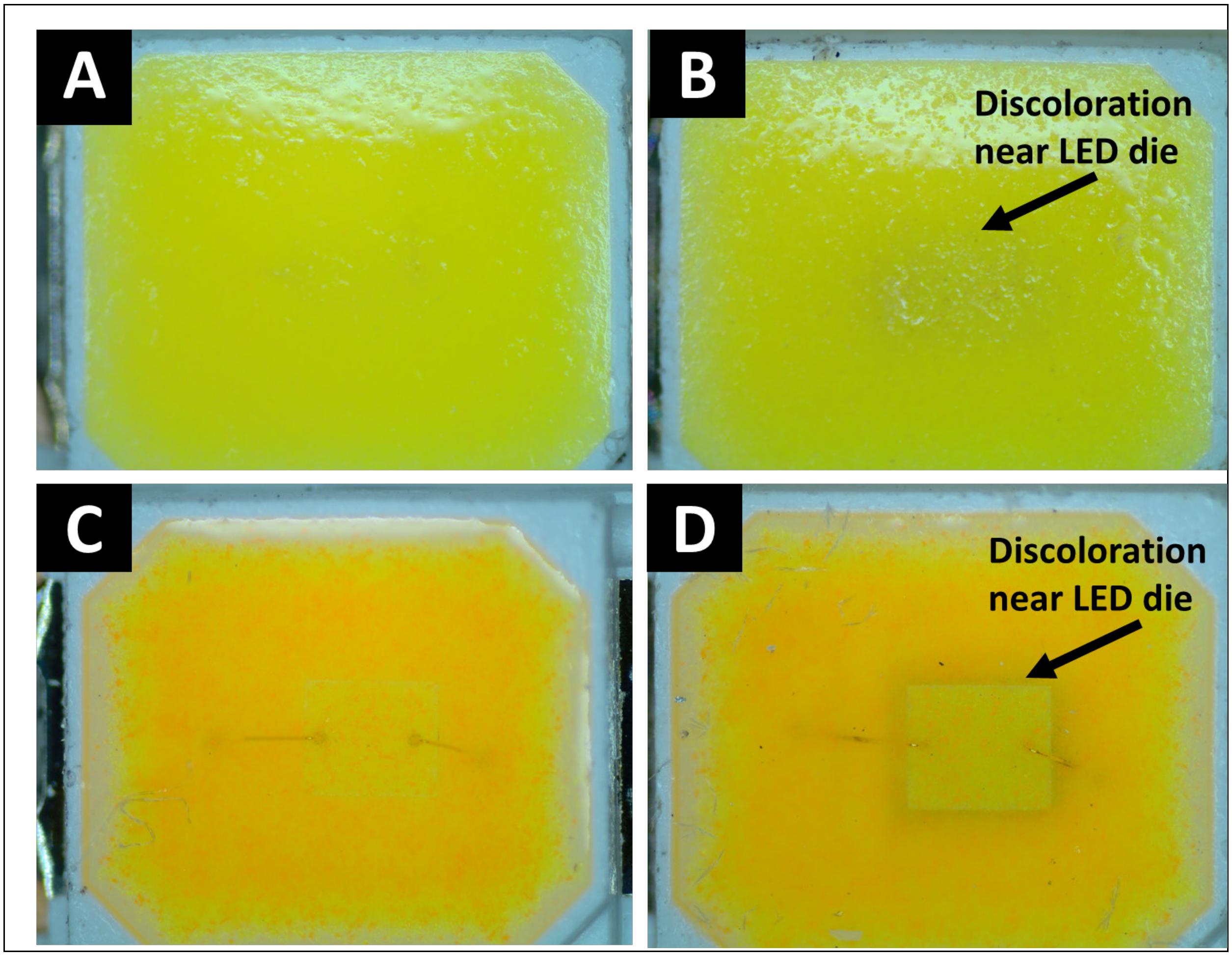

Figure 3-5: Selected LED primaries from the control (A and C) and an aged DUT operated in 7575 post-7,000 hrs (B and D) for Product NB-1. The aged DUT shows discoloration near the LED die (B and D).

3.2 Product NB-2

3.2.1 Luminous Flux Maintenance

The LFM value of Product NB-2 was measured according to IES LM-84-14 with photometric testing after each 1,000 hrs of exposure to the RTOL, 75OL, and 7575 environments. The results were analyzed using an exponential decay model as called for in IES TM-28-14 (though only 5,000 hrs of data were collected and IES TM-28-14 requires a minimum of 6,000 hrs of data), and the findings are presented in **Figure 3-6**. Like Product NB-1, Product NB-2 showed little luminous flux degradation (LFM = 1.00 ± 0.02) over the duration of test for DUTs operated in the RTOL and 75OL environments. The negligible difference between the decay rate constants (α) in RTOL and 75OL suggest that Product NB-2 also does not have much temperature sensitivity over the 25°C to 75°C range. As humidity was introduced into the system (from 75OL to 7575), the luminous flux degraded at a much faster rate and the decay rate constant increased by more than an order of magnitude to $\alpha = 2.5\text{x}10^{-5}$. Assuming an exponential decay model holds, the time to reach L70 can be projected to be approximately 12,800 hrs.

