U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

# Initial Performance and Reliability of Chromaticity Sensors Used for Tunable Lighting Source Systems

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

September 2020

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RTI Project Number
0215939.001.001

# Initial Performance and Reliability of Chromaticity Sensors Used for Tunable Lighting Source Systems

**September 2020**

Prepared for

**U.S. Department of Energy**

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## Acknowledgments

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

## Disclaimer

# Nomenclature or List of Acronyms

| | |
|---|---|
| 7575 | life test conducted at 75°C and 75% relative humidity |
| 75OL | operational life test conducted at 75°C |
| °C | degree Celsius |
| $\Delta u'$ | change in the $u'$ coordinate of chromaticity |
| $\Delta u'v'$ | chromaticity shift or the total change in chromaticity coordinates |
| $\Delta v'$ | change in the $v'$ coordinate of chromaticity |
| AST | accelerated stress test |
| CALiPER | Commercially Available LED Product Evaluation and Reporting |
| CCT | correlated color temperature |
| CIE | International Commission on Illumination (*Commission Internationale de l'Éclairage*) |
| CLE | cognitive light engine |
| CMOS | complementary metal-oxide-semiconductor |
| CTL | color-tunable lighting |
| D2W | dim-to-warm |
| DOE | U.S. Department of Energy |
| DUT | device under test |
| EERE | Office of Energy Efficiency and Renewable Energy |
| hr, hrs | hour, hours |
| K | Kelvin |
| $L_{70}$ | time required for the luminous flux to decay to 70% of the initial value |
| $L_{80}$ | time required for the luminous flux to decay to 80% of the initial value |
| LED | light-emitting diode |
| LGA | land grid array |
| MESA | Mission Execution and Strategic Analysis |
| mm | millimeter |
| ms | millisecond |
| NETL | National Energy Technology Laboratory |
| NIR | near-infrared |

| | |
|---|---|
| NIST | National Institute of Standards and Technology |
| nm | nanometer |
| PAR | parabolic aluminized reflector |
| PCB | printed circuit board |
| pc-LED | phosphor-converted LED |
| RTOL | room temperature operating life |
| SDCM | standard deviation of color matching |
| SPD | spectral power distribution |
| SSL | solid-state lighting |
| TL | test lamp |
| TLS | tunable lighting source |
| UI | user interface |
| USB | Universal Serial Bus |
| $u', v'$ | chromaticity coordinates in the CIE 1976 color space |
| V | volt |
| W/nm | watts per nanometer |
| WTL | white-tunable lighting |
| X, Y, Z | tristimulus values |
| x, y | chromaticity coordinates in the CIE 1931 color space |

# Executive Summary

Tunable lighting source (TLS) systems use different mechanisms to adjust illuminance and chromaticity, and these mechanisms range from simple one-signal controls (e.g., dim-to-warm lamps) to sophisticated feedback systems that are designed to maintain a constant lighting environment. Solid-state lighting (SSL) fixtures that use high-efficiency light-emitting diodes (LEDs) offer rapid response and control flexibility that are desired in a feedback-driven lighting system. The performance of SSL luminaires is known to change over time because of lumen depreciation, shifts in chromaticity coordinates, and changes in the drivers. A sensor-driven feedback lighting system can compensate for these aging-related changes by adjusting the illuminance and chromaticity to maintain a consistent lighting environment. Such a sensor-driven control system can also adjust to changes in room illuminance brought on by variations in the amount of sunlight in the space. However, the impacts of changes in the control sensors over time on the reliability of an SSL device have not been actively investigated.

This report examines the initial performance and aging characteristics under accelerating conditions of a commercial illuminance and chromaticity sensor for use in sensor-driven lighting system controls. The sensor examined during this study consists of a series of six photodiodes. Each photodiode is covered with a different Gaussian interference filter, and these filters are made using inorganic thin films. The photodiode and interference filter combinations are designed to promote a select response to different wavelengths. Of most importance to the use of this sensor in lighting applications are the photodiodes designed to provide responses according to the X, Y, and Z tristimulus values of the 2-degree standard observer from the 1931 convention of the International Commission on Illumination (*Commission Internationale de l'Éclairage* [CIE]). Common lighting parameters such as illuminance, correlated color temperature (CCT), and chromaticity coordinates (e.g., x, y, $u'$, $v'$) can be readily calculated from the response of the tristimulus-sensitive photodiodes.

The chromaticity sensor and other components were placed on a printed circuit board (PCB) according to a reference design from the sensor manufacturer. The sensor devices under test (DUTs) were divided into different populations, with each population being exposed to one accelerated stress test (AST). The ASTs used during this study were a continuous room temperature operating life (RTOL) test, a continuous operational life test at an elevated ambient temperature of 75°C (75OL), and a continuous operational life test in a temperature-humidity environment of 75°C and 75% relative humidity (7575). After AST exposure, the performance of the DUTs was measured using the light from a parabolic aluminized reflector (PAR) lamp on an open optical bench in a dark room. A light diffuser film was placed in front of the sensor prior to collecting measurements to ensure a reproducible collection angle for the sensor. In addition, a calibrated spectrometer was used to measure the stability of the PAR lamp during all tests.

This report focuses on the initial benchmark of the sensor product and the performance of the DUTs after 5,000 hours (hrs) of ASTs. Unlike with luminous flux measurements using standard methods such as LM-80, there are no standard methods to evaluate long-term sensor performance. Initial characterization of the sensor involved flood illumination of the sensor but the measurement variability was high due to the challenge of maintaining a constant angle of incidence. When a light diffuser film was used to control the angular incidence of light on the sensors, reproducible sensor readings could be obtained. Excellent part-to-part reproducibility was found between the different DUTs with the standard deviation for illuminance measurements being less than 3% of the average and the standard deviation for CCT, $u'$, and $v'$ measurements being less than 1% of the average. The reproducibility for measurements from the same sensor was even higher. The within-sample standard deviation of illuminance was less than 0.5% of the average, and the standard deviation for CCT, $u'$, and $v'$ measurements was less than 0.1% of the average. These findings indicate that the initial reliability of the sensor was excellent.

Similar to SSL technologies, the failure criteria used for the sensor in this study after AST exposure included consideration for both abrupt failure and parametric failure. No abrupt failure of the sensor was found after

5,000 hrs of AST exposure even in the relatively harsh 7575 environment. “Parametric failure” of a DUT was defined as either a deviation of the illuminance reading by more than 20% of the true value of the PAR lamp (i.e., illuminance drops to 80% of the initial value) or chromaticity measurements that deviated by more than 0.004 from the true value as measured by the magnitude of chromaticity shift ($\Delta u'v'$). There were no parametric failures in either RTOL or 75OL, but there was one parametric failure of a DUT (12.5% failure rate) after 5,000 hrs of 7575. The failure was characterized by a large (approximately 0.010) deviation in the $+v'$ measurement and a deviation of the CCT reading ranging from -80 K to -350 K depending on the CCT value of the PAR lamp used to characterize the DUT. Illuminance and $u'$ values measured by the DUTs remained acceptable through 5,000 hrs of 7575.

This study demonstrates that a commercial illuminance and chromaticity sensor used in the control system of a TLS installation has high reliability—even under relatively harsh test conditions (e.g., 7575). No abrupt failures in the sensor have been observed during testing to date. However, a parametric failure was found (12.5% failure rate) after 5,000 hrs in the most severe test condition, that resulted in a large increase in the $v'$ coordinate of chromaticity and a significant decrease in the CCT value. The impact of a parametric failure such as the one observed during this study in a TLS luminaire would cause the control system of the luminaire to change to settings that were obviously different from other nearby luminaires. This type of failure would produce a significant mismatch in $v'$ and CCT values of the luminaire compared with neighboring luminaires, and these differences would be visible to an observer; however, the illuminance values would not be significantly changed. Further study is planned for these DUTs and other sensors used in lighting installations to evaluate the impacts of these control mechanisms on the long-term performance of the light system.

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# 1 Introduction

## 1.1 Tunable Lighting Source Systems and the Role of Sensors

Tunable lighting source (TLS) systems are those that can change the properties of the light output (e.g., illuminance, correlated color temperature [CCT]) in response to one or more control stimuli. This type of lighting system typically employs two or more light-emitting diode (LED) primaries*, and changing the properties of the light output is achieved by varying the current between the LED primaries. A change in the total current flowing to the LED primaries produces a corresponding change in illuminance level, whereas a change in light CCT value can be accomplished by changing the current distribution between the primary LEDs. The TLS architecture determines how the control stimuli are applied, and there are multiple control structures employing one, two, or more control stimuli used in different TLS systems as shown in **Figure 1-1**.

In a dim-to-warm (D2W) lighting system, a signal from a dimmer changes the total current flowing to and the current distribution between the LED primaries in a pre-determined manner (**Figure 1-1A**) [1]. The net result is a lighting system that allows the illuminance level and the CCT value to change between the CCT value of the LED primaries (typically between 2,700 K and 1,800 K for a D2W system), according to a single control signal, the dimming level. In this architecture, there is no ability to independently control the current distribution between the LED primaries because this control structure is set in the system hardware by the manufacturer. This architecture was designed to mimic the warm-dimming behavior of incandescent lamps while delivering the energy efficiency of solid-state lighting (SSL) technologies.

A more complicated control structure is used in the common white-tunable lighting (WTL) architecture where the LED primaries are controlled independently, thereby allowing a wider range of illuminance levels and CCT values spanning the LED primaries (**Figure 1-1B**). In this architecture, a user sets the desired illuminance and CCT levels through a user interface (UI) such as a keypad or a telephone application [2, 3]. These control signals are interpreted by the system controller in a manner programmed by the manufacturer to produce the current levels for each LED primary that are needed to deliver the desired illuminance and CCT value. Both illuminance and CCT value can be adjusted independently in this architecture by changing the control inputs through the UI [2]. A similar control scheme can be used for color-tunable lighting (CTL) [3]. A modified version of this basic architecture is used by TLS systems that automatically adjust illuminance and CCT values according to preset algorithm throughout the day to provide a light source similar to natural sunlight [4].

A third control architecture for WTL and CTL systems is the addition of a chromaticity sensor that provides feedback regarding the light level and color point, thereby enabling automatic adjustment of these parameters to maintain a consistent lighting environment (**Figure 1-1C**). This type of control provides for continuous adjustment of the illuminance and CCT values of the lighting system to maintain total room illuminance in the presence of daylight or other factors such as changes in the LED primaries because of aging-induced luminous flux degradation and chromaticity shifts. Such sensors can be incorporated into each light fixture (fixture-level control) or in a central light sensor that controls a group of SSL luminaires (room-level control).

Aging of the light sources [2, 5, 6] and the drivers [2, 7] has been shown to affect the overall performance of TLS systems. In lighting systems that use a sensor in the control circuit, changes in the performance of the sensor can also affect the overall performance of the installation. If the sensor exhibits excessive changes or measurement drift over time, then issues such as poor illuminance or undesirable light color can result. The impact from these control issues would be especially noticeable in fixture-level control installations because each fixture could have a different illuminance and CCT value. Therefore, it is important to understand the

* An LED primary is a group of connected LEDs of the same color. TLS systems have two or more LED primaries. These LED primaries can both be white LEDs with different CCT values (e.g., warm white, cool white) or can be LEDs of different saturated colors (e.g., red, green, blue).

long-term characteristics of sensors that may be used in TLS systems to better understand the ability of such lighting systems to consistently deliver the same light quality over the course of their expected life.

