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Investigation of the Long-Term Aging Characteristics of Chip-On-Board LEDs: Operating Lifetime Study

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Disclaimer

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List of Acronyms

75OL	operational life test conducted at 75°C
7575	operational life test conducted at 75°C and 75% relative humidity
α	decay rate constant in the ANSI/IES TM-21-19 model
$\Delta u'$	change in the u' coordinate of chromaticity
$\Delta u'v'$	chromaticity shift magnitude or the total change in chromaticity coordinates
$\Delta v'$	change in the v' coordinate of chromaticity
$\eta_{LED,EQE}$	external quantum efficiency of an LED
λ_{max}	LED maximum emission wavelength
x_i	value of the x variable in a sample
$\bar{x}$	mean of the values of the x variable
y_i	value of the y variable in a sample
$\bar{y}$	mean of the values of the y variable
°C	degree Celsius
A	ampere
A	absorbance
A/cm^2	amperes per square centimeter
ac	alternating current
Ag	silver
Al	aluminum
Al_2O_3	aluminum oxide or alumina
AlN	aluminum nitride
ANSI	American National Standards Institute
AST	accelerated stress test
b	optical pathlength
B	projected initial constant in TM-21-19
c	concentration of the absorbing species
CCT	correlated color temperature
Ce:YAG	cerium doped yttrium aluminum garnet
CIE	International Commission on Illumination (*Commission Internationale de l'Éclairage*)
COB	chip-on-board
COB-X	COB products in the test matrix where X is a number between 2 and 6
CSM	chromaticity shift mode
CSP	chip-scale package
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
EQE	external quantum efficiency
HP-LED	high-power LED
HP-1	high-power LED product number 1
hr, hrs	hour, hours
HVAC	heating, ventilation, and air conditioning
IES	Illuminating Engineering Society
I_f	forward current
I-V	current-voltage
K	Kelvin
L_{70}	time to reach LFM
LED	light-emitting diode
LES	light-emitting surface
LFM	luminous flux maintenance
lm	lumen
lm/cm^2	lumens per square centimeter
lm/W	lumens per watt
LSRC	LED Systems Reliability Consortium
mA	milliampere
mA/cm^2	milliamperes per square centimeter
MC-PCB	metal-core printed circuit board
MESA	Mission Execution and Strategic Analysis
mm	millimeter
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
PPA	polypththalamade
ppm/V	parts per million per volt
psi	pounds per square inch
Pt	platinum

r	correlation coefficient
R&D	research and development
RH	relative humidity
RTOL	room-temperature operating life
SPD	spectral power distribution
SSL	solid-state lighting
T_c	case temperature
T_j	junction temperature
TM	technical memorandum
u'	chromaticity coordinate in the CIE 1976 color space
UV	ultraviolet
V	volt
v'	chromaticity coordinate in the CIE 1976 color space
V_f	forward voltage
V_{th}	threshold voltage
W	watt

Executive Summary

Chip-on-board (COB) light-emitting diodes (LEDs) are a relatively new LED package platform that provides the highest density lighting flux with the thinnest profile. COB LEDs are formed by interconnecting large numbers of mid-power LED (MP-LED) die to form a dense light-emitting surface (LES). Because the number of LEDs used in the COB LED packaging platform is very large (usually between 12 and 100), more light and waste heat per unit area are produced relative to other LED package platforms. Therefore, it is necessary that the MP-LED die are situated directly on an excellent thermally conductive substrate. The COB-LED assembly is covered by a large silicone–phosphor layer creating a phosphor-converted LED (pc-LED).

This report, which is the second in a series of reports about the reliability of commercial COB LED products, focuses specifically on the long-term aging characteristics of COB LEDs. All five COB-X products examined in this study are from different Tier 1 manufacturers and represent a myriad of LES sizes, die interconnection methods, substrates, and construction techniques. All COB products in the test matrix are pc-LEDs, and the LES of the devices under test (DUTs) varied from 4.5 millimeters (mm) to 14.6 mm. Most DUTs were set to a fixed correlated color temperature (CCT), but one COB (i.e., COB-3) had the ability of white tuning. Three of the COB products examined during this study were built on metal-core printed circuit boards (MC-PCBs), and the remaining two COB products were built on ceramic substrates. Four COB products contained LED die that were interconnected by wire bonding, and the LED die in these products were mounted to the substrate with a thermally conductive adhesive. The LED die in one product was flip chip–bonded to an interposer layer by using solder bumps, and the interposer board was mounted on an aluminum nitride (AlN) substrate for thermal management purposes. The number of LEDs in the LES ranged from 12 (for a 4.5-mm LES) to 108 (for a 14.6-mm LED), and four of the five products had a blue LED pump, and one product had a violet LED pump. The radiant efficiency of these devices ranged from 0.31 to 0.44, and the luminous efficacy of these samples ranged from 83 lumens per watt (lm/W) to 127 lm/W.

This report builds upon the aging data from the previous report [1]. Prior to testing the COB DUTs, the samples were mounted on appropriate heat sinks intended to keep the case temperature (T_c) of the COB package within the manufacturer's specifications. Three different accelerated stress tests (ASTs) were used: room-temperature operating life (RTOL), an elevated ambient environment of 75 degrees Celsius (°C) and 75% relative humidity (7575), and operation in an oxygen-free (anaerobic) environment. The test population for RTOL was expanded from 3 DUTs from the previous report [1] to 10 DUTs for each COB product to comply with American National Standards Institute (ANSI)/Illuminating Engineering Society (IES) technical memorandum (TM) TM-21-19. The test population for 7575 was also set to 10 DUTs, whereas the test population for the anaerobic environment was kept to 2 DUTs because of space limitations in the anaerobic chamber. The RTOL and 7575 DUTs completed 6,000 hours (hrs) of testing, whereas the anaerobic DUTs completed 2,000 hrs.

In the context of this report, reliability is judged by either abrupt (i.e., lights-out) failures caused by electrical open circuits or parametric failures caused by excessive luminous flux depreciation

or chromaticity shifts. The luminous flux maintenance (LFM) data were analyzed by using an exponential decay model as indicated in ANSI/IES TM-21-19. The time to reach an LFM of 0.7 (i.e., L_{70}) was projected by using the exponential model in ANSI/IES TM-21-19. During RTOL testing, the projected time to L_{70} for all COB products (except for Product COB-5, in which L_{70} = 32,200 hrs) was limited by the 5.5 times rule (33,000 hrs for 6,000 hrs experimental time and 10 DUTs), and the largest magnitude of chromaticity shift ($\Delta u'v'$) was 0.0036 for Product COB-5. These results indicate good reliability of the COB products in the RTOL environment. No abrupt or parametric failures were observed through 6,000 hrs of the RTOL tests.

The 7575 tests proved to be a higher stress environment that produced TM-21-19 decay rate constant (α) values significantly higher than those measured during RTOL tests. The α values for the 7575 test were also significantly higher than the α values found in the previous report [1] for testing conducted in an elevated ambient environment of 75°C (75OL). The T_c values of the 7575 test were slightly higher than the RTOL test but not significantly different than the 75OL test, so it is most likely that the additional moisture in the 7575 test environment was responsible for the larger α values. The accelerating nature of the 7575 test led to 35 parametric failures (out of 53 total DUTs) during 6,000 hrs of 7575 exposure because of excessive chromaticity shift (i.e., $\Delta u'v' \leq 0.007$) and 20 parametric failures that also exhibited excessive luminous flux depreciation (i.e., LFM < 0.7). All DUTs that failed parametrically because of low LFM also failed because of excessive chromaticity shift. The parametric failures occurred only in some products: all DUTs for Products COB-2, COB-3, and COB-5 failed parametrically in one or more areas, but Product COB-6 did not experience any failures. Product COB-4 was removed from testing after 4,000 hrs because of cracking of the silicone LES and discoloration of electrical leads, which were soldered on prior to purchase. During testing, it appeared that the leads were unable to handle the forward current load of the COB.

Because of the high-photon-induced darkening effects observed by the lighting industry for some high-power LEDs (HP-LEDs) in low-oxygen environments and the high flux nature of COBs, this study examined whether darkening effects are also observed for COB DUTs in an anaerobic environment. Product HP-1, an HP-LED known by the industry to undergo LES darkening in the anaerobic environment, was used to validate the anaerobic tests. For Products COB-4 and COB-5, LFM was greatly reduced by 240 hrs of operation with LFM less than 0.80 being measured; however, the LFM reduction was not as significant as it was for Product HP-1 (LFM = 0.18 at 240 hrs). By 2,000 hrs, the LFM for 6 of the 10 COB DUTs in the anerobic chamber fell below the parametric failure threshold; the DUTs also exhibited excessive chromaticity shift. For Product COB-5, the anaerobic environment was approximately 16 times more accelerating than the 7575 environment even though the DUT's junction temperature (T_j) value was lower because of the use of the cooling plate in the anerobic environment. Overall, the chromaticity shift and LFM degradation were found to be reversible for the COB DUTs (and Product HP-1) after 100 hrs of operation in air.

A high level of correlation (i.e., absolute value of the correlation coefficient $r > 0.8$) was found between current density, flux density, LFM, and $\Delta u'v'$ for DUTs operated in the r anaerobic environment. For these samples, LFM was found to be negatively correlated to current density, flux density, and $\Delta u'v'$, whereas current and flux densities were found to be positively correlated to $\Delta u'v'$. In contrast, for RTOL, a positive correlation was found between LFM and $\Delta u'v'$ and current density. This correlation is believed to be the result of higher external quantum efficiency (EQE) of the LED ($\eta_{LED,EQE}$) for products capable of operating at higher current densities. Weak or no correlations were observed for the DUTs operated in the 7575 environment, indicating that the high stress environment of added temperature and humidity might outweigh effects because of increased current or flux densities.

All blue pump LED DUTs examined during this study exhibited either shifts in the blue or green direction or a combination of the two during the test period; either shift is indicative of chromaticity shift mode (CSM) behavior that can be classified as CSM-1 or CSM-2. CSM-1 is usually caused by a relative increase in emissions from the LED emitter, whereas CSM-2 is usually caused by a change in the emission spectrum of warm white phosphors. The analysis findings presented in this report indicate that the chromaticity shift of the COB LED products examined during this study was primarily because of package effects arising from the silicone–phosphor composite in the LES. These effects can include increased absorption of light rays with long optical path lengths or chemical changes in the phosphor particle due to the high moisture permeability of silicones. Although contributions from other package factors such as the oxidation of silver (Ag) mirrors cannot be fully eliminated, especially for Products COB-2, COB-3, and COB-5, it is more likely that changes in the silicone–phosphor LES was the primary driver in chromaticity shifts and luminous flux loss.

COB LEDs are an emerging LED packaging platform for solid-state lighting (SSL) products that offer products in high lighting density and in a thin profile. During RTOL testing, the LFM performance of the COB LED products was excellent, with most project lifetime values limited by the 5.5 times rule of ANSI/IES TM-21-19. For 7575, however, 66% of the DUTs failed parametrically because of excessive chromaticity shifts by 6,000 hrs. These findings are consistent with the highly accelerating nature of the 7575 testing environment and demonstrate its utility in reducing the experimental time required for failure so that the failure modes can be studied. Furthermore, for the anaerobic test, 60% of the DUTs failed parametrically by 2,000 hrs. The high light density and thin profile of the COBs may help to create new SSL products with advanced lighting features such as tunable white or unique optical patterns for light delivery. However, COB LED packages also present challenges because of silicone expansion and swelling due to moisture ingress and darkening effects because of high flux. Using AST methods to understand these failure modes and developing new materials and manufacturing methods to overcome these limitations will improve both the energy efficiency and reliability of the COB LED packages in demanding high light–intensity applications. Ultimately, these types of studies help promote energy efficient technology and reduce carbon emissions from lighting systems.

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1 Introduction

The chip-on-board (COB) light-emitting diode (LED) is a high-density LED package consisting of an array of interconnected LED die placed on a low thermal resistance substrate that also provides electrical connections. The array of interconnected LED die is covered by a large silicone–phosphor composite layer to convert the blue light emitted by the LED array into white light. This structure, which is known as the light-emitting surface (LES), makes the COB LED a type of phosphor-converted LED (pc-LED), and it also gives this LED package platform its characteristic appearance. The diameter of the LES in a COB LED can range from as little as 4 millimeters (mm) up to 32 mm; the most common LES size is 13 mm to 14 mm.

This report is the second in a series of reports on the initial performance and long-term reliability of COB LEDs. The previous report provided an initial benchmark of six commercial COB products that represent trends found in COB LED packages [1]. These six products are shown in **Figure 1-1**. The current study expands upon the earlier report by providing reliability data on these products. The data were obtained through at least 6,000 hours (hrs) of operating lifetime testing at either room temperature or in an environmental chamber set to 75 degrees Celsius (°C) and 75% relative humidity (RH).

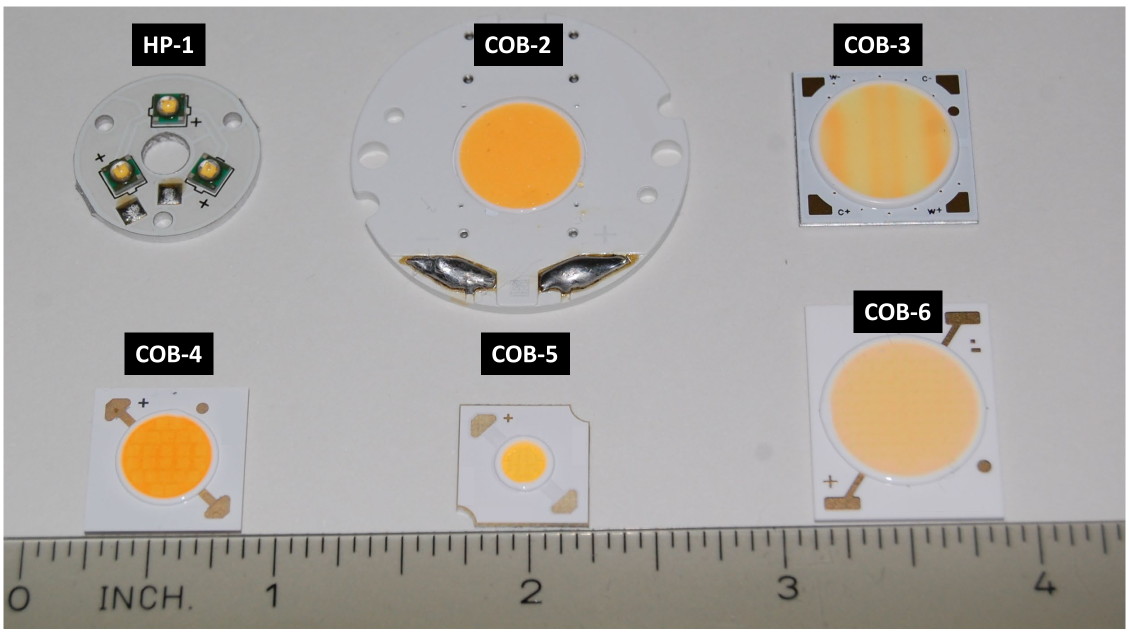

Figure 1-1. Examples of the COB LED packages examined during this study.

COB LED packages have three main components: the large number of individual LED die in the array; the substrate on which all the LED die are mounted and the interconnects (e.g., solder, wire bonds) used for electrical connection; and the large LES consists of silicone and phosphors that cover the LED die array. Each of component is a potential source of failure in COB LEDs. The intent of this report is to examine the relative contributions of the temporal changes in these components to the overall changes in luminous flux and chromaticity of the COB LED package.

The first major component of the COB LED package is the LED array. The LEDs used in the COB LED package are similar in size and current density to those used in mid-power LED (MP-LED) and chip-scale package (CSP) LED platforms; however, the numbers of LED die in the COB LED packaging platform are much higher. For example, although a typical MP-LED or CSP package may house one to three LED die, the number of LED die in the COB package can range from 10 to more than 100. Even though there are many LED die in a COB LED package, there is typically only one set of electrodes—an anode and a cathode. The LED die in the COB LED package are connected in various series and parallel combinations that result in higher forward voltages (V_f) and forward currents (I_f) being required to operate the device than those required for single-die LED packages. It is not uncommon for the V_f value of a COB LED to be between 20 volts (V) and 50 V, with I_f values between 300 milliamperes (mA) and greater than 4,000 mA for large LES devices. These high V_f and I_f values are because of the large number of LED die in the array; however, the per-chip V_f and I_f values of COB LEDs are comparable to those of MP-LED and CSP products. The higher die count of COB LEDs results in the production of more light than the MP-LED or CSP packages, but also produces more waste heat per unit area.

Because of their similar size, the reliability of the LED die used in the COB LED package can be compared with that of the MP-LED and CSP products, provided that the I_f values per LED die are in the same range. A previous study of commercially available MP-LED products showed that this package platform can have high luminous flux maintenance (LFM) values, provided that the current density is within the manufacturer's specifications. In addition, most of the failure modes for luminous flux and chromaticity maintenance associated with the MP-LED package are caused by the polymers used in the package housing (i.e., typically polyphthalamade [PPA], epoxy molding compound [EMC]) [2, 3]. Because the only polymer used in the COB LED package is silicones, failure modes associated with PPA, EMC, and other packaging resins are not a concern in the COB package.

The second major component of the COB package is the substrate and associated electrical interconnections. In MP-LEDs, the LEDs are bonded to a lead frame, which is then encased in a polymer (e.g., PPA or EMC resins). The polymer package is then soldered to a printed circuit board (PCB) that provides connection to electrical power. In contrast, for COB LEDs, the LED die are bonded directly to the exterior package (i.e., the substrate) and interconnected electrically to reduce thermal impedance and improve heat management. As a result, the COB LED package platform offers the highest lighting density that is available from a low-profile LES. There are two main architectures for the COB LED package platform: one using a metal-core printed circuit board (MC-PCB) substrate and the other using a ceramic substrate. The MC-PCB substrate is typically made from aluminum with a smooth reflective surface on one side, usually a silver (Ag) thin film, that will serve as the substrate for mounting the LEDs and the conduit for heat dissipation. The other COB LED structure is a ceramic thick-film package made by co-firing green tape ceramic and conductive thick films. The manufacturing of these substrates is described in other publications [1, 4]. The major failure modes associated with excess heat in an

LED package are generally caused by degradation of the silicone encapsulants. This degradation can include cracking of the silicone or the emergence of darkened areas of silicones because of irreversible damage in the encapsulant. This behavior can potentially occur in all LED package platforms if proper thermal management is not in place [5].

The third major component of the COB LED package is the most visible: the silicone–phosphor mixture that comprises the LES. Silicones are a relatively inert polymer matrix that are low cost, easy to apply, and compatible with most phosphor chemistries [6]. Although silicones have low chemical reactivity, they are generally permeable to water and other vapors. In addition, the optical and mechanical properties of silicone materials tend to change over time under the influence of heat, radiation, and moisture, which can cause many changes in the silicone–phosphor composite. For instance, the alteration of the composite can change light absorption characteristics[5], cause swelling of the silicone [7], alter the chemistry of the phosphor particles [8], promote nano-clustering of the platinum (Pt) catalysts [9], and produce different reaction chemistries in oxygen-containing environments compared with oxygen-free environments [9].

Because of the high luminous flux densities and optical uniformities that are available from the LES of a typical COB, these devices are often used in applications such as street lighting, spot lighting, and high bays that require high-power sources. Traditionally, metal halide and mercury lamps have dominated this application space. However, COB LEDs are making significant inroads; the annual sales of COB LED products were approximately $2.64 billion in 2021, and this segment of the LED lighting industry is growing at a healthy compound annual growth rate of 11.4% [10]. One of the biggest advantages of using COB LEDs is the ease of integration into a finished product because only two electrical leads are required to connect the COB LED to the luminaire. In addition, new capabilities, imparted by new COB LED products to integrated solid-state lighting (SSL) devices, such as tunable-white features and small source size, will help to create new products that will further accelerate the growth of COB LED lighting. Finally, the greater energy efficiency and reduced carbon footprint of COB LEDs compared with metal halide and mercury lamps provide significant environmental and cost benefits when using COB LEDs in high bay, spot lighting, and street lighting applications.

Although the use of COB LEDs in lighting applications is growing, the reliability of this package platform is not as well understood as that of MP-LEDs and high-power LEDs (HP-LEDs). In addition, the COB LED package does not have decades of user experience as compared with metal halide and mercury lamps. In an initial effort to understand the long-term reliability of COB LED products, a previous study from the U.S. Department of Energy (DOE) used LM-80 data to examine the performance of a sampling of commercial products [2]. The findings from this study indicated that COB LEDs could be operated in a way that produces high LFM. However, the chromaticity shift behaviors of the COB LEDs were less uniform, and there was no consensus behavior among different manufacturers [2].

The current study was initiated to help unravel the potential failure mechanisms of COB LEDs. It was anticipated that the primary failure mechanisms of COB LEDs would be related to the large amount of exposed silicone in the LES and the density of waste heat and radiation that are produced during operation. Consequently, it was important to test COB LED devices at both normal operating conditions and at stressed conditions to understand the factors that are responsible for luminous flux decay and chromaticity shifts in this packaging platform. Given the lack of information about COB LED reliability, the goal of this study was to examine the reliability of a matrix of COB products tested under different conditions to begin to unravel the failure mechanisms that can occur with COB LEDs. It is anticipated that this information will aid the lighting industry in designing COB LED products and lamps and fixtures incorporating these new COB products that provide higher reliability, lower energy consumption, and reduce carbon footprint compared with the conventional lighting technologies that they are replacing.

2 COB Samples

Detailed descriptions, including American National Standards Institute (ANSI)/Illuminating Engineering Society (IES) technical memorandum (TM) TM-30-18 reports, of the devices under test (DUTs) examined during this study were reported in a previous report [1]. For convenience, brief product descriptions are provided in this current report.

The DUTs examined in this study are shown in **Figure 1-1**. To maintain manufacturer anonymity, the different COB products are labeled as Product COB-X, in which "X" is a number from 2 to 6. All DUTs of the same designation were equivalent at the beginning of any testing. The COB products were chosen to represent a myriad of technologies with varying LES sizes, substrate types, emitters, and tunability as listed in **Table 2-1**.

