LIGHT FOR LIVING | LIGHT FOR WORKING

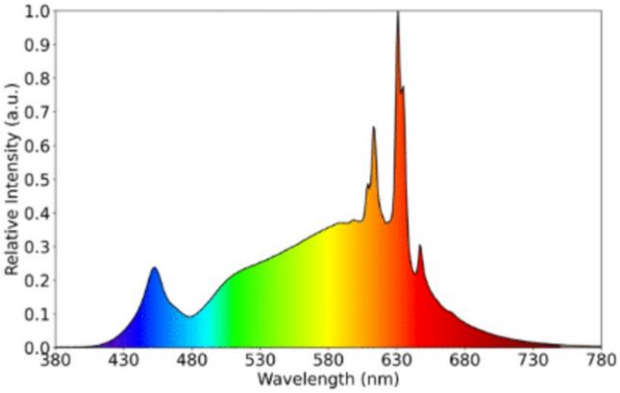
V.01/24

LUX Series COBs

Achieving High CRI Lighting with High Efficacy Using Luminus LUX Technology

Tom Jory
David Davito
Paul Sims
Uwe Thomas

December 2023

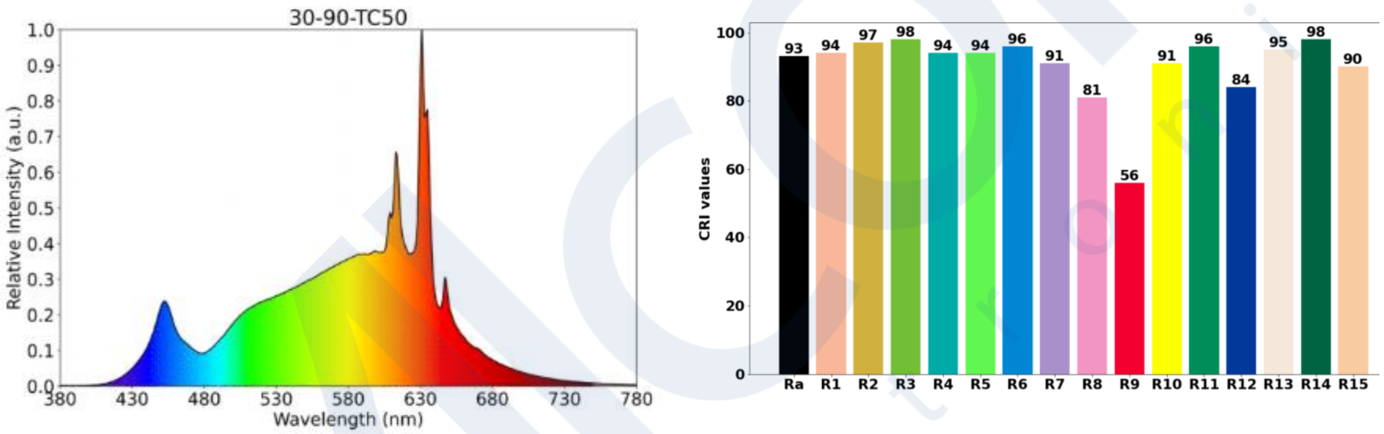


Overview

Luminus has recently announced the availability of the LUX Series COB LEDs using innovative new narrow band red phosphor (KSF) technology. These new COBs have been developed to achieve high color quality with improved energy efficiency. They are available with both 90 and 95 CRI minimums and LES sizes from 4 mm to 22 mm in a variety of flux densities and with a full range of CCT: 2400K, 2700K, 3000K, 3500K, 4000K, 5000K and 6500K.

The 90 CRI minimum LUX series offers high-quality lighting with lumen/Watt efficacy that is comparable to traditional 80 CRI sources. This allows luminaire makers to simplify their Bill of Materials (BOM) by replacing commonly used 80 CRI products with 90 and 95 CRI products. By doing so, they can achieve superior color rendition while maintaining the same level of efficacy. The LUX series provides exceptional performance and quality of light, making it suitable for a wide range of lighting applications including retail, residential, hospitality, architectural, museum, as well as in downlights, track lights, and spotlights.

90 CRI LUX COB LED with TriGain (KSF) Phosphor



Correlated Color Temperatures	CRI Minimum	CRI Typical	TM-30-18 (3000K)	R9
2400K, 2700K, 3000K, 3500K, 4000K, 5000K, 6500K	>90	92	RF=91, Rg=100	>50
2700K, 3000K	>95	97	RF=94, Rg=102	>85
3500K, 4000K, 5000K				>75

Figure 1. Spectra and color quality for LUX COB KSF-Phosphor LEDs demonstrating the high color quality achievable with this technology.

This white paper introduces KSF phosphor and discusses its characteristics, advantages, and application in white LEDs. Topics covered include a performance comparison of KSF phosphor LEDs versus traditional nitride-based white LEDs, how KSF phosphor LEDs provide industry-leading CRI and TM30 performance, and the specific performance features of Luminus LUX COB KSF phosphor LEDs. Information on various testing parameters is also provided, along with guidance on issues such as pulse-width effects and color-shift effects that engineers will want to consider when designing with KSF phosphor white LEDs.

Table of Contents

1.0 LUX Product Features

Luminus has developed the LUX COB (chip-on-board) LED (Light Emitting Diode) product line by harnessing cutting-edge KSF phosphor technology. This innovation enables Luminus to provide a multitude of performance and efficiency benefits. The product's notable features encompass:

- **High Lumen Output and Efficacy:** The LUX COBs distinguish themselves by achieving high efficacy at both 90 and 95 CRI (Color Rendering Index), mirroring that of an equivalent 80 CRI conventional white LED. This heightened efficacy enables the utilization of superior light sources in high CRI applications where energy consumption is also a critical concern.
- **Wide Range of CCTs:** The LUX COBs are offered across a span of correlated color temperatures (CCTs): 2400K, 2700K, 3000K, 3500K, 4000K, 5000K, and 6500K. These options come with exceptional color rendering and the exceptional white light quality that customers have come to associate with Luminus LEDs:
    - At least 90 CRI for the complete LUX COB series.
    - Typically, 97 CRI for 2700K through 5000K color temperatures.
    - Adherence to a 3 SDCM and 2 SDCM color binning standard.
- **Outstanding Color over Angle Performance:** The KSF phosphor-based LUX products exhibit superior optical emission uniformity and consistency of color across optics with different beam angles.
- **Enhanced Thermal Conductivity:** The LUX COB boasts exceptional thermal conductivity, ensuring efficient heat extraction.
- **Eco-Friendly**: These products are environmentally conscious, and comply with both RoHS and REACH regulations.
- **Licensed IP:** Luminus has secured the licensing of the innovative TriGain® PFS/KSF phosphors originally patented by General Electric (GE) for integration into our LUX COB product line. This GE-developed phosphor (now a product of Current Lighting Solutions) was chosen due to exceptional performance.

This integration of KSF phosphors into the LUX COB product line underscores Luminus' commitment to pushing the boundaries of lighting technology and providing customers with advanced solutions that excel in performance, efficiency, and environmental responsibility.

TERMINOLOGY

Color Rendering Index (CRI). The CRI is a commonly used metric created by the CIE in 1965, It measures a light source's ability to reveal the intrinsic colors of the objects it illuminates, referred to as its accuracy, or color fidelity.

Correlated Color Temperature (CCT) is a way to characterize the color appearance of any white light source with a single number. White light is composed of multiple wavelengths in varying amounts, causing the light to appear "cooler" (more blue/cyan wavelengths) or "warmer" (more yellow/orange wavelengths) to the human eye. Referred to as color temperature, these variations are measured in units of Kelvin. Warm light has lower CCT (e.g., 2700 K), neutral light is about 4000 K and cool white has a CCT of 5000 K or more.

To learn more about color rendition and color metrics such as CCT refer to the Luminus white paper *Achieving Optimal Color Rendition with LEDs*.

2.0 KSF Phosphors

2.1 KSF Introduction

KSF (Potassium Fluorosilicate (PFS), K_2SiF_6: Mn^{4+})* phosphor is a red powder engineered to emit a narrow-band spectrum around 630 nm when illuminated with blue light. It's used in the packaging of high-color-gamut liquid crystal LED-based display backlights and high-color-rendering white LEDs. It is reliable and long-lasting: "the red KSF phosphor is an excellent narrow-band color converter."[1] It emits five peaks in the red spectrum, each exhibiting "an ultra-narrow 5-nm FWHM"[1] (see **Figure 2**) with the main peak centered around 631 nm. "It is a stable material under high light flux and high temperature conditions."[1]

Red KSF phosphor technology is a cutting-edge advancement used in the development of high-CRI and high-efficacy white LEDs.[2] The primary goal of this technology is to improve the quality and efficacy of white light produced by LEDs for a wide range of applications, particularly those requiring accurate color rendering and energy efficiency. KSF phosphors are new in commercial white LED technology and have significant advantages over traditionally employed nitride-based red phosphors. The KSF phosphor provides high efficacy and highly visible saturated red in LEDs and has no self-absorption, as shown in **Figure 2**.[3]

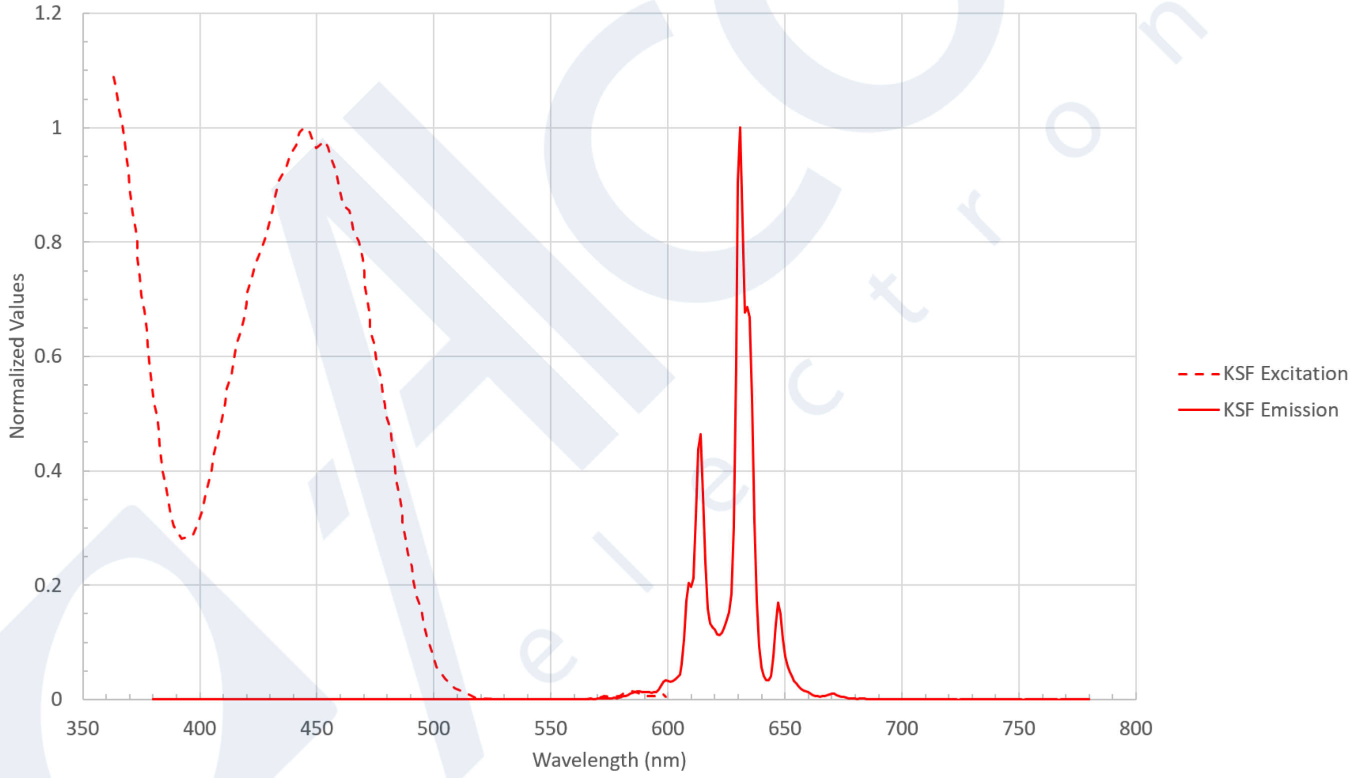


Figure 2. The spectral power distribution (SPD) of KSF phosphor demonstrates its unique narrow-band intensity in the red spectral region between 600 and 650 nm. The excitation curve is completely separated from the emission curve, so KSF has no self-absorption.