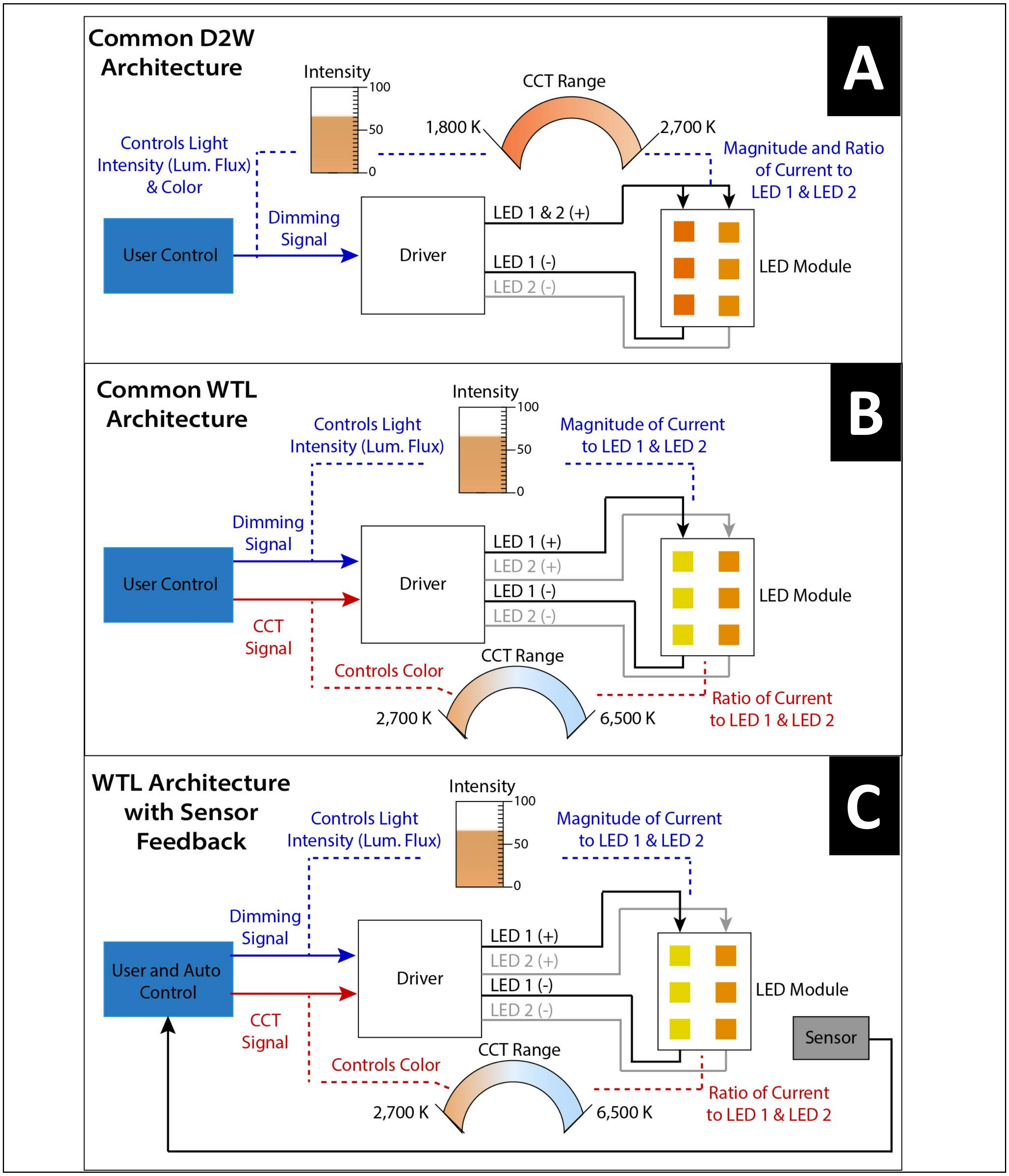


Figure 1-1: Common TLS system architectures. (A) Dim-to-warm systems, (B) standard WTL system, and (C) WTL systems with sensor feedback.

This report provides information about the initial benchmarks and lifetime aging characteristics, gained through accelerated stress tests (ASTs), of a combined illuminance and chromaticity sensor that could be used in a tunable lighting system. This report describes the test method developed to evaluate such sensors, as well as their initial reliability (e.g., part-to-part variability), and the long-term changes observed in the sensor after being exposed to AST conditions. A follow-up report is planned to provide additional information about the aging characteristics of these devices.

## 1.2 Metrics for Sensor Failure

Sensors used in TLS system controls may measure illuminance and color point of the lighting source, although additional capabilities such as measuring occupancy, air quality, or sound levels can also be built in the sensors used in these controls [8]. To assess the reliability of sensors used in TLS systems, the accuracy of illuminance and chromaticity readings can be used as key performance metrics. In addition, other metrics such as part-to-part variability and the reading tolerances of individual sensors can be useful in assessing the reliability of TLS sensors. Obviously, if a sensor is not working and does not produce a control voltage, then an abrupt failure has occurred. However, a parametric failure in the lighting system can also occur when a control sensor is operational but providing the wrong control voltages because of an incorrect reading. Such a situation would result in the lighting system producing light at the wrong illumination level or chromaticity setting.

When determining the parametric failure limits for illuminances and chromaticity of a sensor, consideration should be given to the changes in performance that can be observed by humans. Two common metrics for tracking luminous flux and chromaticity maintenance are the rated luminous flux maintenance life (i.e., the time required for the luminous flux of the LED source to decay to a pre-determined percentage of the initial value) and the chromaticity shift magnitude ($\Delta u'v'$). During early SSL reliability studies, either a decrease in luminous flux to 70% ($L_{70}$) of the initial value or a chromaticity change of $\Delta u'v' \geq 0.007$ was an indication of a parametric failure of the device. As SSL technologies have improved, these parametric failure thresholds have narrowed to the point where either a decrease in luminous flux to 80% of the initial value ($L_{80}$) or a change in chromaticity magnitude of $\Delta u'v' \geq 0.004$ are often used as indicators of parametric failure. Such large changes would be visually apparent to an observer and would meet the parametric failure threshold requirements previously mentioned.

Ideally, all TLS sensors of a given model will provide the same reading for illuminance and chromaticity when they are new. However, that situation is not likely, and the initial readings for illuminance and chromaticity will be distributed at approximately an average value according to the population statistics for that TLS sensor. If the initial reliability of the sensors is good, then the variation in initial sensor readings will be low (i.e., the standard deviation around the average value will be low). As the sensor undergoes accelerated aging in the AST environment, the variation in sensor readings can be expected to increase to the point where a statistically significant change in the population average from the initial reading has occurred. Statistically significant changes in sensor readings are necessary for parametric failure but do not necessarily indicate parametric failure because statistical significance is also a function of the reproducibility of the measurement system. This report classifies a parametric failure for a TLS sensor as either a deviation of 20% or greater in the observed illuminance from the initial population average illuminance or a chromaticity change of $\Delta u'v' \geq 0.004$. Therefore, any measurement system must produce much lower standard deviations than these threshold values.

# 2 Sample Description and Experimental Procedures

## 2.1 Sample Description

All of the samples characterized in this report were a chromatic white sensor product that provides calibrated data for tristimulus values (X, Y, and Z) according to the 2-degree standard observer from the 1931 convention of the International Commission on Illumination (*Commission Internationale de l'Éclairage* [CIE]). A reference design supplied by the sensor manufacturer was used to integrate the sensor into a sensor module test board. The sensor module test board was classified as the device under test (DUT). A reader board was used to measure the performance of the DUTs. This section of the report provides more details about the sensor, the sensor module test board, and the reader board.

### 2.1.1 Sensor

The chromatic white sensor product on the DUTs that were studied and the findings of which are described this report provide calibrated data for tristimulus values (X, Y, and Z). The physical dimensions of the sensor are 4.5 mm × 4.7 mm × 2.5 mm, and the sensor is housed in a 20-pin land grid array (LGA) epoxy package with a small aperture on the top surface. The sensor mechanism is located behind a lens beneath the aperture on the package.

The sensor determines the tristimulus values by using a cognitive light engine (CLE) that is a next-generation digital color sensor device. At the heart of the CLE is an array of six complementary metal-oxide-semiconductor (CMOS) silicon photodiodes with each photodiode covered by a different inorganic Gaussian interference filter to provide selective response to light. The six interference filters are (1) clean (i.e., no filter), (2) dark (i.e., a completely absorbing filter), (3) tristimulus X function of the human eye, (4) tristimulus Y function of the human eye, (5) tristimulus Z function of the human eye, and (6) near-infrared (NIR). The current from each photodiode is integrated by separate digital-to-analog converters (16-bit resolution) and is transferred to a data registry where the values can be read later. The minimum integration time for a channel is 2.8 ms. A schematic illustration of the photodiode array is presented as **Figure 2-1**.

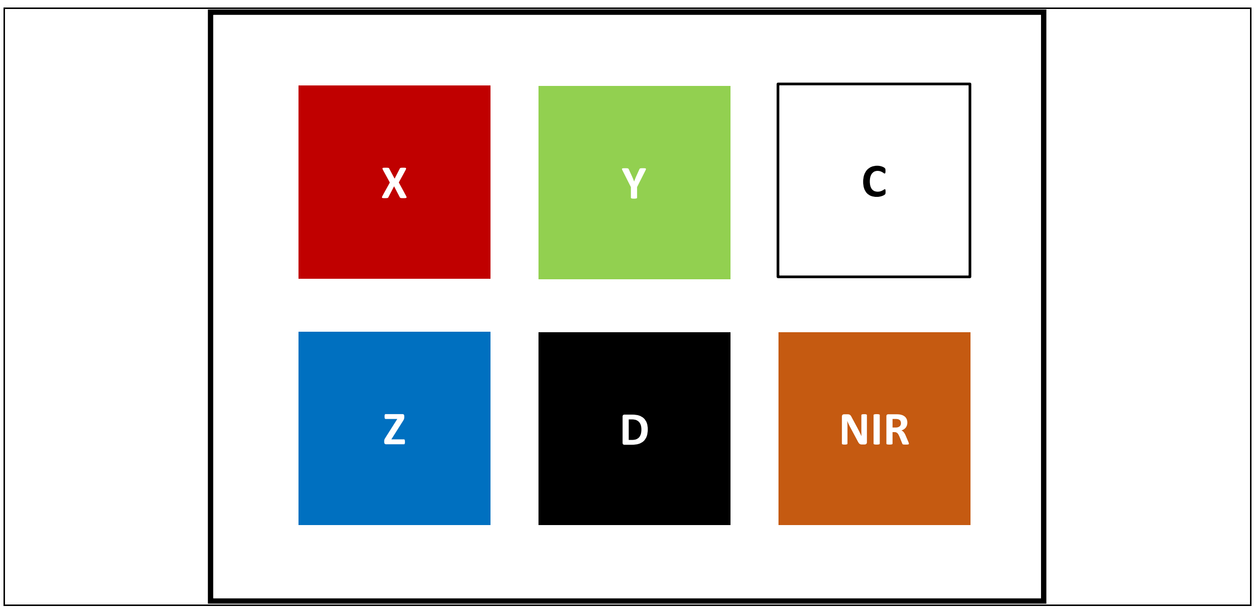


Figure 2-1: Arrangement of the photodiodes and inorganic interference filters in the DUTs.