A white HP-LED (denoted as Product HP-1) product was also included in the test matrix for comparison purposes. The manufacturer and DOE LED Systems Reliability Consortium (LSRC) identified Product HP-1 as having reduced LFM when operating in anaerobic conditions. Product HP-1 served as a control to monitor the nitrogen chamber setup and experiment for the COBs.

Table 2-1. Construction and Physical Characteristics of the DUTs Examined During This Study

Product	Package Size (mm x mm)	LES Diameter Size (mm)	Nominal CCT (K)	Substrate	Emitters
COB-2	36.2[a]	13	2,700	MC-PCB	Blue LED; yellow and red phosphors
COB-3	18.8 × 18.8	14.2	Variable (2,700–6,500)	MC-PCB	Blue LED; yellow and red phosphors
COB-4	15.9 × 15.9	8.9	2,700 K	Ceramic	Blue LED; yellow and red phosphors
COB-5	13.4 × 13.4	4.5	2,700 K	MC-PCB	Blue LED; yellow and red phosphors
COB-6	24 × 24	14.6	5,000 K	Ceramic	Violet LED; blue, yellow, and red phosphors

[a] The package size for Product COB-2 is circular with a diameter of 36.2 mm and includes the COB LED holder. The MC-PCB size is 16.5 mm × 16.5 mm.

The products in this study were operated at various accelerated stress test (AST) conditions under which different I_f values were used. The manufacturer-rated maximum I_f and associated case temperature (T_c) or LED junction temperature (T_j) are listed in **Table 2-2**.

Table 2-2. Maximum Operating Values

Product	Rated Maximum dc Current (mA)	Rated Maximum T_c or T_j (°C)
COB-2	1,050	T_c = 105°C
COB-3 (2,700 K)	700[a]	T_c = 105°C
COB-3 (6,500 K)	700[a]	T_c = 105°C
COB-4	1,400[b]	T_c = 85°C[b]
COB-5	700[c]	T_c = 85°C[c]
COB-6	810	T_j = 120°C

[a] The maximum direct current (dc) current for Product COB-3 is the maximum combined drive current between both the 2,700 K and 6,500 K LED channels. For example, if 700 mA is applied to the 2,700 K channel, then no current may be applied to the 6,500 K channel.

[b] The maximum dc current for Product COB-4 depends on the T_c when the LED has reached thermal equilibrium under steady-state operation. Therefore, at the manufacturer's reported maximum I_f equal to 1,400 mA, T_c must remain below 85°C. For the I_f of 1,000 mA used in room-temperature operating life (RTOL) and 7575, T_c must remain below 103°C.

[c] The maximum dc current for Product COB-5 depends on the T_c when the LED has reached thermal equilibrium under steady-state operation. Therefore, at the manufacturer's reported maximum I_f equal to 700 mA, T_c must remain below 85°C. For the I_f of 500 mA used in RTOL and 7575, T_c must remain below 103°C.

3 Experimental Methods and Procedures

This report is the second in a series of reports about the investigation of COB construction and reliability. As discussed in the previous report, the initial properties of the COB products were investigated through photometric and decapping methods to determine the optical signature and construction (e.g., number of LED die, LED die size, connection methods) of each product [1]. The previous study also reported on the reliability of the COB-X products through 6,000 hrs of a room-temperature operating life (RTOL) test and an operational lifetime temperature test at 75°C (75OL). In this current report, the test matrix was expanded for the RTOL test from 3 DUTs per product to 10 DUTs per product to comply with ANSI/IES LM-80-20 [11] and ANSI/IES TM-21-19 [12] standards and updated results are provided for a minimum of 10 samples through 6,000 cumulative hrs. In this current report, AST results are also provided for an elevated temperature and humidity test of 75°C and 75% RH (7575) through 6,000 hrs of cumulative testing. In addition, the report discusses the anaerobic effects on COBs and Product HP-1 through 2,000 hrs of cumulative testing.

3.1 Testing Environments and Procedures

Stress testing has been recognized as the optimal approach to study the likely failure modes of LED packages in a reasonable amount of time [13]. This method was previously applied to MP-LEDs [14, 15, 16] and HP-LEDs [14–16]. However, there are far fewer reports of stress testing of the COB LED package in the lighting literature.

There were three principal testing environments that were used for this study, and separate populations of samples were used for each environment. The test environments were as follows:

1. RTOL studies conducted on all products (except Products COB-1 and HP-1) at mostly mid-range values of I_f for each product
2. 7575 studies conducted on all products (except Products COB-1 and HP-1) at mostly mid-range values of I_f for each product
3. Anaerobic studies conducted on all products (except Product MS-2) at I_f values approaching the specified maximum for the product.

The samples of each product were divided into separate populations for the RTOL, 7575, and anaerobic tests, and no sample was subjected to more than one test environment. A total of 10 different samples were used for each COB-X product in RTOL and 7575, whereas only 2 samples were used for COB-X products in the anaerobic test. The sample population for Product MS-2 was three DUTs in both RTOL and 7575. There were three samples for product HP-1 in the anaerobic test.

Photometric measurements were taken for all DUTs before testing and after at least every 1,000 hrs (RTOL, 7575) of test by using the procedures described in **Section 3.3** of this report. Anaerobic samples were photometrically tested more frequently as described in **Section 3.1.3**. After photometric testing, the DUTs were returned to RTOL, 7575, or anaerobic exposure for continued testing.

For all ASTs, the DUTs were mounted on appropriate heat sinks as described in the previous report [1]. In addition, all DUTs were continuously operated (i.e., no power cycling) in their respective environments. The temperatures of DUTs in all ASTs were monitored by using a combination of thermocouples and thermal imaging. More details about the exact experimental conditions, including I_f values, heat dissipation techniques, and heat sink temperatures, for each AST, are provided in the remainder of **Section 3**.

3.1.1 RTOL

This current work expanded the COB-X RTOL population from three or four DUTs per product to 10 DUTs per product. All DUTs were used as received from the manufacturer and mounted to heat sinks as described in the previous report [1]. The COBs were powered by a dimmable LED driver. Heat sink temperatures were monitored at the start of testing, but generally were not monitored through aging unless an issue was observed. The specific operating conditions, including I_f of the COB package and current density of the individual LEDs within the COB package, are listed in **Table 3-1**.

Table 3-1. Operating Values for RTOL DUTs

Product	Number of DUTs	Nominal I_f (mA)	Current Density (A/cm²)	T_c (°C)	Manufacturer's Maximum I_f at T_c (mA)
COB-2	10	500	23.1	63	1,050
COB-3[a] (2,700 K)	10	350	15.6	68	700[b]
COB-3[a] (6,500 K)	10	350	20.8	68	700[b]
COB-4	10	1,000	41.3	80	1,400
COB-5	10	500	44.5	72	700
COB-6	10	500	11.3	76[c]	810

Note: A/cm² = amperes per square centimeter.

[a] There are 10 total DUTs for Product COB-3. Each DUT has both the 2,700 K and 6,500 K channels operated continuously during AST.

[b] The maximum dc current for Product COB-3 is the maximum combined drive current between both the 2,700 K and 6,500 K LED channels. For example, if 700 mA is applied to the 2,700 K channel, then no current may be applied to the 6,500 K channel.

[c] The value reported for Product COB-6 is T_j.

3.1.2 7575 Environment

For each COB-X product in 7575, there were at least 10 DUTs. All DUTs were used as received from the manufacturer and mounted to heat sinks as described in the previous report [1]. The COB–heat sink ensemble was placed into a temperature and humidity chamber, and the COB was powered by a dimmable LED driver. The LED driver was placed external to the temperature and humidity chamber so that it was operated at only at room temperature conditions. Heat sink temperatures of COB-2 were monitored at the start of testing, and T_c values remained below 87°C. The rest of the COB-X products were expected to have similar T_c values but generally were not monitored through aging unless an issue was observed. The specific operating conditions, including I_f of the COB package and current density of the individual LEDs within the COB package, are listed in **Table 3-2**.

Table 3-2. Operating Values for 7575 DUTs

Product	Number of DUTs	Nominal I_f (mA)	Current Density (A/cm²)	Manufacturer's Maximum I_f at T_c (mA)
COB-2	10	500	23.1	1,050
COB-3[a] (2,700 K)	10	350	15.6	700[b]
COB-3[a] (6,500 K)	10	350	20.8	700[b]
COB-4	10	1,000	41.3	1,400
COB-5	10	500	44.5	700
COB-6	10	500	11.3	810

[a] There are 10 total DUTs for both tunable products (i.e., Products COB-3). Each DUT has both the 2,700 K and 6,500 K channels operated continuously during AST.

[b] The maximum dc current for Product COB-3 is the maximum combined drive current between both the 2,700 K and 6,500 K LED channels. For example, if 700 mA is applied to the 2,700 K channel, then no current may be applied to the 6,500 K channel.

[c] The value reported for Product COB-6 is T_j.

3.1.3 Anaerobic Environment

The anaerobic chamber used for this study was previously used for another program and is shown in **Figure 3-1**. The anaerobic chamber is 32.25 inches × 33 inches × 34 inches and has a sample door with dimensions 8 inches × 14 inches. The chamber has glass walls, whereas the ceiling and bottom are composed of Lexan and painted medium-density fiberboard. The ceiling of the chamber contains ports and tubing where inert gases are introduced and where sensors (e.g., internal pressure gauge) are connected. The bottom of the chamber contains a vacuum port constructed of copper tubing and a one gang electrical alternate current (ac) power box as shown in **Figure 3-2**. The chamber maintains an inert environment by introduction of an inert gas through four tubes in its ceiling, which places positive pressure inside the chamber.

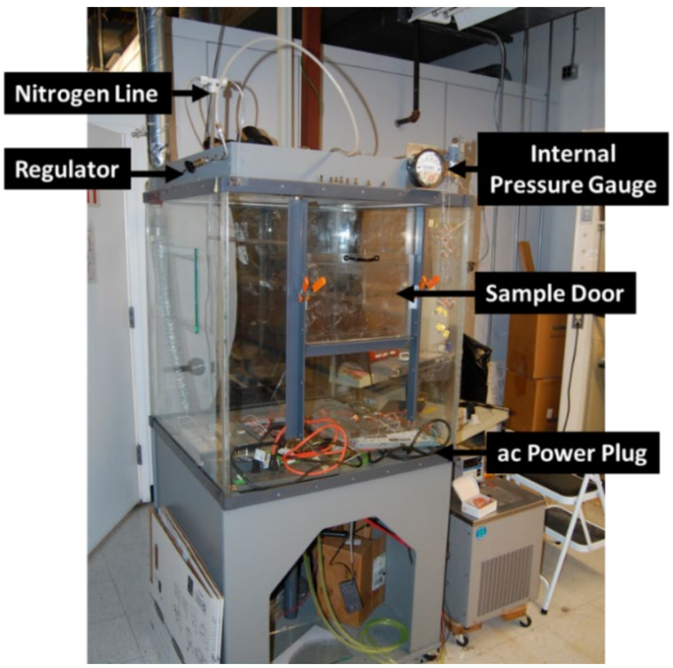

Figure 3-1. Anaerobic chamber used in this study.

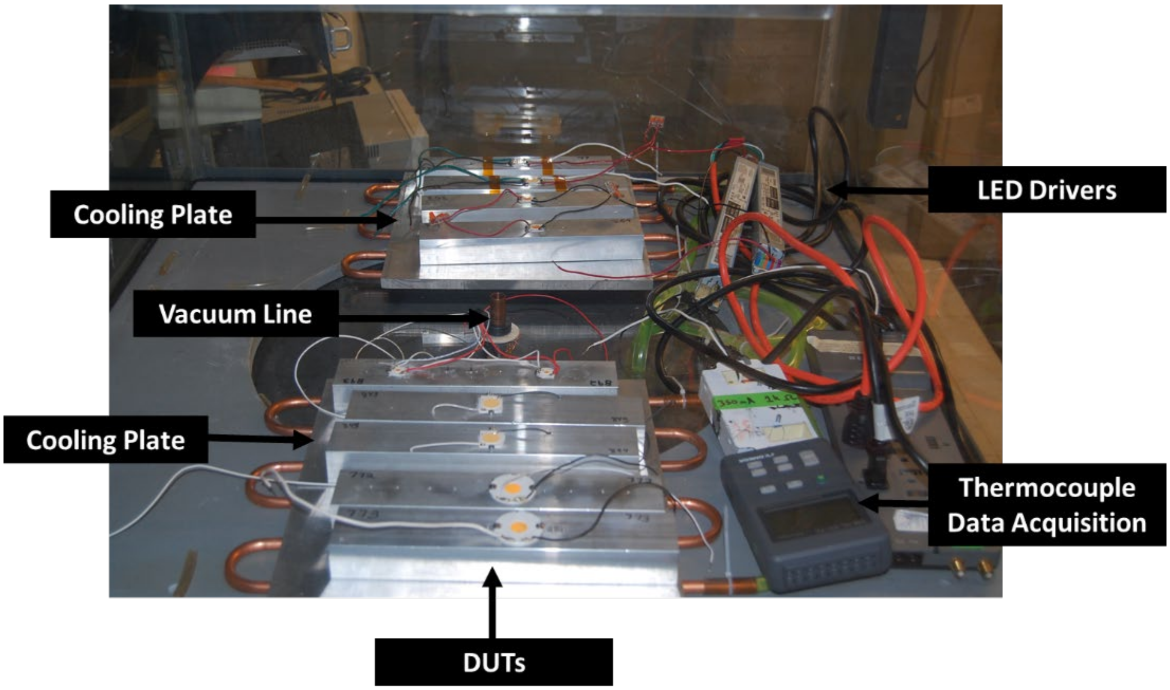

Figure 3-2. DUT setup for the anaerobic tests.

For the experiments detailed in this report, nitrogen was used as the inert gas. The nitrogen was medical grade (purity post-fill = 99.9999%, oxygen = 0.50 parts per million per volt [ppm/V], carbon monoxide = 0.43 ppm/V), and the regulator was set to 35 pounds per square inch (psi). After the DUTs and associated equipment (e.g., LED drivers, power strip, thermocouples, data logger, cooling plates) were placed inside the chamber as shown in **Figure 3-2**, a purging procedure was used to flush oxygen from the system. At first, the vacuum port was used to help during this procedure, but the vacuum port could not be sealed well from outside the chamber and continuous operation of the vacuum during testing consumed too much nitrogen. Therefore, the vacuum port was internally plugged, and the entire chamber was flushed with high-pressure nitrogen for at least 30 minutes. The chamber was then sealed (while still under high nitrogen flow), and subsequently regulated to maintain an internal positive pressure of 0.07 inches of water. After the purge process was complete, the DUTs were turned on.

The anaerobic chamber and experimental process was validated by using the commercial HP-1 LED that has been shown by others to display a darkening LES effect under high photon flux in low oxygen environments. The population size of Product HP-1 during the proof-of-concept work was three DUTs. The population size of each COB product was only two DUTs. All DUTs were used as received from the manufacturer and mounted to heat sinks as described in the previous report [1]. To maintain a sealed and inert environment, the COB–heat sink ensembles, a surge protector power strip, and the dimmable LED drivers were placed inside the chamber. In initial experiments, the COB–heat sink ensembles were placed directly onto the bottom of the chamber with no further heat dissipation aside from the heat sink. Because it was unknown whether the COBs would experience darkening effects in anaerobic environments, mild conditions (i.e., modest I_f values) were chosen first to prevent rapid darkening. If no effect was observed in 240 hrs, then I_f was increased toward the maximum I_f. During this preliminary testing, it was apparent that temperature regulation was necessary at the higher I_f values when temperature-induced failures similar to those shown in **Figure 3-3** were observed. Two cooling plates, each with dimensions 12 inches × 12 inches, were constructed, and the COB–heat sink ensembles were set on top of them while they were operating as shown in **Figure 3-2**. A single water line was fed to the cooling plates through one of the chamber ports by an external water chiller set to 3°C. During testing, the temperatures of the heat sinks were monitored with an eight-channel thermocouple data acquisition logger.

Figure 3-3. Temperature-induced failure of Product COB-4.

After the drive current of each product was established and cooling plates were constructed, new DUTs were constructed for each product and anaerobic testing was started. Heat sink temperatures were monitored for at least a few hours during each experiment. The specific operating conditions, including I_f of the COB package and current density of the individual LEDs within the COB package, are shown in **Table 3-3**. The COB DUTs were evaluated photometrically and microscopically at 240 hrs; 1,000 hrs; and 2,000 hrs. Electrical characterization was performed at the end of test (i.e., at 2,000 hrs).

Table 3-3. Operating Values for Anaerobic DUTs

Product	Number of DUTs	Nominal I_f (mA)	Current Density (A/cm²)	T_c (°C)	Manufacturer's Maximum I_f at T_c (mA)
COB-2	2	1,040	48.2	56	1,050
COB-3 (2,700 K)	2	350	15.6	42	700[b]
COB-3 (6,500 K)	2	350	20.8	42	700[b]
COB-4	3	1,340	55.4	73	1,400
COB-5	2	500	44.6	43	700
COB-6	2	765	17.3	64[a]	810

[a] The value reported for COB-6 is T_j.

[b] The maximum dc current for Product COB-3 is the maximum combined drive current between both the 2,700 K and 6,500 K LED channels. For example, if 700 mA is applied to the 2,700 K channel, then no current may be applied to the 6,500 K channel.

3.2 I-V Measurements

During the study, current-voltage (I-V) measurements were collected on selected samples from RTOL, 7575, the anaerobic chamber, and their control DUTs at the end of test by using a calibrated and programmable Keithley 2410 1100 V source meter operating under computer control. The computer program operating the source meter changed V_f of the DUT in a linear ramp between a preset initial value and final value. This source meter can measure currents as low as 10^{-12} amperes (A).

3.3 Photometric Measurement Methods

The spectral power distribution (SPD) of all samples were measured at room temperature and luminous flux, radiant flux, chromaticity, and other related items were calculated. The samples were measured in a calibrated 65-inch integrating sphere where they were mounted in the center of the sphere (4π geometry). Regular calibrations of the integrating sphere were performed by using a calibrated spectral flux standard 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; this process is in accordance with procedures in the joint ANSI and IES standard ANSI/IES LM-79-19 [17]. The center post was used to supply dc current to all DUTs. For the COB LEDs and Product HP-1, dc power was provided by a driver preset to the appropriate I_f value.

Due to temperature-dependent semiconductor properties, an LED experiences a loss in efficiency with increasing T_j (referred to as thermal droop). Therefore, it is well-known that under normal conditions (e.g., the LED is resting at room temperature with no outside influence), luminous flux is highest directly after an LED is turned on, and then reaches a steady-state value after thermal equilibrium is reached as shown for Product HP-1 (DUT-822) in **Figure 3-4A**. For

RTOL and 7575 DUTs, a warmup period of at least 1 hr prior to photometric measurement was followed to allow for thermal equilibrium to be reached.

However, after Product HP-1 (DUT-822) is operated in an anaerobic environment for 240 hrs, it experiences a drastic decline in LFM (i.e., 0.19). Upon operation in air, the loss in LFM for Product HP-1 is reversible, and its reversibility is faster than the effects of thermal droop as shown in **Figure 3-4B**. The integrating sphere is not an anaerobic environment, and because operation of the anaerobic samples in air can possibly change the DUTs as shown in **Figure** 3-4**B**, no warmup period was used for the DUTs during the anaerobic test. Instead, a two-person team was used in which one person would turn on the sample (already inside the integrating sphere) and the other person would measure the sample as quickly as possible (i.e., "0 minutes" measurement). The researchers would leave the COB turned on inside the integrating sphere and would also measure it after 1 minute, 2.5 minutes, and 5 minutes of warmup. As a result, each DUT in the anaerobic environment was photometrically measured 4 times within 5 minutes to watch the effects of air on the sample. A sampling of the luminous flux over this 5-minute period during different days and months of the study for Product HP-1, control DUT-818, is shown in **Figure 3-5**.

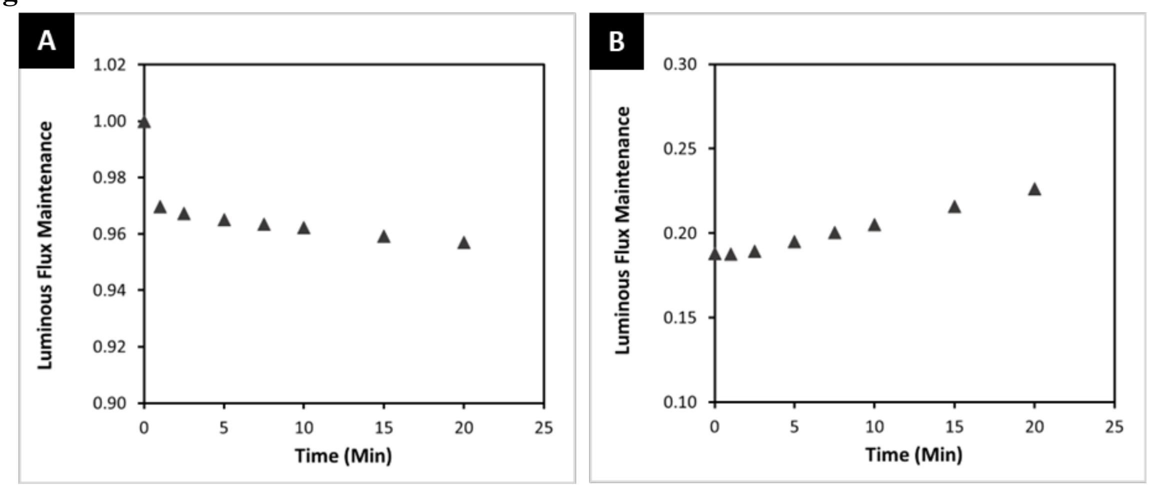

Figure 3-4. The LFM of Product HP-1 (DUT-822) during the first 20 minutes after the LED is turned on (from T_j = 22°C) (A) before anaerobic test and (B) after 240 hrs of anaerobic test.

The two-person team found that the measurements at 0 minutes provided luminous flux values that were reproducible enough (±1%) for Products COB-2, COB-3, COB-5, COB-6, and HP-1. The Product COB-4 control DUT experienced a systematic decrease in LFM down to 0.97 at the 0-minutes timepoint, likely because of LED burn-in at the high flux densities. No attempt was made to correct for this decrease in LFM. For simplicity and unless otherwise noted, luminous flux and chromaticity values are reported at the 0 minutes warmup timepoint for all anaerobic samples.