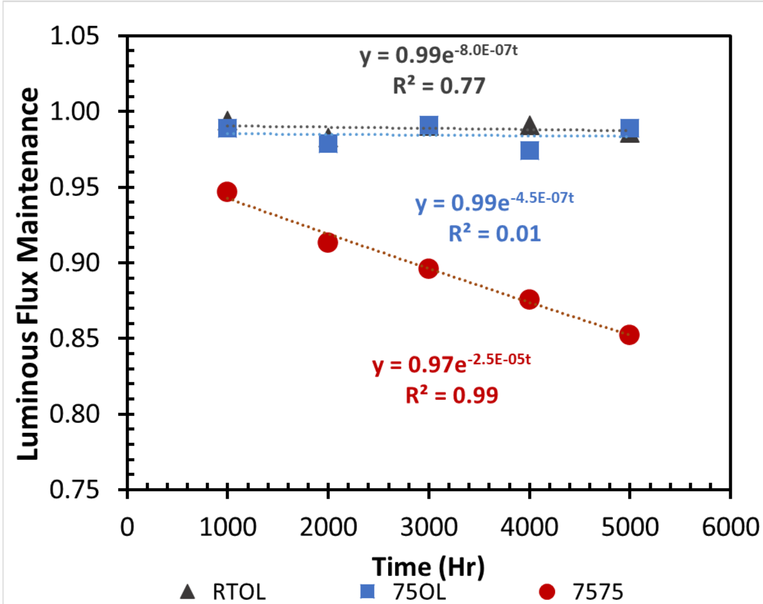

Figure 3-6: LFM of Product NB-2 during RTOL, 75OL, and 7575 according to IES LM-84-14 and IES TM-28-14.

3.2.2 Chromaticity Maintenance

The chromaticity coordinates of the Product NB-2 DUTs were very stable with negligible chromaticity shift through 5,000 hrs of operation in both RTOL and 75OL test conditions as shown in **Figure 3-7**. Upon introduction of humidity in the 7575 environment, the Product NB-2 DUTs exhibited large chromaticity shifts, with three of the four tested DUTs failing parametrically (i.e., $\Delta u'v' > 0.007$) by 2,000 hrs and the fourth DUT failing parametrically by 3,000 hrs due to excessive chromaticity shift. For all DUTs operated in 7575, the chromaticity shifted in the generally green direction along the $-\Delta u'$ axis in a CSM-2 mechanism [11,12]. The magnitude of this shift, $\Delta u'v'$, was approximately 0.011 after 5,000 hrs of 7575 test conditions.

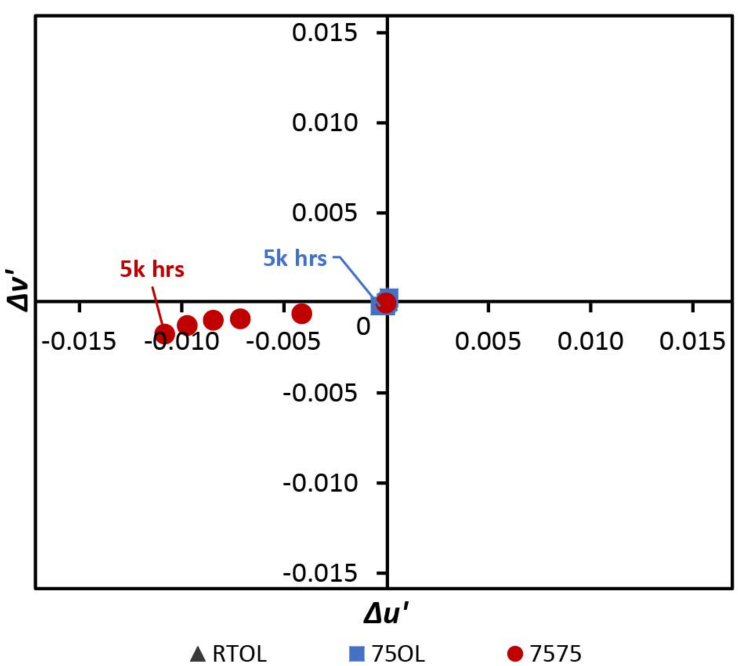

Figure 3-7: Chromaticity shift of Product NB-2 during RTOL, 75OL, and 7575.

An examination of the SPD changes during 7575 exposure explains the observed chromaticity shift in the generally green direction. As shown in **Figure 3-8A**, after 5,000 hrs of exposure to the 7575 environment, the phosphor emission peak is greatly reduced and shifted toward lower wavelengths. The shift in peak wavelength emissions for the phosphor-QD hybrid toward higher energies (i.e., lower wavelengths) was observed for all DUTs operated in the 7575 environment, and no wavelength shift was observed for DUTs operated in RTOL and 75OL environments (**Figure 3-8B**). The shift in emission peak wavelength for the QD-phosphor mixture suggests a change in composition of the red emitters. It is well-known that nitride and oxynitride phosphors undergo oxidation, leading to a green shift of emission peaks [11,12]. In addition, oxygen and moisture ingress are known to affect lifetime and reliability of QDs. [5,13,14,15]. Therefore, it is suspected that a combination of phosphor and QD oxidation and degradation caused the green shift and lower luminous flux observed at red wavelengths for Product NB-2.