---

[*] A potassium fluorosilicate (PFS)-based phosphor patented by GE Lighting as part "of its TriGain® family of potassium fluorosilicate (PFS)-based phosphors for LED-based backlighting in displays, along with a broader licensing program for packaged LED manufacturers. The PFS technology enables LCD-based TVs, monitors, and mobile devices to produce richer reds with truer color control."[4] KSF and PFS are equivalent terms. Both are abbreviations for K_2SiF_6: Mn^{4+}.

White LEDs with KSF phosphors are specially blended to produce a light source with a high CRI and high R9 (red) values to give illuminated objects very high color realism with less energy expenditure.

By replacing the red emitting nitride phosphor with KSF phosphor, the color quality of 80 CRI white LEDs can be improved to 90 CRI while maintaining a similar LED efficacy. The narrow red spectrum contributed by the KSF phosphor increases red light efficacy (lm/W) by moving the radiant power in the SPD from the barely visible long wavelength tail of typical nitride-based red phosphors to a more visible wavelength range.

Adding KSF to a 3000K 90 CRI LED phosphor blend increases the Luminous Efficacy of Radiation (LER) from 283 lm/W to 334 lm/W. Nitride phosphors have broad red emission bands that extend considerably beyond the visible range, lowering their attainable luminous efficacy of radiation.

Figure 3 illustrates the strategy to increase the LPW (Lumens per Watt) of a 3000K 90 CRI LED while maintaining CRI quality. This is achieved by replacing most of the nitride red phosphor components (blue line) with a blend of red KSF phosphor and some nitride, resulting in the desired spectral shape in the 530 – 600 nm region (red line). Nitride phosphors emit a significant amount of invisible light, whereas the KSF spectra only emit visible light. By reducing the invisible light component, the LER is increased as shown.

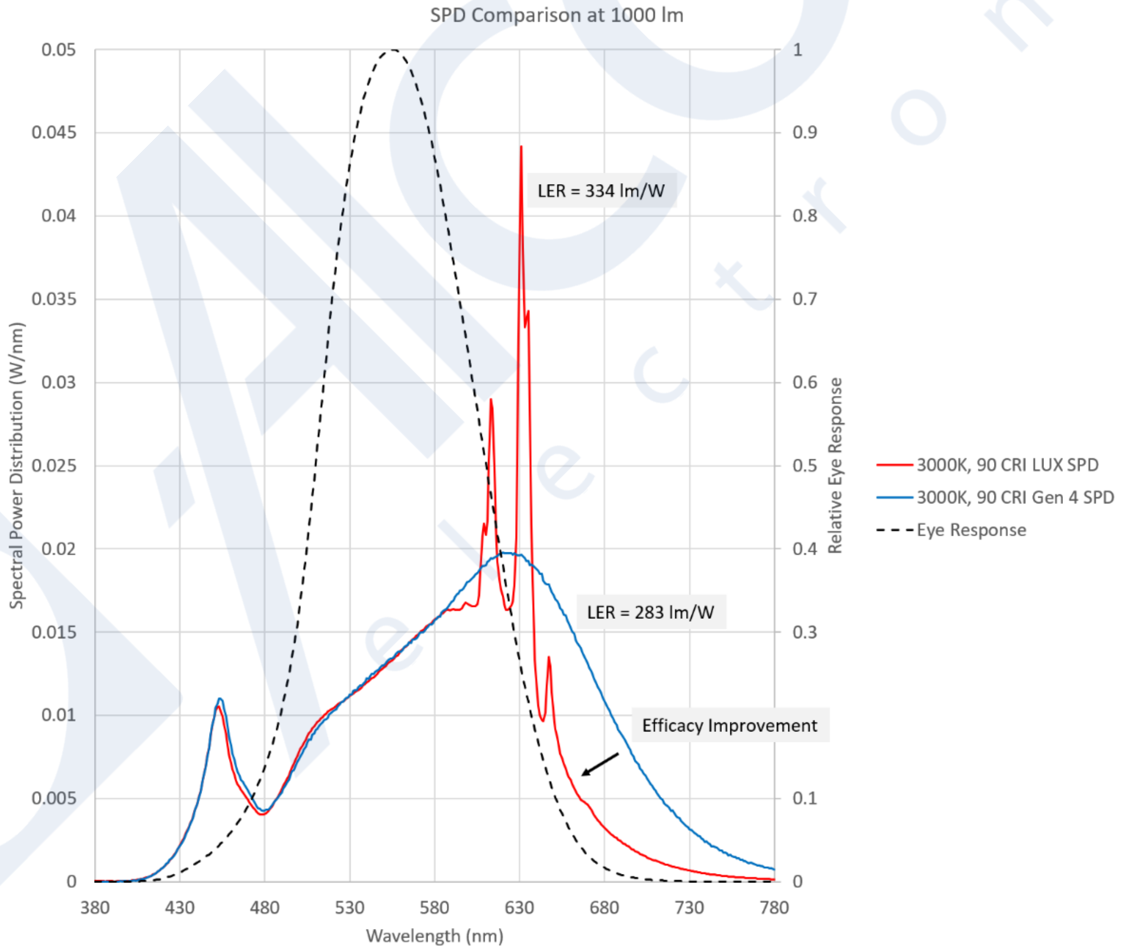


Figure 3. Increasing LPW of a 3000K 90 CRI LED while maintaining CRI quality.

2.2 Advantages of KSF phosphors

KSF has advantages in both display and general lighting applications [4, 5]. For general lighting, these advantages include: a narrow emission band, improved color rendering, a favorable excitation spectrum, good thermal quenching, improvements in concentration quenching, higher efficacies, and they are free of any rare-earth minerals. These advantages are discussed below.

Narrow Emission Band: KSF phosphors exhibit a narrow emission band, leading to more visible red light and higher attainable luminous efficacy of the radiation. This narrow emission band contributes to the overall energy efficiency of the LEDs.

Improved Color Rendering: KSF phosphors offer the ability to produce saturated red emission below 650 nm, without low visibility red "tails" in the SPD, which is desirable for achieving better color rendering in white LEDs while maintaining a high efficacy.

TERMINOLOGY

Spectral Power Distribution (SPD) – result of a measurement, usually in an integrating sphere, of an LED's radiant power per unit wavelength. SPDs have units of W/nm and the area under the curve is the total optical power measured for that LED. SPDs can be scaled to model different LED power levels. To learn more refer to the Luminus Help Center

Lumens per watt (LPW) – lumens produced by an LED per electrical watt applied to the system. This has a strong dependence on operating conditions (temperature, injection current) and is not constant. Typically, datasheet LPW are stated for the production test conditions. LPW has units of lumen / electrical watt.

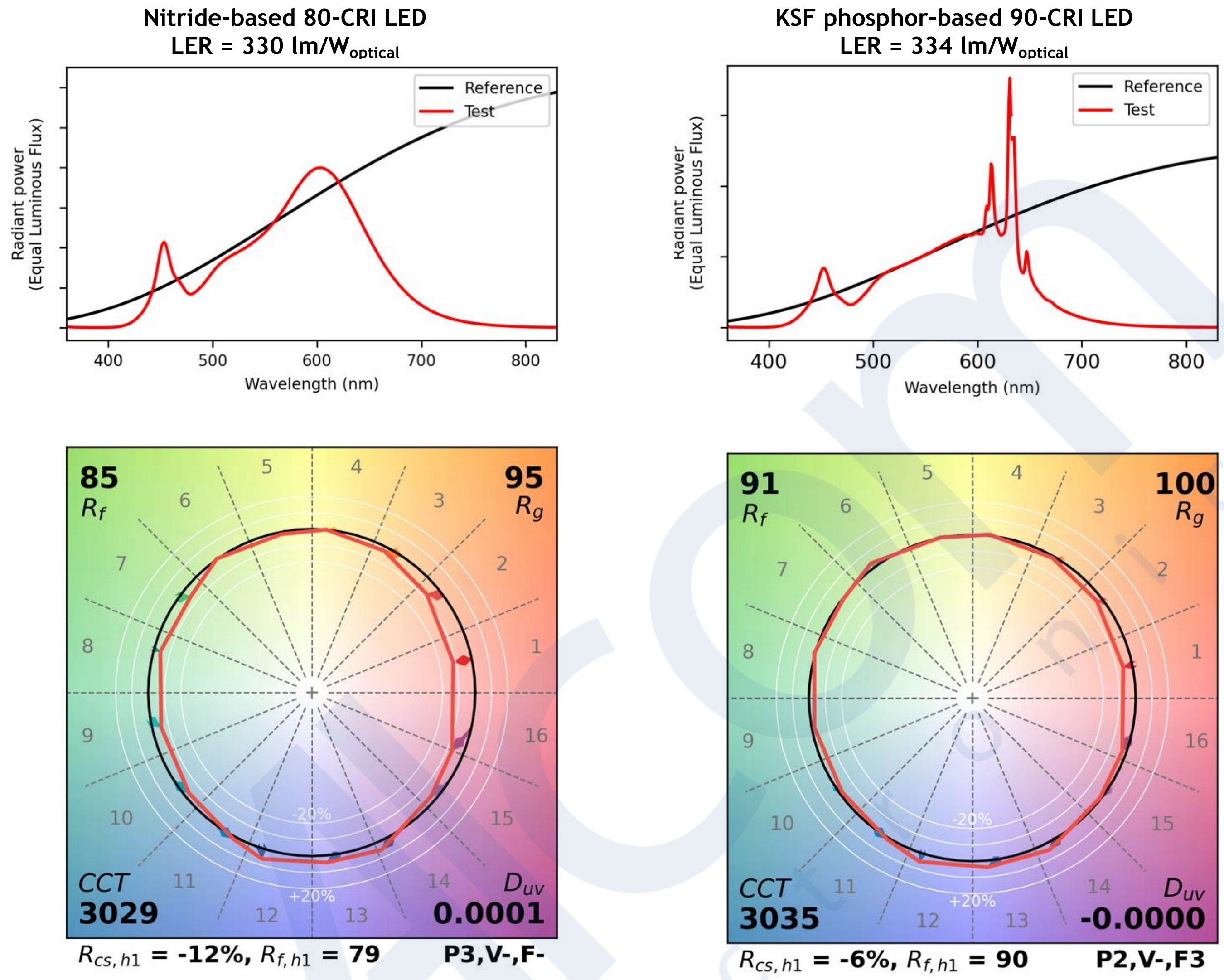
Luminus KSF development has focused on high-CRI products. There is no real advantage in developing a low-CRI KSF product they typically use more yellow and green content to improve efficacy at the expense of color rendering accuracy.

The images in **Figure 4** are abbreviated TM-30-18 reports (based on the internationally accepted ANSI/IES color rendition standards). Some examples of full TM-30 reports are included in Appendix B. A more detailed explanation of TM-30 and other color quality metrics can be found in the Luminus White Paper "*Achieving Optimal Color Rendition with LEDs*". The TM-30 method uses 99 color samples to calculate the reflection from the test spectrum and a black body reference spectrum (100 CRI) which has the same CCT as the sample.

The circle graphic is a concise summary of the differences between these two spectra where the 99 samples are grouped into 16 color bins. The reference source is always a black circle, and the red polygon shows the fit of the product to the reference spectrum by color bin: the closer the fit, the more accurate color rendition.

Modifying the spectral composition of specific colors can have a negative impact on the naturalness and accuracy of illumination. This effect is particularly noticeable when it comes to red hues. **Figure 4** provides a visual representation of this phenomenon, highlighting the significant difference in R9 values between the 80 CRI and 90 CRI parts. The R9 value for the 80 CRI part is only 6, while the 90 CRI part boasts a much higher R9 value of 55.