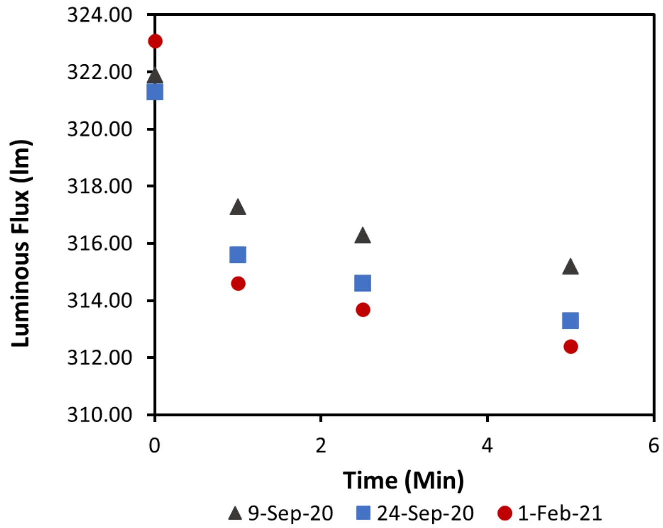

Figure 3-5. Luminous flux values (in lumens [lm]) of Product HP-1, control DUT-818, of during the 5-minute photometric measurement window show reproducibility at the 0-minutes timepoint.

Chromaticity coordinates (i.e., u', v') were calculated from the SPDs by using standard formulas. By monitoring the chromaticity at each measurement time, the change in individual chromaticity coordinates (i.e., $\Delta u'$, $\Delta v'$) and the magnitude of the total chromaticity change ($\Delta u'v'$) can be calculated. The chromaticity of a COB LED is a balance of light emissions from the pump LED and the phosphors. When the balance changes, the chromaticity will shift. There are four primary directions in which the chromaticity can shift, as shown in **Figure 3-6** using the International Commission on Illumination (*Commission Internationale de l'Éclairage* [CIE]) 1976 color space [3, 18]. Chromaticity shifts in each of these directions can be assigned to different chromaticity shift modes (CSMs), with the assignment of the CSM being determined by the direction of the chromaticity shift [3, 18]. The most common CSM assignments are presented in **Table 3-4**.

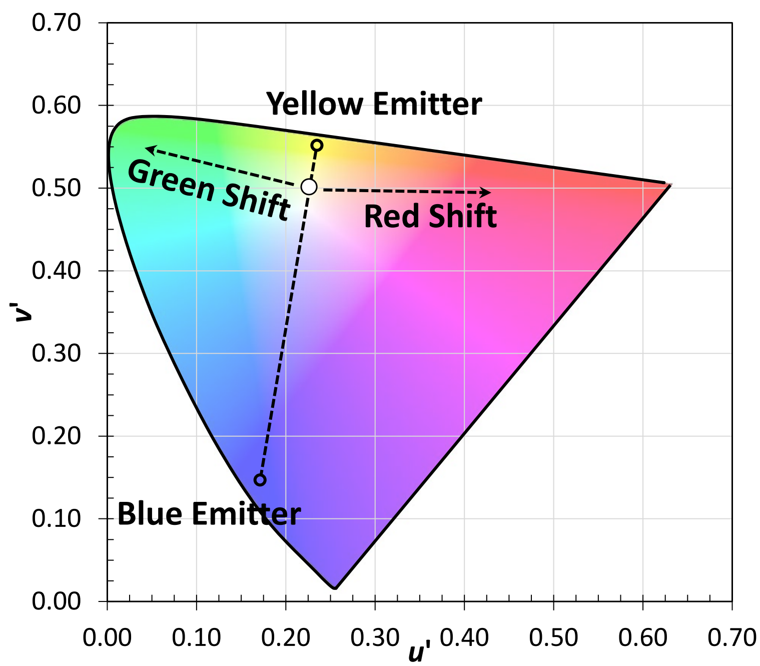

Figure 3-6. The four major directions of chromaticity shift in a COB are toward the blue emitter, toward the green emitter, toward the yellow emitter, and toward the red emitter [18].

Table 3-4. Primary CSMs Observed in LEDs [3, 18–20]

CSM	Direction of Shift	Changes in *u'* and *v'*
CSM-1	Blue	During a blue shift, both *u'* and *v'* decrease.
CSM-2	Green	During a green shift, *u'* decreases and *v'* changes little.
CSM-3	Yellow	During a yellow shift, both *u'* and *v'* increase, with the change in *v'* being larger.
CSM-4	Complex shift first shift blue, then yellow, then blue	During a blue shift, both *u'* and *v'* decrease. During a yellow shift, both *u'* and *v'* increase, with the change in *v'* being larger.
CSM-5	Red	During a red shift, *v'* changes little and *u'* increases.

4 Results

4.1 RTOL Testing

RTOL consisted of operating all COB DUTs at intermediate I_f values (**Table 3-1**). To align with the minimum sample population requirements of ANSI/IES TM-21-19 [12], the test population for each product was set to 10 DUTs. Products COB-2, COB-5, and COB-6 were purchased and started at two separate times: prior to June 2020 and July 2021. The original testing for these three products began in June 2020 with original COB population set to three DUTs for Products COB-2 and COB-6 and four DUTs for Product COB-5. During July 2021, additional COBs were purchased and added to the initial test population to bring the total number of DUTs to 10 for each product. For Products COB-3 and COB-4, all 10 DUTs were started at the same time after

July 2021 (but some of the DUTs may have been purchased during the June 2020 acquisition). All DUTs were operated until they reached at least 6,000 hrs, and no parametric or abrupt failures occurred for any COB product in the RTOL environment during that time.

4.1.1 Luminous Flux Maintenance

The LFM of the COB products was measured by photometrically testing the DUTs after every 1,000 hrs of operational exposure in the RTOL environments according to ANSI/IES LM-80-20 [11]. The average LFM measurements of all 10 DUTs for each COB product were analyzed and fitted with an exponential decay model according to ANSI/IES TM-21-19 [12] as presented in **Figure 4-1**. In general, the average LFM of all COB DUTs tested in the RTOL environment were excellent throughout the 6,000 hrs, with all products except COB-6 having an LFM above 0.90 at the end of the test. Product COB-6 experienced a sharp drop in emissions during the first 1,000 hrs of testing, but then experienced very small changes in LFM after the initial drop.

One of the restrictions of ANSI/IES TM-21-19 is that the decay rate constant (α) cannot be less than 2.0×10^{-6} [12]. Computed values of α below that threshold must be given the value of 2.0×10^{-6}. In addition, luminous flux values must not be projected beyond 5.5 times the total test duration of measured data for samples sizes between 10 and 19 units. Using these two restrictions, the least-squares calculated values of α and the projected initial constant (B), and the projected time to reach an LFM of 0.7 (i.e., L_{70}) for the COB products is given in **Table 4-1**. In general, the projected time to reach L_{70} for the COB products was greater than 33,000 hrs, which is the maximum projection time allowed by the 5.5 times rule of ANSI/IES TM-21-19, demonstrating that the COBs have good LFM at RTOL conditions.

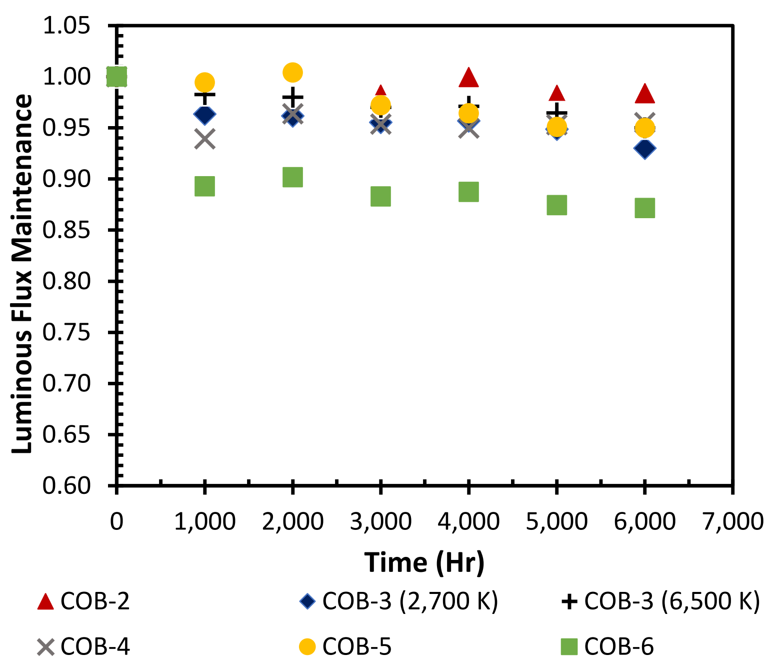

Figure 4-1. Average LFM of the COB product populations during RTOL.

Table 4-1. Projected Time to Reach L_{70} for the RTOL DUTs According to ANSI/IES TM-21-19

Product	Decay Rate Constant (α)	Projected Initial Constant (B)	TM-21-19 L_{70} Projection (hrs)
COB-2	2.0×10^{-6} [a]	0.98	> 33,000[b]
COB-3 (2,700 K)	6.2×10^{-6}	0.97	> 33,000[b]
COB-3 (6,500 K)	6.1×10^{-6}	0.99	> 33,000[b]
COB-4	2.0×10^{-6} [a]	0.95	> 33,000[b]
COB-5	1.1×10^{-5}	1.01	32,200
COB-6	5.9×10^{-6}	0.90	> 33,000[b]

[a] According to ANSI/IES TM-21-19, α cannot be less than 2.0×10^{-6} [12].

[b] According to IES TM-21-19, for sample sizes between 10 and 19 DUTs, L_{70} projection is limited to 5.5 times the total test duration of measured data [12].

As previously mentioned, three DUTs each of Products COB-2 and COB-6 and four DUTs of Product COB-5 were purchased and entered testing prior to June 2020. Then, after July 2021, the sample population was increased to 10 for all COB products. For all RTOL DUTs, the room temperature fluctuated between 22 ± 2°C, and the RH fluctuated between 25% and 85% and was not explicitly controlled (other than by the building's heating, ventilation, and air conditioning [HVAC] unit) during that time. During testing, it was observed that the average LFM of Products COB-2 and COB-6 were higher for the DUTs started in June 2020 than for those started in July 2021 as shown in **Figure 4-2**. A two-sample *t*-test indicated that there was a significant difference between the two means of the DUTs operated during June 2020 and July 2021 for Products COB-2 and COB-6, but not for Product COB-5. The difference in these populations could be because of differences in manufacturing techniques between the two purchase times, slight differences in the RTOL test conditions, or both.

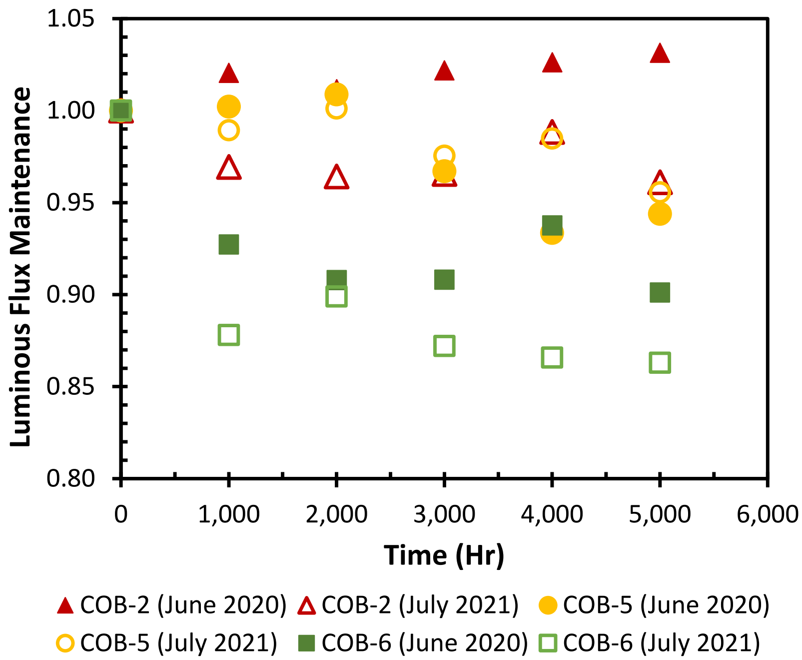

Figure 4-2. Average LFM of the separate populations of Products COB-2, COB-5, and COB-6 that started operation in June 2020 and July 2021.

4.1.2 Chromaticity Maintenance

The evolution in the change of the average chromaticity shift of the DUTs for each product is shown in **Figure 4-3**. There are two elements of chromaticity shift that must be examined: (1) the magnitude of the chromaticity shift reported as $\Delta u'v'$ and (2) the direction of the chromaticity shift, which is best viewed as a graph of $\Delta u'$ versus $\Delta v'$. As part of the parametric failure criteria, if $\Delta u'v'$ for a DUT exceeds 0.007, then the DUT is considered to be a parametric failure because of excessive chromaticity shift [3]. In general, the magnitude of chromaticity shift of the COB products operated at RTOL remained good through 6,000 hrs of test, and no parametric failures were observed.

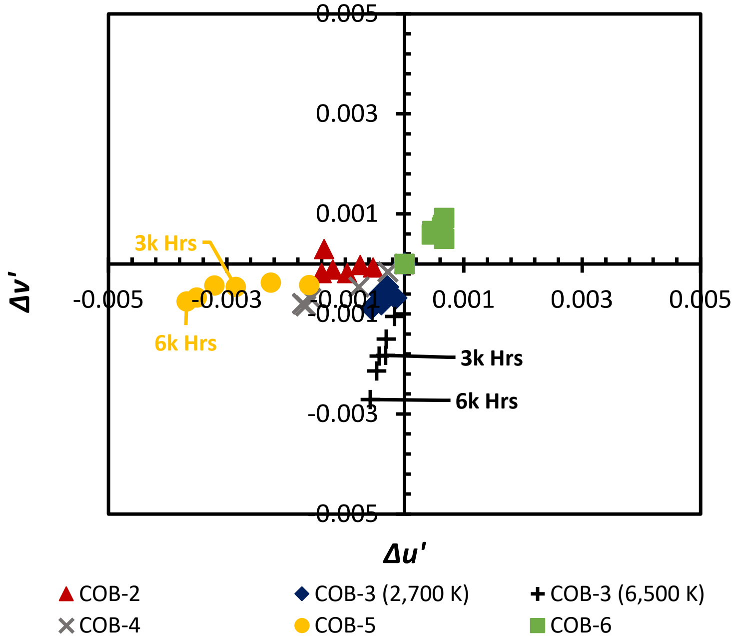

Figure 4-3. Chromaticity shifts of the COB products during RTOL testing.

There are five likely CSMs as shown in **Table 3-4** that have been described [3, 18, 19]. Three of the COB products (i.e., COB-2, COB-4, and COB-5) displayed the behavior of CSM-2: a shift mainly in the $-\Delta u'$ chromaticity coordinate toward the generally green direction. Both LED primaries (i.e., 2,700 K and 6,500 K) of Product COB-3 experienced a shift in the $-\Delta v'$ chromaticity coordinate toward the generally blue direction, indicative of CSM-1 behavior. Product COB-6 experienced a shift in the $+\Delta u'$, $+\Delta v'$ direction along the red-yellow axis. There are a variety of factors can cause chromaticity shifts in LEDs and SSL luminaires. Some of these factors include changes in the direct emitter, changes in the phosphors, changes in the optical system (e.g., lenses, reflectors), and, in some cases, changes in the electrical system [5, 18, 20]. Further analysis of the chromaticity shifts of the COB products is provided for the 7575 DUTs in **Section 4.2.3** of this report.

4.1.3 Current-Voltage Measurements

I-V measurements were taken on select samples of the COB LED upon completion of RTOL testing. The I-V curves for these samples are shown in **Figure 4-4**. The threshold voltages (V_{th}) for these samples are compared to the control samples in **Table 4-2**. The findings from these measurements indicate that the electrical characteristics of the COB LED DUTs during RTOL testing changed little between the beginning and end of the study which is in sharp contrast to the recent study of ultraviolet (UV) LEDs. In the study of UV LED I-V characteristics, significant changes in the electrical properties of the UV LEDs occurred during I-V measurements as a result of trap-assisted tunneling at sub-threshold voltages [21]. These electrical changes accounted for some of the radiant flux depreciation in UV LEDs. Because much less flux depreciation was found for the COB LEDs in the RTOL test, the observed LFM and chromaticity changes must be due to optical changes in the COB LED package.

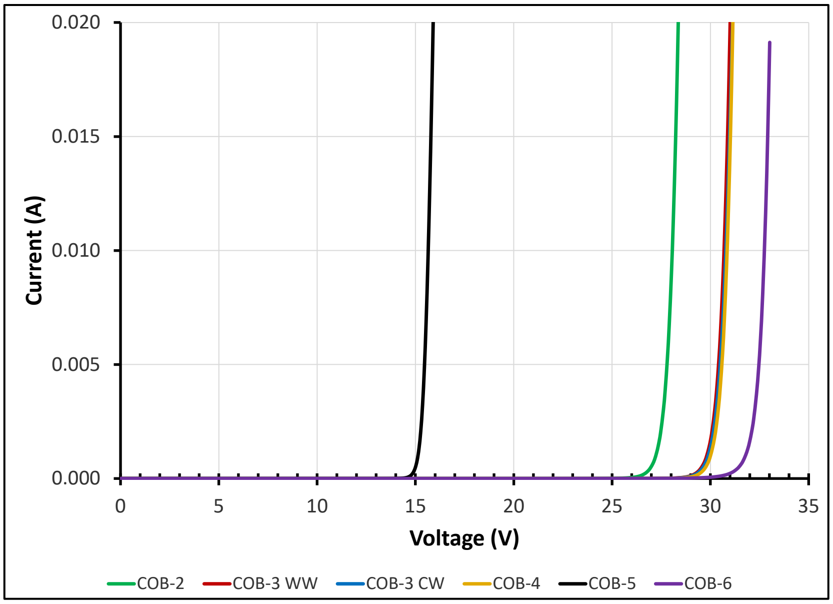

Figure 4-4. I-V measurements of select RTOL DUTs of each product after the completion of RTOL testing.

Table 4-2. Comparison of the V_{th} Values for RTOL DUTs and the Controls for Each Product

Product	V_{th} Control (V)	V_{th} RTOL Samples (V)
COB-2	27.847	27.850
COB-3	30.395	30.420
COB-4	30.618	30.608
COB-5	15.624	15.668
COB-6	32.462	32.493

4.2 7575 Testing

During 7575 testing, all COB DUTs were operated at intermediate I_f values (**Table 3-2**). The test population for each product was set to 10 DUTs except for Product COB-2, which had a test population of 13 DUTs. Products COB-2, COB-5, and COB-6 were purchased and started at two separate times: prior to June 2020 and in July 2021. The original testing for these three products began in June 2020 with the original COB population set to three DUTs for Products COB-2 and COB-6 and four DUTs for Product COB-5. During July 2021, additional COBs were purchased and added to the initial test population to bring the total number of DUTs to 10 for each product. For Products COB-3 and COB-4, all 10 DUTs were started at the same time after July 2021 (but some of the DUTs may have been purchased during the June 2020 acquisition).

In the 7575 environment, many DUTs experienced abrupt or parametric failures as described in **Section 4.2.1** of this report. For the purposes of this report, abrupt failure is defined as a complete loss of light from the DUT or a change in the DUT's physical properties that make it unsafe to operate. A parametric failure is defined as an LFM < 0.70 or $\Delta u'v' \geq 0.007$. When an abrupt failure occurred, the DUT was removed from test and excluded from the calculation of LFM and chromaticity shift averages. When a parametric failure occurred, the DUT was still considered operational, remained in test, and was still included in calculating the LFM and chromaticity shift averages. All operational DUTs were tested until they reached at least 6,000 hrs.

4.2.1 Failures Observed During 7575

There were multiple DUT failures for all COB products operated in the 7575 environment except for Product COB-6. The most common failure mode in 7575 was parametric failure because of excessive chromaticity shift. As shown in **Figure 4-5**, all DUTs (33 total) for Products COB-2, COB-3, and COB-5 failed because of excessive chromaticity shift. Some of these DUTs exhibited an LFM < 0.7 at the same time or after chromaticity shift failure occurred, but the LFM failure was not observed before chromaticity shift failure for any DUT in the test matrix. A detailed analysis of chromaticity shift failures for Products COB-2, COB-3, and COB-5 is presented in **Section 4.2.3** of this report. Parametric failures because of LFM are shown in **Figure 4-6**, and further analysis is provided in **Section 4.2.2** of this report.

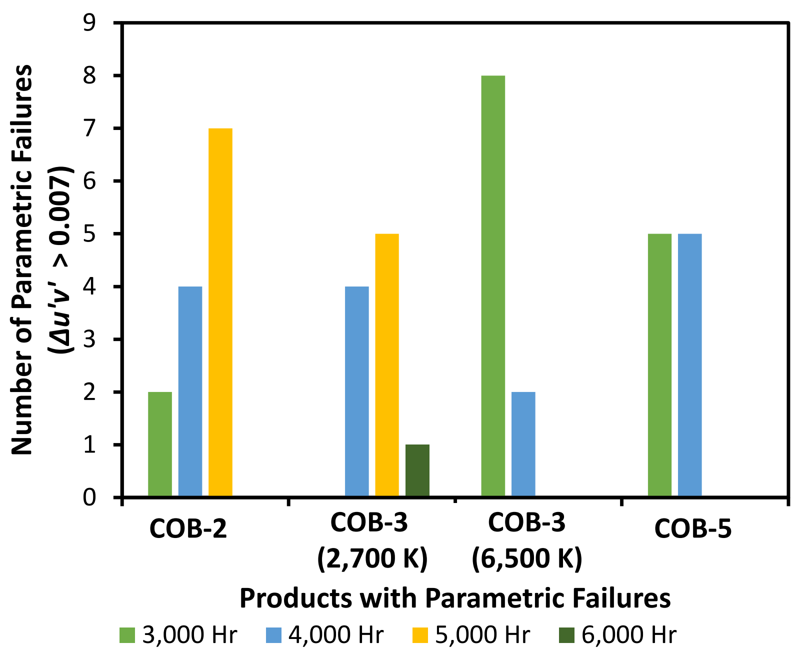

Figure 4-5. Products with parametric failures because of excessive chromaticity shift.