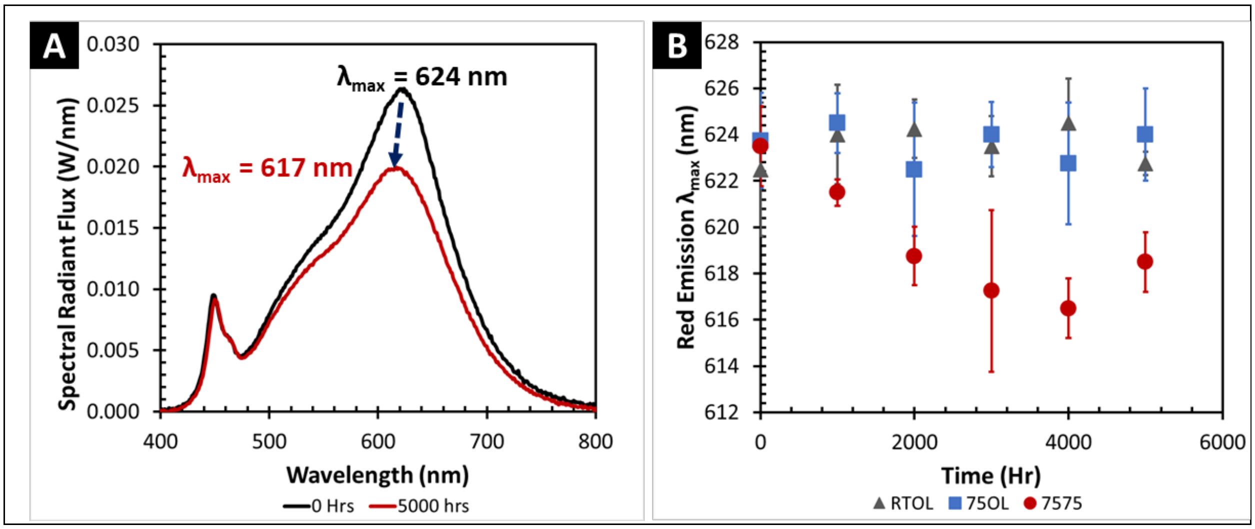

Figure 3-8: Product NB-2 (A) SPD as initially measured and after 5,000 hrs of 7575 exposure and (B) average red emission peak maxima for the DUTs subjected to the different ASTs. The average red emission peak maxima in the 7575 conditions changed throughout testing while no noticeable change occurred in RTOL and 75OL environments, suggesting phosphor and QD oxidation and degradation was largest in the high humidity environment.

3.2.3 Failure Analysis and Post-mortem Examination

There were no abrupt, lights-out failures in any AST for Product NB-2. However, all four DUTs operated in 7575 exhibited excessive chromaticity shift and were classified as parametric failures as described in **Section 3.2.2**. At the end of 5,000 hrs of exposure to the 7575 environment, the solder mask of the LED modules changed from a white appearance to a darker color as shown in **Figure 3-9**. The change in reflectance of the solder mask is not anticipated to have caused the CSM-2 behavior experienced by these DUTs since such changes usually cause a shift in the yellow direction due to increased blue-light absorption [2].

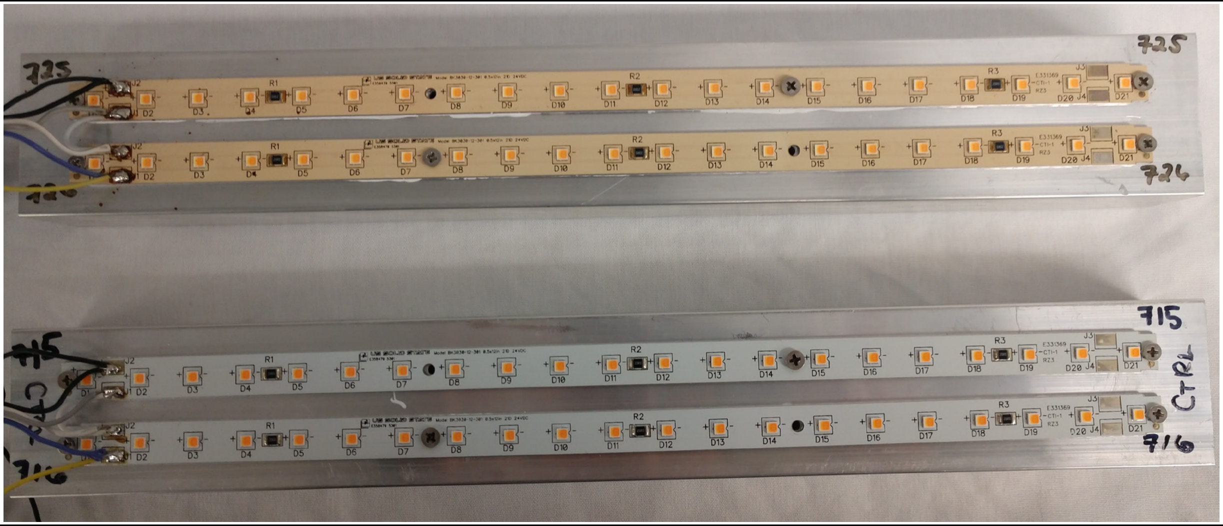

Figure 3-9: The control (bottom) and a tested LED module (top) after 5,000 hrs of exposure to the 7575 environment.

The electrical properties of the DUTs operated in RTOL and 7575 were examined at the end of testing as shown in **Table 3-1**. The electrical analysis of the DUTs showed a very small increase in power consumption for the aged DUTs relative to each other and the control. While the increase in power consumption was found to be significant by Student's t-test at the 95% confidence level, the magnitude of the power increases was not consistent with the magnitude of the chromaticity shifts. At the end of testing (5,000 hrs in 7575), there were no obvious signs of EMC cracking upon inspection of the LED packages. This finding supports that most of the chromaticity shift in these devices was caused by changes in the phosphor-QD composition.