When we compare the spectral power distribution (SPD) and fit to the hue bins in the circle graphic, we observe that the 80 CRI plots lack the same level of balance between the red, green, and blue spectral contributions as the 90 CRI plots. The KSF phosphor based 90 CRI part has nearly the same LER but significantly better color rendition.



x	0.4350
y	0.4036
u'	0.2495
v'	0.5209

CIE 13.3-1995 (CRI)	
R_a	83
R_9	6

x	0.4344
y	0.4031
u'	0.2494
v'	0.5206

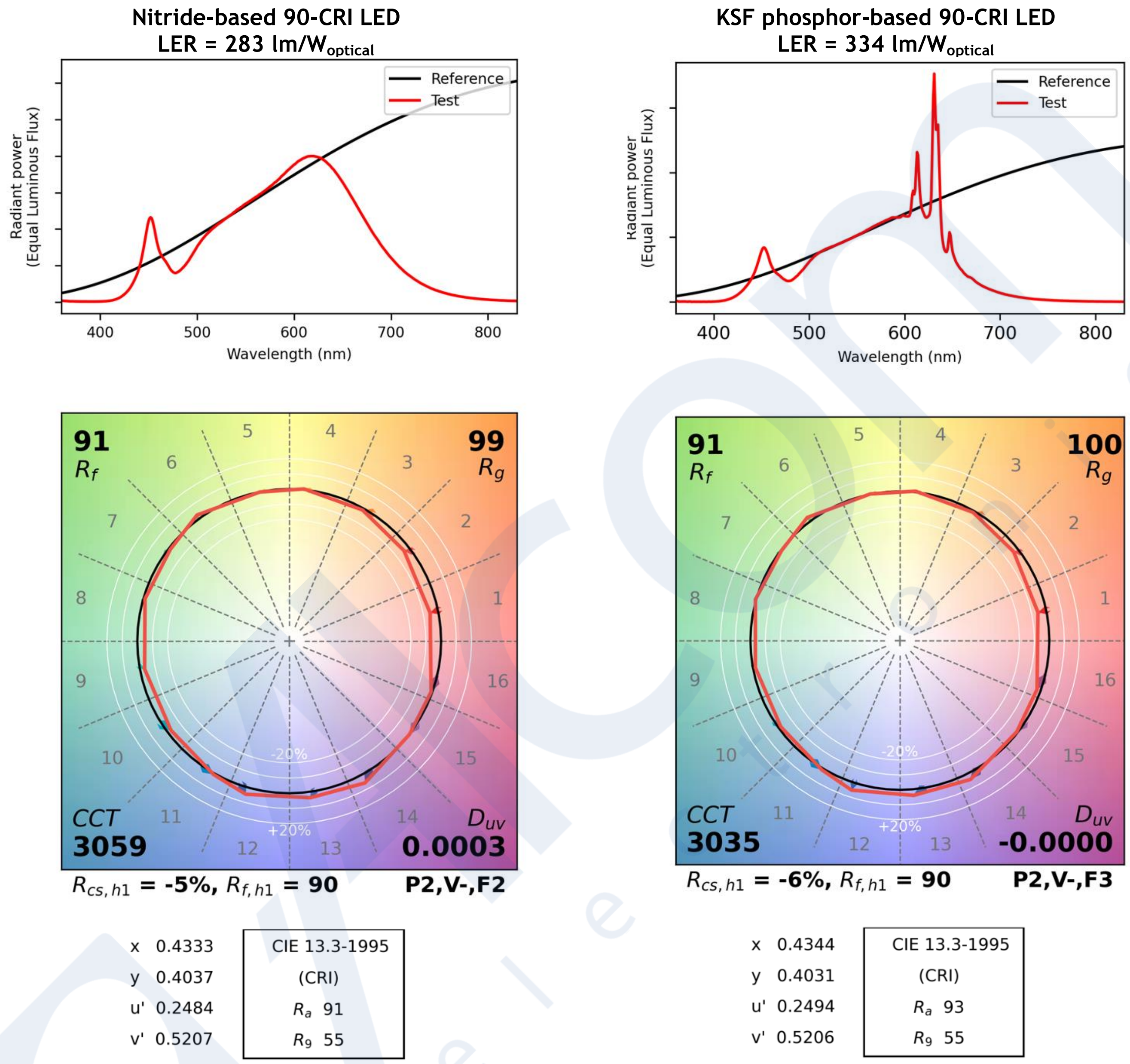
CIE 13.3-1995 (CRI)	
R_a	93
R_9	55

Figure 4. Comparison of TM-30-18 for nitride-based phosphor Gen 6 80 CRI and KSF phosphor-based LUX 90 CRI 3000K COBs. These two parts have equivalent LER and LPW metrics, but the LUX part has superior color rendition.

TERMINOLOGY

Luminous Efficacy of Radiation (LER) refers to the number of lumens produced by an LED per optical watt it generates (the ratio of its luminous flux to its optical radiation power). This value remains constant for each specific spectral power distribution (SPD) used as an input. When the same SPD shape is applied at different optical power levels, the LER remains unchanged. LER is quantified in units of lm/optical watt to convert between lumens and optical power output for an LED. It's important to note that LER only changes if there is an alteration in the SPD shape.

Figure 5 compares the color quality metrics of the SPDs previously compared in **Figure 3**. These two parts have very similar color quality, but the LUX part has a significantly higher efficacy.



		CIE 13.3-1995 (CRI)
x	0.4333	
y	0.4037	
u'	0.2484	R_a 91
v'	0.5207	R_9 55

		CIE 13.3-1995 (CRI)
x	0.4344	
y	0.4031	
u'	0.2494	R_a 93
v'	0.5206	R_9 55

Figure 5. Comparison of TM-30-18 Gen 6 90 CRI and LUX 90 CRI 3000K COBs showing better efficacy for the KSF system with similar color quality.

Favorable Excitation Spectrum: Unlike some other phosphors, the TriGain KSF that Luminus uses has broad excitation bands that are separated from the emission bands. This minimizes reabsorption issues when combined with yellow or green phosphors, resulting in improved light conversion efficiency.[6] Excitation curves (**Figure 6**) show the wavelengths where a phosphor absorbs photons and emits longer wavelength photons, comparing KSF, a nitride, and a YAG (yttrium aluminum garnet) phosphor.[7]

There is a strong excitation peak near 450 nm for all of these phosphor types that enables a single blue pump LED to be used in this type of white LED system. The efficiency associated with each phosphor type is based on some fraction of the absorbed photons that generate heat instead of light. KSF does not absorb YAG or Nitride light emission. This increases efficacy and reduces phosphor heating for lower-CCT color temperature parts with high red nitride phosphor loading.

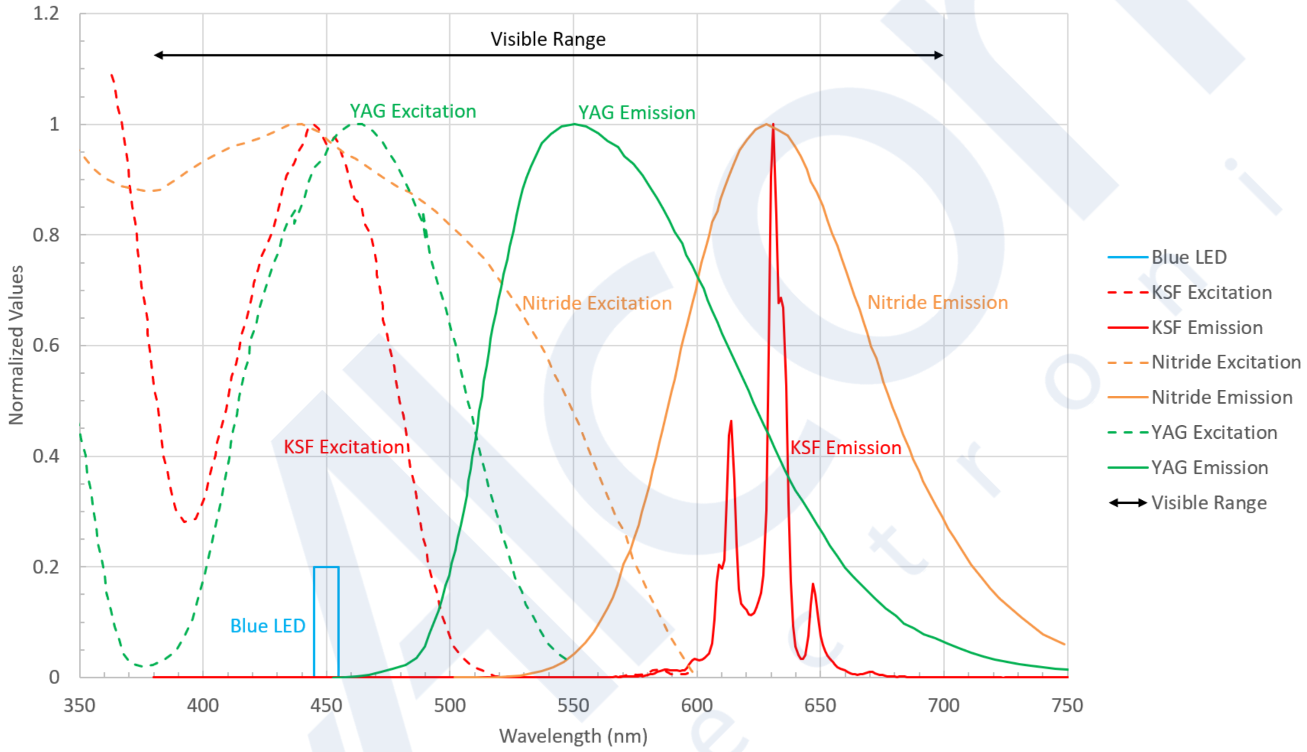


Figure 6. Excitation and emission spectrums for KSF, a comparable nitride and a typical YAG phosphor showing that KSF-phosphors have a favorable excitation spectrum. Overlap between an excitation curve and any of the emission curves shown indicates absorption at these wavelengths. Some of this absorption generates heat in the system. KSF phosphors have very little overlap. (Note: There are many varieties of yellow, green, and red phosphors and these are just exemplars.)

The nitride excitation curve in **Figure 6** shows that YAG phosphor emission is affected by the amount of nitride phosphor in the system, which lowers efficacy and contributes to phosphor heating for warmer CCT parts. The nitride excitation curve shows that there is significant absorption of the YAG phosphor and also some from the nitride itself (self-absorbing).

Good Thermal Quenching Threshold: A key performance metric of a phosphor is its thermal quenching (TQ). TQ is a decrease in the photoluminescence intensity (luminance efficiency) of phosphors as temperature increases. During operation. KSF phosphors demonstrate thermal quenching behavior comparable to traditional red nitride phosphors.[8]

Concentration Quenching Improvements: Concentration quenching is the loss of phosphor quantum efficiency (QE) at high activator concentrations, a common issue with phosphor materials. The critical activator concentration is the point where the fluorescent intensity of the blue-pumped phosphor starts to decrease. GE reports on improvements that can be gained using phosphor synthesis process optimization.[6]

Rare-Earth-Free Composition: KSF phosphors belong to a new class of rare-earth-free red fluoride phosphors. This composition is environmentally friendly, making them a sustainable choice for white light technology.

2.3 KSF Performance Compared to Traditional Nitride-based White LEDs

The performance advantage of using white LEDs with KSF phosphor are evident when compared against traditional nitride-based white LEDs. **Figure 7** shows a comparison of nitride-based LEDs to a 95 CRI KSF-based LED. The LER of the 80 CRI nitride-based LED and the 95 CRI KSF-based LED are very similar while the higher CRI nitride-based parts have lower LER. The data shown in **Table 1** provides a more detailed comparison of the LER efficiency advantages of LUX LEDs.

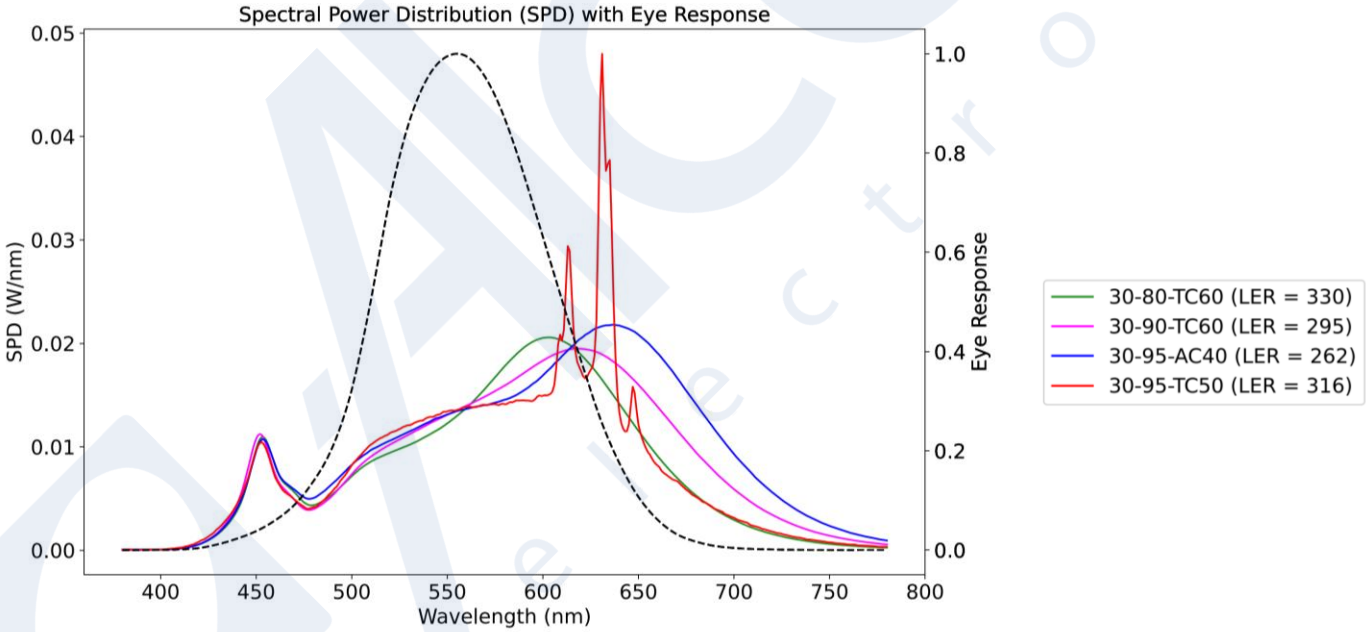


Figure 7. Comparison of 80, 90, 95 CRI nitride-based white LEDs to a 95 CRI KSF-based LED. The 95 CRI sources have 262 LER for nitride and 316 LER for KSF-based LUX.