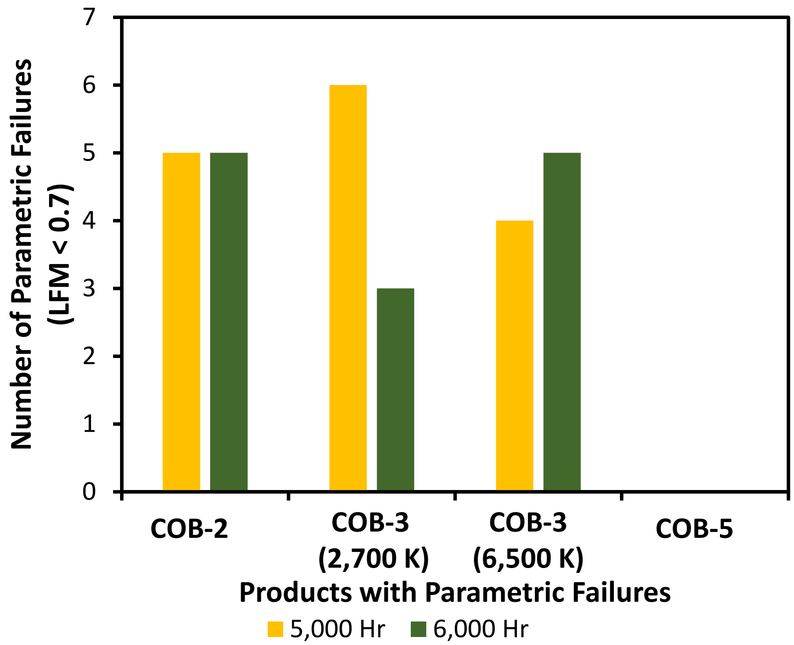

Figure 4-6. Products with parametric failures because of low LFM.

Although Products COB-2, COB-3, and COB-5 experienced a multitude of parametric failures, they did not experience any abrupt failures. However, all DUTs for Product COB-4 were removed from 7575 testing after 4,000 hrs because of discoloration of the electrical leads, oxidation of the conductor wires, and the emergence of silicone cracking as shown in **Figure 4-7**. In most cases, the cracks were entirely within the LES; however, in one case (i.e., Product COB-4 [DUT-947]), the cracks extended all the way into the silicone dam around the LES and even involved delamination of the solder mask from the aluminum nitride (AlN) substrate. In addition, for DUT-947, the silicone cracking was so severe that the LES began to flake off, and the underlying LEDs were left exposed. The discoloration of the electrical leads and oxidation of the conductor wire were the result of the combination of high photon flux, high heat, and high humidity. The Product COB-4 components were purchased from the supplier with the leads already soldered to the board, and, in hindsight, the type of wiring that was chosen was not adequate for the 7575 test. The cracked silicone LES was likely caused by thermal and mechanical stress induced by the high radiant flux of the DUT, the 7575 environment, or both. Such environmental factors can lead to overcuring of the silicone, which reduces its pliability and increases its brittleness [6]. A total of six Product COB-4 DUTs from 7575 had cracked silicones, and all 10 Product COB-4 DUTs in 7575 had cracked and discolored leads.

Figure 4-7. The abrupt failure of Product COB-4 (DUT-944) showing cracked silicones and discolored electrical leads.

The COB-4 DUTs with cracked silicone LESs and damaged leads still produced light within parametric limits except for DUT-944 and DUT-947. Even though there was cracking in the silicone LESs for the DUTs, their SPDs maintained a consistent trend of a stable amount of blue emissions and a gradual decrease in phosphor emissions. However, the consistent decrease in phosphor emissions for DUT-944 led to parametric failure at 4,000 hrs ($\Delta u'v'$ = 0.0090). The SPDs measured for DUT-947 showed much more drastic changes than DUT-944 and the remainder of the COB-4 DUTs with cracked silicone LESs. For DUT-944, the LFM value drastically changed from 0.84 after 3,000 hrs of 7575 to 0.68 after 4,000 hrs. In addition, there was a sudden change in the chromaticity of the DUT with the $\Delta u'v'$ value changing from a relatively modest 0.0049 to 0.071 after 4,000 hrs. The latter value is more than 10 times the parametric limit. The direction of the chromaticity shift is mainly along the $-\Delta v'$ axis, indicating a shift in the blue direction and CSM-1 behavior. As shown in **Figure 4-8**, the significant changes in the SPDs of DUT-947 that occurred between 3,000 and 4,000 hrs of testing can be attributed to a sharp increase in blue emissions and a sharp decrease in phosphor emissions. The root cause of these changes was the loss of part of the phosphor layer in the LES of DUT-947. Although other Product COB-4 DUTs in 7575 exhibited similar cracking, only DUT-947 exhibited significant loss of the phosphor in the LES after 4,000 hrs. It is expected that with continued testing, the other devices would also exhibit this behavior. As a consequence, all 10 Product COB-4 DUTs were removed from testing after 4,000 hrs.

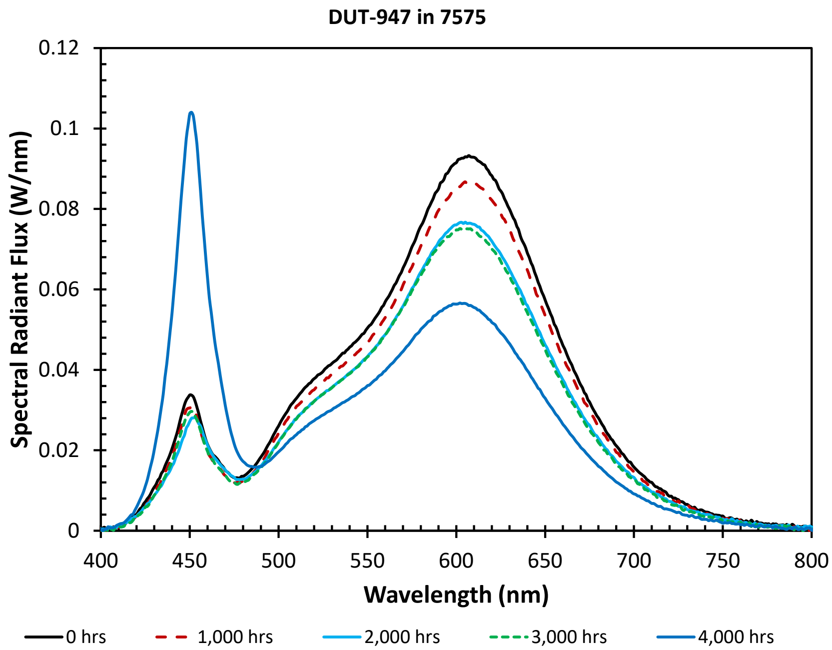

Figure 4-8. SPDs of DUT-947 throughout 7575 AST.

4.2.2 Luminous Flux Maintenance

The average LFM of the COB DUTs examined in the 7575 environment are shown in **Figure 4-9**. The data are shown for all COB products throughout 6,000 hrs except for Product COB-4, which was removed from testing after 4,000 hrs. Prior to being removed from testing, the DUTs from Product COB-4 exhibited the highest LFM value of 0.92 after 4,000 hrs of exposure to the 7575 environment.

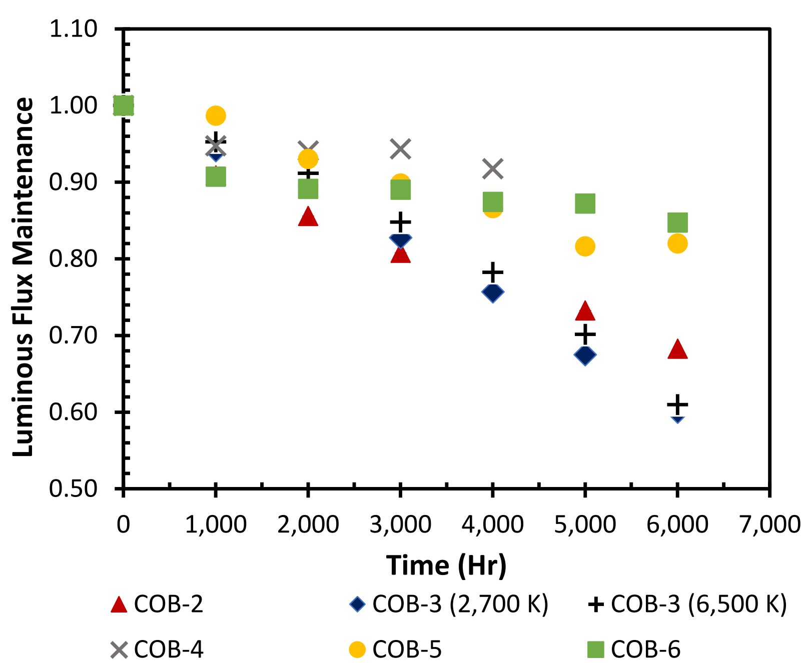

Figure 4-9. Average LFM of the DUTs in the 7575 environment.

Products COB-2 and COB-3 both experienced a steady decline in LFM throughout the entire test, and L_{70} was reached by the end of test for both products. Product COB-5 also experienced a steady decline in LFM, with a decay rate of $\alpha = 4.5 \times 10^{-5}$, which was determined from IES/ANSI TM-21-19. Although it is possible that more than one mechanism is contributing to luminous flux losses for Products COB-2, COB-3, and COB-5, direct observation of more than one mechanism was not observed for the DUTs studied herein. Product COB-6 experienced a sharp drop in emission during the first 1,000 hrs of testing in the 7575 environment, but then experienced a very small emission loss between 1,000 hrs and 6,000 hrs. This finding suggests that there are likely two separate mechanisms contributing to luminous flux degradation for Product COB-6: (1) a fast, initial process and (2) a slower, long-term process. Fitting the Product COB-6 LFM to an exponential model gave the smallest decay rate ($\alpha = 9.7 \times 10^{-6}$) for the 7575 DUTs.

The time to L_{70}, either from interpolation (i.e., Products COB-2 and COB-3) or extrapolation by ANSI/IES TM-21-19 (i.e., Products COB-5 and COB-6) are listed in **Table 4-3**.

Table 4-3. Interpolated and ANSI/IES TM-21-19 Projected Lifetimes for DUTs Examined During 7575 Tests

Product	Nominal CCT (K)	Test Duration (Hrs)	LFM at Test Termination	Time to L_{70} (Hrs)
COB-2	2,700	6,000	0.68	5,656[a]
COB-3 (2,700 K)	2,700	6,000	0.60	4,710[a]
COB-3 (6,500 K)	6,500	6,000	0.61	5,000
COB-4	2,700	4,000	0.92	[b]
COB-5	2,700	6,000	0.82	9,470[c]
COB-6	5,000	6,000	0.85	22,400[c]

[a] L_{70} was determined through linear interpolation of test data.

[b] Testing did not reach the 6,000-hr minimum duration required in ANSI/IES TM-21-19; therefore, L_{70} could not be calculated.

[c] L_{70} was determined by using the α and B parameters found during the ANSI/IES TM-21-19 modeling.

4.2.3 Chromaticity Maintenance

The chromaticity shift and chromaticity maintenance behavior were recorded every 1,000 hrs after 7575 exposure for all COB products through the end of test. As discussed in **Section 4.2.1** of this report, all DUTs for Products COB-2, COB-3, and COB-5 in the 7575 test population failed parametrically because of excessive chromaticity shift (i.e., $\Delta u'v' > 0.007$). DUTs that failed parametrically were not removed from test or from the calculation of the chromaticity shift averages, and the average chromaticity shifts during 7575 testing for all COB products are listed in **Figure 4-10**. The final magnitude of chromaticity shift and CSM are listed in **Table 4-4**.

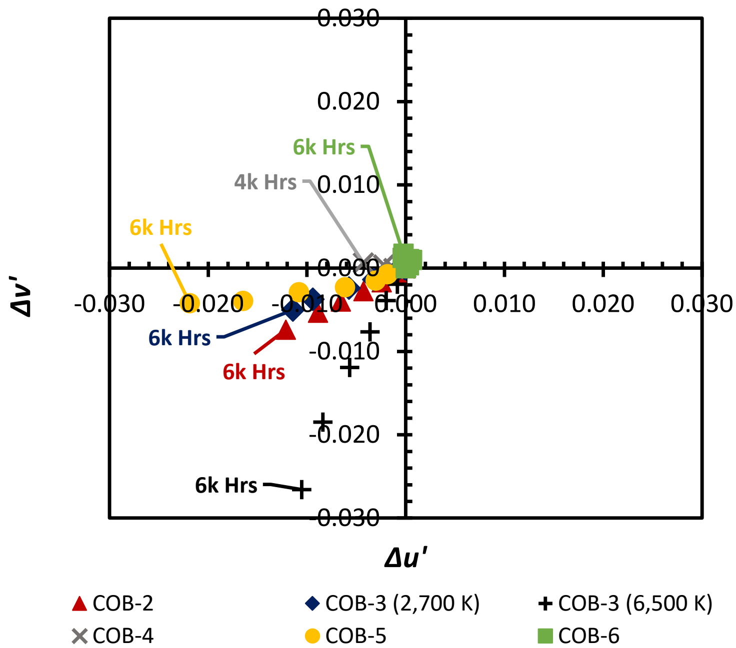

Figure 4-10. Average chromaticity shift for the COB DUTs during 7575 testing.

Table 4-4. Chromaticity Shift Magnitude (*Δu'v'*) and CSM Behavior Observed for 7575 Tests of the DUTs Examined During This Study

Product	Nominal CCT (K)	Test Duration (Hrs)	*Δu'v'*	CSM
COB-2	2,700	6,000	0.0142	CSM-2 + CSM-1
COB-3 (2,700 K)	2,700	6,000	0.0125	CSM-2 + CSM-1
COB-3 (6,500 K)	6,500	6,000	0.0286	CSM-1
COB-4	2,700	4,000	0.0043	CSM-2
COB-5	2,700	6,000	0.0223	CSM-2
COB-6	2,600	6,000	0.0017	CSM-2 + CSM-3

Product COB-2, the warm white channel of Product COB-3 (2,700 K), and Product COB-5 all have nominal CCT of 2,700 K and experienced large changes in *Δu'v'* that were at least partly due to a CSM-2 chromaticity shift that was generally in the green direction. Closer inspection of the SPDs for the DUTs of Products COB-2 and COB-3 (2,700 K) revealed a loss of emissions across the entire SPD, but the loss of red emissions was greater than that of the green emissions, which was greater than for blue emissions for both products. The net result of emission loss contributed to the predominantly CSM-2 and partial CSM-1 mechanism for these products. In contrast, Product COB-5 experienced minimal emission loss at blue and green wavelengths and large emission losses at red wavelengths as shown in **Figure 4-11**. The reduction in red emissions was also accompanied by a shift in the maximum emission wavelength location (λ_{max}) toward lower, green wavelengths. The magnitude of this peak shift was anywhere between 3–8 nanometers (nm) for the DUTs in the Product COB-5 test population.

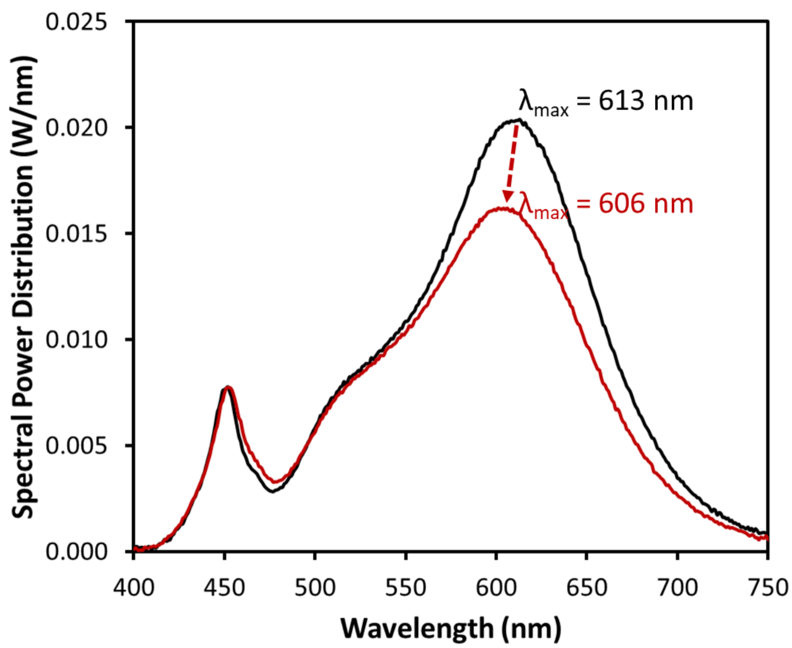

Figure 4-11. Representative DUT-972 from the 7575 test population for Product COB-5 before (black trace) and after 6,000 hrs of operation in the 7575 environment (red trace).

For the cool white channel of Product COB-3 (6,500 K), a predominantly CSM-1 behavior was observed. To understand more about the CSM for Product COB-3, the SPDs were deconvoluted into individual emitters to determine how the relative contributions of individual emitters changed with time. The model used a logistic power peak function to model the blue LED. Two asymmetric Gaussian functions were used to model the broad emission profile of cerium-doped yttrium aluminum garnet (Ce:YAG). Ce:YAG is a commonly used phosphor in white LEDs because of its suitability for use with blue LED chips and reliable aging. Many white LEDs with CCT equal to 6,500 K use the Ce:YAG phosphor so when a spectral model of Product COB-3 was created, Ce:YAG was assumed to be part of the emission profile. The remainder of the emission profile for Product COB-3 (6,500 K) was deduced with a single asymmetric Gaussian for the red phosphor and a single asymmetric Gaussian for a green phosphor as shown in **Figure 4-12**. The parameters of the skewed Gaussian were minimized through the sum of squared errors through a non-linear regression analysis. The radiant power of each emitter was estimated at each timepoint by using the trapezoid rule to approximate the definite integrals of the logistic power peak function and the asymmetric Gaussian that composed the SPD. These results are presented in **Figure 4-13**. The deconvolution shows that the radiant power from the yellow (Ce:YAG) and red phosphors decreases faster than higher energy blue LED and green phosphor emissions (**Figure 4-13A**). The overall effect of the loss of yellow and red emissions is an SPD that increases in relative blue and green emissions with time (i.e., a predominantly CSM-1 mechanism, **Figure 4-13B**).

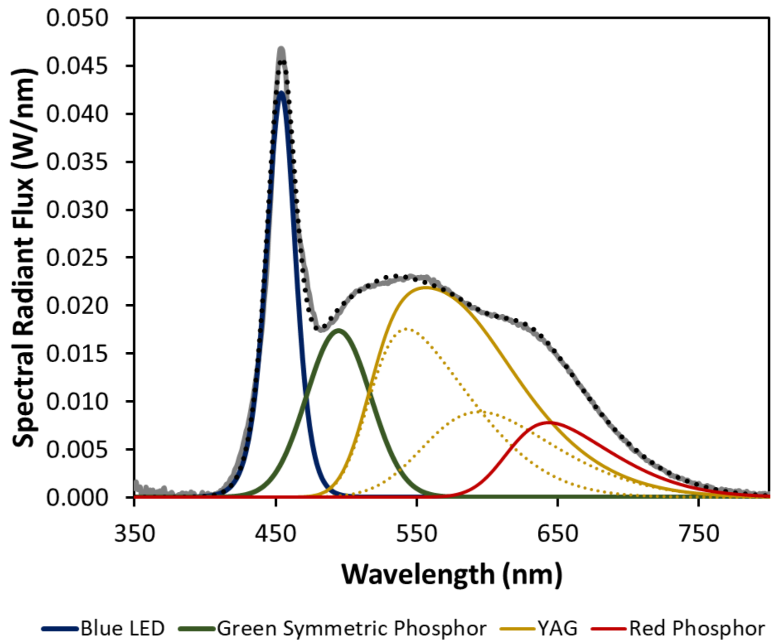

Figure 4-12. Spectral model of the possible individual components for Product COB-3 (6,500 K channel). The gray trace is the original SPD of DUT-928, the black dotted trace is the predicted model, and the yellow dotted traces are the contributions to the Ce:YAG emission profile.

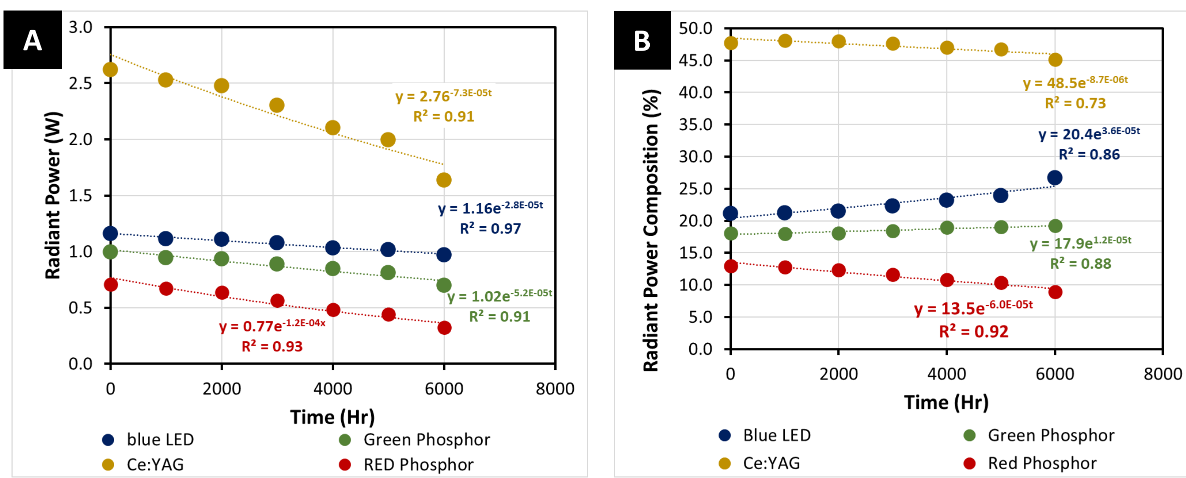

Figure 4-13. Representative DUT-928 of Product COB-3 (6,500 K) from the 7575 test population shows how the (A) radiant power and B) radiant power (in watts [W]) composition of the individual emitters evolved throughout testing.