Table 3-1: Electrical Properties of Product NB-2 with Aging

AST	dc Voltage (V)	dc Current (A)	dc Power (W)
Control	23.06	0.443	10.21
RTOL (post-5,000 hrs)	23.10	0.443	10.23
7575 (post-5,000 hrs)	23.21	0.443	10.28

4 Discussion

This report provides a benchmark of two commercially available LED products with narrow-band red emitters intended to improve the overall performance of SSL devices. The spectral efficiency, color rendering, and overall reliability of these products is examined in this section and compared to a conventional all-phosphor LED product.

4.1 Spectral Efficiency

SSL technologies that use LED packages provide large improvements in efficacy compared to conventional incandescent and fluorescent lighting technologies. For example, a typical 800 lm LED product requires 7 to 10 W to operate, whereas 800 lm fluorescent and incandescent products require 13 to 18 W and about 60 W, respectively. While the efficacy for LED products is much-improved compared to traditional lighting technologies, the efficiency of a state-of-the-art, warm-white MP-LED package that uses conventional phosphors is only 33%. This low efficiency is the net product of several LED loss mechanisms including blue LED inefficiency (33%), phosphor and mixing/scattering/absorption inefficiency (37%), and white light spectral inefficiency (22%) [16,17]. Some inefficiencies cannot be eliminated (e.g., Stokes losses from converting blue photons to green and red photons), but the white light spectral inefficiency provides an opportunity for improvement. To minimize the white spectral inefficiency, emitters with a combination of narrow emission bands (less than 20 nm) and peak maxima position in the visible wavelength region (such that there is no spillover into UV or near-IR regions) must be used [16,17].

The SPDs of Products NB-1 and NB-2, a conventional all-phosphor MP-LED product (MS-4), and the photopic sensitivity curve are shown in **Figure 4-1**. The red down-converters, with their traditional FWHMs of 100 nm, account for most of the spectral efficiency losses in LED products. The photopic sensitivity curve shows that much of the light produced by the conventional MP-LED Product MS-4 at 2,700 K is either not observable by the human eye (wavelengths above 700 nm) or it is emitted at a wavelength for which the human eye has lower sensitivity (660 to 700 nm) but are important for color rendering. Product NB-2 and Product MS-4 have similar blue and red emission peak maxima ($\lambda_{max} \approx 622$ nm), but by using a QD-phosphor mixture, the FWHM centered at 622 nm is narrowed from 151 nm for Product MS-4 to 132 nm for Product NB-2. This adjustment in FWHM is at least partially responsible for the 4% increase (from 35.5% to 39.5%) in radiant efficiency and 3% increase in luminous efficacy of radiation (LER) observed for Product NB-2 over Product MS-4 as shown in **Table** 4-1.

While the radiant efficiency of Product NB-2 is increased relative to a conventional warm-white MP-LED package, there are still substantial emissions in the 660 to 800 nm wavelength range where photopic sensitivity is reduced or not active. Product NB-1 uses the PFS/KSF phosphor, which reduces emission at these less sensitive wavelengths, increasing the device radiant efficiency and LER of Product NB-1 by 4.4% and 16.6%, respectively, over the traditional Product MS-4.

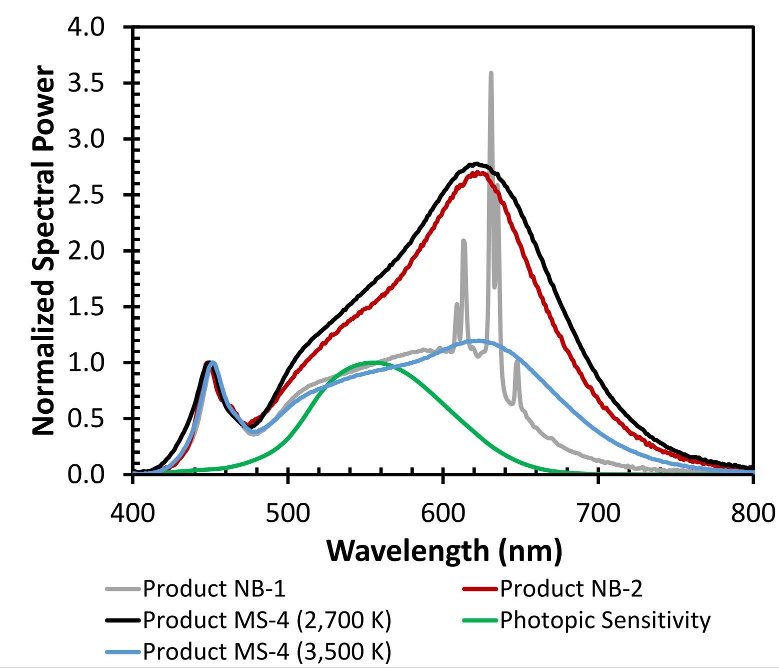

Figure 4-1: The normalized SPDs of the narrow-band red emitter products examined in this study compared to an all-phosphor product (MS-4) and the photopic sensitivity curve. The SPDs are normalized to the blue peak.

Table 4-1: Spectral Efficiency Parameters

Label	Ballast/Driver Output Power (W)	Radiant Flux (W)	Device Radiant Efficiency (%)	LER (lm/W)
Product NB-1	8.98	4.03	44.9	329
Product NB-2	10.23	4.04	39.5	294
Product MS-4 (2,700 K)	7.68	2.73	35.5	285
Product MS-4 (3,500 K)	7.49	3.03	40.5	282

4.2 Color Rendering Properties

As discussed in **Section 2.1** and shown in **Appendix A**, the color rendering quality of narrow-band red emitters is excellent and on par with traditional warm-white MP-LEDs; both Products NB-1 and NB-2 had initial R_f value equal to 92 and R_g value equal to 99. After 5,000 hrs of exposure to the 7575 test environment, these narrow-band red-emitting products maintained good color rendering ($R_f = 91$ for both products, $R_g = 99$ and $R_g = 97$ for Products NB-1 and NB-2, respectively). These data show that there does not need to be a tradeoff between color rending quality and spectral efficiency.