Table 1. LER Comparisons for KSF and Nitride-based White LED Spectra.

Part Number	Phosphor Type	CCT (K)	CRI	LER
24-90-TC50	KSF	2400	90	324
24-90-TC60	Nitride	2400	90	279
27-80-TC60	Nitride	2700	80	324
27-90-TC50	KSF	2700	90	334
27-90-TC60	Nitride	2700	90	294
27-95-TC50	KSF	2700	95	311
27-95-TC60	Nitride	2700	95	257
30-80-TC60	Nitride	3000	80	330
30-90-TC50	KSF	3000	90	334
30-90-TC60	Nitride	3000	90	295
30-95-TC50	KSF	3000	95	316
35-80-TC60	Nitride	3500	80	328
35-90-TC50	KSF	3500	90	336
35-90-TC60	Nitride	3500	90	294
35-95-TC50	KSF	3500	95	310
35-95-TC60	Nitride	3500	95	269
40-80-TC60	Nitride	4000	80	330
40-90-TC50	KSF	4000	90	328
40-90-TC60	Nitride	4000	90	296
40-95-TC50	KSF	4000	95	312
40-95-TC60	Nitride	4000	95	275
50-80-TC60	Nitride	5000	80	324
50-90-TC50	KSF	5000	90	321
50-90-TC60	Nitride	5000	90	287
50-95-TC60	Nitride	5000	95	277
65-80-TC60	Nitride	6500	80	309
65-90-TC50	KSF	6500	90	302
65-90-TC60	Nitride	6500	90	284

Across the Luminus COB product lines, the LUX KSF Phosphor LEDs offer higher efficacy while delivering high color rendition. The improvement from nitride LEDs to LUX is a paradigm shift in phosphor technology.

Understanding Luminus Product Codes

The Luminus COB LEDs discussed in this white paper are identified by part number codes (for example: 30-95-AC40). These codes provide specific information about each LED product. The format used is always **XX-YY-ZZZZ**, where XX = CCT of the product, YY = CRI value, and ZZZZ includes the 2-character Product Series identifier (e.g., AC, TC).

The last 2 numbers after Series identifier provide additional information. The first numeral indicates the product line (4= Gen 4, 5 = LUX, 6 = Gen 6) The second numeral "0" indicates that the color point is on the black body locus. Thus:

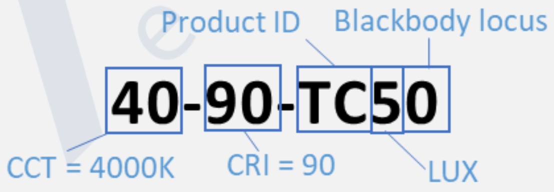


Figure 8 shows the distributions of LER versus red phosphor type for all of the CCTs in the LUX product portfolio. The LERs of 90 and 95 CRI KSF-based LEDs are similar to 70 and 80 CRI LEDs while the LERs of nitride-based LEDs are significantly lower at 90 and 95 CRI.

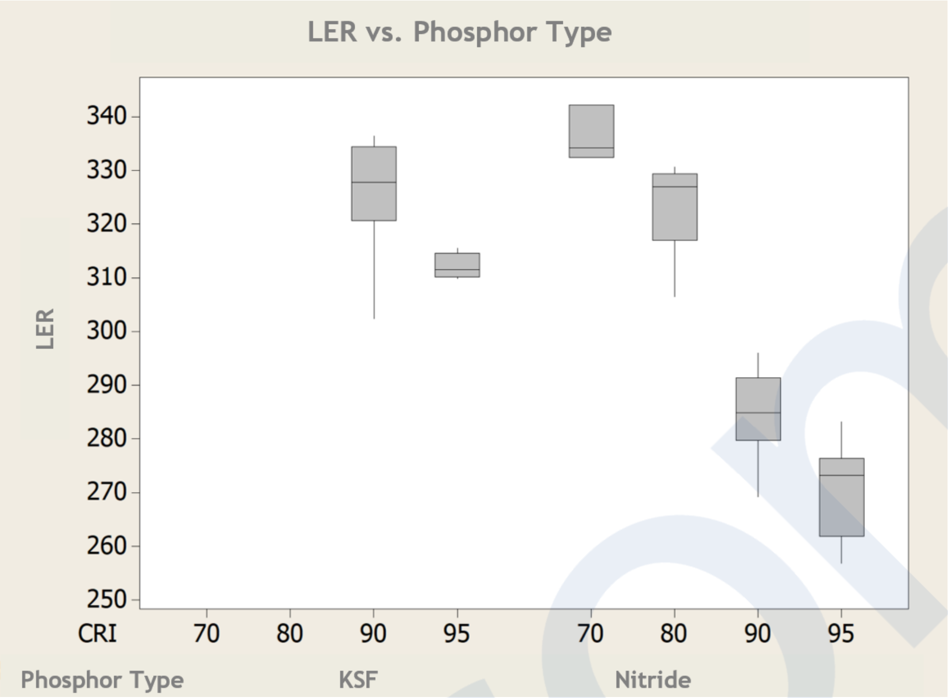


Figure 8. Boxplot of LER vs. CRI for KSF and nitride-based white LEDs. The 90 CRI KSF version is the sweet spot for efficacy parity with 80 CRI nitride-based LEDs.

It can sometimes be difficult to do an apples-to-apples product comparison of the various KSF Phosphor LEDs due to the rapid emergence of many new products on the market. However, not all KSF COB LEDs are the same. An important quality consideration to keep in mind is Phosphor quality**.** There are multiple phosphor-based products offered by multiple manufacturers, using red phosphor that can vary in quality. Luminus uses only high-quality Current Lighting Solutions TriGain phosphor.

2.4 KSF Reliability

GE holds the original patent for Potassium Fluorosilicate (PFS) red phosphor and has been producing it the longest, resulting in high-quality phosphors. Luminus uses KSF/PSF (K_2SiF_6: $Mn4^+$) sold as TriGain® technology by Current Lighting Solutions to ensure product quality. When it comes to reliability, not all KSF phosphors are the same. Issues such as impurities or moisture in the synthesis process can affect optical performance and chemical stability of the phosphor.[9]

The TriGain KSF phosphor red LEDs have also established an extensive track record of reliability from their initial use in the display industry since 2014. From 2014 to 2023, more than 60 billion KSF-based LEDs have been fabricated for use in displays.[10] GE reports that there are 19 worldwide licensees using these LEDs in their display products, including all of the major manufacturers in the industry.[11]

GE reports that its technology can be found in (among other products):[12]

- Smart phones by Samsung, Apple, Huawei, LG, BLU, Razer, Red
- Laptops and monitors by HP, Lenovo, Dell, Asus, Apple, Microsoft, Razer, MSI, Samsung, LG
- Tablets by Apple, Samsung, Lenovo, Huawei, Microsoft, Asus
- Televisions by Samsung, LG, Sony, Vizio, TCL, Hisense, Toshiba, Insignia, Sharp

Additionally, this same technology has been incorporated into a variety of GE Lighting products to produce more energy efficient warm white light. In 2017, GE announced that it would begin to manufacture the phosphor powder itself “to ensure a reliable source for the LED manufacturers that license the technology. This breakthrough was only possible through GE’s prevailing leadership in the advancement of LED technology,” said Jerry Duffy, GE Lighting global product general manager. “Adding to the breakthrough is GE’s proprietary improvements to phosphor synthesis, including decreased particle sizes, higher quantum efficiencies and longer life when compared to standard PFS. Many devices currently on the market offer lower-quality red components in LEDs,” he concluded.[13]

Overall, this enhanced reliability has led to the commercialization of KSF phosphor for on-chip applications. The reliability and performance enhancements outlined below are why Luminus selected TriGain phosphors for our industry leading LUX products.

High Temperature and High Humidity (HTHH) Performance
PFS/KSF can be sensitive to temperature and humidity. KSF can darken when exposed to prolonged periods of high temperature and high humidity (HTHH) conditions. However, TriGain phosphors have improved HTHH performance compared to traditional nitride-based phosphors, exhibiting minimal temperature quenching below 150°C. To further enhance the temperature and humidity resilience of the KSF phosphors, GE outlines some processing optimization steps in a 2015 study.[6]

Improved Lumen Output & Color Stability
Through significant process improvements, TriGain provides a notable reduction (approximately nine times – 9X) in blue light photodamage to the phosphor compared to other commercial KSF samples. These process enhancements result in a combination of reduced concentration quenching (absorption of light by the manganese) and higher stability under high excitation flux and HTHH conditions.

Luminus KSF Phosphor Reliability Test Results
Luminus has performed qualification testing on our KSF product line, including a High Temperature Operating Life (HTOL) test using the IES LM-80 method to ensure performance. These tests are described in detail and the results of Luminus LUX KSF Phosphor LED tests are provided below (refer to **Table 2** and **Table 3**).

High Temperature Operating Life (HTOL) is a qualification test where the LEDs are subjected to a set of temperature and bias current conditions to generate data that can be used for lifetime predictions. The Lumen Maintenance (LM-80) test is a variant of HTOL where there is a standardized set of test conditions and methodology (LM-80) and a standard method for lifetime prediction calculations (TM-21).

TERMINOLOGY

LM-80, Lumen Maintenance (LM) – Lumen Maintenance is an industry standard to determine the lifetime of an LED. Typically, as operating time increases, the output of a device will have diminishing returns. LM-80 is an IES Lighting Memorandum defining the "*Approved Method for Measuring Lumen Maintenance of LED Light Sources*". This document defines the method to accurately test LED long term performance for 6,000 (minimum) to 10,000 (preferred) hours. To learn more refer to the Luminus Help Center.

There are a number of testing standards for LED product performance. For convenience, some of these are summarized below:

- LM-80, Measuring Maintenance of Light Output Characteristics of Solid-State Light Sources, defines the test procedure for lumen maintenance of LED components.[14]
- TM-21, Projecting Long-Term Luminous, Photon, and Radiant Flux Maintenance of LED Light Sources, defines the data analysis procedures for LM-80 data.[15] Lumen Maintenance (L_x) defines the percentage of lumens compared with the initial lumens. Typically, L_{70} data is reported.
- LM-79, Optical and Electrical Measurements of Solid-State Lighting Products, defines the test procedure for a luminaire product.[16] LM-79 is not a reliability test and is not discussed below. LM-79 testing is of interest because it is a test our customers often perform before product release.
- It is possible to calculate L_xB_y using commercial reliability software packages. The additional parameter, B_y, defines the percentage that is expected to be below the specified L_x-value at a particular time. So, for example, $L_{70}B_{50}$ indicates that half of the lamps are expected to have less than 70 percent lumen maintenance for a specific test condition. TM-21 does not include a method for these calculations.

Table 2 and **Table 3** show the results of screening tests performed at Luminus as part of the process used to down select to the TriGain phosphor. These tables compare LUX with a Luminus nitride-based component and a white LED that uses a KSF phosphor other than TriGain. **Table 4** shows the LM-80 qualification test data performed by a certified test lab. **Table 5** shows the L_xB_y reportable hours calculation results using the LM-80 test data. Luminus KSF with TriGain technology has excellent reliability performance, similar to that of nitride technologies and superior when compared with other KSF technologies in the industry.