4.3 Anaerobic Testing

Product HP-1 is known by the industry to undergo darkening effects in low-oxygen environments as shown in **Figure 4-14**. These darkening effects, which are most prevalent at high photon–flux density in an anaerobic environment, can lead to drastically lower LFMs (**Figure 3-4B**). Therefore, the validity of the anaerobic chamber and experimental setup were verified through testing of Product HP-1.

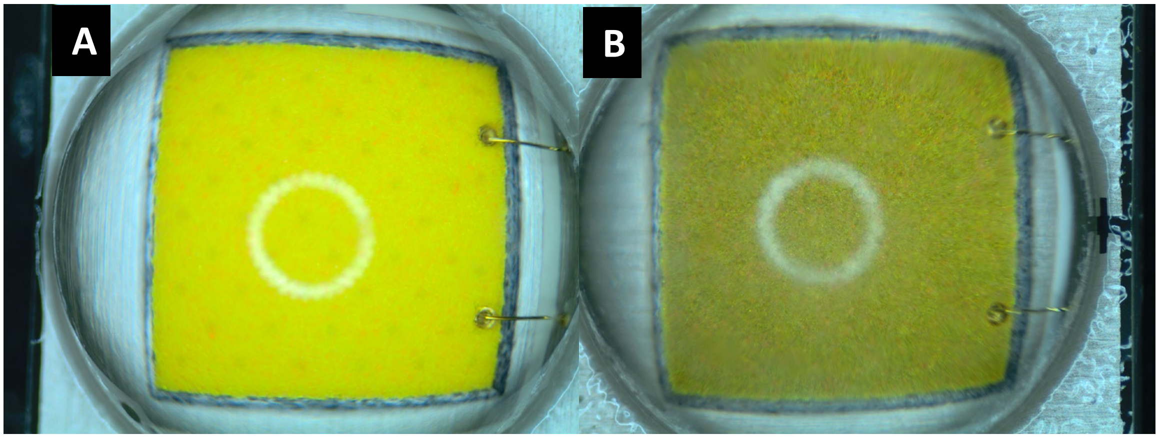

Figure 4-14. Microscope images of a Product HP-1 DUT (A) before and (B) after anaerobic testing. (Photo courtesy of the LSRC).

Anaerobic studies were performed on the COB products through 2,000 hrs of testing. In general, the COB products were operated near their maximum I_f values, as shown in **Table 3-3**, to achieve the high photon–flux densities necessary to initiate the darkening effects. Because Product HP-1 was shown to undergo darkening in a relatively short period (i.e., 240 hrs), COB-X products were photometrically and microscopically measured at 240 hrs; 1,000 hrs; and 2,000 hrs. Microscopic images before testing ("0 hrs") and at the end of anaerobic testing are shown in **Appendix A**, SPDs are presented in **Appendix B**, and electrical data are shown in **Appendix C** of this report.

4.3.1 Failures Observed During Anaerobic Testing

During the proof-of-concept work involving Product HP-1, several DUTs failed because of poor thermal management; these failures are not discussed in this report. After these initial failures (and as described in **Section 3.1.3** of this report), a cooling plate was designed and set to 3°C to carefully control the temperature of the DUTs in the anaerobic chamber. After this adjustment was made, one DUT (i.e., DUT-860) from Product COB-4 was classified as a parametric failure by 1,000 hrs. DUT-860 was still operating at the end of test with an LFM = 0.44 and $\Delta u'v'$ = 0.0065 along the $+\Delta u'$, $+\Delta v'$ (red-yellow) axis. However, the silicone–phosphor mixture on DUT-860 showed evidence of damage (the cause remains unknown, see **Figure 4-15**); therefore, the DUT was removed from testing.

Figure 4-15. DUT-860 failed in the anaerobic environment after 1,000 hrs.

4.3.2 Luminous Flux Maintenance

The LFM of the COB DUTs in the anaerobic environment are shown in **Figure 4-16**. As discussed in **Section 3.3** of this report, the LFM values shown in **Figure 4-16** are representative of the 0-minutes timepoint (i.e., the photometric measurement was taken as quickly as possible after the device was turned on). All DUTs reached 2,000 hrs of testing except DUT-858, which was added after DUT-860 failed, and only reached 1,000 hrs of testing.

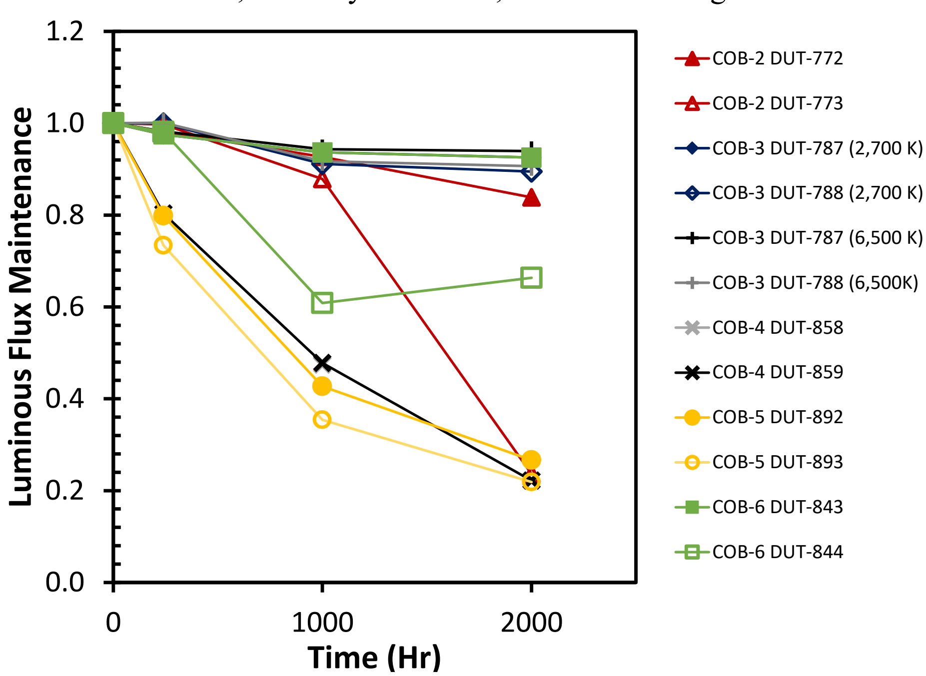

Figure 4-16. Luminous flux maintenance for the DUTs in the anaerobic environment.

Product COB-3 showed the greatest LFM stability in the anaerobic environment, with both LED primaries having LFM values greater than 0.89 at the end of test for all DUTs. In contrast, all DUTs of Products COB-4 and COB-5 experienced large drops in LFM values when operating in the anaerobic environment. Microscopic images before test ("0 hrs") and at the end of anaerobic testing for these products are shown in **Figure A-5** through **Figure A-8** of **Appendix A**. These images show darkening of the LES concentrated around the individual LEDs of the COBs. After just 2,000 hrs, the average LFM value for Product COB-5 was 0.24. For Product COB-4, DUT-858 had an LFM of 0.47 by 1,000 hrs, whereas the LFM of DUT-859 dropped to 0.22 by 2,000 hrs. For Products COB-4 and COB-5, the anaerobic environment greatly accelerated luminous flux depreciation relative to the 7575 environment. The acceleration factor could not be calculated for Product COB-4 because the 7575 DUTs only reached 4,000 hrs at the end of test. However, for Product COB-5, the anaerobic environment was approximately 16 times more accelerating than the 7575 environment even though the T_j value of the DUT was undoubtedly lower because of the use of the cooling plate in the anerobic environment.

For Product COB-2, both DUTs had LFM values greater than 0.87 at 1,000 hrs. By 2,000 hrs, however, the LFM of DUT-773 dropped to 0.24, and the LFM of DUT-772 only dropped to 0.84. A similar behavior was observed for Product COB-6 (in which one DUT experienced much lower LFM than the other DUT). A possible explanation for the LFM difference between two DUTs of the same product is that there was an induction period for the anaerobic darkening to take effect. However, the testing window and number of DUTs in this study were not sufficient to explore the magnitude of the induction effect, and more testing is needed to fully understand the behavior.

4.3.3 Chromaticity Maintenance

The chromaticity maintenance of the COB DUTs in the anaerobic environment are shown in **Figure 4-17**. As discussed in **Section 3.3** of this report, the values shown in **Figure 4-17** are representative of the 0-minutes timepoint (i.e., the photometric measurement was taken as quickly as possible after the device was turned on).

All DUTs of Products COB-4 and COB-5 showed large chromaticity shifts ($\Delta u'v' > 0.031$) in the generally blue-green direction ($-\Delta u'$, $-\Delta v'$). The chromaticity shifts were caused by large reductions in the red phosphor emissions relative to the blue LED and green phosphor emissions for both products. Peak shifting of the red phosphor or blue LED pump was not observed for either product.

Products COB-2, COB-3, and COB-6 all showed more modest chromaticity shifts as shown in **Figure 4-17** and **Table 4-5**. The two DUTs for Product COB-2 experienced chromaticity shifts in the generally blue-green direction (changes along the $-\Delta u'$ and $-\Delta v'$ axis), albeit at different magnitudes correlated with LFM (larger LFM losses resulted in larger magnitude of chromaticity shift). In general, Product COB-3 experienced chromaticity shifts in the blue ($-\Delta u'$) direction because of greater loss of emissions from phosphors than the blue LEDs during anaerobic testing. For Product COB-6, DUT-843 experienced a negligible chromaticity shift, whereas DUT-844 experienced a large shift along the $+\Delta u'$, $-\Delta v'$ axis (blue-red direction) at 1,000 hrs, and then turned back along the $+\Delta v'$ axis (yellow direction) at 2,000 hrs. The SPDs of DUT-844 are given in **Figure 4-18**. The large blue-red shift observed at 1,000 hrs for DUT-844 appeared to be caused by greater loss of emissions from phosphors than the violet LEDs. By 2,000 hrs, phosphor emissions appeared to start recovering while the violet emissions remained stable and a yellow shift was observed. A closer inspection of DUT-844 revealed that approximately one-third of the LEDs were dimly lit while others remained bright, suggesting that a failure of one or more of the LED strings within the COB of the DUT occurred. This phenomenon may be the reason for chromaticity shift for DUT-844.

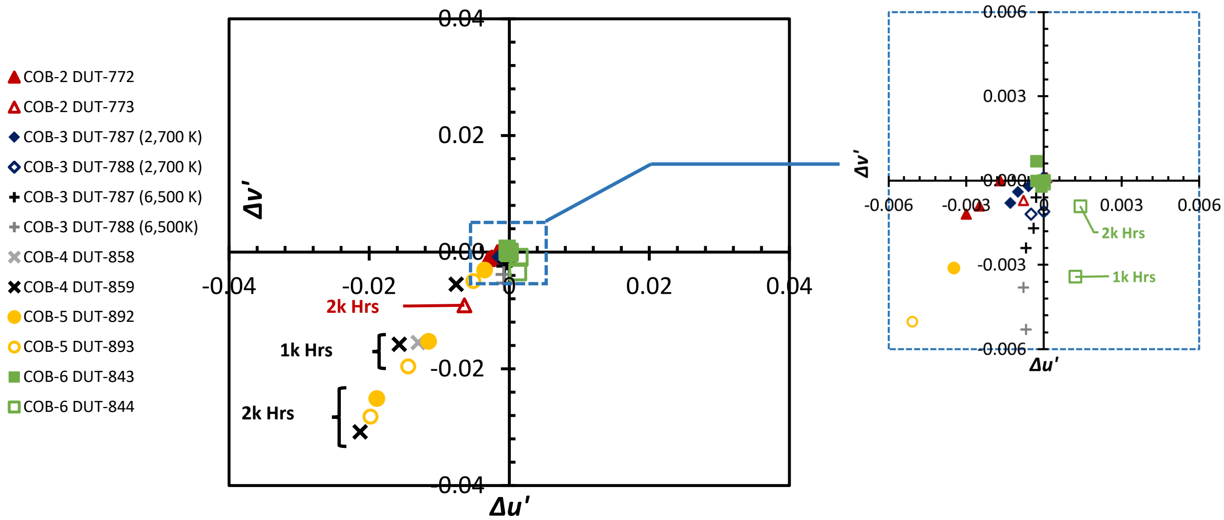

Figure 4-17. Chromaticity maintenance for the DUTs in the anaerobic environment.

Table 4-5. Chromaticity Shift Magnitude ($\Delta u'v'$) and CSM Behavior Observed for Anaerobic Tests of the DUTs Examined During This Study

Product	DUT	$\Delta u'v'$	CSM
COB-2	772	0.0032	CSM-2, and then CSM-1 + CSM-2
COB-2	773	0.0111	CSM-1 +CSM-2
COB-3	787 (2700 K)	0.0015	CSM-1 + CSM-2
	787 (6500 K)	0.0025	CSM-1
COB-3	788 (2700 K)	0.0013	CSM-1
	788 (6500 K)	0.0053	CSM-1
COB-4	858[a]	0.0226	CSM-1 + CSM-2
COB-4	859	0.0374	CSM-1 + CSM-2
COB-5	892	0.0314	CSM-1 + CSM-2
COB-5	893	0.0344	CSM-1 + CSM-2
COB-6	843	0.0002	unassigned
COB-6	844	0.0017	CSM-1 + CSM-5, and then CSM-3

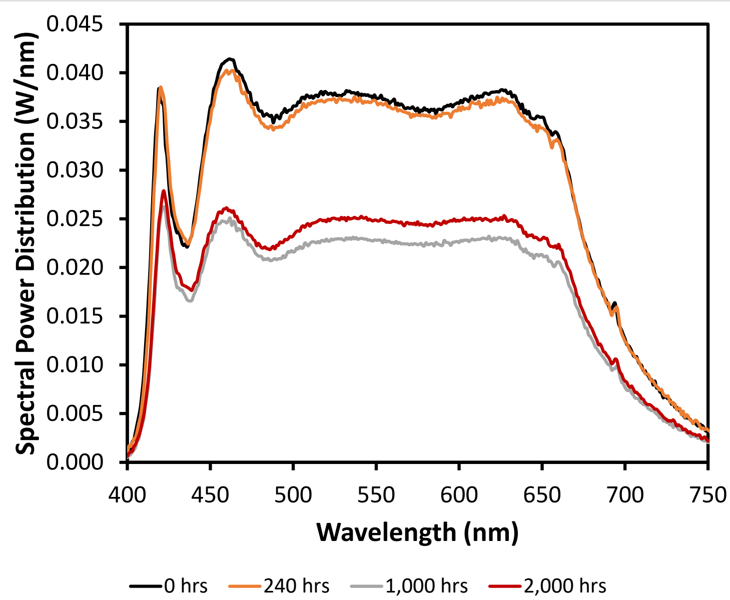

Figure 4-18. SPDs of Product COB-6 (DUT-844) throughout anaerobic testing.

4.3.4 Aerobic Operation

The silicone darkening for Product HP-1 that was observed in low oxygen environments is completely reversible through normal operation in air as shown in **Figure 4-19**. Additionally, subsequent operation of the same DUTs in the anaerobic environment after LFM recovery in air led to lower LFM than the initial drop in LFM for the same 240-hr period (**Figure 4-19**). This phenomenon is not well-understood, but it was not known whether the COB DUTs would undergo the same darkening of the silicone LES in the anaerobic environment.

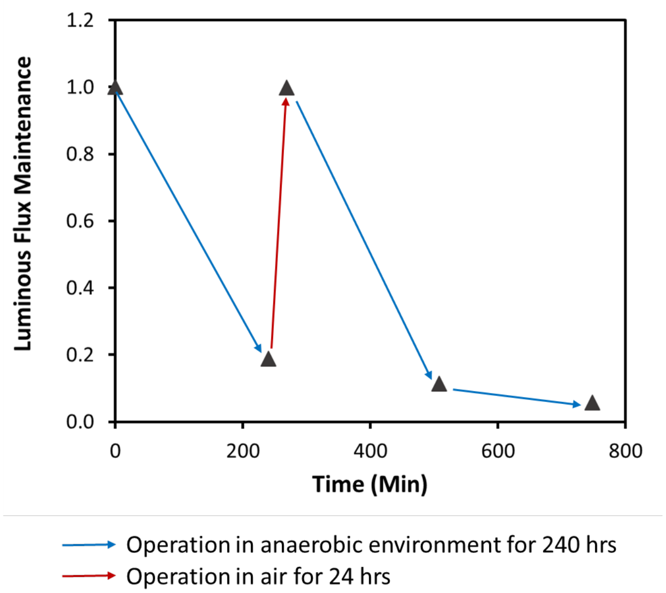

Figure 4-19. SPDs of Product HP-1 throughout anaerobic testing.

Select COB DUTs (i.e., the COB DUTs that experienced the greatest change in LFM after 2,000 hrs in anaerobic conditions) were operated in air for 100 hrs. The DUTs were then photographed and measured photometrically, and the results are presented in **Table 4-6**. For all COB DUTs in the test, the LFM after operation in air was greater than 0.9. This finding suggests that the darkening effects that occur for these COBs in anaerobic conditions can be reversed in a short timeframe by operation in air. Because the DUTs were operated for 2,000 hrs near maximum I_f values, it is expected that some degradation of the COBs occurred that is not attributed to the anaerobic environment. For example, the Product COB-6 DUTs experienced an LFM of 0.90 during RTOL and an LFM of 0.89 during 7575 after 2,000 hrs of operation at 500 mA. Product COB-6 (DUT-843) during anaerobic testing also experienced an LFM of 0.90 after 2,000 hrs (albeit I_f = 780 mA). Subsequent operation of DUT-843 in air did not improve the LFM above 0.90. This finding leads to the conclusion that the initial LFM loss for Product COB-6 DUTs was not affected by oxygen or ambient temperature and humidity in the 22°C–75°C, 25%–75% RH range.

Aside from Product COB-6, Product COB-5 DUTs had the next lowest LFM after operation in air. During RTOL testing, Product COB-5 DUTs were operated at the same I_f as the anaerobic DUTs, and the LFM was 1.0 and $\Delta u'v'$ was 0.0023. It is possible that more time was needed to fully reverse the darkening effects for Product COB-5 DUTs, but this was not explored further.

Table 4-6. Properties of the Anaerobic DUTs After 100 Hrs of Operation in Air

Product	DUT	LFM	$\Delta u'v'$
COB-2	773	0.97	0.0013
COB-4	858	1.02	0.0001
COB-4	859	0.97	0.0002
COB-5	892	0.93	0.0022
COB-5	893	0.96	0.0035
COB-6	843	0.91	0.0003

5 Discussion

5.1 Correlation Effects Among Electrical and Photometric Variables

COB LED packages contain many LED die in a common LES, but still are energized through only two electrodes. As a result of the inherent high LED die count, the COB LED package platform offers the highest lighting flux density available in a thin, low-profile package. Although COB LED packages produce large amounts of light per unit area, they also produce more waste heat per unit area. During this study, it was ensured that adequate heat sinks, cooling plates, and forward currents were used to keep all products within manufacturers' specifications during testing.

In the previous report [1], a silicone decapping method was used to determine the number of LEDs and arrangement of those LEDs (e.g., parallel, in series). The current density and radiant flux per unit area of the LED package (henceforth referred to as "package radiant flux density") were then calculated for the COB products in RTOL and 7575 and summarized with LFM and $\Delta u'v'$ in **Table 5-1**. The current density and flux per unit area were also calculated for the COB products in the anaerobic environment and summarized with LFM and $\Delta u'v'$ in **Table 5-2**.

Table 5-1. Average Properties of RTOL and 7575 DUTs After 6,000 Hrs of AST

Product	Current Density (A/cm²)	Package Radiant Flux Density (lm/cm²)	RTOL		7575	
			LFM	$\Delta u'v'$	LFM	$\Delta u'v'$
COB-2	23.1	1,340	0.98	0.0012	0.68	0.0142
COB-3 (2,700 K)	15.6	864	0.93	0.0010	0.60	0.0125
COB-3 (6,500 K)	20.8	1,015	0.95	0.0028	0.61	0.0286
COB-4	41.3	7,102	0.96	0.0017	[a]	[a]
COB-5	44.5	6,061	0.95	0.0036	0.82	0.0223
COB-6	11.3	704	0.87	0.0010	0.85	0.0017

Note: lm/cm² = lumens per square centimeter.

[a] Product COB-4 did not reach 6,000 hrs of 7575 test and was therefore not considered in this analysis.

Table 5-2. Average Properties of DUTs in the Anaerobic Environment After 2,000 Hrs of AST

Product	Current Density (A/cm²)	Package Radiant Flux Density (lm/cm²)	Anaerobic	
			LFM	$\Delta u'v'$
COB-2	48.1	2,467	0.54	0.0072
COB-3 (2,700 K)	15.6	864	0.91	0.0014
COB-3 (6,500 K)	20.8	1,015	0.92	0.0039
COB-4[a]	55.4	9,273	0.22	0.0375
COB-5	44.6	6,061	0.24	0.0329
COB-6	17.3	1,609	0.79	0.0009

[a] The LFM and $\Delta u'v'$ of Product COB-4 are the values for DUT-859 because it was the only Product COB-4 DUT that reached 2,000 hrs of anaerobic testing.

The data in **Table 5-1** and **Table 5-2** were analyzed to determine whether there was a linear dependence between any of the variables for the different ASTs. To determine linear dependence, the correlation coefficient r was calculated and displayed in **Table 5-3** by using **Equation 5-1** as follows:

$$r = \frac{\Sigma\big((x_i-\bar{x})(y_i-\bar{y})\big)}{\sqrt{\Sigma(x_i-\bar{x})^2\Sigma(y_i-\bar{y})^2}} \qquad \text{(Eq. 5-1)}$$

Where

x_i = The value of the x variable in a sample

$\bar{x}$ = The mean of the values of the x variable

y_i = The value of the y variable in a sample

$\bar{y}$ = The mean of the values of the y variable.