4.3 Reliability

In recent years, improvements in encapsulation technologies in polymer-based packages has led to better LFM for MP-LEDs. A collection of LM-80 data from 2015 to 2019 (223 separate data sets) showed that 78 of 81 polymer-based LED packages had TM-21-11 α values less than 6×10^{-6} when I_f is less than 200 mA [18]. Because both Products NB-1 and NB-2 are polymer-based packages, this LM-80 data provides a benchmark for performance for the narrow-band red emitter products studied in this report. In the 75OL test conditions, Product NB-1 had a TM-28-14 α value of -8.1×10^{-7}, which implies that LFM is still increasing through the test duration considered in this study. Although Product NB-2 did not complete 6,000 hrs of testing necessary for TM-28-14, the first 5,000 hrs of data collected for the DUTs operated in the 75OL environment show good LFM; $\alpha = 4.5 \times 10^{-7}$ through 5,000 hrs. Both of the α values calculated for the narrow-band red emitter products are just as good or better than conventional warm-white LED packages, implying high LFM reliability.

About two-thirds of the LM-80 data in the recent summary from DOE were reported in the LM-80-15 format, which includes chromaticity coordinates [18]. A study of those data revealed that over 80% of polymer-based LED packages undergo CSM-1 shifts (general blue direction) due to polymer photo-oxidation, encapsulant cracking, or both. The other 20% of polymer-based LED packages experience CSM-2 behavior (general green shifting) due to changes in the phosphor material. Product NB-1 experienced a CSM-1 shift of magnitude $\Delta u'v' = 0.0050$ in 7575 test conditions. In the less aggressive 75OL conditions, Product NB-1 experienced minor shifts in the generally green direction with magnitude $\Delta u'v' = 0.0005$. Product NB-2 experienced CSM-2 behavior in 7575 ($\Delta u'v' = 0.011$) but negligible shift in 75OL. The chromaticity maintenance of both products was acceptable and typical of polymer-based packages in 75OL, but the magnitude of shift for Product NB-2 reached parametric failure when humidity was introduced in the 7575 environment. Further, the peak shift of the QD-phosphor mixture was 7 nm toward lower wavelength values for Product NB-2, implying that this product might not be suitable for applications where moisture ingress is pervasive.

5 Conclusions

SSL sources utilizing LEDs can provide significant improvements in luminous efficacy over traditional incandescent and fluorescent sources. Additional gains in SSL source efficacy are possible through spectral engineering that reduces radiant emissions to which humans are not sensitive (e.g., far-red, near-IR). For example, the conventional red phosphors used in many SSL devices have FWHM values of approximately 100 nm, which results in emissions at wavelengths that are not visible to the human eye. Reducing the amount of radiation produced at non-visible wavelengths will provide more usable light for illumination and increase both the luminous efficacy and LER of the source.

This report examined two approaches to reduce non-visible emissions from LEDs in the red and near-IR spectral regions. These approaches, which can be broadly classified as the use of narrow-band red emitters, consist of either using LEDs that include a PFS/KSF phosphor or LEDs that incorporate a small amount of red-emitting QDs with a broader emitting phosphor. The PFS/KSF phosphor emits narrow-band red light at five distinct wavelengths between 609 nm and 648 nm. The FWHM value of each emission peak is less than 2 nm. QDs are also narrow-band emitters (FWHM is typically less than 30 nm) with a λ_{max} value that depends on the diameter of the QD. However, QDs often contain Cd or other substances that are restricted by the RoHS Directive, which limits that amount of QDs that can be used in an LED. As a result, a phosphor-QD blend is currently required to provide full spectrum coverage in these products.

Initial benchmarks and AST findings of up to 7,000 hrs are contained in this report for two products with narrow-band red emitters—a linear LED lamp that used MP-LEDs incorporating the PFS/KSF phosphor and MP-LED packages that utilize a phosphor-QD blend. The performance of these products was compared to a switchable downlight using two LED primaries. The CCT value of the switchable downlight can be changed in set increments of 2,700 K, 3,000 K, 3,500 K, 4,000 K, and 5,000 K. All products described in this report were high color rendering products with R_f values of at least 92 and R_g values of at least 99.

This analysis demonstrated that the incorporation of narrow-band red emitters can improve the radiant efficacy by up to 4.4% and the LER by up to 16.6% over traditional SSL sources. The largest gains were found for devices that incorporate the PFS/KSF phosphor over the phosphor-QD hybrid structure. In addition, both structures exhibited excellent luminous flux and chromaticity maintenance through 5,000 hrs of testing (7,000 hrs for Product NB-1) at 75°C, indicating that the temperature stability of the products is excellent. However, the luminous flux and chromaticity maintenance of both products were significantly less in the presence of humidity in a 7575 test. The magnitude of the chromaticity shifts was large for both products in 7575 with the PFS/KSF product tending to shift toward a generally blue direction (i.e., CSM-1 behavior) while the phosphor-QD product tended to shift toward a generally green direction (i.e., CSM-2 behavior). In addition, the λ_{max} value of the phosphor-QD emission shift shifted by 7 nm toward lower wavelength values after 5,000 hrs of exposure to 7575 further indicating a strong effect from humidity. These results demonstrate that both approaches to incorporating narrow-band red emitters into LEDs can increase efficacy and provide high reliability in indoor environments where humidity levels are controlled. Additional testing is required to determine if the initial efficacy gains that were measured in this testing are sustainable for longer periods.