Table 2. HTOL Lumen Maintenance Test Results

Product	Test Condition	168 Hours	500 Hours	1000 Hours	2000 Hours	3000 Hours	3800 Hours.	5000 Hours	6000 Hours
LUX	85°C	+ 0.4%	+ 0.2%	- 0.8%	- 0.6%	- 1.2%	-1.0 %	- 2.9%	-3.7%
Nitride	85°C	+ 0.7%	+ 0.6%	- 0.4%	- 0.5%	- 1.3%	- 2.3%	- 3.9%	- 3.7%
Other KSF	85°C	- 0.9%	- 1.3%	-3.2%	- 4.1%	- 4.8%	- 4.5%	- 6.2%	- 6.8%
LUX	95°C	0.0%	- 0.7%	- 0.7%	- 0.7%	- 1.3%	- 1.3%	- 2.5%	- 2.8%
Nitride	95°C	+ 0.4%	0.0%	+ 0.6%	0.0%	- 0.5%	- 1.2%	- 2.5%	- 2.9%
Other KSF	95°C	- 0.8%	- 3.2%	- 4.3%	- 5.1%	- 6.3%	- 7.1%	- 9.1%	- 9.8%
LUX	105°C	+ 0.1%	- 0.5%	- 0.7%	- 0.9%	- 1.3%	- 1.8%	- 3.5%	- 3.2%
Nitride	105°C	+ 0.3%	+ 0.1%	-0.8%	- 1.7%	- 2.3%	- 3.2%	- 5.5%	- 6.0%

Note: test at 130% of maximum rated current

Table 3. HTOL Color Stability Test Results (Du'v').

Product	Test Condition	168 Hours	500 Hours	1000 Hours	2000 Hours	3000 Hours	3800 Hours.	5000 Hours	6000 Hours
LUX	95°C	0.0006	0.0010	0.0012	0.0013	0.0018	0.0019	0.0020	0.0015
LUX	105°C	0.0005	0.0010	0.0012	0.0014	0.0016	0.0019	0.0020	0.0018

Note: test at 130% of maximum rated current

Table 4. LM-80 Lumen Maintenance of LUX Samples (Per Certified Test Lab Data).

Temperature	55˚C	85˚C	105˚C	55˚C	85˚C	105˚C
% Max Current	75	75	75	100	100	100
0 hrs.	1	1	1	1	1	1
168 hrs.	1.000	1.000	1.000	1.000	0.999	0.999
500 hrs.	1.000	1.000	0.999	0.996	0.997	0.997
1000 hrs.	0.998	0.997	0.996	0.994	0.993	0.993
2000 hrs.	0.996	0.995	0.993	0.992	0.991	0.990
3000 hrs.	0.994	0.992	0.991	0.989	0.987	0.987
4000 hrs.	0.992	0.990	0.988	0.986	0.984	0.983
5000 hrs.	0.989	0.988	0.985	0.984	0.981	0.980
6000 hrs.	0.987	0.985	0.982	0.981	0.978	0.977

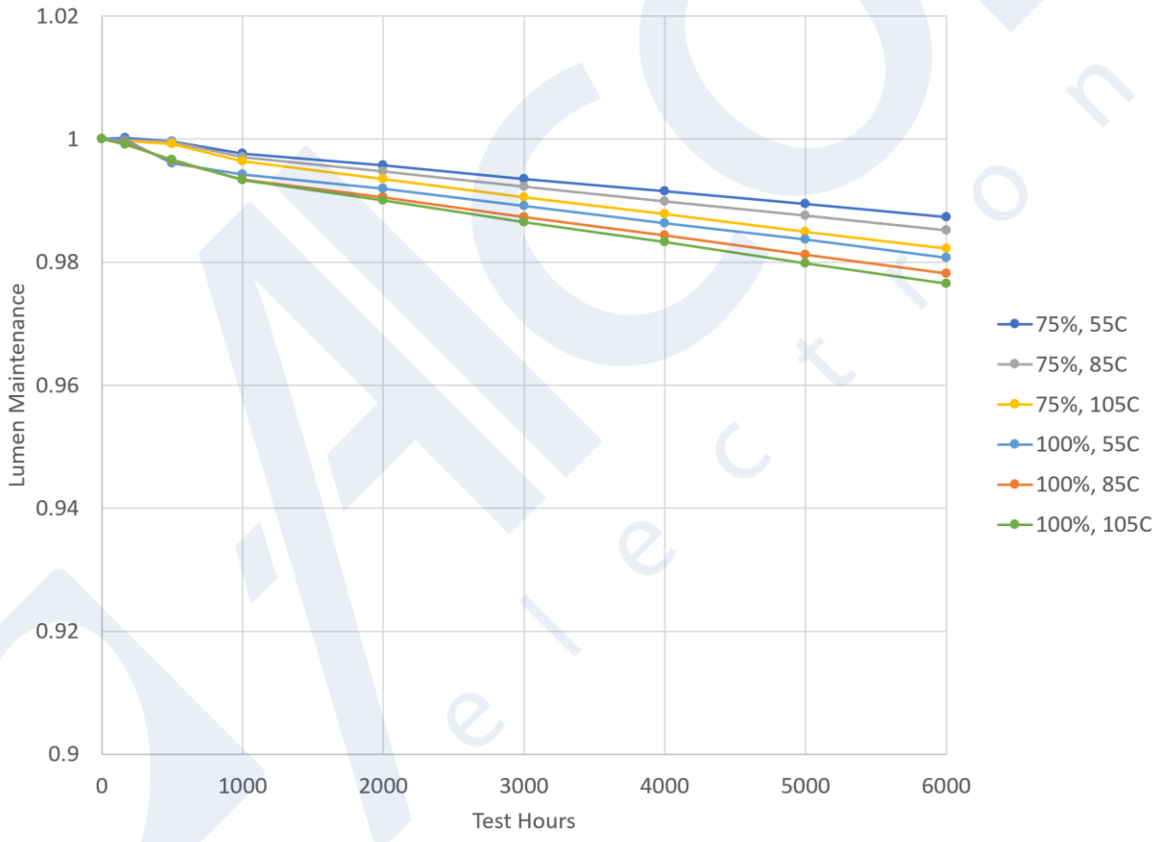


Figure 9. Plot of the LM-80 data shown in **Table 4**.

Table 5 shows the calculated reportable values for L_xB_y of the LUX series using 6000 hours of LM-80 data. The TM-21 standard which specifies the calculation procedures for LM-80 data has a limit on the number of reportable hours, which in this case is 33,000 hours. The L_xB_y calculations below follow these rules but most of the calculated values are well above the reporting limit. As more test hours are acquired, the reportable hours in this table will be updated.

Table 5. LUX Reportable L_xB_y Values for 6000 Hours of LM-80 Condition Test Data.

Case Temp.	% of Rated Current	L70			L80			L90		
		B10	B20	B50	B10	B20	B50	B10	B20	B50
55°C	75	>33000	>33000	>33000	>33000	>33000	>33000	>33000	>33000	>33000
	100	>33000	>33000	>33000	>33000	>33000	>33000	32000	>33000	>33000
	115	>33000	>33000	>33000	>33000	>33000	>33000	27000	29000	>33000
	135	>33000	>33000	>33000	>33000	>33000	>33000	23000	25000	28000
85°C	75	>33000	>33000	>33000	>33000	>33000	>33000	>33000	>33000	>33000
	100	>33000	>33000	>33000	>33000	>33000	>33000	27000	27000	>33000
	115	>33000	>33000	>33000	>33000	>33000	>33000	23000	25000	28000
	135	>33000	>33000	>33000	>33000	>33000	>33000	19000	21000	24000
105°C	75	>33000	>33000	>33000	>33000	>33000	>33000	32000	>33000	>33000
	100	>33000	>33000	>33000	>33000	>33000	>33000	24000	26000	30000
	115	>33000	>33000	>33000	>33000	>33000	>33000	21000	22000	26000
	135	>33000	>33000	>33000	>33000	>33000	>33000	18000	19000	22000

WHTOL Test Results

The Wet High Temperature Operating Lifetime (WHTOL) test was conducted by a certified test lab under controlled conditions of 85°C and 85% relative humidity for a duration of 1000 hours. The primary objective of LED WHTOL testing is to ensure that LEDs can maintain their functionality and reliability even in demanding operating conditions.

The WHTOL test was conducted using by driving the LED samples at 80% of the maximum rated current using a one hour on/off cycle. This allows the LED package to saturate with water vapor during the off portion of the cycle.

The WHTOL results are presented in Table 6. To establish a baseline for comparison, Luminus Gen 6 LED samples were used as a control. The lumen maintenance of the tested LEDs is on par with the Gen 6 nitride control samples, demonstrating LUX with TriGain KSF reliability performance being on par with standard Nitride devices.

Table 6. WHTOL % Lumen Maintenance for LUX and Gen 6 LEDs

Part Number	Test Condition	0 hours	168 hours	500 hours	1000 hours
CXM-14-35-90-36-TC50 (LUX)	85°C/85%RH 1-hr on / 1-hr off	100	98.98	98.08	96.33
CLM-22-27-80-36-TC60 (nitride)	85°C/85%RH 1-hr on / 1-hr off	100	98.90	97.94	96.18

3.0 KSF Testing Considerations

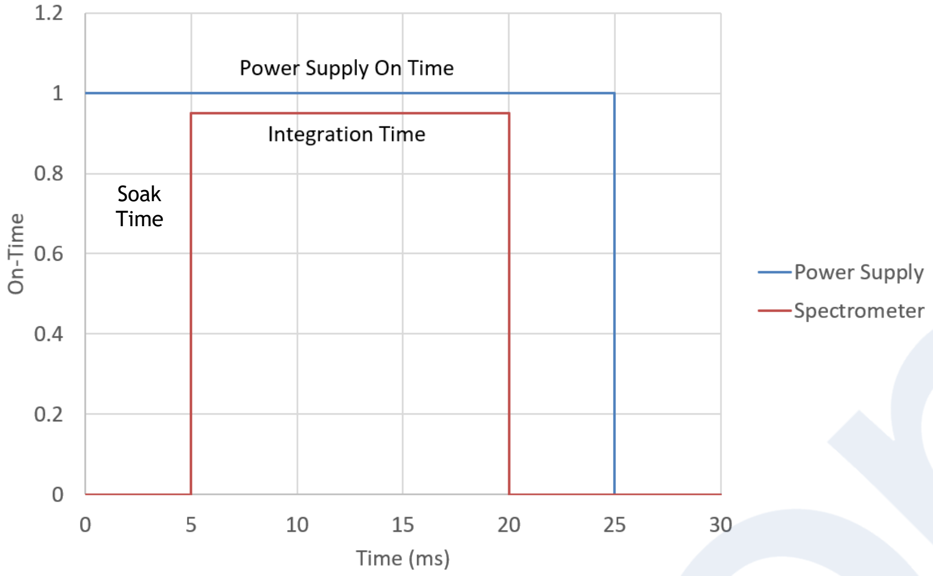
Testing KSF products requires a different approach from typical (non-KSF Phosphor) LED tests to get reliable results. Different settings and high-quality equipment are needed. Primarily considerations are:

- **Soak time.** Slowing down the test so that the KSF phosphor has stabilized before capturing the spectrum (soak time). This consideration is discussed below in Section 3.1
- **Measurement accuracy.** Measurement accuracy can be challenging; thus, customers should take care to use higher resolution test equipment with pulse-width for true measurement accuracy of Luminus phosphor devices compared to standard phosphor devices. This consideration is discussed below in Section 3.2.
- **Measurement parameters.** In some cases, phosphor parts are measured at lower drive currents, which enables test results to be reported that show higher efficacy. Similarly, manufacturers might quote 25°C performance data, showing performance at best case conditions. Data that is shown at 85°C conditions typically provide a more realistic performance indication. Some parts also exhibit a larger CCT-temperature shift. It’s critical to compare test parameters in combination with reported results to ensure an apples-to-apples comparison can be made and to ensure purchased parts do not deliver lower performance than expected.

3.1 Soak Time

KSF is a slow reacting phosphor and takes longer than most standard phosphors to reach a stabilized (saturated) state: >40 ms according to the manufacturer. When characterizing the performance of LEDs that contain KSF phosphors, the soak time before spectrometer data acquisition (integration time) needs to be adjusted. For traditional phosphor systems, a soak time based on electronics settling times is common (**Figure 10).**

For KSF systems, the soak time needs to be increased to better reflect values that will be obtained in LM-79 luminaire tests.[1] KSF phosphors take longer than traditional LEDs to reach full intensity. Thus, the soak time is too short, the LED is measured before the KSF phosphor has fully saturated. **Figure 11** illustrates this effect. The red line is for too short of a soak time where the KSF phosphor has not developed full intensity (saturation). The blue line shows the saturated KSF measurement. The inset box lists the effects of undersaturated KSF on the spectrometer calculations.