The r is a number between −1 and +1. Correlation coefficients with values closer to +1 indicate a positive correlation (i.e., if the values in one variable increase, then the values in the other variable will also increase). In contrast, an r value close to −1 indicate negative correlation (i.e., if the values in one variable increase, then the values in the other variable will decrease). Correlation coefficients with values closer to 0 indicate no or weak correlation; therefore the team did not assign great significance to correlations with an absolute value less than 0.5.

Overall, the anaerobic test produced strong correlations between all electrical and photometric variables as shown in **Table 5-3**. LFM was negatively correlated to both current density and flux density. Current and flux densities were positively correlated to $\Delta u'v'$, indicating that the magnitude of chromaticity shift increased as LFM decreased. These results suggest that the darkening of the silicone material in the LES observed in the anaerobic test conditions is promoted by light, and there may be some minimum dose or photon flux needed to initiate the process.

Table 5-3. Correlation Values Between Parameter 1 and Parameter 2 for Each AST

Parameter 1	Current Density (A/cm^2)			Package Radiant Flux Density (lm/cm^2)		LFM
Parameter 2	Package Radiant Flux Density (lm/cm^2)	LFM	$\Delta u'v'$	LFM	$\Delta u'v'$	$\Delta u'v'$
RTOL	0.95	0.56	0.65	0.38	0.49	0.32
7575	0.96	0.29	0.57	0.48	0.39	−0.45
Anaerobic	0.83	−0.92	0.81	−0.93	0.97	−0.94

As expected for a COB LED, higher current densities are closely correlated to higher flux densities for the products in this study. The current densities of each AST were also compared with respective $\Delta u'v'$ and LFM values at the end of testing. All ASTs were found to have a positive correlation between current density and $\Delta u'v'$ values at the end of testing. The LFM was found to be positively correlated to current density for RTOL (i.e., COB products operating at higher current densities ended test with higher LFM) but strongly negatively correlated to current density for the anaerobic test. Because increasing current density within the same model of LED is known to accelerate aging and luminous flux degradation (i.e., a negative correlation exists between current density and LFM for the same model of LEDs), the RTOL result is interesting. It is unlikely that temperature is a leading factor that contributed to this positive correlation because even though T_c for the product with the highest current density (i.e., Product COB-4) was the highest, T_c for the products with the second and third highest current densities (i.e., Products COB-5 and COB-2, respectively) were the lowest (**Table 3-1**). In the previous report [1], the external quantum efficiency (EQE) of the LED ($\eta_{LED,EQE}$) was determined for the products in this study (except for the 2,700 K channel of Products COB-3 and COB-5). It was found that Product COB-4 had the best $\eta_{LED,EQE}$ (0.67), Product COB-2 had the next highest $\eta_{LED,EQE}$ (0.57), and Product COB-6 had the lowest $\eta_{LED,EQE}$ (0.46). Therefore, at the mild RTOL conditions, it seems that the properties that lead to better $\eta_{LED,EQE}$ (i.e., more efficient epitaxial layer in the LED and higher extraction efficiency) allow for higher current densities without penalty to LFM.

5.2 Chromaticity Shift

Producing an amount of radiation that is acceptable for illumination (i.e., near the Planckian locus) requires balancing the emissions from the primary source (i.e., the pump LED) and any secondary sources (i.e., phosphors) that are activated by the pump wavelength. Balancing the color across the emission angle of a large LES source such as a COB LED requires blending light of not just the various colors (e.g., blue, green, red), but also numerous light rays for each color that are traveling through the LES at various angles. As shown in **Figure 5-1**, blue photons emitted by the LEDs in a COB package enter the silicone matrix at all angles up to the critical angle of the LED–silicone interface. These blue photons will continue along their emission rays through the silicone matrix until they either arrive at the silicone–air interface or they interact with a phosphor particle. Blue photons that arrive at the silicone–air interface along a ray above the critical angle will be refracted into the air and emerge from the light source. To reach the emission point, some blue photon rays (e.g., those perpendicular to the LED die surface) can proceed through the silicone matrix on a direct path of the shortest distance. However, other blue photon rays traveling through the silicone layer are at a more oblique angle, which would require a longer path to arrive at the silicone air interface. As long as the ray is at an angle that is above the critical angle, the ray will be refracted at the interface and emerge from the light source.

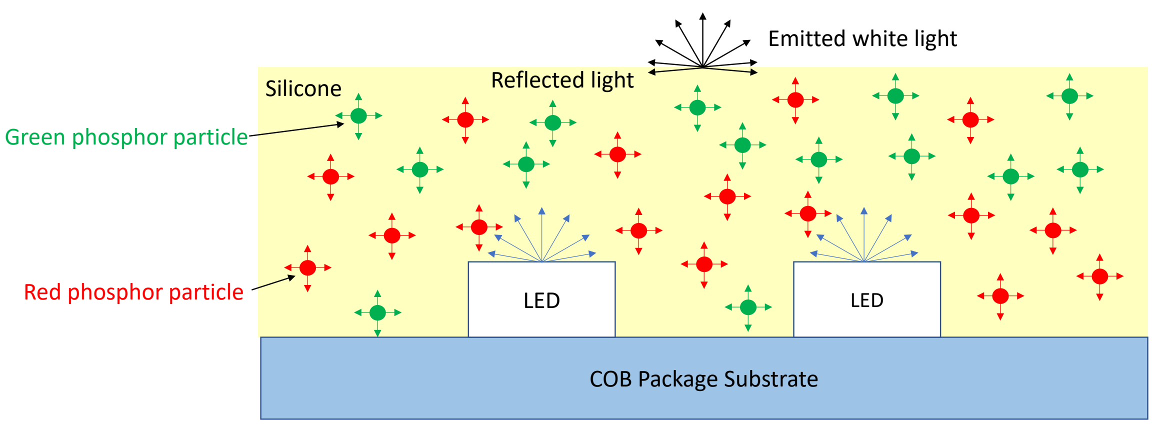

Figure 5-1. Schematic illustration of a portion of the light emission sources and possible light emission angles for a COB LED package. There can be 100 or more LEDs in the package.

The length that the light rays travel through the LES can vary widely in the COB LED package due in part to the size of the LES. This finding is in contrast to the pathlength of light rays through the LES in MP-LEDs and HP-LED, which are shown in **Figure 5-2**. In the MP-LED package, the side walls of the package serve as a reflector and limit the pathlength of light rays before they are reflected. Consequently, the time variation of the side wall reflectance plays a big in the overall changes in luminous flux and chromaticity from this package [3, 22]. For the COB

LED package, side walls effects are expected to be significantly lower (because of the size of the LES). For the HP-LED package, the LES is typically much smaller than found in the COB LED package, so the pathlength for any light ray is less. In addition, there are essentially no side walls to reflect the light ray back through the LES. As a result, most light rays travel through the LES and emerge from the HP-LED package. The only reflections that occur in this package are Fresnel effects as the interfaces between layers.

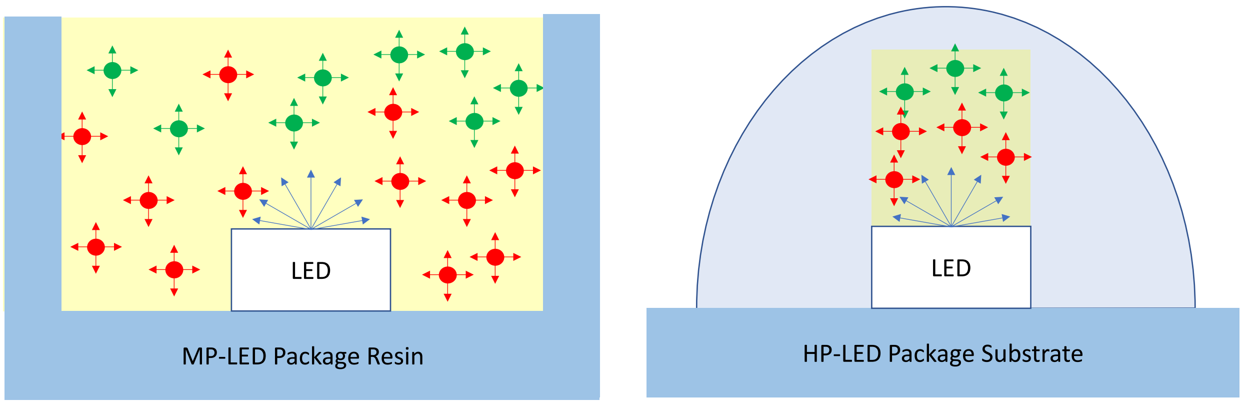

Figure 5-2. Schematic illustration of the light emission sources and possible light emission angles for the MP-LED (left) and the HP-LED packages. Each of these packages contains only one to three LED die.

A blue photon traveling along a ray that is either normal to the surface or at an oblique angle may encounter a phosphor particle and be absorbed. The phosphor will emit light at its characteristic wavelength (e.g., green, red) with a quantum efficiency that is characteristic of the material. Because phosphors are multi-faceted grains, their emission profile is assumed to be isotropic for simplicity [23]. This means that secondary photons may travel within the silicone matrix in a direction that is normal to the silicone–air interface (i.e., the direction of shortest travel) or they may travel along a ray that is oblique to the silicone–air surface. As long as the angle of these secondary photons is above the critical angle of the silicone–air interface, the photons will be refracted and will be emitted from the LES.

The angle of travel of a photon through the silicone–phosphor matrix plays a key role in the likelihood that the photon will be absorbed during its travel. This effect was first realized for the MP-LED package [3, 22], but the effect holds for the COB package as well. As a light ray travels through the silicone–phosphor composite, the photon can undergo a light absorption process that can be described by the Beer-Lambert equation, which is shown as **Equation 5-2** as follows:

$$A = \varepsilon bc \qquad \text{(Eq. 5-2)}$$

Where

A = Absorbance

ε = The molar absorptivity of the absorbing species

b = The optical pathlength

c = The concentration of the absorbing species.

In a nominally static material such as a silicone–phosphor LES, the value of ε and c can be assumed to be constant. However, the value of b will depend on the angle of travel of the photon through the material. Photons traveling the minimal distance until emission (i.e., those traveling normal to the silicone–air surface) will have a lower absorbance (i.e., A) because b is smaller. Therefore, these photons will have a higher likelihood of not being converted by the phosphor and emerging as blue photons. However, photons traveling at an oblique angle to the surface have a longer pathlength through the silicone–phosphor composite (i.e., b is larger) and are more likely to be absorbed by a phosphor particle and re-emitted as downconverted light. Hence photons emerging from these trajectories will have a higher percentage of secondary emissions (e.g., green, red). In addition to the light rays shown in **Figure 5-1**, there are also multiple points within the LES structure where photons can be scattered, absorbed, or reflected, creating a complicated picture of photon pathways in the LES. The total light emissions from the LES is the sum all the light vectors (both blue photon and secondary emissions) from all of the LEDs in the COB array that emerge at the silicone–air interface. Some of these photons may have traveled a direct path to the emission point (i.e., b is small); other photons may have taken a circuitous route involving oblique emission angles and scattering/reflection from multiple surfaces (i.e., Ag mirror, phosphor particles). On average, the light emitted from the LES surface is white (e.g., CCT value of 2,700 K; 6,500 K; or another desired value), but at an individual ray level, there will likely be an angular dependence of the emission color.

By comparison with the previous work on MP-LEDs [22], photons that emerge along normal or near-normal light rays from the LES surface are likely to have a bluer content, whereas those emerging at oblique angles are likely to have more phosphor emissions. Unlike MP-LEDs, the light rays emerging from a COB LES will not be reflected off a polymer side wall that is known to show increased light absorption with use [3, 22]. However, the light rays within the COB LES will be subjected to any changes in optical properties (e.g., absorbance, reflectance) of the materials within the LES.

A chromaticity shift in LEDs has been shown to primarily arise from changes in the primary emitter (e.g., the blue pump LED), changes in the secondary emitters (e.g., the phosphors), and changes in the package materials [3, 18]. Secondary lenses can also cause a chromaticity shift [5], but that is less of a concern for the COB LEDs examined during this study because all DUTs were tested without secondary optics (e.g., secondary reflectors, secondary lenses). The primary CSMs observed during this study for COB LEDs were CSM-1 and CSM-2 for the blue-pumped systems. Product COB-6 also exhibited CSM-3 behavior, but this product employed a violet LED pump and had a different phosphor mixture compared with the remainder.

When evaluating whether changes in the primary emitter were responsible for the observed chromaticity shifts, there are two main pieces of data that can be examined. The first piece of data is the I-V measurements taken before and after RTOL, 7575, and anaerobic environment testing indicated that no significant changes occurred in the electrical properties of the COB LED DUTs. Only minor variation in V_{th} were measured for any samples regardless of AST environment, as judged by the standard deviations of the means being within 0.050. Perhaps more important, the second piece of data, which was a review of the change in emission maximum wavelength (λ_{max}) of the primary emitter (i.e., blue LED for Products COB-2 through COB-5, and violet LED for Product COB-6), showed that the standard deviation of λ_{max} was less than the instrument resolution of 1 nm. Therefore, any temporal changes in the LEDs during the AST exposure is not expected to account for the change of chromaticity that was observed during these experiments.

Likewise, reflectors have been shown to have a potential impact on chromaticity of LED sources [20]. In the COB LED package, the substrate serves as the primary reflector in the package because the substrate dominates the package footprint. In the ceramic COB package used in Products COB-4 and COB-6, this substrate material was either alumina (Al_2O_3) or a polymer film placed on top of the AlN substrate. Al_2O_3 is chemically stable and not likely to undergo reactions that would change its reflectance [24]. The stability of the polymer dielectric used on the AlN substrate for Product COB-4 is unknown, but there is no evidence that it is degrading during use. Consequently, it not likely that changes in the substrate contributed to the chromaticity shifts found in this study for Products COB-4 and COB-6.

For the COB LEDs that are built on an MC-PCB substrate, an Ag thin film deposited on top of an aluminum (Al) sheet is the most common reflector. This reflector structure is used in Products COB-2, COB-3, and COB-5. Exposure of a pure Ag, thin-film reflector to high humidity has been shown to result in preferential absorption of short wavelengths (e.g., blue) of light [24]. Such a change in the reflector absorbance profile for Products COB-2, COB-3, and COB-5 would result in less blue light emerging from the COB LES (because of increased blue absorbance in the reflector), and the effect would be greater for blue photons at oblique angles (which are more likely to interact with the phosphor), which would cause a chromaticity shift in the blue direction at some point. The measurements reported herein showed chromaticity shifts through CSM-1 (i.e., blue) and CSM-2 (i.e., green) mechanisms. Therefore, the contribution of mirror oxidation cannot be ruled out based on these experiments. However, it is well-known that the addition of an Al nanolayer of 1- to 5-nm thickness will completely passivate Ag thin films in high humidity environments [24]. Perhaps, the Ag reflectors in Products COB-2, COB-3, and COB-5 are using such technology to prevent the Ag reflector from contributing to a chromaticity shift.

Based on this analysis, two of the primary components of the COB LED package are not likely to have significant impacts on chromaticity shifts, at least for the samples in this test matrix. However, the third component, which is the LES composed of silicone and phosphor particles, may be the primary source of chromaticity shifts during these tests. When deciding the impact of the silicone–phosphor composite on chromaticity shift, it is instructive to look at the chromaticity maintenance behavior of the DUTs in the anaerobic environment (**Figure 4-17**). All of these samples have a darkened LES with increased light absorbance (i.e., higher ε in **Equation 5-2**) after operation in the anaerobic environment. The greater light absorbance of the LES will be especially impactful at oblique angles (i.e., larger b values in **Equation 5-2**). Consequently, the oblique light rays are more likely to be absorbed, and the light rays normal to the surface, which are more likely to have higher blue content, are less likely to be absorbed. As a result, the light emissions—while significantly attenuated (**Figure 4-18**)—have a relatively higher proportion of blue light than the starting light emissions, and the chromaticity shift is in the blue direction.

Although preferential attenuation of green, yellow, and red emissions helps to explain the CSM-1 chromaticity shift found for DUTs in the anaerobic environment, it does not explain the observed behavior in the RTOL and 7575 test environments. To understand the behavior of the DUTs during these tests, additional characteristics of silicones must be examined. Silicone is known to be highly permeable to water and other vapors [5, 6], and in some case, the imbibing of moisture into the silicone can cause swelling of the LES [7, 25, 26]. When the silicone–phosphor component swells, the number of phosphor particles is unchanged, but their concentration (i.e., the c term in **Equation 5-1**) is reduced because of expansion of the silicone along the z-axis. The lower concentration of phosphor particles in the LES may reduce the rate that blue photons are converted by the phosphor. This reduced conversion rate would increase blue emissions from the LES, consistent with a chromaticity shift in the blue direction. In addition to the swelling effect, moisture ingress into silicones has been shown to attack phosphor particles in HP-LEDs, resulting in a decrease in phosphor quantum efficiency [8] and a change in the physical color of the phosphors in some cases [26]. The combined effects of lower phosphor quantum efficiency and swelling of the silicone layer during use could be responsible for the CSM-1–type chromaticity shifts observed during these tests. In addition, the CSM-2–type chromaticity shifts can be caused by either photo-oxidation of nitride phosphors [3, 27] or a greater reduction in the quantum efficiency of red emitters than green emitters.

The findings from this analysis indicate that the chromaticity shift of the COB LED products examined during this study was primarily due to package effects arising from the silicone–phosphor composite in the LES. Although contributions from other package factors, such as the oxidation of Ag mirrors, cannot be fully eliminated, it is more likely that changes in the silicone–phosphor LES was the primary driver in chromaticity shifts and luminous flux loss. The combined effects of heat and humidity likely reduced the quantum efficiency of the phosphors, resulting in the observed chromaticity shifts.

6 Conclusions

COB LEDs offer the advantages of high luminous flux and a thin, compact profile that is significant smaller than conventional light sources of other LEDs arrayed on a PCB. The COB LED is a compact light source with an LES that varies between 4 mm and 20 mm, whereas other LED packages are arrayed on PCBs that can vary in size from 4 inches in diameter to 2 feet × 4 feet. Although COB LEDs have emerged as the natural outcome of the evolution of SSL technologies, less is known about their long-term reliability, despite their relatively simple construction. The COB LED package consists of three main components: (1) an array of LEDs containing 10 to more than 100 individual die; (2) a thermally conductive substrate that provides electrical interconnection and thermal management of the LED array; and (3) a silicone–

phosphor composite, the LES, that converts primary radiation from the LED array into white light.

To assess the reliability of COB LEDs, three different levels of stress testing were applied to representative examples of this LED package platform, as had been conducted previously with MP-LEDs and HP-LEDs. A text matrix consisting of six different COB LED products were chosen, with the number of LED die, thermal substrate, and pump LED varying in the test matrix. Separate populations of these six COB LED products were exposed to stress testing environments, consisting of operation at moderate I_f values in RTOL and 7575 environments and operation at high I_f values in an anerobic (i.e., oxygen-free) environment. These tests were chosen to accelerate the aging of the COB LEDs so that their reliability could be assessed in a reduced time frame. The intent was to identify failure modes of the COB LED package to compare the findings with earlier studies of MP-LEDs and HP-LEDs and to identify failure modes that may limit the reliability of the COB LED technology.

Based on this study, the LES appears to have the greatest influence on the long-term performance of the COB LED package. The impact of the LES was most clearly demonstrated in the experiments in the anerobic (i.e., oxygen-free) environment, where the LES underwent a reversible darkening reaction that significantly reduced LFM values and generally produced a chromaticity shift in the blue direction (i.e., CSM-1 behavior). There was no evidence of a green shift for any product in the anerobic environment, perhaps because of the lack of oxygen. However, when the DUTs tested in the anerobic chamber were operated in air, they quickly returned to their normal lighting parameters, and the darkening of the LES disappeared. These findings indicate that reactions in the silicone material in the LES can have significant impacts on LFM and chromaticity maintenance, and some, but not all, reactions can be reversed in an oxygen-containing environment.

However, the LES also had a significant influence on the performance of the COB package in RTOL and 7575 environments, although reversible darkening of the silicone was not as readily observed. In the oxygen-rich 7575 environment, many failures attributable to excess chromaticity shift and, in some cases, excess luminous flux loss were found. In this oxygen-rich environment, the chromaticity shift was predominantly in the green direction for three products in the test matrix (Products COB-2, COB-3 [2,750 K], and COB-5). However, Products COB-2 and COB-3 also displayed a chromaticity shift toward the blue direction (CSM-1), which could be caused by a secondary mechanism such as reflector oxidation. These findings clearly demonstrates that the introduction of oxygen into the operating environment can cause a shift of warm white phosphor emissions toward the green direction because of several factors. Some factors include phosphor oxidation and phosphor quenching that are facilitated by the high moisture permeability of silicones. The products that exhibit chromaticity shifts in the blue direction (Product COB-3) and in the yellow direction (Product COB-6) also exhibited evidence of strong quenching of phosphor emissions likely facilitated by the permeability of silicone. In the RTOL environment, the chromaticity shifts of Products COB-2 and COB-5 were almost exclusively in the green direction (CSM-2) and in a manner similar to that observed in the 7575 environment, although the magnitude was smaller during RTOL testing. The chromaticity shift of Product COB-3 (both 2,700 K and 6,500 K primaries) was primarily in the blue direction (CSM-1) and can be attributed to mainly to phosphor quenching based on the observed changes in the SPD. However, the magnitude of these chromaticity shifts was much smaller than in the 7575 environment or the anerobic environment, and no parametric failures were observed during RTOL testing.

Based on the findings from this reliability study of five commercial COB products, the COB package can be assumed to exhibit high reliability and high efficacy when operated according to the manufacturers' directions. There are a wide variety of options available in the COB package, including luminous flux output, power consumption, fixed or variable CCT values, and thermal management options. Although the COB LED package in general is not quite as efficient as MP-LEDs or HP-LEDs, the efficiency of the COB LED package greatly exceeds that of conventional light sources (e.g., fluorescent, halogen) that are used in high intensity lighting applications. This high efficiency coupled with the simple design and ease of connectivity provide the COB LED package with a compact, energy efficient form factor that will help reduce carbon dioxide emissions from lighting throughout its life cycle.