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Appendix A

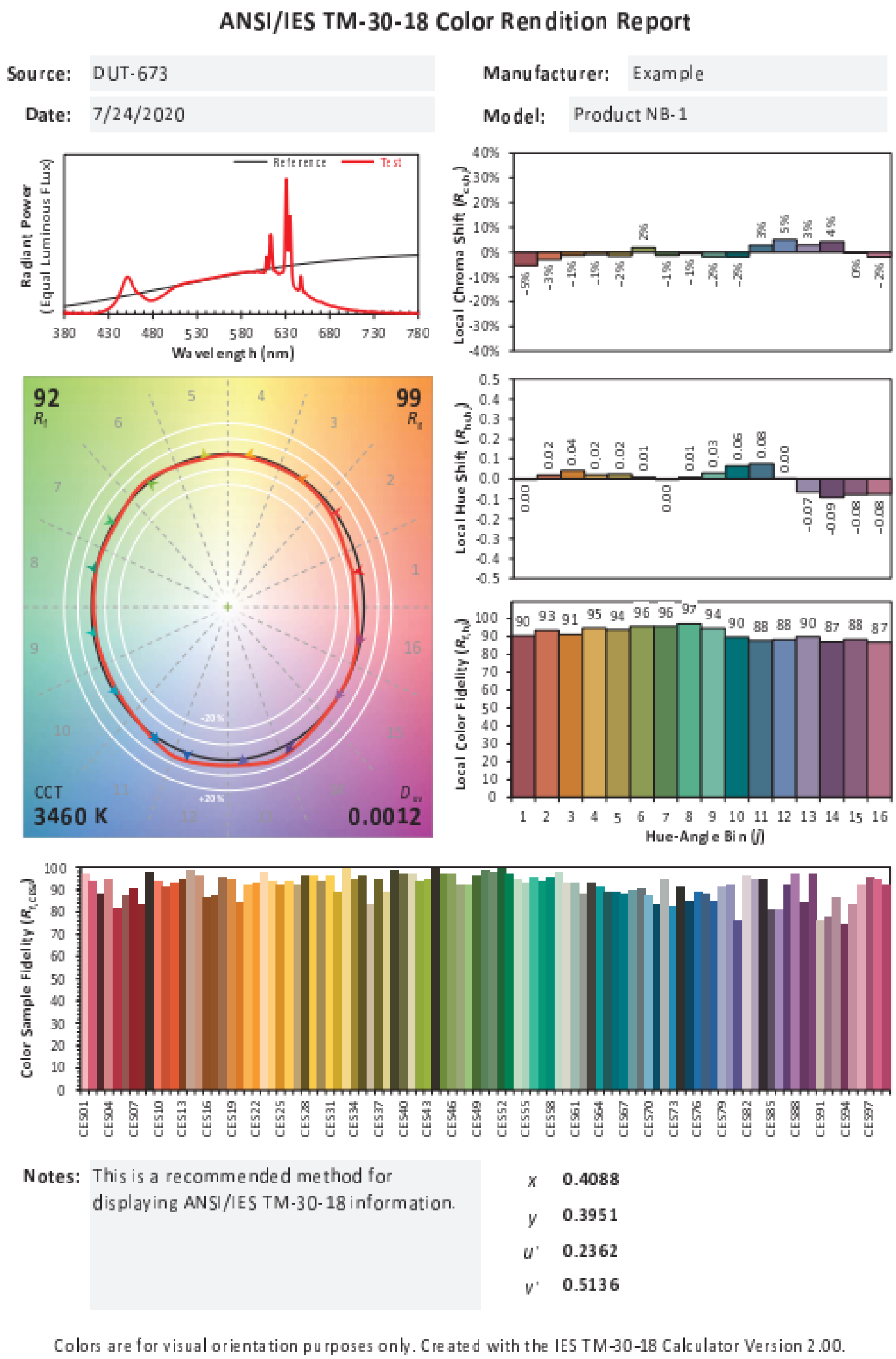

Figure A-1. ANSI/IES TM-30-18 analysis for Product NB-1.