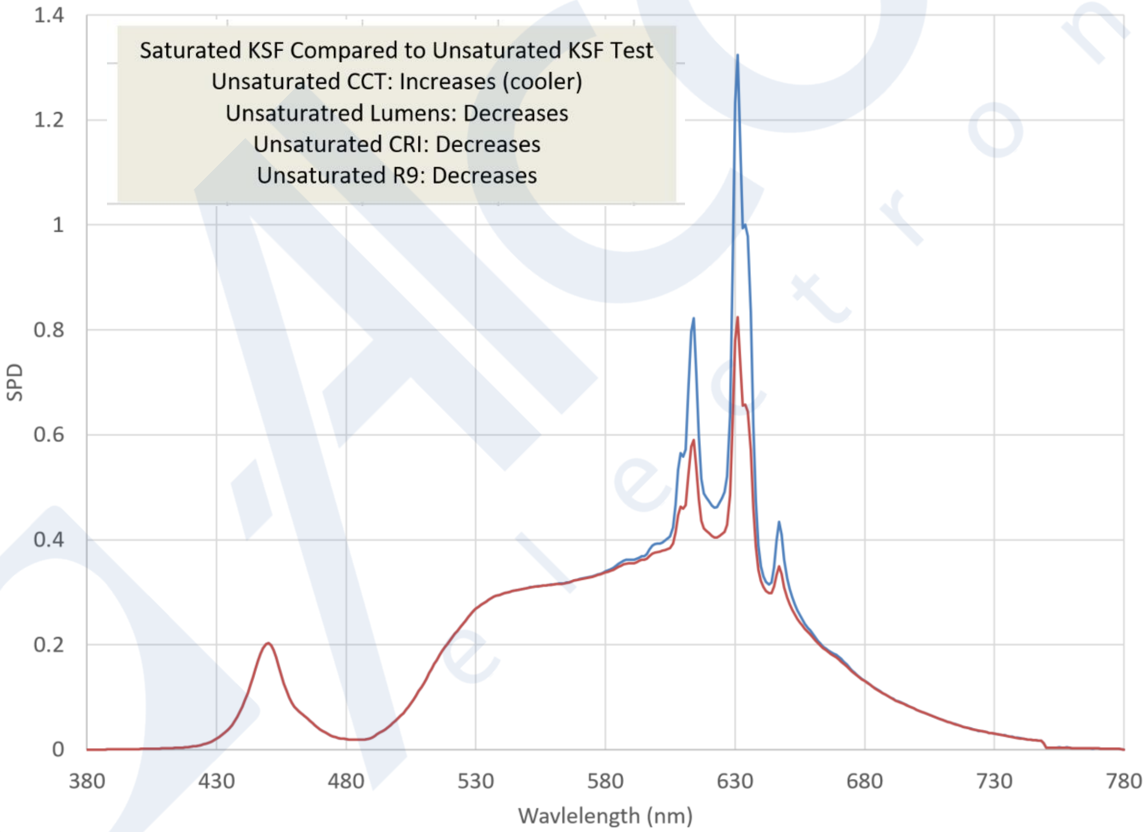


TERMINOLOGY

Integration time is the length of time the spectrometer captures data from the LED.

Soak time is the amount of time the power supply is on before spectrometer integration starts

Figure 10. During an LED integrating sphere test, the timing of the drive electronics and the spectrometer acquisition time is coordinated. Soak time is 5 ms in this example.



Saturated KSF Compared to Unsaturated KSF Test
Unsaturated CCT: Increases (cooler)
Unsaturatred Lumens: Decreases
Unsaturated CRI: Decreases
Unsaturated R9: Decreases

Figure 11 – Saturated KSF (blue with sufficient soak time) compared to unsaturated KSF (red with insufficient soak time) test results. If the soak time is too short, the errors that occur are as listed in the inset. Insufficient soak times to allow the KSF intensity to fully develop leads to undermeasuring the steady state red spectral content.

3.2 Spectrometer Resolution

To achieve the accuracy required for KSF LED testing, Luminus recommends using a spectrometer with a minimum 1-nm resolution to resolve the narrow spectral peaks in KSF phosphor spectra. A lower spectrometer resolution has limited ability to pick out some of the spiky peaks and valleys shown around the main red spectral peaks. This will affect the accuracy of the intensity reading.

Figure 12 simulates the spectrum of 3000K, CRI90 Lux COB when the spectral resolutions are 1 nm and 5 nm respectively. The left curve represents the original data from the integrating sphere with 1-nm resolution. The right curve shows the spectrum sampled in every 5-nm step. One can see that the 5-nm step sampling data does not distinguish the fine peak structure. **Figure 13** shows the TM-30-18 differences that occur when the spectrometer resolution is too low.

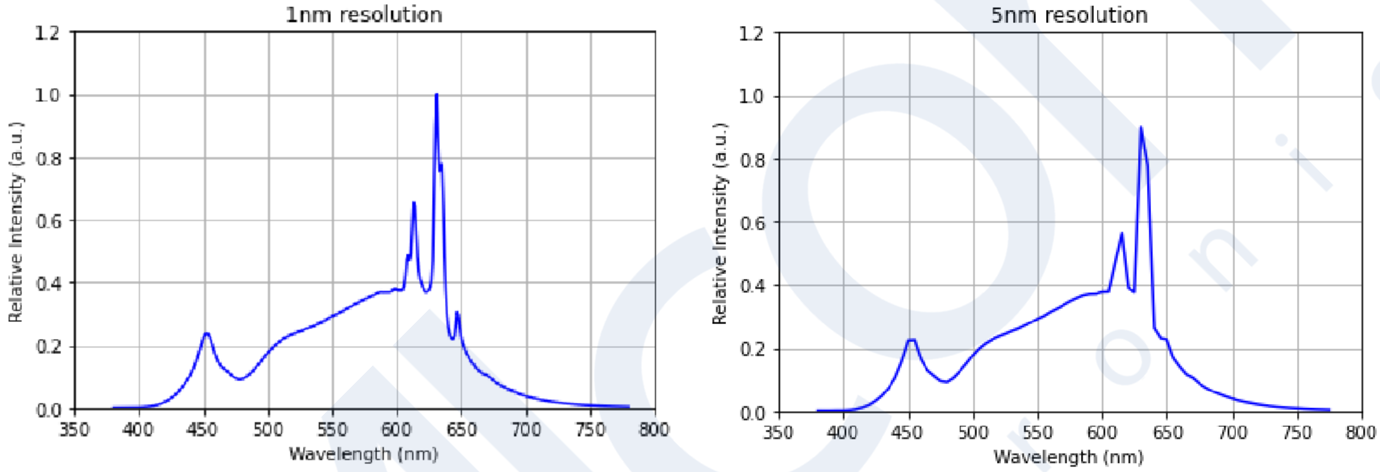
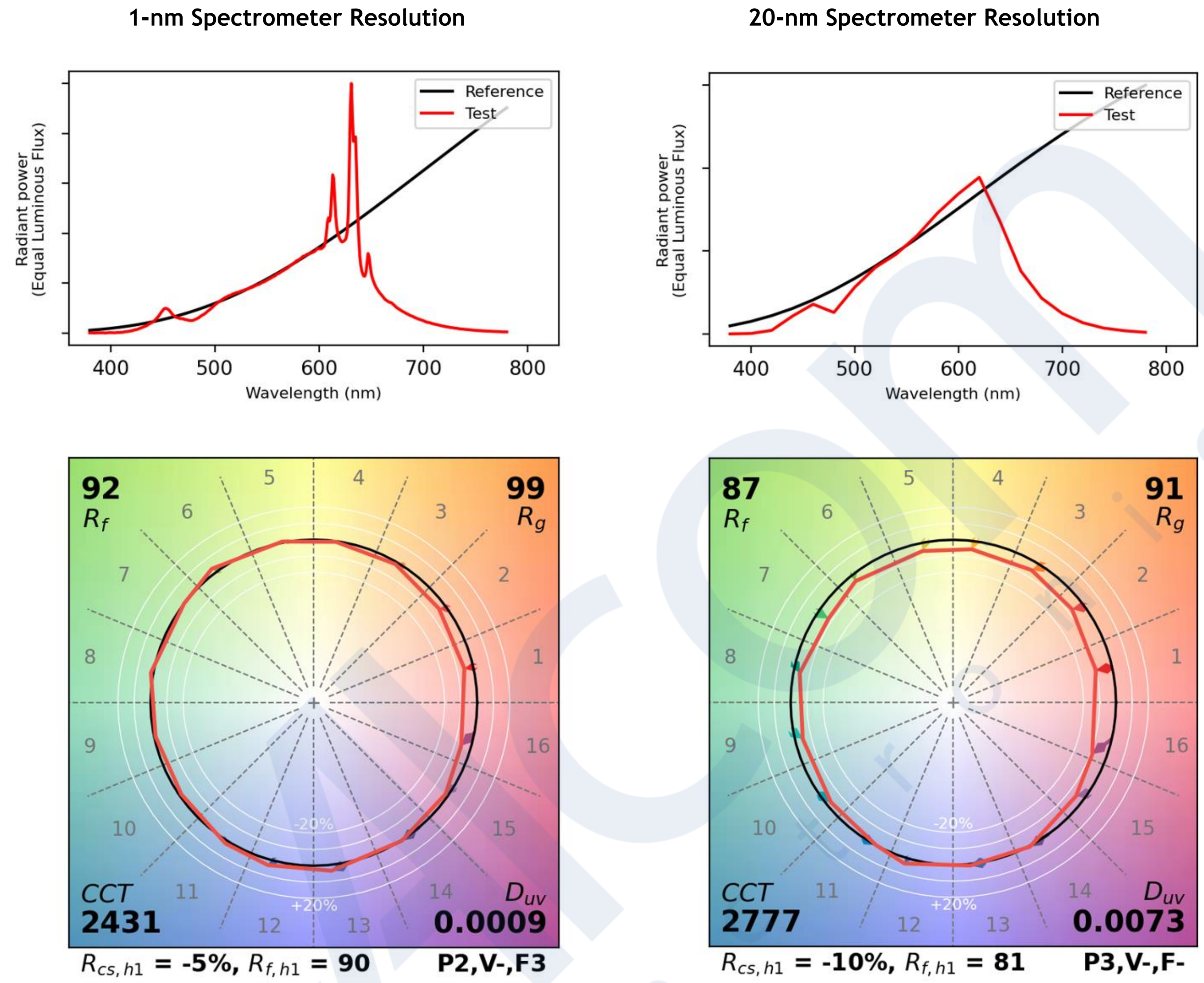


Figure 12. Comparison of 1-nm resolution (left) and 5-nm spectrometer resolution (right) of the peaks in KSF phosphors.



x	0.4849
y	0.4171
u'	0.2757
v'	0.5336

CIE 13.3-1995
(CRI)
R_a 94
R_9 53

x	0.4662
y	0.4324
u'	0.2570
v'	0.5363

CIE 13.3-1995
(CRI)
R_a 85
R_9 14

Figure 13. Comparison of TM-30-18 metrics for the same LED using 1-nm and 20-nm spectrometer resolution. The differences in this extreme case are significant. If this comparison was done with smooth phosphors, the differences would be less and mainly due to inaccuracy in the fairly narrow blue-chip spectra.

4.0 Conclusion

In conclusion, KSF phosphors, comprised of $K_2SiF_6:Mn^{4+}$, offer significant advantages over other non-KSF red phosphor materials for solid-state white light technology. These advantages include higher efficacy with improved color rendering, better stability performance, narrow emission bands, reduced reabsorption issues, and rare-earth-free composition. Users can expect to see superior color performance, stability, combined with higher efficacy using the LUX KSF-Phosphor LEDs.

Typically, LED manufacturers engineer the LED emission spectrum to match the reference curve at the target CCT to achieve high color quality. Higher percentages of red light are usually needed to increase CRI, but nitride-based red phosphors have significant non-visible emission, so the efficacy is reduced. Using narrow-band red phosphors eliminates this problem since there is no non-visible emission.

These products have been tested extensively with demonstrably superior performance. Additionally, KSF Phosphor LEDs require some different testing approaches to account for their unique characteristics. For example, measurement with higher-resolution spectrometers and using appropriate soak times are recommended.