Covering the interference filters and photodiodes is a lens structure that collects the light entering the sensor and directs it through the optical filters. In addition to the lenses, a 0.75-mm aperture on the outside of the sensor package acts to limit the acceptance angle of the sensor to ±20.5 degrees from the surface normal. The packaged sensor and the sensor with the outer package removed are shown in **Figure 2-2**. The sensor manufacturer states that the filter accuracy is affected by the angle of incidence of light, which is limited by the aperture and the internal lens structure. As described in **Section 2.3.2** of this report, understanding the geometric constraints of the sensor was found to be very important in obtaining reproducible results from the sensor.

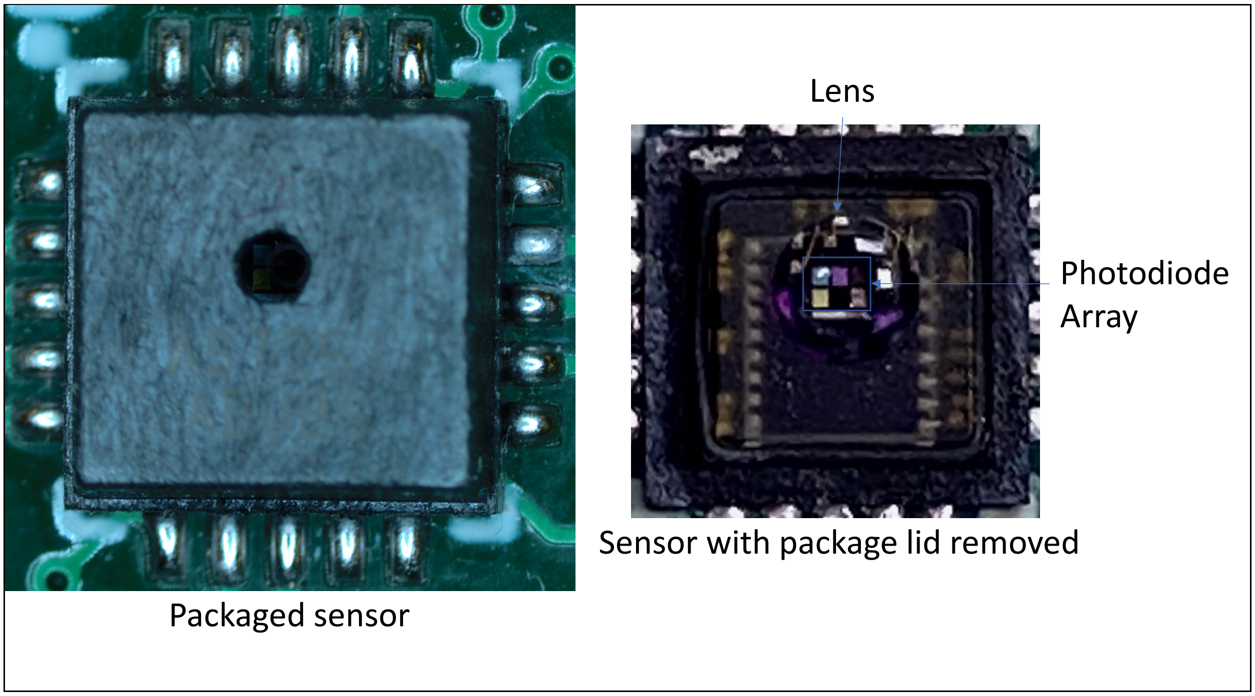


Figure 2-2: Packaged sensor on test board (left) and sensor elements after the package top was removed (right).

The photodiode configuration greatly simplifies the ability of the sensor to provide both luminance and chromaticity information. The luminance is given by the response of the Y photodiode. The x and y chromaticity coordinates in the CIE 1931 color space can be calculated from the responses of the X, Y, and Z photodiodes as follows:

$$x = \frac{X}{X + Y + Z} \qquad \text{and} \qquad y = \frac{Y}{X + Y + Z}$$

Once the x and y chromaticity coordinates are known, other properties such as $u'$, $v'$, and CCT values can be calculated with built-in algorithms.

### 2.1.2 Sensor Module Test Board

Using a reference design supplied by the sensor manufacturer, a sensor module test board was developed and built using surface-mount components and an in-line solder reflow oven. This sensor module test board was the DUT in all instances mentioned in this report. The sensor module test board contains the chromaticity sensor, a serial flash memory chip, and various surface mount resistors, capacitors, and inductors on one side of the printed circuit board (PCB). The PCB also contained a blue indicator LED (turned off while collecting measurements) and a white LED that was not used. On the other side of the PCB, a 10-pin female socket was placed on the board to provide serial port, power, and ground connections to the next layer of packaging. During AST, the next-level package was a power distribution board that accommodated four sensor modules and provided the operation voltage (3.3 V) for each during AST. During sensor measurement, the next layer of package was a reader board (described in **Section 2.1.3** of this report) that provided power and enabled reading of the output voltage from the sensor. The test boards used during this study are shown in **Figure 2-3**.

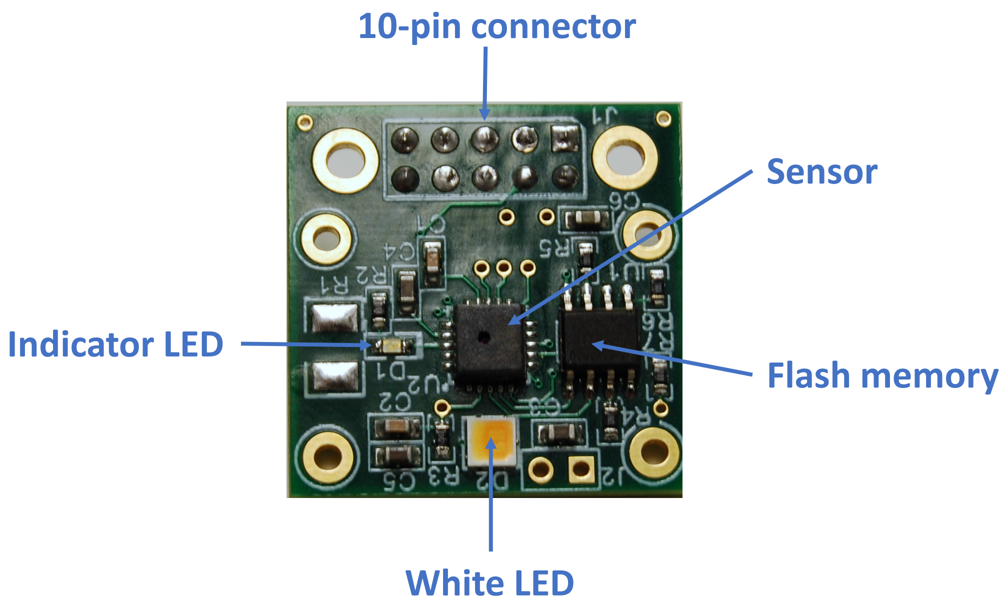


Figure 2-3: Sensor test boards used during this study.

### 2.1.3 Reader Board

While collecting measurements from each DUT, the reader board provided the interface between the data collection computer and the DUT. The reader board is connected to a computer through a Universal Serial Bus (USB) cable and interfaces to the DUT through the 10-pin connector. The reader board contains a liquid crystal display that provides the capability of manually displaying the measurements (not used in this study) and a serial port pass-through connector interface from the DUT and the USB connector to the computer. The same reader board was used to measure the output from all test samples. The reader board that was used to test the DUTs is shown in **Figure 2-4**. The reader board was used solely to connect the DUT with the data collection computer, and this PCB did not undergo any AST exposure.

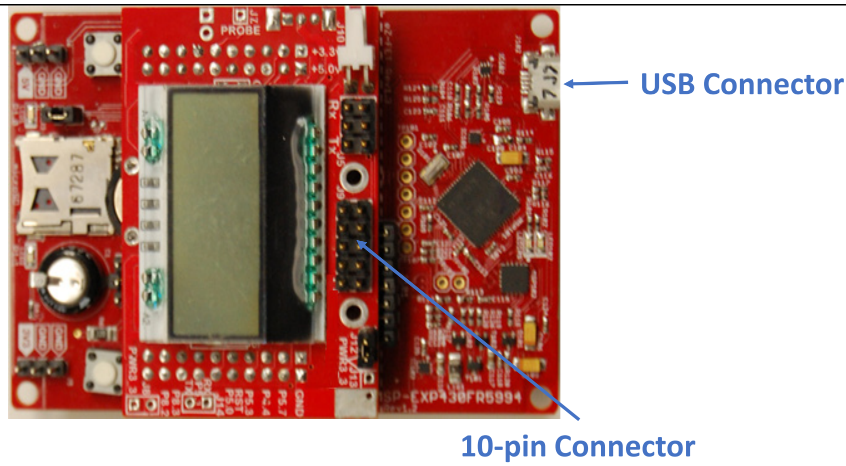


Figure 2-4: Reader board used to test the DUTs.

## 2.2 Stress Testing Methods

The DUTs were separated into four populations (i.e., a control and separate populations for testing in one of three possible exposure conditions). The three conditions are as follows: room temperature operating life (RTOL) test, an operational life test at an elevated ambient temperature of 75°C (75OL), and an operational life test in a temperature-humidity environment of 75°C and 75% relative humidity (7575). Either a temperature oven or a temperature-humidity environmental chamber was used for the 75OL and 7575 ASTs, but humidity was not explicitly controlled in either RTOL or 75OL (ambient humidity was determined by the air handling system of the building). All DUTs were continuously powered at 3.3 V during the ASTs. The back of each DUT was numbered to identify the DUT throughout testing. The DUT number and the test environments to which they were exposed are presented in **Table 2-1**.

Table 2-1: Assignment of DUT numbers and test environments.

| DUT Numbers | Test Environment |
|---|---|
| 1 through 4 | Control |
| 5 through 8 | 75OL |
| 9 through 12 | RTOL |
| 13 through 20 | 7575 |

## 2.3 Measurement Methods

### 2.3.1 Test Method

Each DUT underwent the assigned AST protocol according to the DUT numbers and test environments presented in **Table 2-1**. After every 1,000 hrs of AST exposure, the DUTs were removed from the exposure environment and photometric measurements were collected of their performance. Currently, no known standard test methods are in place for evaluating chromaticity sensors. To perform this work, a test method had to be developed that ensured excellent reproducibility in order to determine when a parametric failure occurs. The photometric testing apparatus developed for this study consisted of an optical bench with a parabolic aluminized reflector (PAR) lamp of a fixed CCT value at one end and a reader board containing the sensor module DUT at the other end (**Figure 2-5**). The distance between the PAR lamp and the sensor on the DUT was approximately 34 inches. All lights in the laboratory were turned off before collecting the measurements so that the PAR lamp was by far the dominant light source present during the measurement. Computer monitors used during testing were placed so that the screen was pointing away from the sensor, and the monitors were displaced from the sensors by approximately 36 inches.