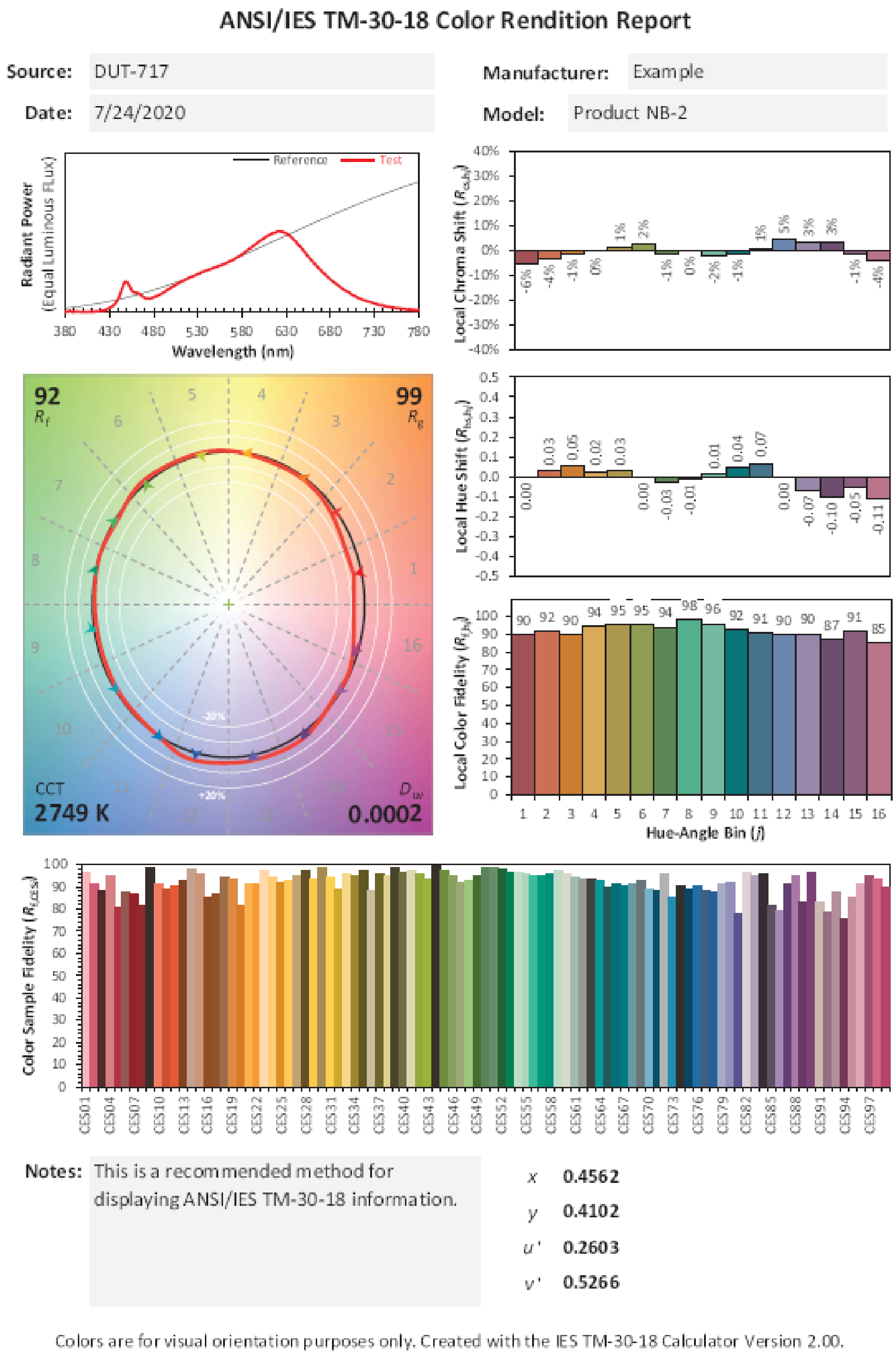

Figure A-2: ANSI/IES TM-30-18 analysis for LEDs from Product NB-2.