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Appendix A: Anaerobic Devices Under Test (DUTs) Before and After Aging: Microscopy

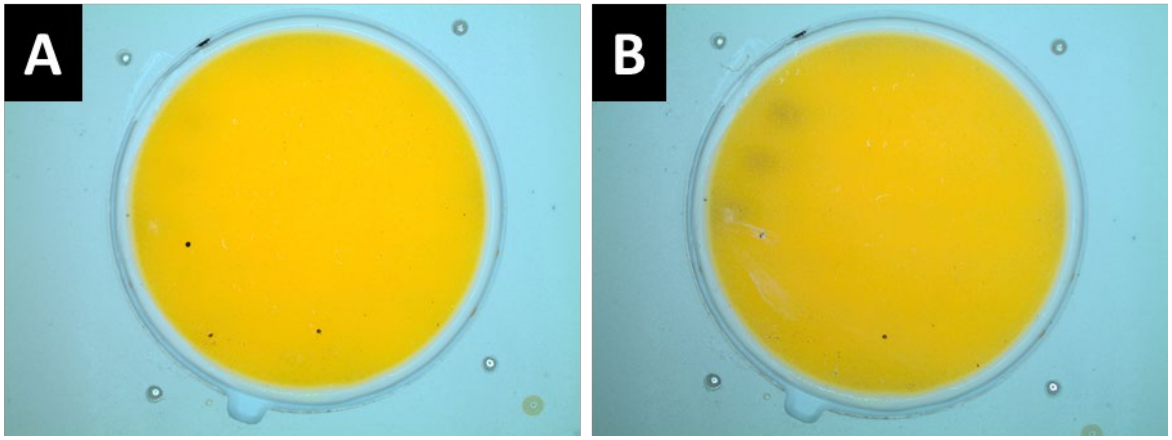

Figure A-1. Product COB-2 (DUT-772) (A) prior to anaerobic test (0 hours [hrs]) and (B) after 2,000 hrs of operation at 1,042 milliamperes (mA) in a nitrogen environment.

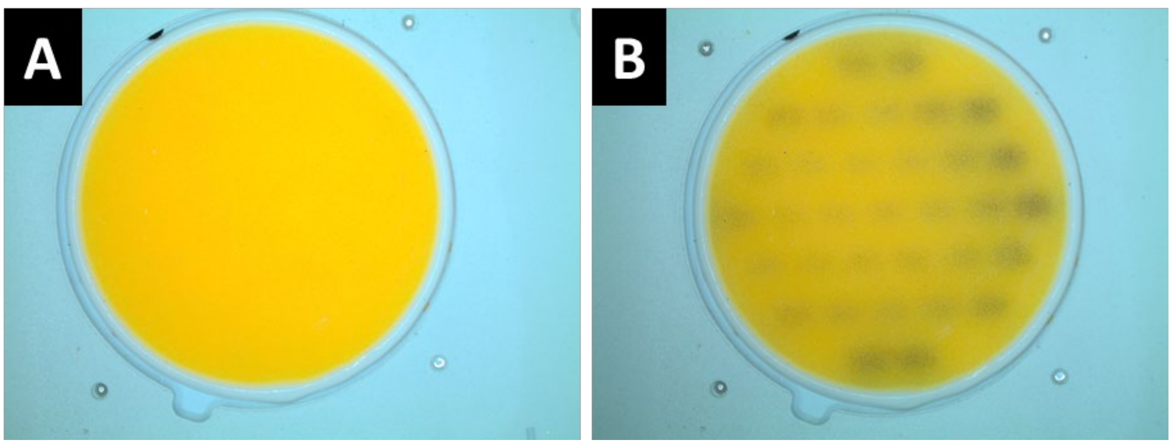

Figure A-2. Product COB-2 (DUT-773) (A) prior to anaerobic test (0 hrs) and (B) after 2,000 hrs of operation at 1,042 mA in a nitrogen environment.

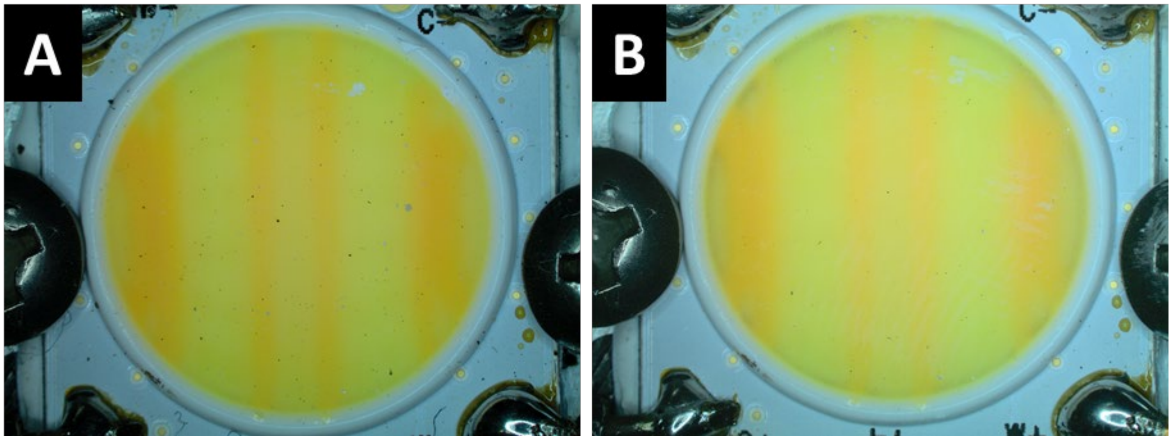

Figure A-3. Product COB-3 (DUT-787) (A) prior to anaerobic test (0 hrs) and (B) after 2,000 hrs of operation at 350 mA per channel in a nitrogen environment.

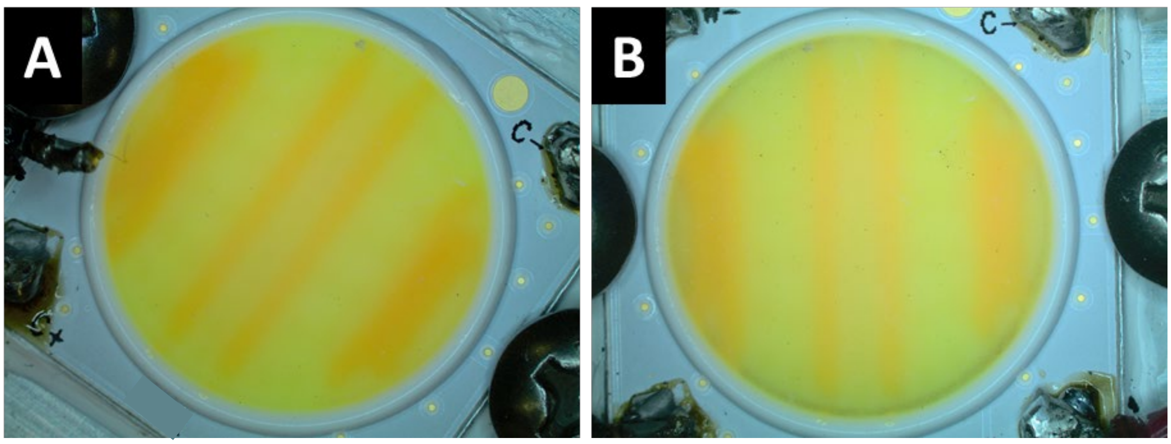

Figure A-4. Product COB-3 (DUT-788) (A) prior to anaerobic test (0 hrs) and (B) after 2,000 hrs of operation at 350 mA per channel in a nitrogen environment.

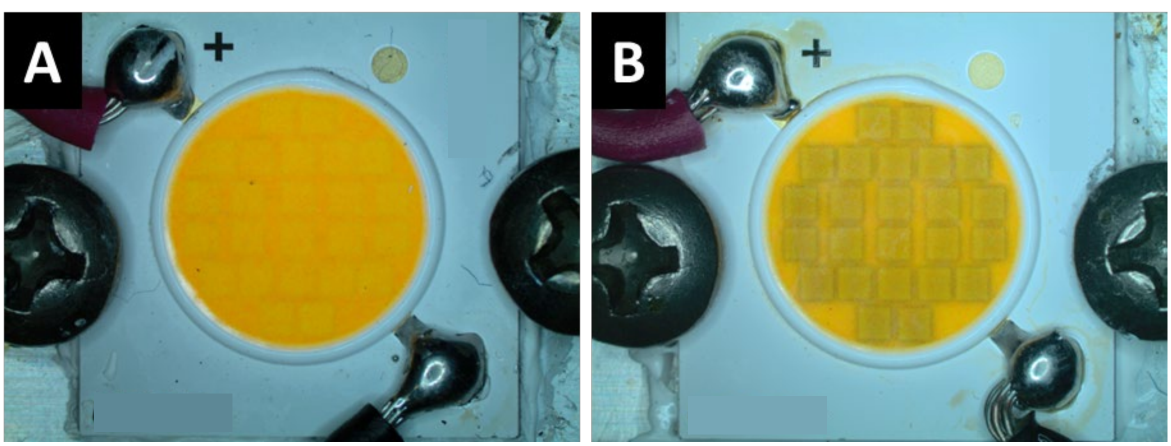

Figure A-5. Product COB-4 (DUT-858) (A) prior to anaerobic test (0 hrs) and (B) after 1,000 hrs of operation at 1,350 mA in a nitrogen environment.

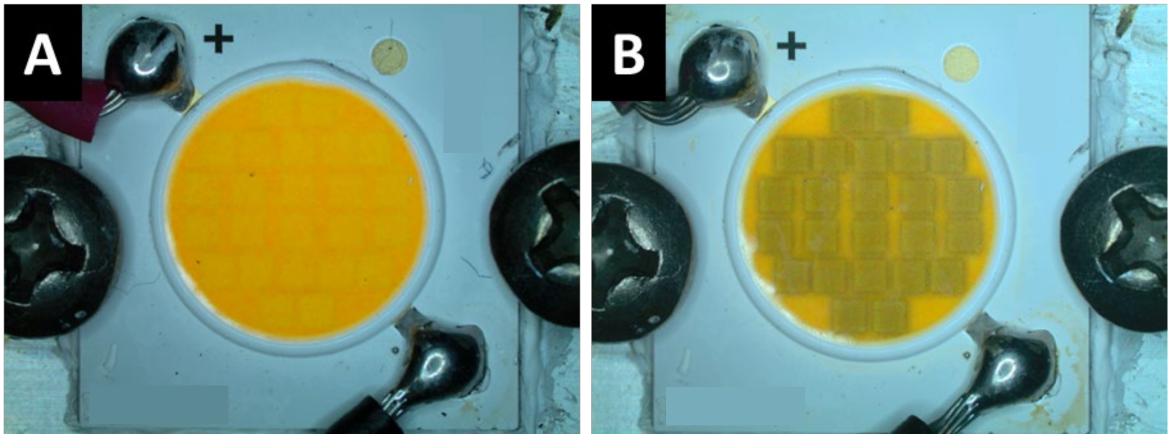

Figure A-6. Product COB-4 (DUT-859) (A) prior to anaerobic test (0 hrs) and (B) after 2,000 hrs of operation at 1,350 mA in a nitrogen environment.

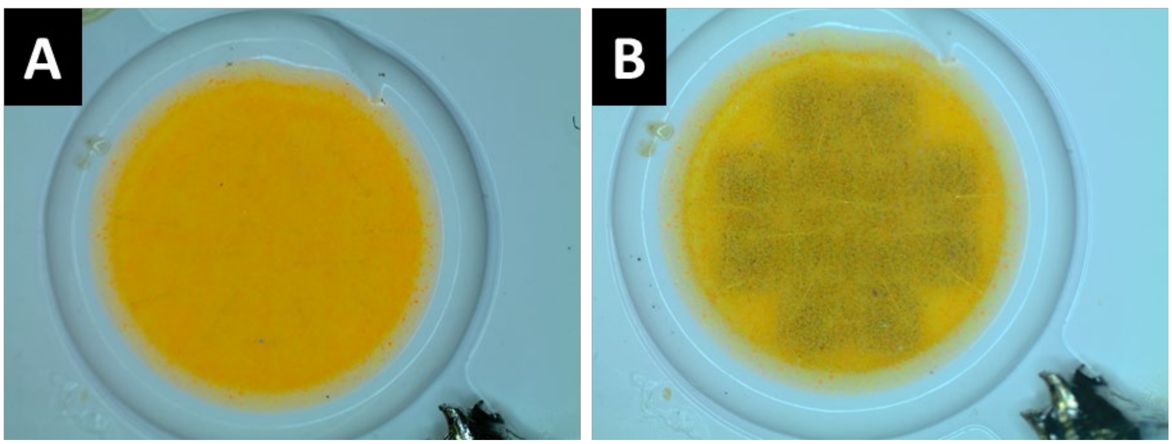

Figure A-7. Product COB-5 (DUT-892) (A) prior to anaerobic test (0 hrs) and (B) after 2,000 hrs of operation at 500 mA in a nitrogen environment.

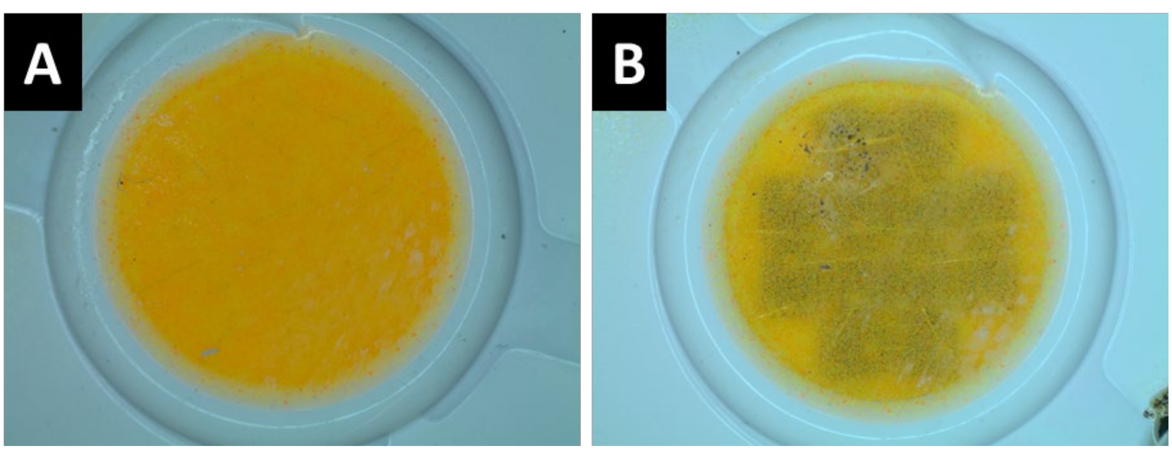

Figure A-8. Product COB-5 (DUT-893) (A) prior to anaerobic test (0 hrs) and(B) after 2,000 hrs of operation at 500 mA in a nitrogen environment.

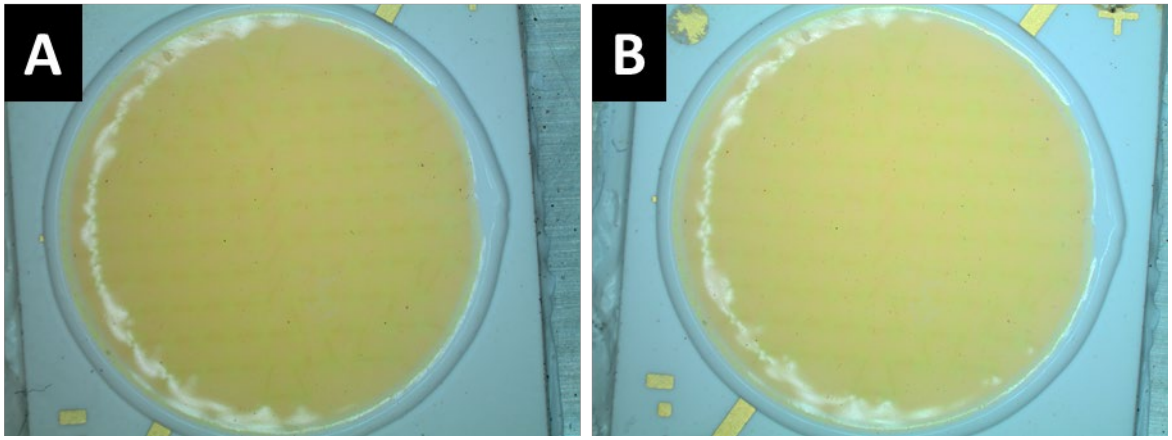

Figure A-9. Product COB-6 (DUT-843) (A) prior to anaerobic test (0 hrs) and (B) after 2,000 hrs of operation at 760 mA in a nitrogen environment.

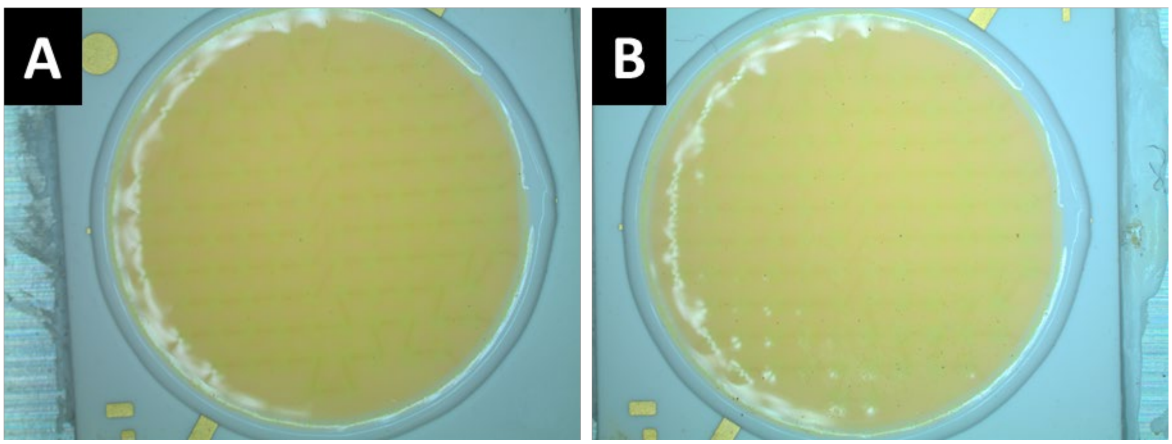

Figure A-10. Product COB-6 (DUT-844) (A) prior to anaerobic test (0 hrs) and (B) after 2,000 hrs of operation at 760 mA in a nitrogen environment.

Appendix B: Anaerobic Devices Under Test (DUTs) Before and After Aging: Spectral Power Distribution (SPD)

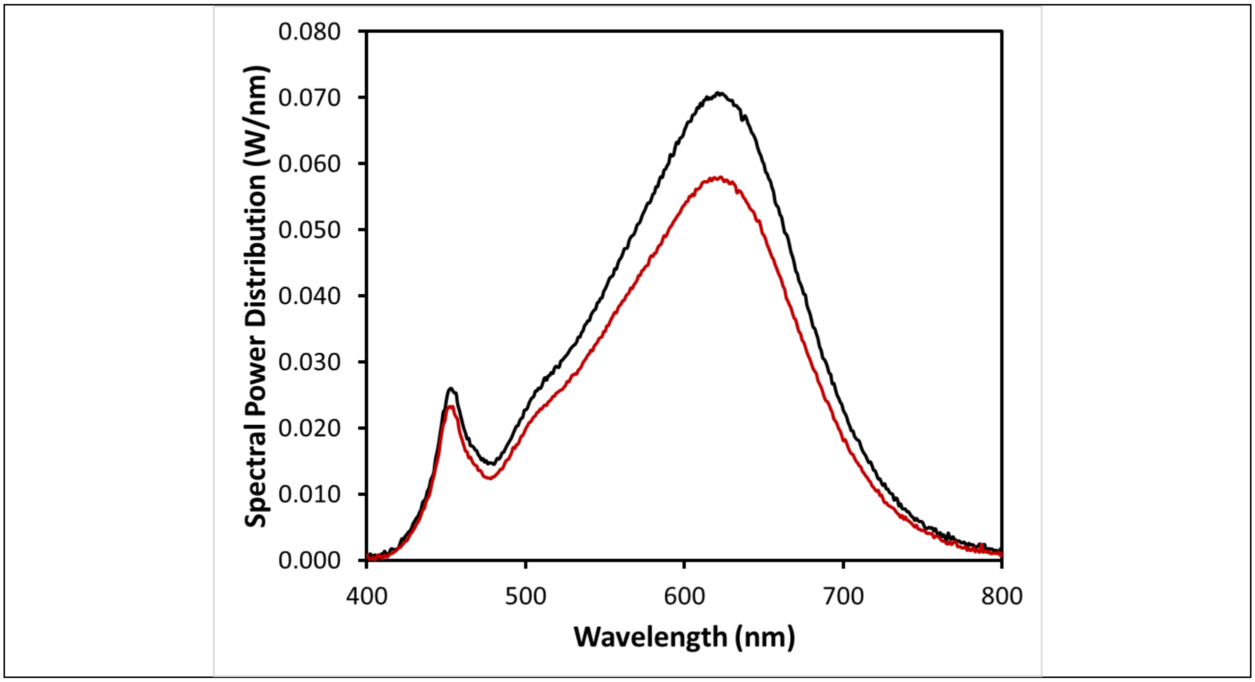

Figure B-1. SPD of Product COB-2 (DUT-772) before anaerobic test (black) and after 2,000 hrs of operation at 1,042 mA (red) in a nitrogen environment.