Directly in front of the DUT was an optical filter holder that contained a commercially available, double-sided light diffuser film (10-mm thick with a circular diffusion pattern). The use of the light diffuser was found to increase measurement reproducibility. The filter holder was on a linear slider on the optical table, thereby allowing the DUT to be changed on the reader board and the diffuser to be repositioned before collecting any measurements. The diffuser film was positioned to touch the surface of the optical sensor (see **Figure 2-6**) before measurements were collected.

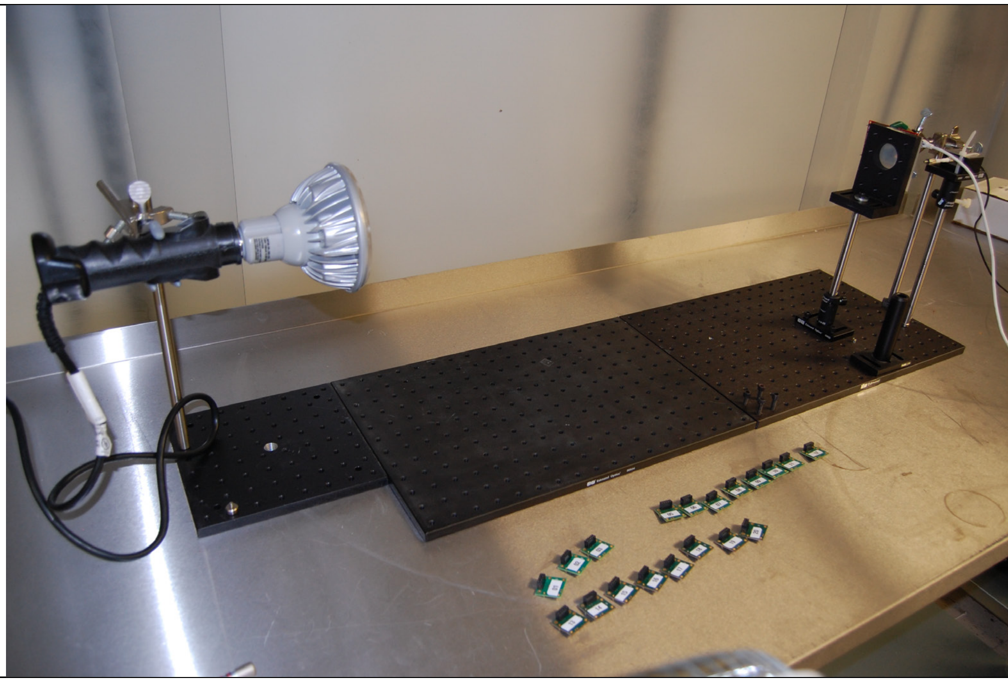

Figure 2-5: Experimental arrangement used to measure the sensor DUTs after AST exposure.

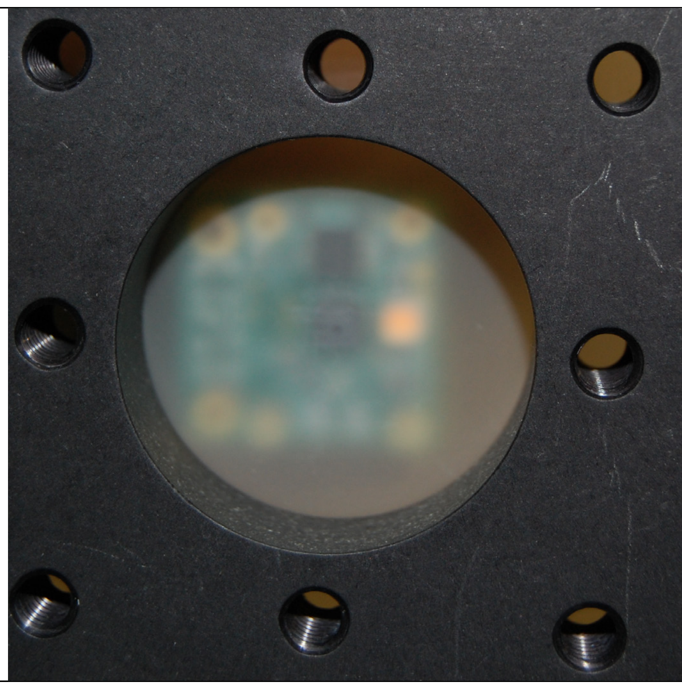

Figure 2-6: The optical diffuser film is positioned to just touch the surface of the sensor element.

A fiber-optic spectrometer (3648-element detector with optics to facilitate collecting radiation between 200 nm and 1,100 nm) was displaced approximately 2 inches laterally from the sensor DUT and was used as an independent measure of the stability of the light sources. The spectrometer and fiber-optic cable were calibrated by using a radiant flux standard that was traceable to standards from the National Institute of Standards and Technology (NIST). A duplicate of the light diffuser film used with the sensor was also placed in front of the fiber-optic spectrometer to ensure that the two beam paths were comparable.

After the PAR lamp had been on for at least 30 minutes, a data acquisition program was activated on a laptop computer, and a single measurement of the sensor readings was collected. A minimum of two additional readings were collected on the same sensor for a total of at least three readings from each sensor. Each reading provided data about illuminance, CCT, x, y, *u′*, *v′*, u, v, X, Y, Z, temperature, and integration time for that sensor with the PAR lamp. The illuminance, CCT, *u′*, and *v′* values measured by the spectrometer were also recorded. Throughout the tests, all light sources were found to be very stable, with the CCT values varying by no more than 20 K and the *u′* and *v′* values changing by less than 0.0005 during a typical experiment (which lasted for approximately 3 hrs). Statistical analysis software (MiniTab v19, State College, PA) was then used to analyze the data.

### 2.3.2 Geometric Considerations

As noted in **Section 2.1.1** of this report, the accuracy of the readings from the DUT is affected by the angle of light incidence as limited by the aperture and the internal micro-lens structure of the DUT. For some DUTs, the angle of incidence of the light beam could be made to vary by up to 10 degrees simply by wiggling the sensor module DUT on the reader board. This variation in sensor position in the light beam was found to produce large changes in output values likely because of variations in the angle of incidence of light relative to the lens. For example, the illuminance reading could change by as much as 6%, and the chromaticity point could change by as much as a five-step standard deviation of color matching (SDCM) depending on sensor position in the test apparatus. Such variability would be too large for meaningful measurements to be collected unless a more reproducible method was found.

To eliminate this variability, care was taken to align the sensor perpendicular to the PAR lamp by using the markings on the optical table, and a diffuser film was placed immediately in front of the sensor. This approach produced greater measurement repeatability to the point where valid statistical comparisons could be made. To assess the reproducibility of the readings, each control DUT was placed on the reader board, measured, removed from the reader board, repositioned on the reader board, and then remeasured. A total of six different measurements were collected for each of the control sensors. The average values and standard deviations of these measurements by using Test Lamp (TL)-3 are presented in **Table 2-2**. Similar measurement variations were observed for TL-1 and TL-2. The Gage repeatability and reproducibility study shows that there are some minor variations in readings between the different DUTs. However, the standard deviations are small (i.e., <3% for illuminance and <1% for CCT, *u′*, and *v′*) by using this experimental setup. Consequently, this measurement system is more than capable of identifying parametric failures according to the failure criteria discussed in **Section 1.2** of this report.

Table 2-2: Average and standard deviations from multiple measurements of control samples.[a]

| Control Sample | Illuminance (lux) | CCT (K) | *u′* | *v′* |
|---|---|---|---|---|
| DUT–1 | 614.2 (9.6) | 4,382 (31) | 0.2205 (0.0004) | 0.4923 (0.0004) |
| DUT–2 | 577.6 (7.3) | 4,334 (16) | 0.2209 (0.0003) | 0.4933 (0.0004) |
| DUT–3 | 587.0 (9.1) | 4,356 (46) | 0.2210 (0.0007) | 0.4924 (0.0004) |
| DUT–4 | 595.4 (10.5) | 4,375 (35) | 0.2205 (0.0004) | 0.4927 (0.0007) |
| All controls | 593.7 (15.3) | 4,358 (36) | 0.2208 (0.0005) | 0.4927 (0.0006) |

[a] These measurements were taken with Test Lamp 3 (see **Section 2.4** of this report). Standard deviation values are provided in parentheses.

## 2.4 Test Lamp Description

A series of different PAR test lamps was used to evaluate the DUTs after AST exposure. The lamps were placed in the test fixture shown in **Figure 2-5**, and readings were collected for each DUT. The intent of using different lamps in the test apparatus was to investigate the effects of different lighting conditions on sensor performance. TL-1 and TL-2, which represent warm white lighting, were previously evaluated during a study for the U.S. Department of Energy's (DOE's) Commercially Available LED Product Evaluation and Reporting (CALiPER) program, and the findings were presented in the CALiPER 20.5 report [9]. As described in the report, TL-1 is a phosphor-converted LED (pc-LED) source using a chip-on-board array, whereas TL-2 is a hybrid LED source combining a red LED with a pc-LED. The two different warm white sources were used to represent two possible configurations of a TLS system. The cool white test lamp, TL-3, was purchased new for this test and uses a pc-LED source. The photometric properties of all test lamps were measured by using a 65-inch integrating sphere calibrated by using a NIST-traceable radiometric standard. Measured values are provided in **Table 2-3,** and the spectral power distributions (SPDs) produced by the test lamps are presented in **Figure 2-7**.

Table 2-3: Test lamp properties.

| Test Lamp Designation | Lamp Source Structure | Beam Angle | CCT (K) | Nominal Luminous Flux | Color Rendering Index |
|---|---|---|---|---|---|
| TL-1 | pc-LED | 24 degrees | 3,092 | 1,092 lumens | 94 |
| TL-2 | Hybrid LED | 12 degrees | 3,004 | 1,020 lumens | 96 |
| TL-3 | pc-LED | 40 degrees | 4,895 | 698 lumens | 87 |

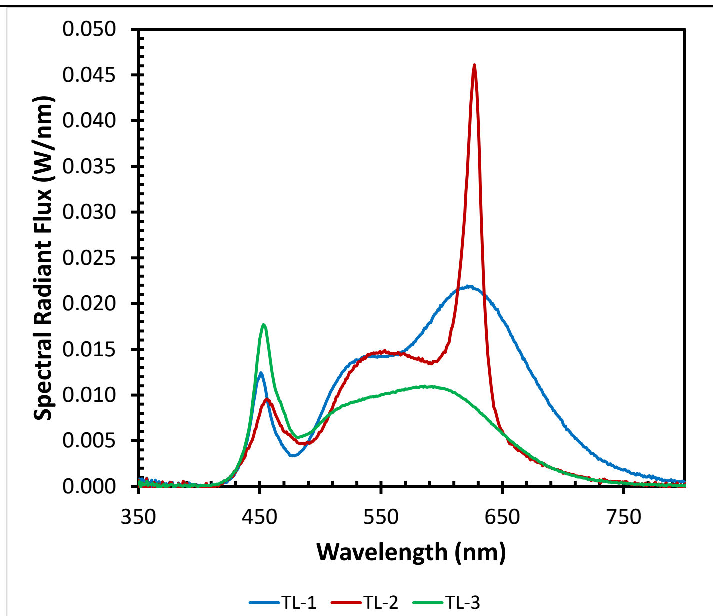


Figure 2-7: SPDs of the test lamps.