Luminus maintains transparency in our test parameters and results. Our LUX COB phosphor LEDs consistently deliver outstanding performance for efficacy/flux without compromising color quality.

5.0 Contact Customer Support

For assistance with questions about KSF Phosphor LUX COBs and how to work with them, please contact: techsupport@luminus.com.

6.0 References

[1] Ghaffarzadeh, K., “Phosphors or QDs for color conversion in LCD and microLED?” Wevolver, August 16, 2022.

[2] Cohen, W.E., *et al.*, “Review—The $K_2SiF_6:Mn^{4+}$ (PFS/KSF) Phosphor”, *ECS Journal of Solid State Science and Technology,* 12 076004, 2023. DOI: 10.1149/2162-8777/ace47a

[3] Setchell, J., “Chapter 4: Colour description and communication,” pages 99-129 in *Colour Design (Second Edition)*, Janet Best (Ed.), Woodhead Publishing, 2012. DOI: 10.1016/B978-0-08-101270-3.00004-7

[4] Osborne, R., Cherepy, N., et al. “New Red Phosphor Ceramic K2SiF6:Mn4+” *Optical Materials*, Volume 107, September 2020, 110140. DOI: 10.1016/j.optmat.2020.110140

[5] Hendy, I, Murphy, J., and Setlur, A., “Latest Advances in Narrow-Band Phosphors and their Role in Color Management.” *Information Display*, May/June 2023.

[6] Murphy, J., Garcia-Santamaria, F., et al. “PFS, $K_2SiF_6:Mn^{4+}$: The Red-line Emitting LED Phosphor behind GE’s TriGain Technology™ Platform. Presented at SID Display Week 2015, San Jose, CA.

[7] Sijbom, H., Joos, J., et al. “Luminescent behavior of the K2SiF6:Mn4+ Red Phosphor at High Fluxes and at the microscopic level.” The Electrochemical Society, *ESC Journal of Solid State Science and Technology*. 5(1)R3040-R3048 (201

[8] Amachraa, M., Wang, Z., et al., “Predicting Thermal Quenching in Inorganic Phosphors.” *Chemistry of Materials*, 2020. DOI: 10.1021/acs.chemmater.0c02231.

[9] Reinert Verstraete, Heleen F. Sijbom, et al. “Red Mn4+-Doped Fluoride Phosphors: Why Purity Matters.” *ACS Applied Materials & Interfaces* 2018 *10* (22), 18845-18856. DOI: 10.1021/acsami.8b01269

[10] Murphy, J., “Market-leading wide color gamut narrow-band phosphors by GE,” presented at SID Display Week 2023, Los Angeles, CA, May 2023.

[11] Murphy, J., “Phosphors for Next Generation Solid-State Lighting/Displays,” presented at 2021 DOE Lighting R&D Workshop Panel-Lighting & Display Cross-Cutting R&D, February 3, 2021.

[12] “Project: Narrow-Band LED Phosphors Enabling Wide Color Gamut Displays,” GE Research website, https://www.ge.com/research/project/narrow-band-led-phosphors-enabling-wide-color-gamut-displays (Retrieved Oct. 2, 2023)

[13] Wright, M., “GE Lighting manufactures PFS red phosphor for LED display backlight applications,” *LEDs Magazine*, March 13, 2015.

[14] *Approved Method: Measuring Maintenance of Light Output Characteristics of Solid-State Lighting Sources,* ANSI/IED LM-80-21. Published by the Illuminating Engineering Society

[15] *Technical Memorandum: Projecting Long-term Luminus, Photon, and Radiant Flux Maintenance of LED Light Sources, ANSI/IES TM-21-21.Published by the Illuminating Engineering Society*

[16] *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*, IES LM-79-08, 2008. Published by the Illuminating Engineering Society.

[17] He, G., and Yan, H., "Optimal spectra of the phosphor-coated white LEDs with excellent color rendering property and high luminous efficacy of radiation," *Optics Express* 19(3):2519-2529, 2011. DOI: 10.1364/OE.19.002519

APPENDIX A – Phosphor Development and Full TM-30 Reports

A.1 Developing White LED Recipes

White LEDs are engineered using a combination of blue LEDs and various red, yellow, and green phosphors to achieve specific color coordinates and color quality ratings. To achieve high-quality white light, white LEDs use multiple phosphors to convert blue-LED “pump” light into a broader spectrum that closely resembles the reference curve for the targeted color temperature. There is a large set of possible phosphors that can be blended together to achieve a desired white SPD. Examples of individual phosphor SPDs are shown in **Figure 14**. The phosphor engineer has a large palate of color components to work with.

The general method of developing a white LED is as follows.

1. Find a phosphor mixture that “hits” the desired color point. This might have one blue LED and a number of phosphor components.
2. Analyze the TM-30-18 data for this result and determine what color components need to be adjusted to better achieve the CRI specification.
3. Adjust the phosphor mixture and iterate to an acceptable result.

Phosphors can be characterized by their peak wavelength and a width parameter, usually full width half max (FWHM). They can also be characterized by the phosphor’s color point expressed in CIE 1931 x and y coordinates. **Figure 15** shows this representation on the CIE 1931 diagram. The color point of a mixture of light sources is subject to metamerism. There are an infinite number of SPD combinations that can achieve a specified color point if the light sources have variable spectra, but if a specific phosphor blend is specified and the SPDs are fixed, there is only one solution that can achieve a desired system color point. Normal production variations produce a distribution of color points and manufacturers use binning based on color perception to group parts into specified ranges.

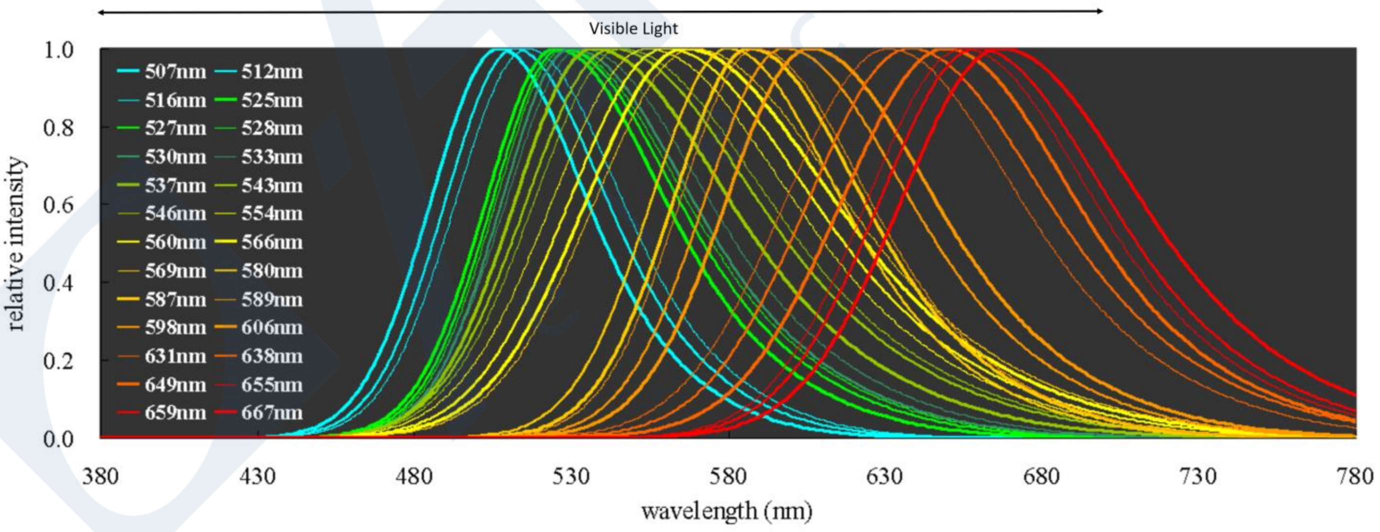


Figure 14. Phosphor emission SPDs.[17]

The equations to calculate the color point of a mixture sources use the CIE x, y coordinates and the lumen output of each source are shown below. This example is for a three-component system where the subscripted L is lumens, and x, y are the CIE color coordinates of each source. This equation can be expanded for any number of sources.