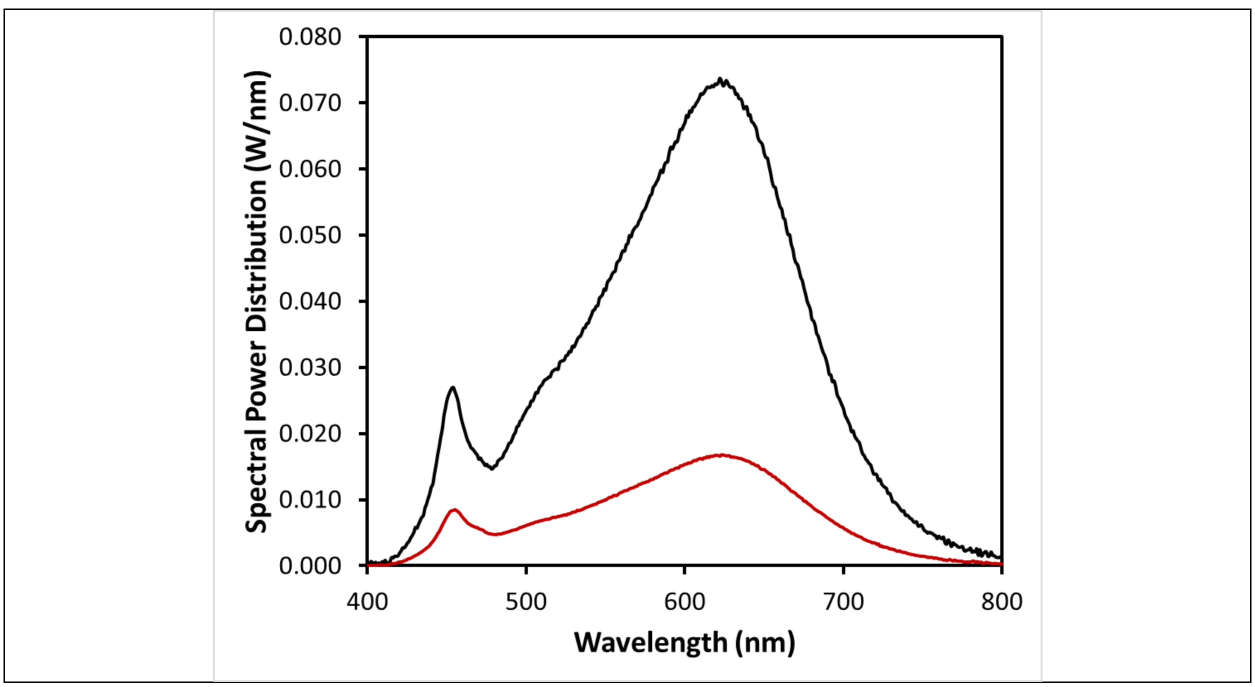

Figure B-2. SPD of Product COB-2 (DUT-773) before anaerobic test (black) and after 2,000 hrs of operation at 1,042 mA (red) in a nitrogen environment.

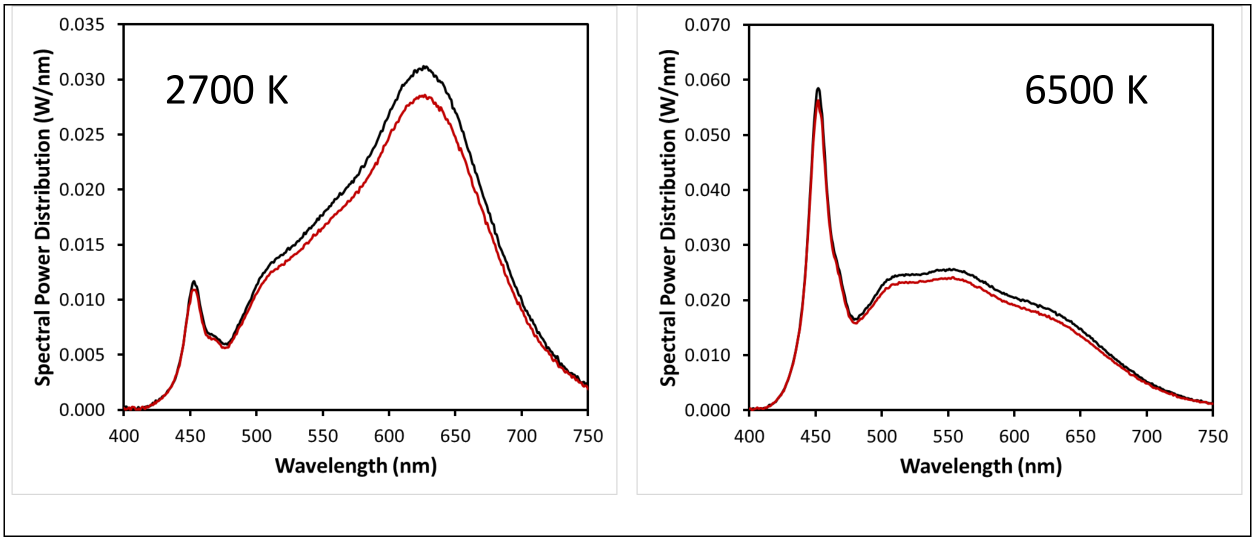

Figure B-3. SPD of Product COB-3 (DUT-787) before anaerobic test (black) and after 2,000 hrs of operation at 350 mA (red) in a nitrogen environment.

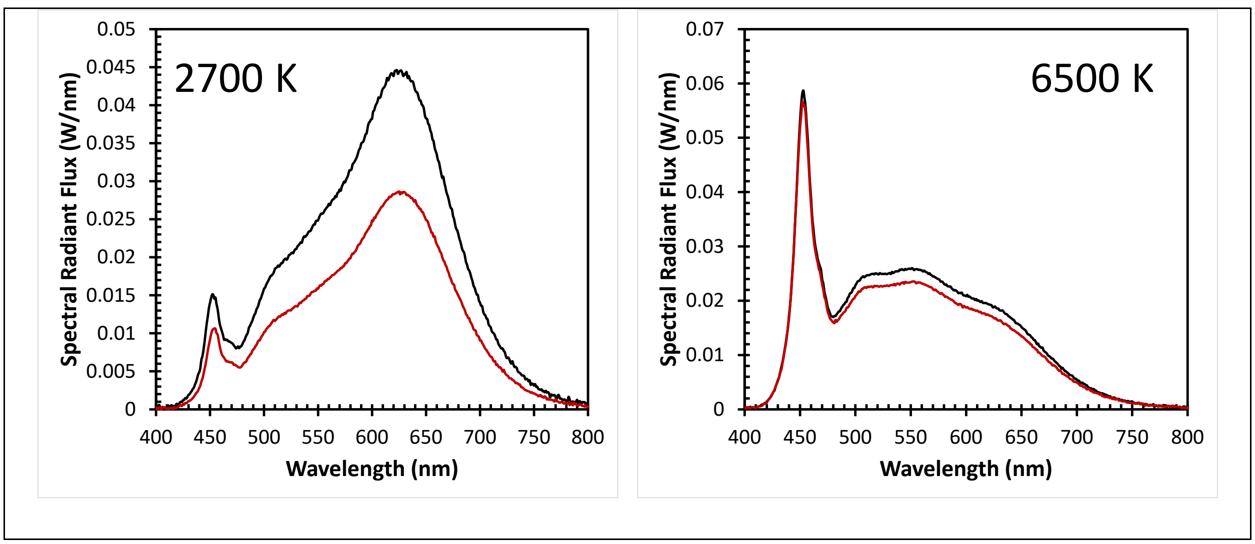

Figure B-4. SPD of Product COB-3 (DUT-788) before anaerobic test (black) and after 2,000 hrs of operation at 350 mA (red) in a nitrogen environment.

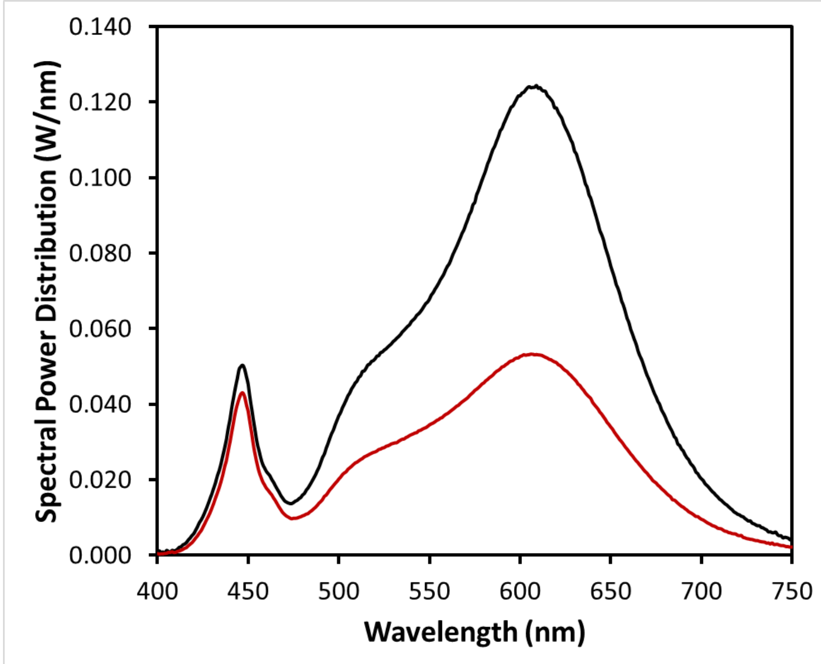

Figure B-5. SPD of Product COB-4 (DUT-858) before anaerobic test (black) and after 2,000 hrs of operation at 1,350 mA (red) in a nitrogen environment.

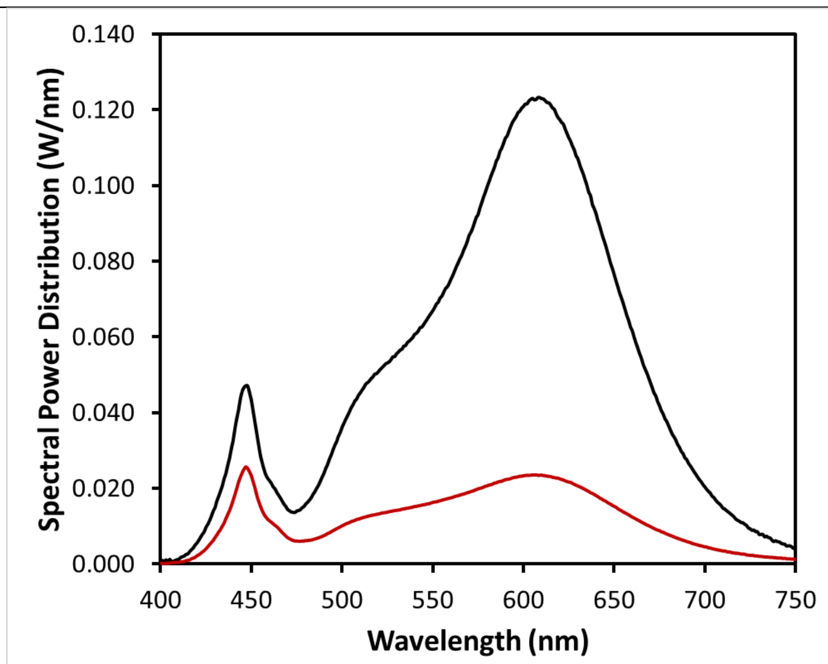

Figure B-6. SPD of Product COB-4 (DUT-859) before anaerobic test (black) and after 2,000 hrs of operation at 1,350 mA (red) in a nitrogen environment.

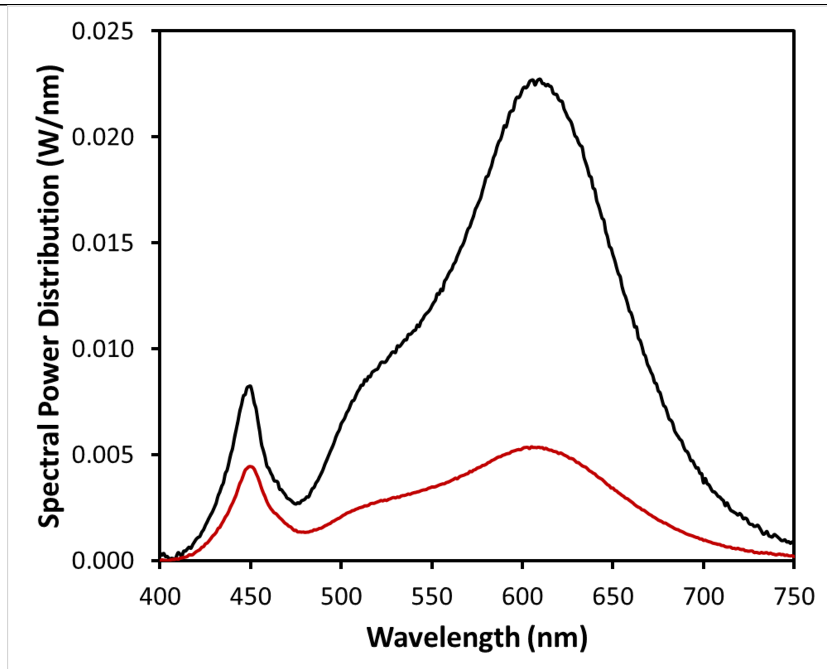

Figure B-7. SPD of COB-5 (DUT-892) before anaerobic test (black) and after 2,000 hrs of operation at 500 mA (red) in a nitrogen environment.

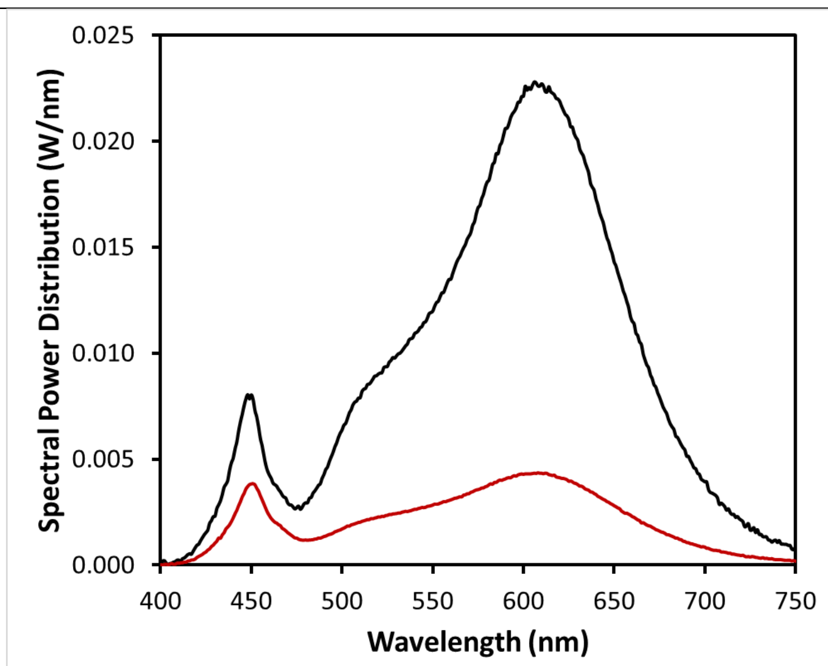

Figure B-8. SPD of Product COB-5 (DUT-893) before anaerobic test (black) and after 2,000 hrs of operation at 500 mA (red) in a nitrogen environment.

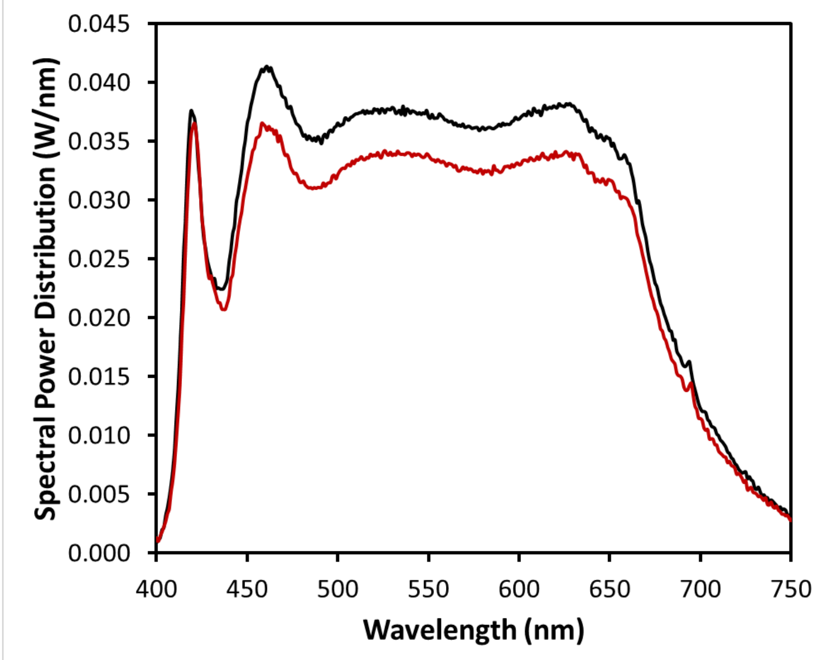

Figure B-9. SPD of COB-5 (DUT-843) before anaerobic test (black) and after 2,000 hrs of operation at 760 mA (red) in a nitrogen environment.

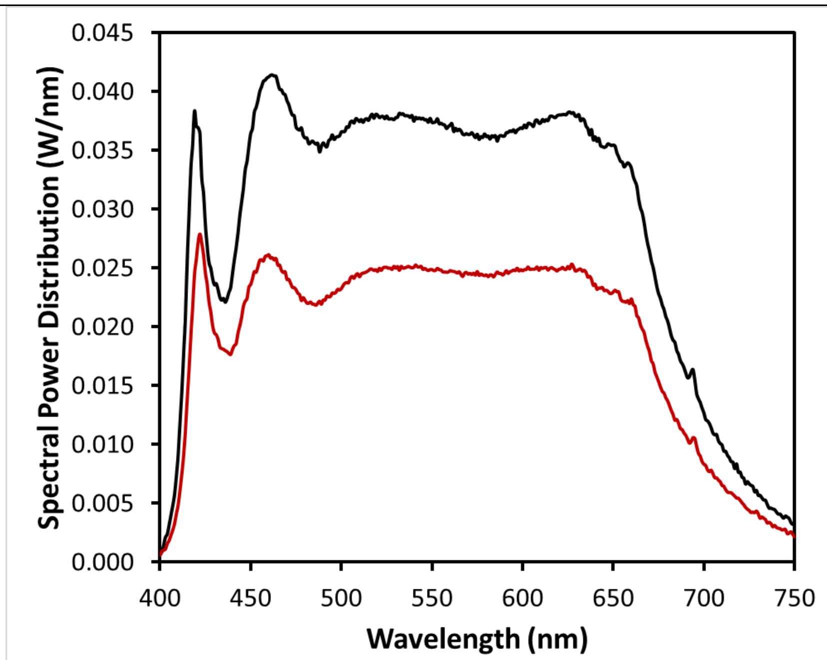

Figure B-10. SPD of Product COB-6 (DUT-844) before anaerobic test (black) and after 2,000 hrs of operation at 760 mA (red) in a nitrogen environment.

Appendix C: Current-Voltage (I-V) Measurement of Chip-on-Board (COB) Light-Emitting Diodes (LEDs) in This Study

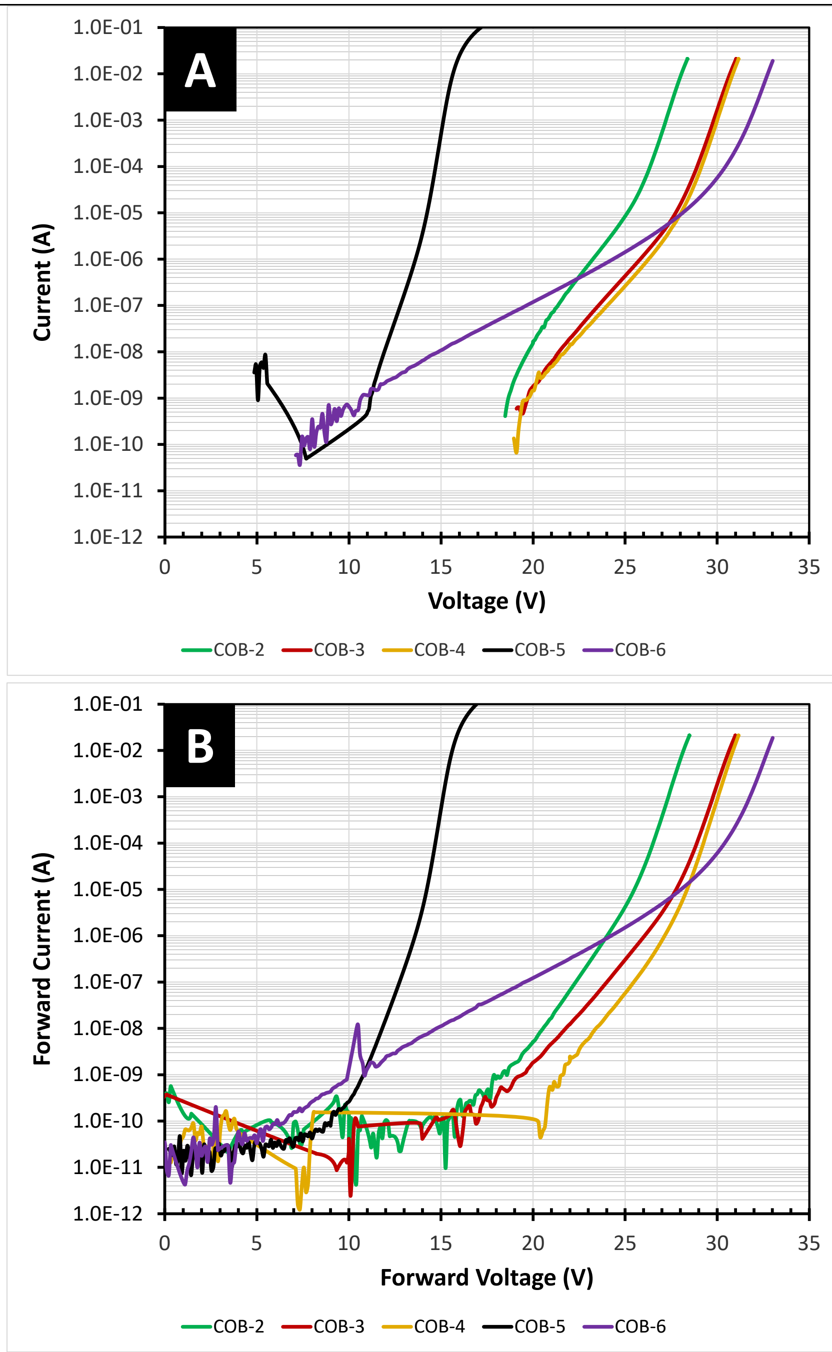

Figure C-1. I-V curves of the COB products examined in this study: (A) the I-V curves as received in the initial condition, and (B) the I-V curves after 2,000 hours (hrs) of testing in the anaerobic environment.

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