# 3 Results

## 3.1 Initial Reliability

During the study, the initial reliability of the DUTs was assessed, and the initial measurement values of all DUTs was statistically similar to the values shown in **Table 2-2** demonstrating that the part-to-part variability of the DUTs was low. In addition, the variation in measurement values from the same sensor was even lower. Measurement-to-measurement variation of the same sensor was less than 0.5% for illuminance values and less than 0.1% for CCT, *u'*, and *v'* values. Therefore, based on initial measurements, no DUTs were excluded from testing as being unrepresentative of the general population. The measurements of the unexposed controls during photometric testing of the DUTs were used to provide a baseline to measure any expected changes in sensor performance caused by operating in the different AST environments.

## 3.2 Chromaticity Stability

The reliability of the DUTs was measured after every 1,000 hrs of AST exposure, but this report will only focus on the reliability after 5,000 hrs of exposure to the respective ASTs (i.e., RTOL, 75OL, and 7575). The reliability performance of the DUTs can be most easily assessed by examining the changes in the *v′* chromaticity coordinate, which are presented in **Figure 3-1** (for TL-1), **Figure 3-2** (for TL-2), and **Figure 3-3** (for TL-3). Each figure provides the individual measurement data on the left side of the graph and the corresponding box plot on the right side. The box plots display the median value (the solid line for each DUT) and the first and third quartiles of the measurement distribution (i.e., the top and bottom of the box). A solid black vertical line is used to segment each graph by AST (see **Table 2-2**). In addition, all graphs display the control average value for the measured parameter (dotted blue line). The *v′* limit, as determined by the parametric failure criterion of a four-step SDCM, is also shown as a horizontal dashed red line.

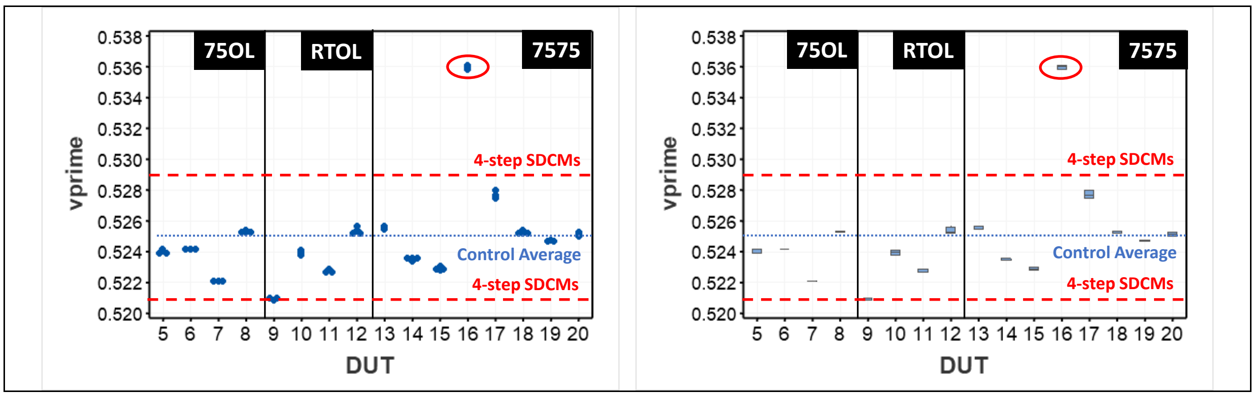


Figure 3-1: The *v′* readings from DUTs using TL-1 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

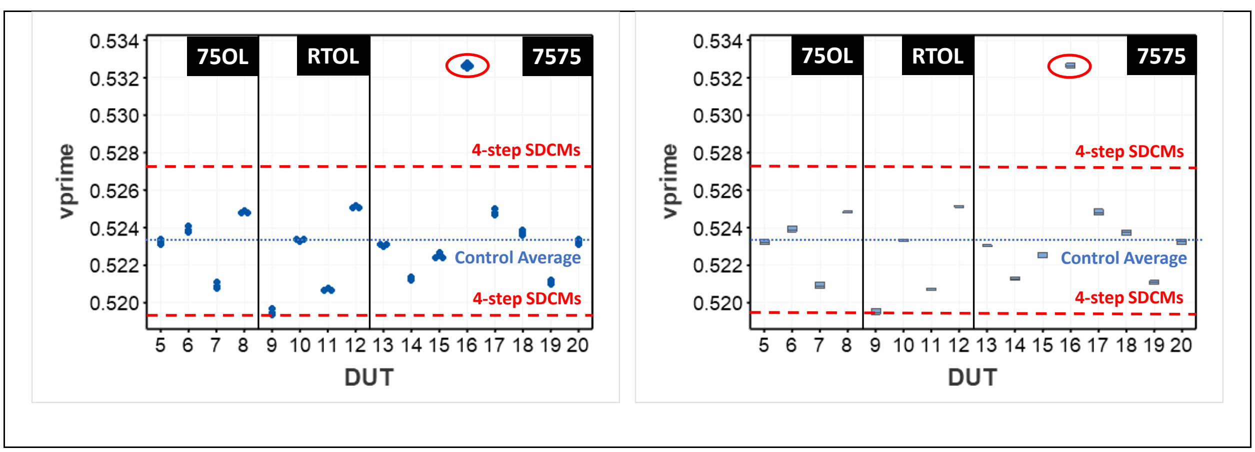


Figure 3-2: The *v′* readings from DUTs using TL-2 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

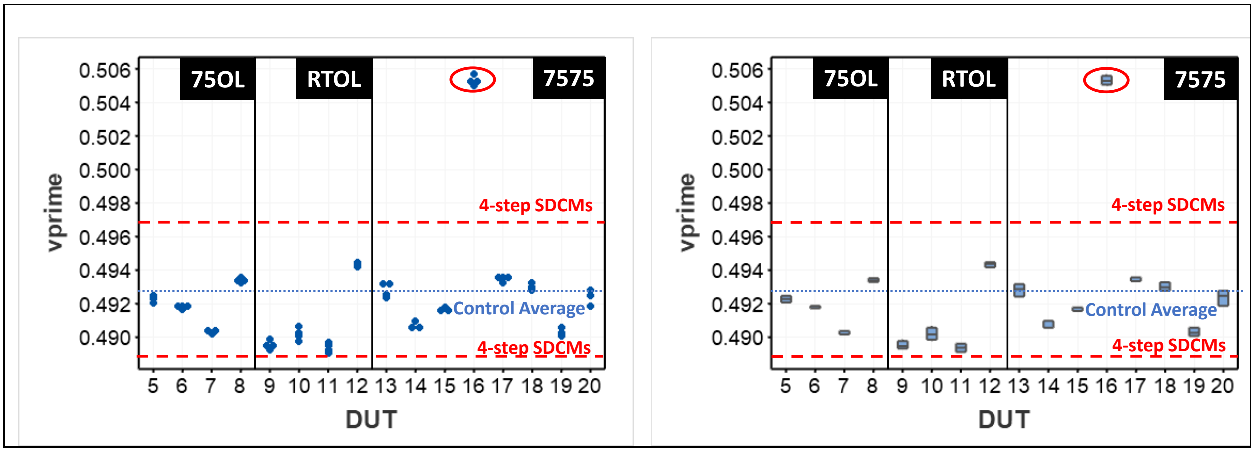


Figure 3-3: The *v′* readings from DUTs using TL-3 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

As shown in **Figure 3-1**, **Figure 3-2**, and **Figure 3-3**, most DUTs exhibited a *v′* value that was within a two-step SDCM of the control average for the particular light source. Although there are some part-to-part variations in readings, the values remain within the parametric failure threshold (e.g., $\Delta u'v' \leq 0.004$ or $\Delta v' \leq 0.004$). A very small variation was found for the readings from a single DUT, indicating excellent reproducibility. This finding indicates that the *v′* readings of most sensors was not significantly affected by the AST environment through 5,000 hrs of exposure. The lone exception was DUT-16 (highlighted by the red ovals in **Figure 3-1**, **Figure 3-2**, and **Figure 3-3**), which consistently exhibited a higher than expected reading for *v′* for all three test lamps. Such a large deviation in the $+\Delta v'$ direction is equivalent to a chromaticity shift in the yellow direction. This deviation not only exceeded the four-step SDCM threshold, but also exceeded seven-step SDCMs in all cases. Consequently, DUT-16 can be considered a parametric failure after 5,000 hrs of 7575 exposure by using the guidelines in **Section 1.2**, corresponding to a failure rate of 12.5% of the 7575 test population. No other parametric failures were observed in the 7575 population; however, the blue indicator LED stopped working on most DUTs and the PCBs were noticeably darker, suggesting that the aggressive 7575 environment had a significant impact on the DUTs.

The changes in the *u′* chromaticity coordinate are much smaller and are provided in **Figure A-1**, **Figure A-2**, and **Figure A-3**. The total range in *u′* readings at the 5,000-hr measurement point was only $\Delta u' \leq 0.0025$ for TL-1, $\Delta u' \leq 0.003$ for TL-2, $\Delta u' \leq 0.005$ for TL-3. Although DUT-16 deviated from the control average value of *u′* by <0.003 for TL-3, the value was still within the pre-determined parametric failure criterion. As a result, no parametric failures were counted based on the *u′* measurement alone. This finding further reinforces that the parametric changes of these sensors over time appears to be in the +*v′* direction (i.e., yellow shift).

## 3.3 CCT Values

In a similar manner, changes in the CCT readings from the DUTs measured for the three light sources provided confirmation of the reliability of these sensors. The CCT values after 5,000 hrs of AST exposure are shown in **Figure 3-4** (for TL-1), **Figure 3-5** (for TL-2), and **Figure 3-6** (for TL-3). In general, the sensors measured a lower CCT value than would be expected from the integrating sphere photometry (see **Table 2-2**). However, some of this difference can be accounted for by the diffuser film placed in front of the sensor. Other differences are likely attributed to differences in measurements in the controlled environment of the integrating sphere compared with the open test bench of this photometric measurement method. In general, the measured CCT values agreed within 50 K to that of the calibrated spectrometer, which was laterally displaced from the sensor by 2 inches as shown in **Figure 2-5**.

The CCT readings measured by the DUTs were randomly distributed about the control average for each test lamp, suggesting that a minimal change has occurred in CCT readings from the sensors because of the ASTs. The lone exception was DUT-16 which exhibited a statistically significant lower CCT value, as would be expected from the observed behavior in $v'$. This deviation varied from approximately 80 K for TL-1 and TL-2 to 350 K for TL-3, suggesting that the magnitude of the deviation is dependent upon the light source CCT.