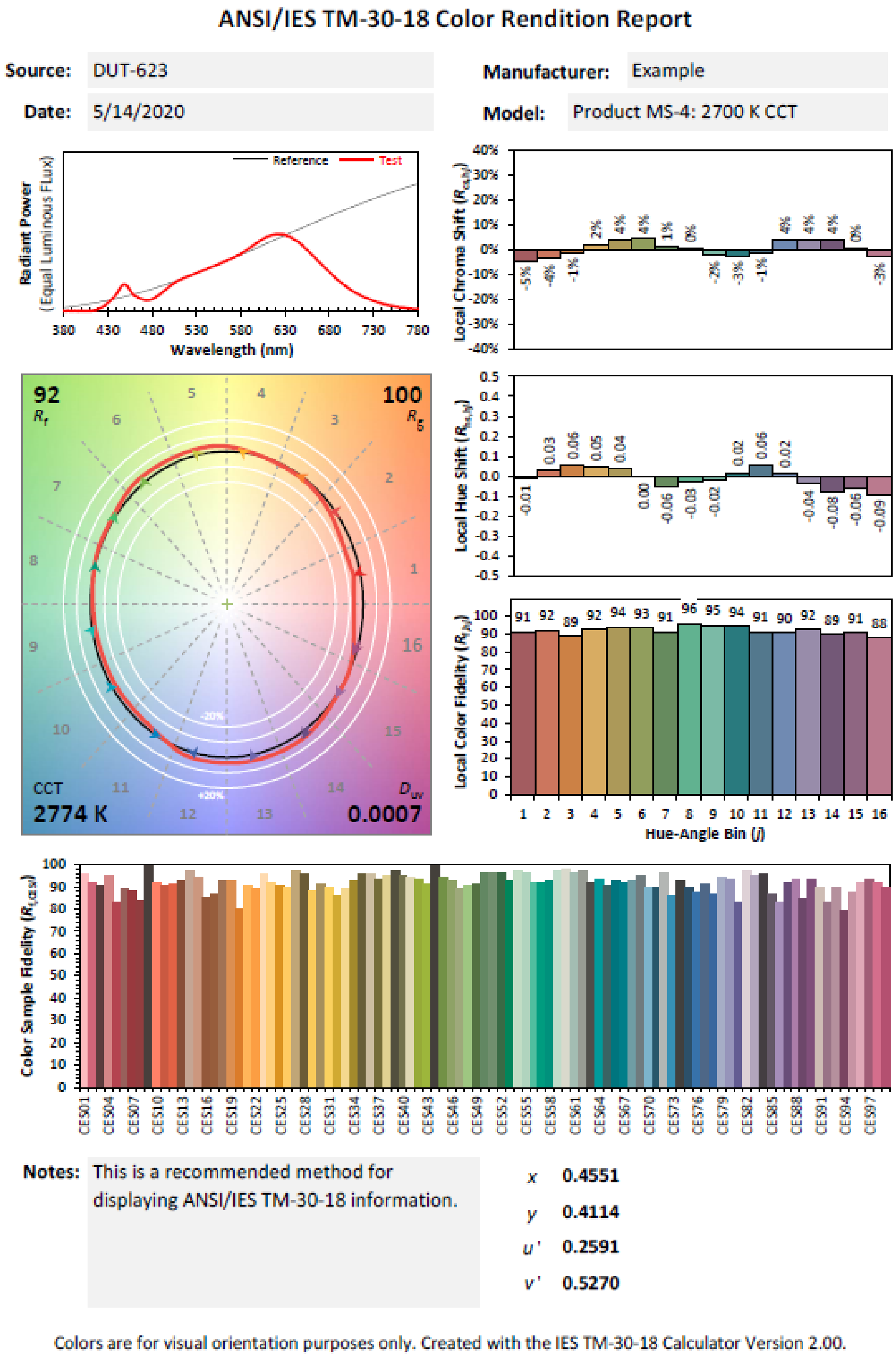

Figure A-3: ANSI/IES TM-30-18 analysis for Product MS-4 set to a CCT value of 2,700 K.

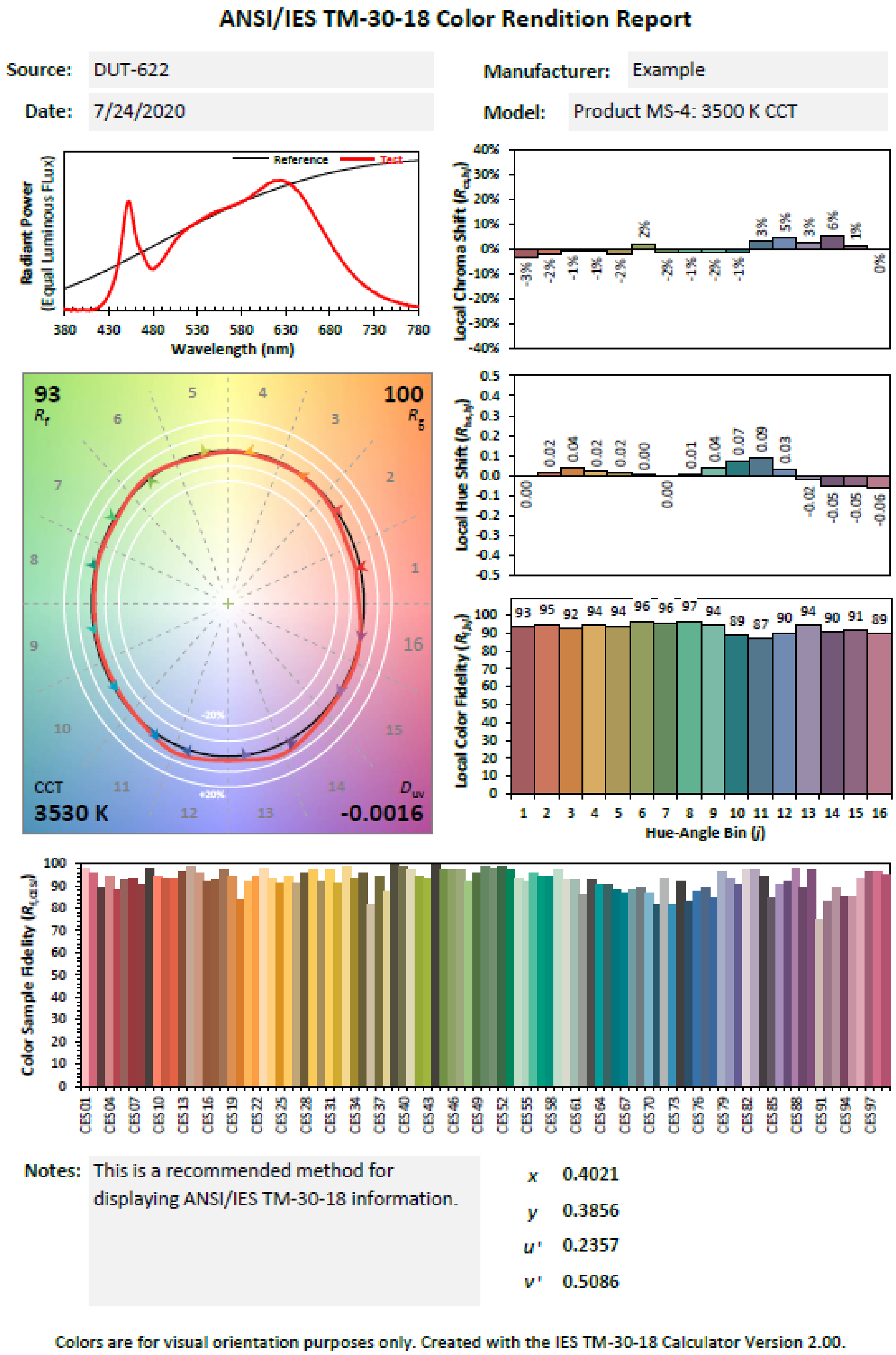

Figure A-4: ANSI/IES TM-30-18 analysis for Product MS-4 set to a CCT value of 3,500 K.

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