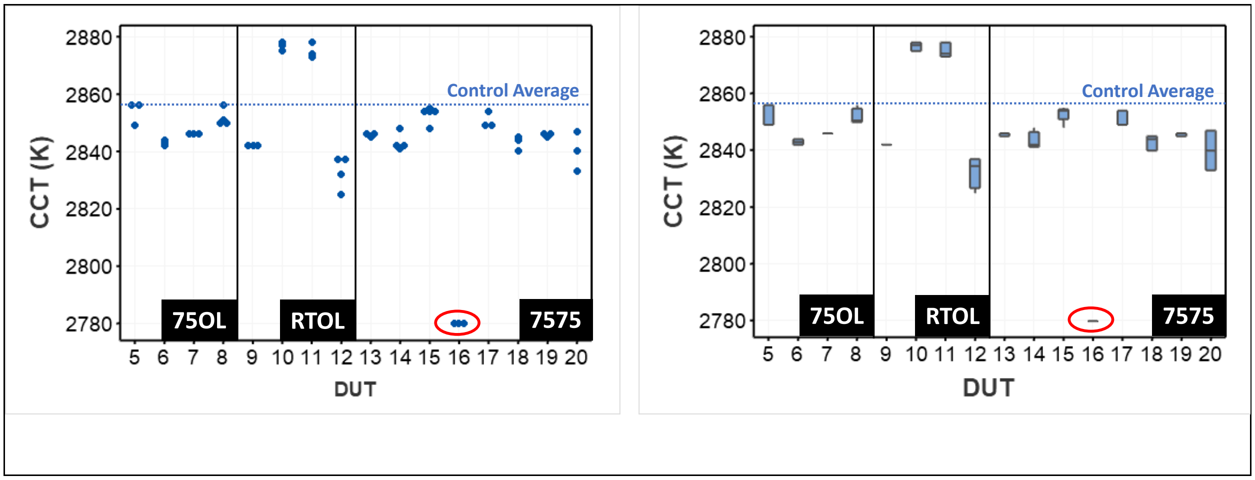


Figure 3-4: The CCT readings from the DUTs using TL-1 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown are the dotted blue line.

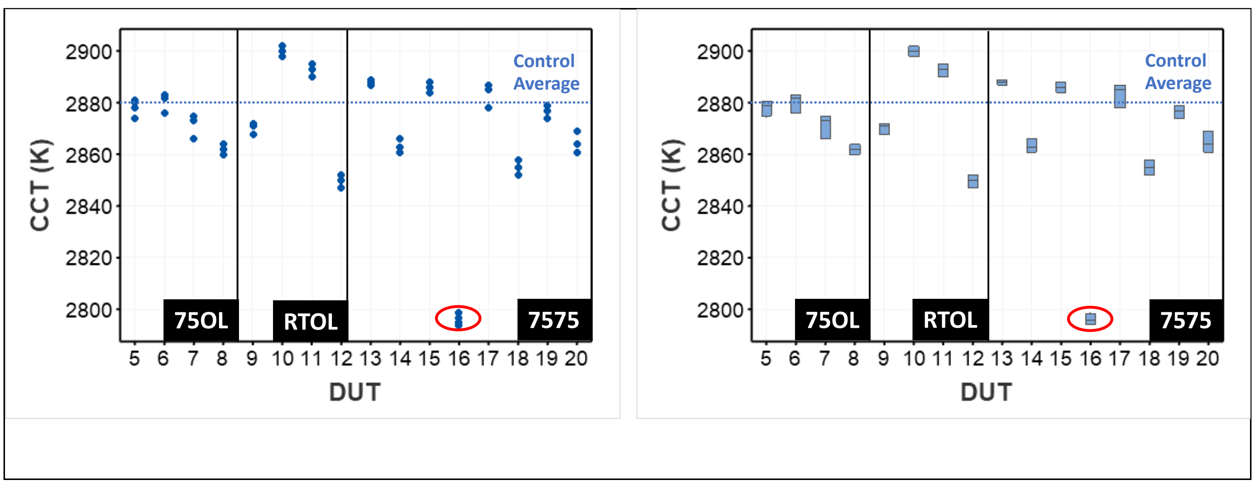


Figure 3-5: The CCT readings from the DUTs using TL-2 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

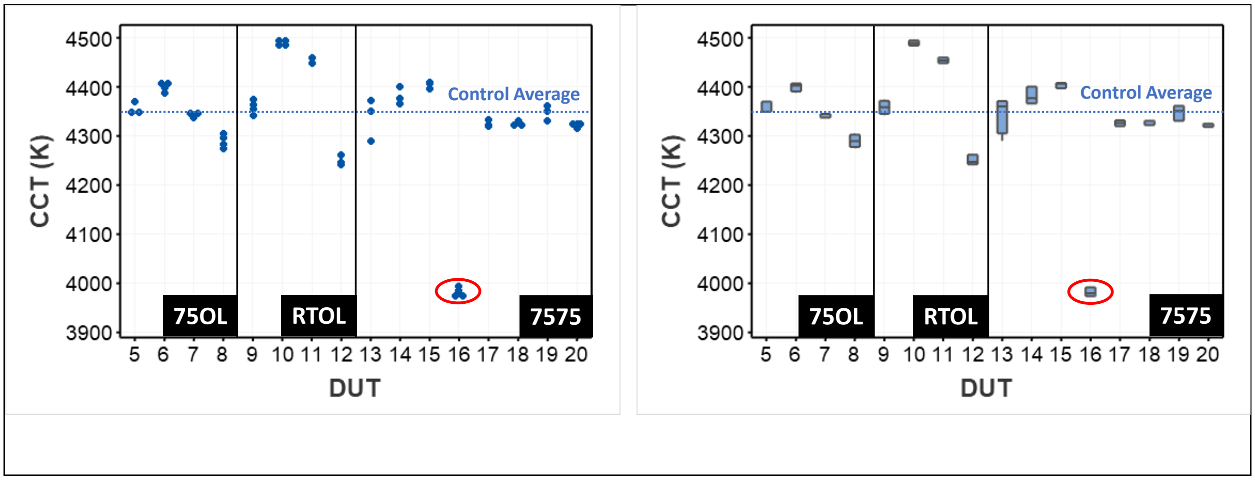


Figure 3-6: The CCT readings from the DUTs using TL-3 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

## 3.4 Illuminance

Illuminance measurements were also taken after 5,000 hrs of AST exposure for all of the DUTs, and the data are provided in **Figure A-4**, **Figure A-5**, and **Figure A-6** in **Appendix A** of this report. The average illuminance value and standard deviation measured for the DUTs under the different test lamps are presented in **Table 3-1**. An unpaired two-sample *t*-test (with variable standard deviations) was used to compare all average illuminance readings with the control readings for each test lamp. Only the illuminance values for the RTOL and 75OL populations (shown in bold in **Table 3-1**) when measured with TL-1 and TL-3 were found to be statistically different from the control. The RTOL and 75OL values were not statistically different from the control value for TL-2. The average illuminance value of the 7575 DUTs was also not statistically different from the controls for any of the test lamps, regardless of whether DUT-16 was included in the analysis. We speculate that the illuminance reading may have increased initially (as observed during RTOL and 75OL) but began to decrease from this maximum such that its value after 5,000 hrs of 7575 is not statistically different from the control. Further testing is needed to confirm this hypothesis.

Table 3-1: Average illuminance values for the DUTs after 5,000 hrs of different ASTs for different test lamps.[a]

| AST | TL 1 | TL 2 | TL 3 |
|---|---|---|---|
| Control (DUT-1 through DUT-4) | 1474.3 (32.3) lux | 6493.5 (204.4) lux | 593.7 (15.3) lux |
| RTOL (DUT-5 through DUT-8) | **1515.2 (66.8) lux** | 6582.2 (305.0) lux | **606.1 (18.2) lux** |
| 75OL (DUT-9 through DUT-12) | **1515.3 (41.6) lux** | 6419.7 (130.5) lux | **604.1 (8.0) lux** |
| 7575 (DUT-13 through DUT-20) | 1456.6 (42.8) lux | 6401.9 (213.9) lux | 588.5 (21.0) lux |
| 7575 (DUT-16 excluded) | 1466.6 (33.4) lux | 6432.0 (221.1) lux | 594.5 (15.8) lux |
| Failure criteria | 1179 lux | 5195 lux | 475 lux |

[a] Standard deviations are provided in parentheses. Bolded numbers are statistically significant from the control values for that test lamp.

A failure threshold can be defined as 80% of the average control illuminance for each test lamp. Illuminance measurements from a DUT less than this value would likely constitute a parametric failure for low luminous flux. Given the population statistics for the DUTs in the various ASTs, this failure probability can be calculated by using the values in **Table 3-1**. The findings from the calculations show that after 5,000 hrs of

ASTs, there is essentially no probability of parametric failure of the sensors due to a luminous flux reading that is <80% of the true value. This finding holds for all the AST environments (i.e., RTOL, 75OL, and 7575).

The deviation of DUT-16 from the control reading is statistically significant for all lamps, but the level of change from the control reading is below the parametric failure threshold. Therefore, no DUTs are considered to be parametric failures by the illuminance threshold. More study is needed to determine whether any of the DUTs exceed the parametric threshold in the future.

# 4 Discussion

Once a suitable test method was developed, the performance of the chromaticity sensor examined in this study could be accurately measured as a function of AST exposure. The initial readings of all DUTs were found to be similar, with a tight distribution of readings across the test population. The readings varied by <3% for illuminance and <1% for CCT, $u'$, and $v'$ (see **Table 2-2**). The reproducibility of readings from the same sensor was even better. These findings suggest that the initial reliability of the DUTs was high, as indicated by the excellent reproducibility of the sensor readings. In addition, measurement readings from the same DUT were highly reproducible.

The angle of incidence of the light on the DUT was found to have the largest impact on the initial reading. During the initial test without a light diffuser in front of the sensor, the sample-to-sample reproducibility was poor, and it would have been difficult to determine any statistically significant changes in the sensors resulting from AST exposure. However, the addition of a light diffusing film in front of the DUTs (see **Figure 2-6**) significantly improved the part-to-part measurement reproducibility, thereby allowing statistically valid conclusions to be made. Although the manufacturer of the sensor does acknowledge some change in the accuracy of sensor readings depending on the angle of light incidence to the sensor, the manufacturer recommends direct illumination of the sensor from a mirror. The manufacturer's literature did not mention the use of a light diffuser. Given the observed change in accuracy of the sensor's readings to small angular changes in incident light, such a configuration would likely require tight tolerances on the placement of the mirror relative to the sensor. Manufacturing variables such as the placement of component or solder paste height may also have an impact on sensor accuracy, requiring additional compensation in the control circuit. However, as demonstrated during this study, flood irradiation of a light diffusing film placed in front of the sensor greatly increases the measurement tolerances and allows for reproducibility measurements to be made between DUTs by using different light sources.

In general, the chromaticity sensor examined during the study and discussed in this report exhibited excellent reliability through 5,000 hrs of AST exposure. No abrupt failures occurred, and only DUT-16 exhibited parametric failure during this AST exposure period. Otherwise, the measured chromaticity and CCT values for the DUTs were within $\Delta u'v' < 0.001$ and $\Delta CCT \leq 50$ K of the independent measurement of the light source with a fiber-optic spectrometer. These deviations are viewed as acceptable because the sensor and fiber-optic spectrometer are not measuring the same location on the lighting plane. The independent spectrometer used in the test apparatus also demonstrated that all test lamps were extremely stable during the measurement period.

Although most samples changed little after AST exposure, readings from DUT-16 changed significantly after 5,000 hrs of 7575 exposure. The measure of $v'$ values for DUT-16 under the different test lamps provided evidence of a parametric failure (**Figure 4-1**). The box plot provides the median of the 7575 test population (i.e., the horizontal line in the interior of the box), the first and third quartiles of the population distribution (i.e., the top and bottom of each box), and the range of values (i.e., the "whiskers" extended from the top and bottom of each box). In addition, each box plot shows the outlying values measured for DUT-16 as "*". A similar plot can be constructed for CCT values, but it is not provided here for brevity. If a sensor responded to aging in this manner in a field installation that used a fixture-control architecture, then this parametric failure would result in a mismatch of CCT values of adjacent luminaires that would be noticeable to an observer.

However, the effect may be less noticeable in a room-level control architecture where the physical separation between rooms of a different CCT value would provide some insulation from the change.

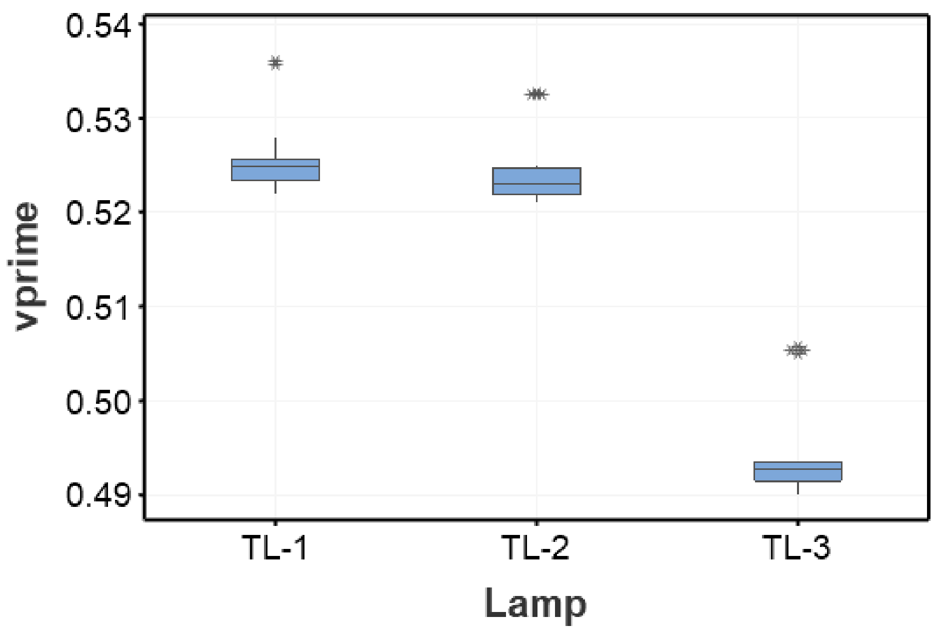


Figure 4-1: Box plot for $v'$ measurements for the 7575 DUTs using different test lamps.

When a chromaticity sensor is used in a TLS luminaire, the specific response of the luminaire depends upon the design of the control system used by the manufacturer. However, examining a common configuration can provide insights into some potential ramifications of faulty $v'$ and CCT readings from the sensor. In a typical WTL installation, the two LED primaries are often chosen to have CCT values of approximately 2,750 K and 6,500 K. CCT values between these two end points can be achieved by changing the current distribution between the LED primaries, which results in linear tuning of the CCT value [2, 3]. Because the chromaticity values of such a WTL system are confined to the line connecting the chromaticity coordinates of the two LED primaries, the WTL luminaire is not capable of reaching chromaticity values not on this line. If we remove DUT-16 from the 7575 test population and assume that the chromaticity and CCT readings from the remainder of the DUTs are accurate, then the warm white chromaticity point on this tuning line is given by the average TL-1 response ($u'$ = 0.2564, $v'$ = 0.5258) and a second chromaticity point on this tuning line is given by the TL-3 response ($u'$ = 0.2212, $v'$ = 0.4922). Extending this line to 6,500 K gives the chromaticity value ($u'$ = 0.1917, $v'$ = 0.4695) of the theoretical cool white primary that would be used in the WTL device. These points are connected by the blue line shown in **Figure 4-2**, which we will take as the true representation of the chromaticity and CCT value of the WTL luminaire. As is typical in WTL devices, the two LED primaries are above the blackbody locus, whereas some intermediate values are below the locus.

However, if a sensor that exhibited the same characteristics as DUT-16 was used in this device, then the sensor readings would result in higher $v'$ measurement than the true value. Such faulty measures are represented by the black dots and black line in **Figure 4-2**. In a case such as the one for DUT-16, these readings would lie completely above the blackbody locus. Typically, WTL systems are designed to control CCT values based on set points delivered to the system through the UI or feedback circuits. If we assume that the hypothetical WTL luminaire is set to the CCT value of TL-3, then the actual luminaire would initially produce a reading of 4,348 K but the sensor would read a value of 3,983 K. Therefore, the control system of the SSL device would alter the current distribution to the LED primaries until the faulty sensor produces a reading of 4,348 K for CCT. This setting would require the control system to tune the luminaire to the chromaticity point shown in red in

**Figure 4-2**. Assuming that the error in the chromaticity sensor occurs solely in the *v′* reading, as found during this analysis, the actual CCT value of the light produced by the luminaire would be 4,626 K. This CCT value corresponds to a chromaticity shift of $\Delta u'v' = 0.0058$ from the control value, which is outside of our failure criteria and would be noticeable by an observer. Furthermore, as shown in **Table 3-1**, the illuminance reading of such a sensor may be statistically different from the control but not to the point of triggering a parametric failure by itself. Consequently, only select photometric properties of the TLS device would be affected by such a faulty sensor, but other properties would be within acceptable limits.

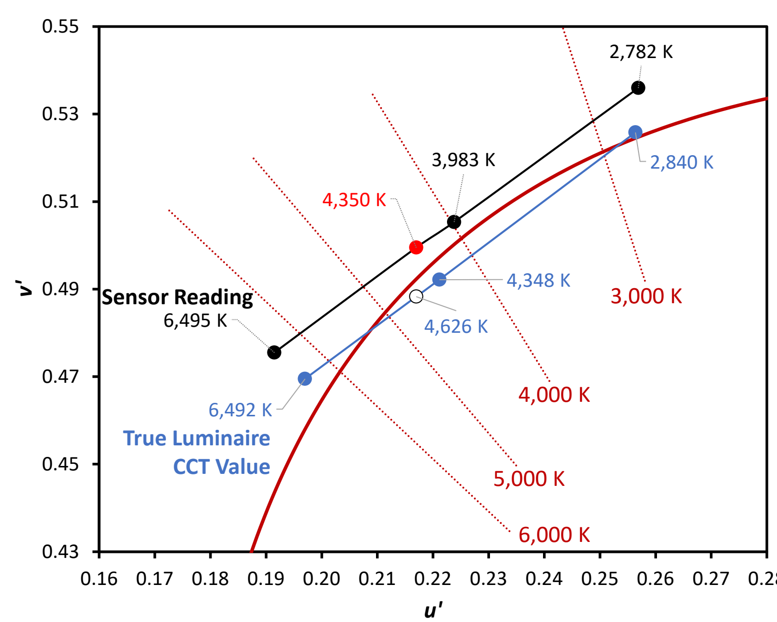


**Figure 4-2: Potential impact of a faulty chromaticity sensor reading on CCT value of light from a TLS system. The blue dots and line represent the true luminaire values, and the black dots and line represent the readings from a faulty chromaticity sensor.**

During the analysis, there was evidence that the illuminance reading from the sensors increased during early operation and began to decrease under more severe test conditions. The average illuminance readings from the DUTs exposed to RTOL and 75OL were statistically higher than that of the controls for TL-1 and TL-3. However, no statistically significant difference was observed between the control and the DUTs from 7575 when measured by using either TL-1 or TL-3. In addition, no statistically significant difference in illuminance was observed when the DUTs were tested by using TL-2, possibly due to a larger measurement variance when testing with TL-2. Because illuminance is only one parameter used to characterize a TLS system, it does not appear to be a parameter that is overly sensitive to changes in sensor performance. Instead, changes in *v′* and CCT values were found to be much better indicators of the performance of the control system.

In many current lighting systems, the main control parameter is illuminance on the work plane or vertical surfaces. This parameter is often measured with a photocell that is mounted in the ceiling. However, as the lighting paradigm shifts to TLS systems, these installations will increasing rely on illuminance and chromaticity sensors for control. This work has shown that the use of such sensors raises new questions about the long-term reliability of the sensor when it is used as part of the lighting control system.

# 5 Conclusions

The reliability of a commercially available chromaticity sensor was measured after exposure to different AST environments. The sensor operates by measuring X, Y, and Z tristimulus chromaticity values by using a series of photodiodes whose top surface was covered with inorganic Gaussian interference filters. After compensating for the light incident angle sensitivity of the DUTs with an external light diffusing film, reproducible readings were obtained from the DUTs and the impacts of the different AST environments could be assessed. After 5,000 hrs of AST exposure, one parametric failure was observed during 7575 (12.5% failure rate) because of excessive shifts in $v'$ and CCT values, but not in $u'$ and illuminance values. One parametric failure during 7575 was readily detected by a large increase in the $v'$ chromaticity coordinate that exceeded both the $\Delta u'v' \leq 0.004$ and $\Delta u'v' \leq 0.007$ thresholds. No parametric failures occurred during RTOL and 75OL. A significant change in CCT values was also observed for the DUT (i.e., DUT-16) that exhibited the parametric failure. In contrast, measurements for illuminance and the $u'$ chromaticity coordinate changed less from the control values, and no DUTs evaluated during this study would be classified as parametric failures based on illuminance or $\Delta u'$ values alone.

When used in a lighting control system for a luminaire, a deviation from the true value (as was observed for the parametric failure that occurred during the 7575 AST environment) would produce a change in a TLS device that would be noticeable to an observer. Light from the TLS luminaire would likely be blue-shifted (relative to the true value) to compensate for the yellow-shifted readings of the chromaticity sensor. However, minimal changes in illuminance would occur because the accuracy of this sensor reading appears to be less affected by the 7575 environment. This finding underscores that moving from traditional lighting measurements involving mainly surface and vertical illuminance to dynamic lighting systems controlling illuminance, chromaticity, and CCT will require greater understanding of the long-term performance of the sensors controlling such systems and the changes in their reliability caused by aging and environmental exposure.

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# Appendix A

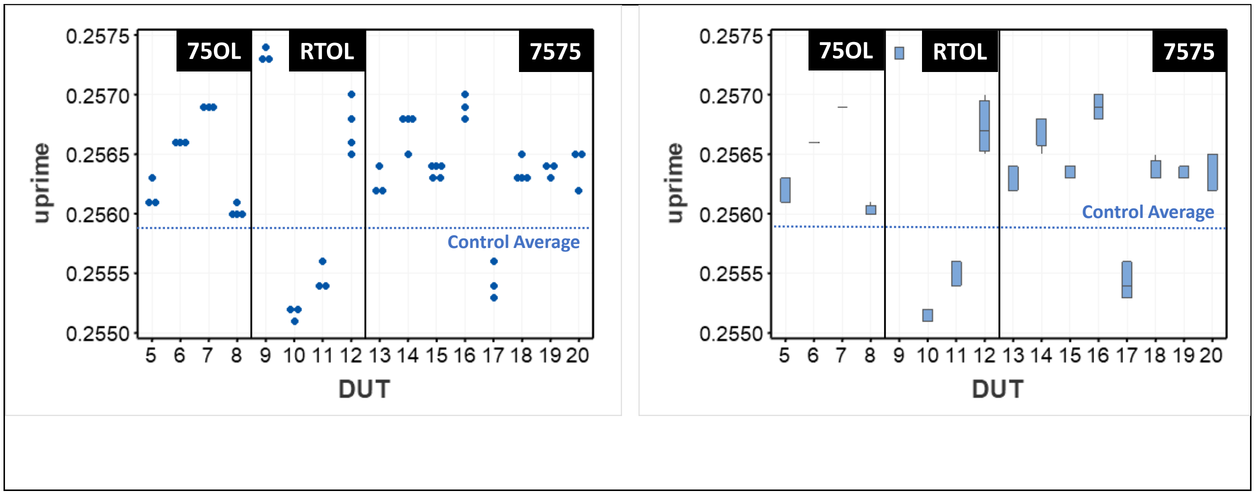


Figure A-1: The $u'$ readings from the DUTs using TL-1 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

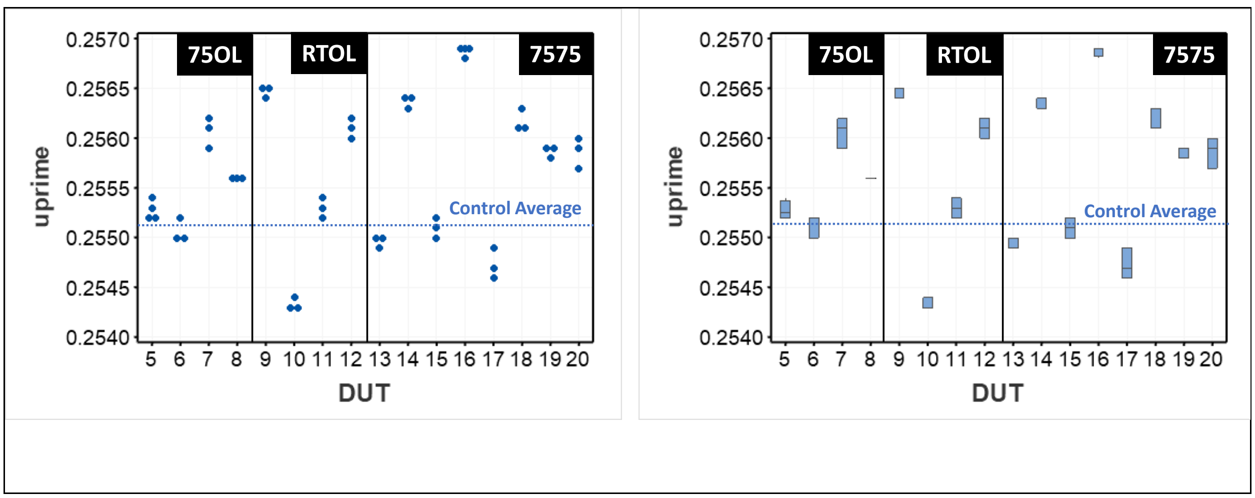


Figure A-2: The $u'$ readings from the DUTs using TL-2 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

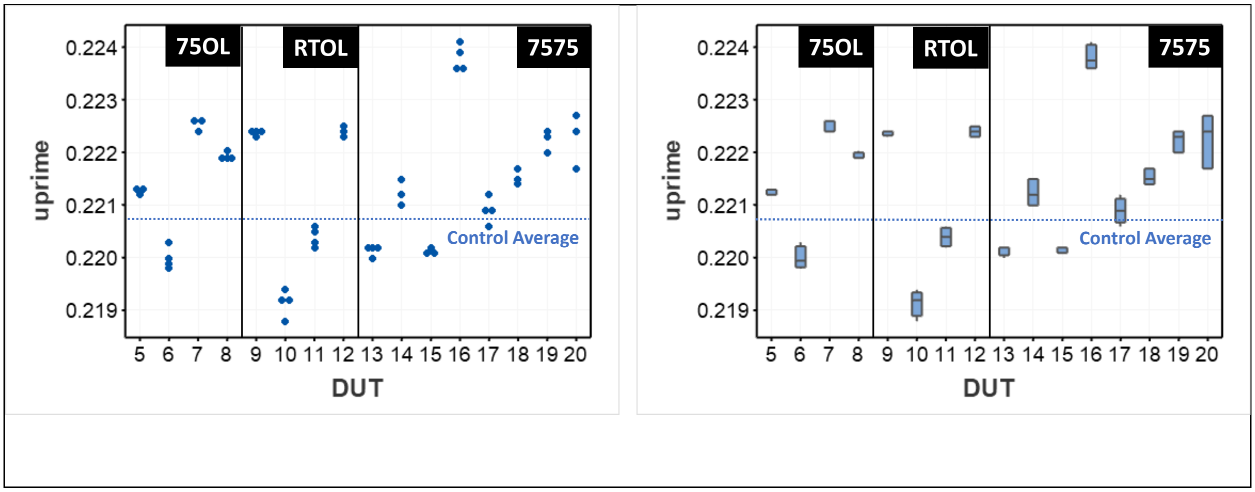


Figure A-3: The $u'$ readings from the DUTs using TL-3 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

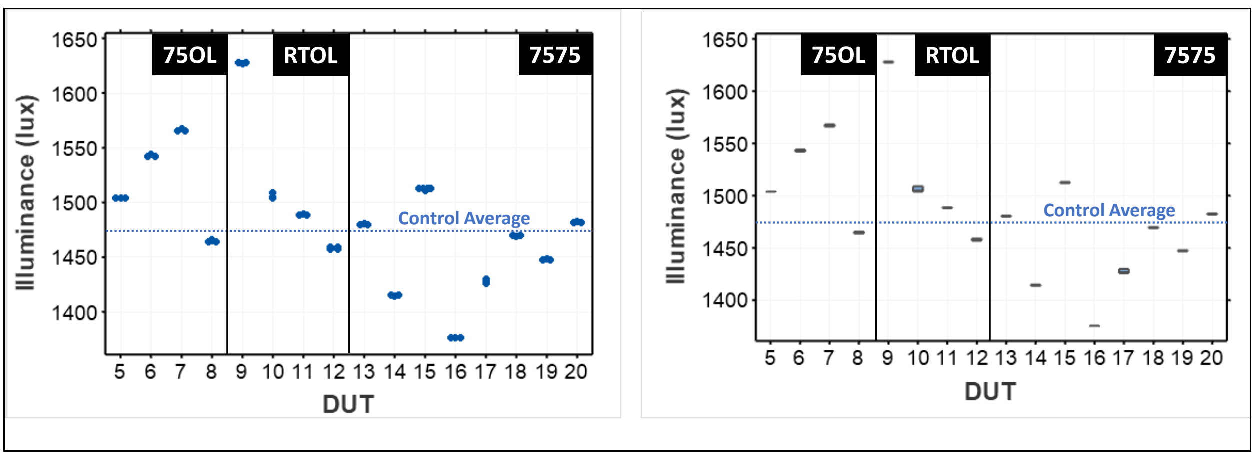


Figure A-4. Illuminance readings from the DUTs using TL-1 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

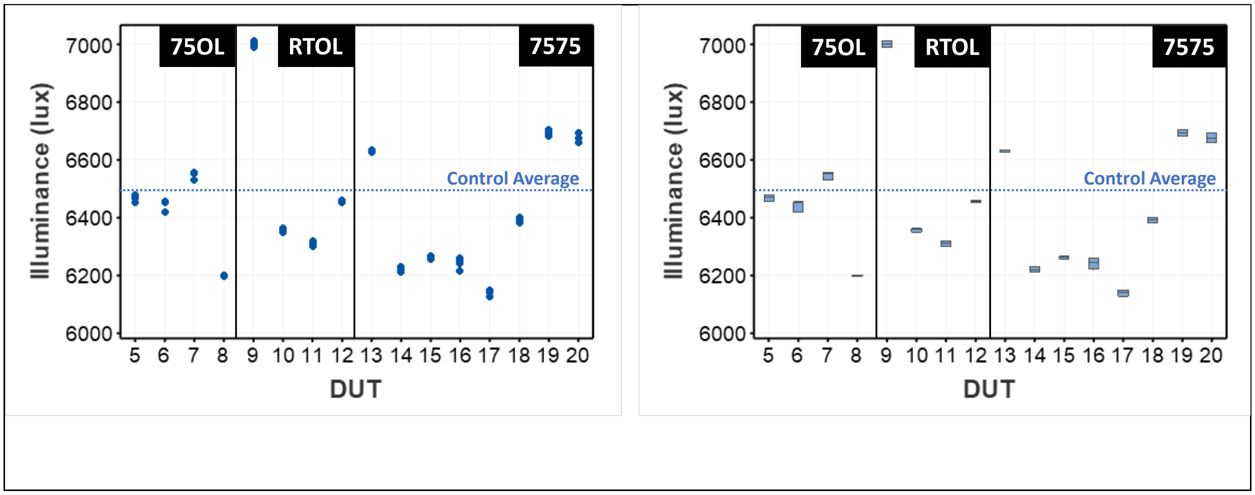


Figure A-5: Illuminance readings from the DUTs using TL-2 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

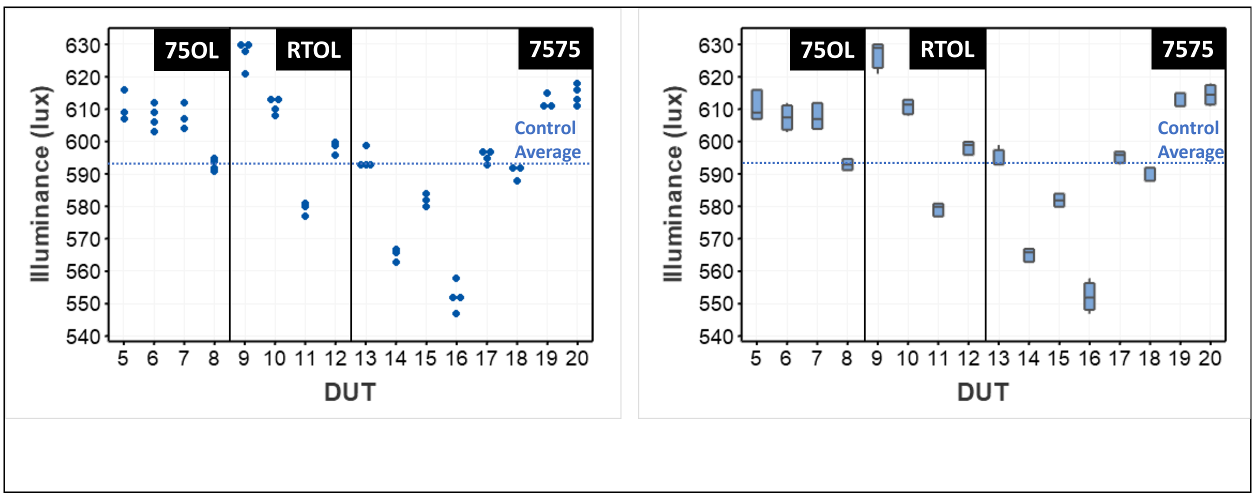


Figure A-6: Illuminance readings from the DUTs using TL-3 after 5,000 hrs of AST exposure. The actual readings are shown on the left, and the corresponding box plot is shown on the right. The average readings from the control samples are shown as the dotted blue line.

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DOE/EE-2278 • September 2020