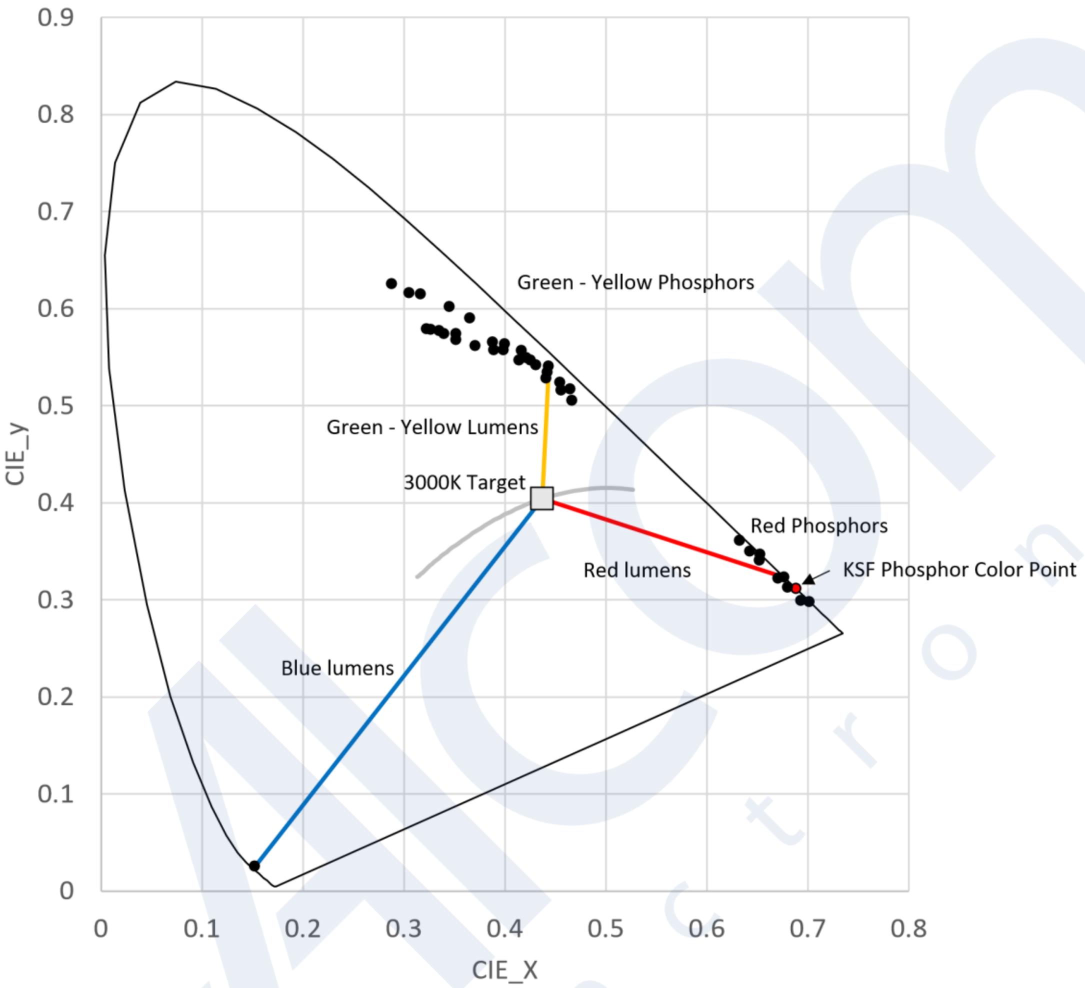


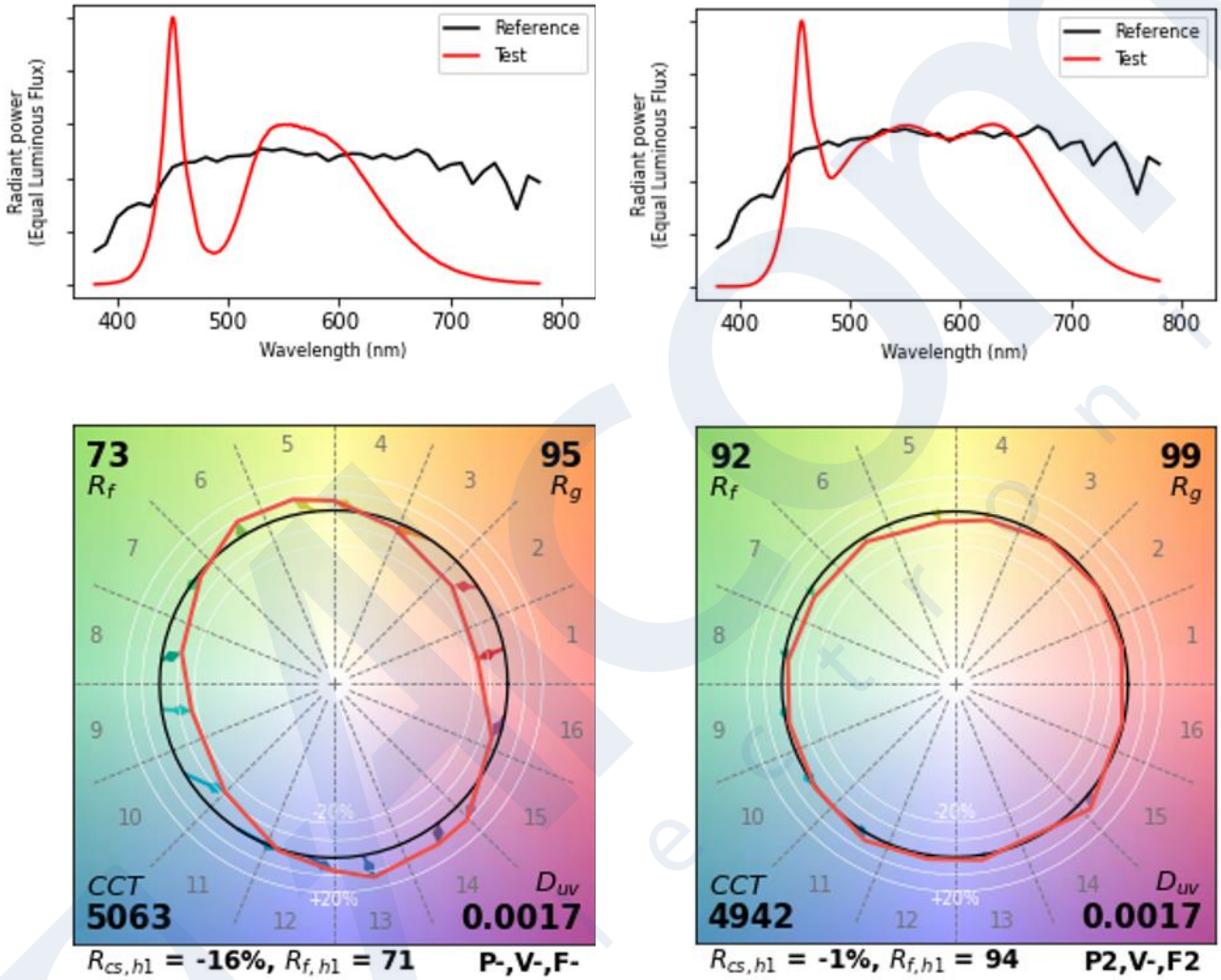
Figure 15. CIE 1931 diagram illustrating the variety of phosphor color points that are available to achieve a specified white LED color point. Increasing the lumen contribution of a component pulls the color point towards the color point of that component. This information is combined with the data in a TM-30-18 report to develop a phosphor recipe meeting color temperature and color quality goals.

$$CIEx = \frac{x_R \cdot \frac{L_R}{y_R} + x_G \cdot \frac{L_G}{y_G} + x_B \cdot \frac{L_B}{y_B}}{\frac{L_R}{y_R} + \frac{L_G}{y_G} + \frac{L_B}{y_B}}$$

$$CIEy = \frac{L_R + L_G + L_B}{\frac{L_R}{y_R} + \frac{L_G}{y_G} + \frac{L_B}{y_B}}$$

White LED phosphor recipe development involves blending a phosphor mixture to achieve the desired color point (as shown in **Figure 15**) and the desired CRI specification.

If a phosphor engineer wanted to improve the 70 CRI part shown in **Figure 16**, it is immediately apparent that adding red is needed and the "cyan gap" needs to be closed by adding shorter wavelength green phosphors. However, after adding red and green, all other values shift. Phosphor tuning is an iterative process of making small changes and evaluating each step using color quality data. The visualizations (**Figure 14**, **Figure 15**, and **Figure 16**) are all used during this process.

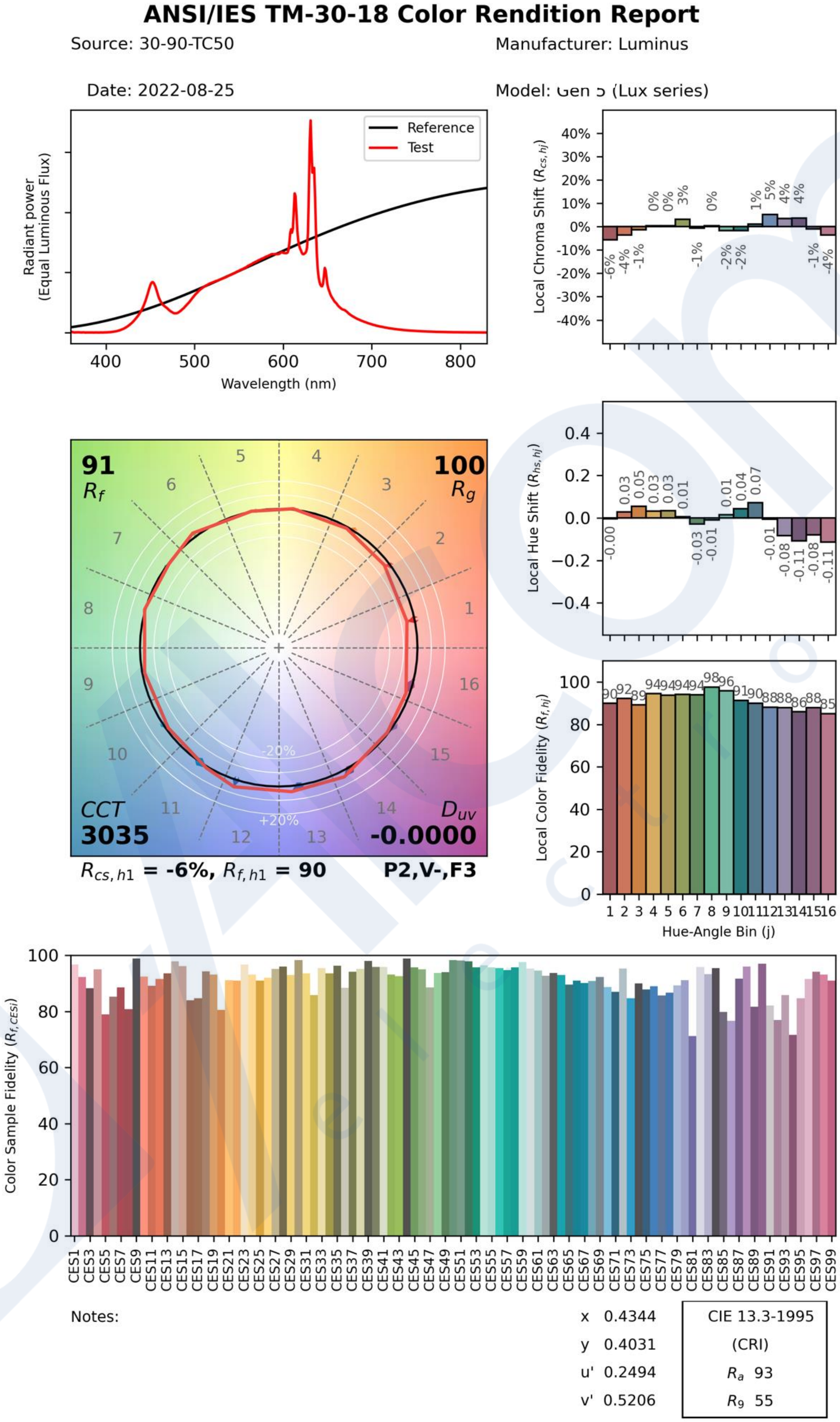


70 CRI

95 CRI

Figure 16. Comparison of the TM-30 measurements for 70 and 95 CRI, 5000K COBs. The reference curve for higher CCT components uses an idealized solar spectrum which in this case is called D50.

A.2 Full TM-30-18 Reports



ANSI/IES TM-30-18 Color Rendition Report

Source: 30-90-TC50

Manufacturer: Luminus

Date: 2022-08-25

Model: Gen 5 (Lux series)

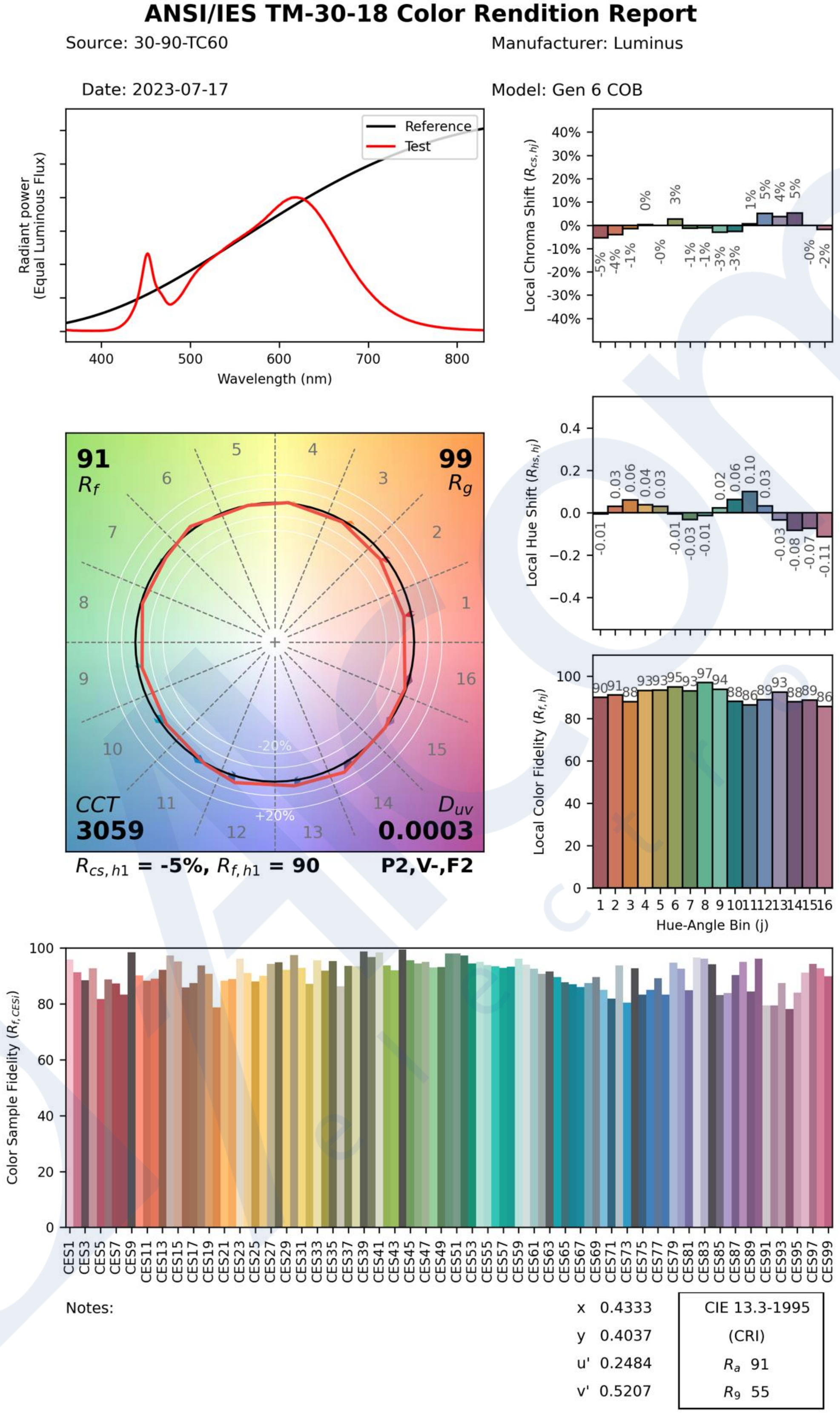
$R_{cs,h1}$ = -6%, $R_{f,h1}$ = 90 **P2,V-,F3**

Notes:

x	0.4344
y	0.4031
u'	0.2494
v'	0.5206

CIE 13.3-1995
(CRI)
R_a 93
R_9 55

Figure 17. Full TM-30-18 report for the 30-90-TC50 LUX COB component.



ANSI/IES TM-30-18 Color Rendition Report

Source: 30-90-TC60

Manufacturer: Luminus

Date: 2023-07-17

Model: Gen 6 COB

$R_{cs,h1}$ = -5%, $R_{f,h1}$ = 90

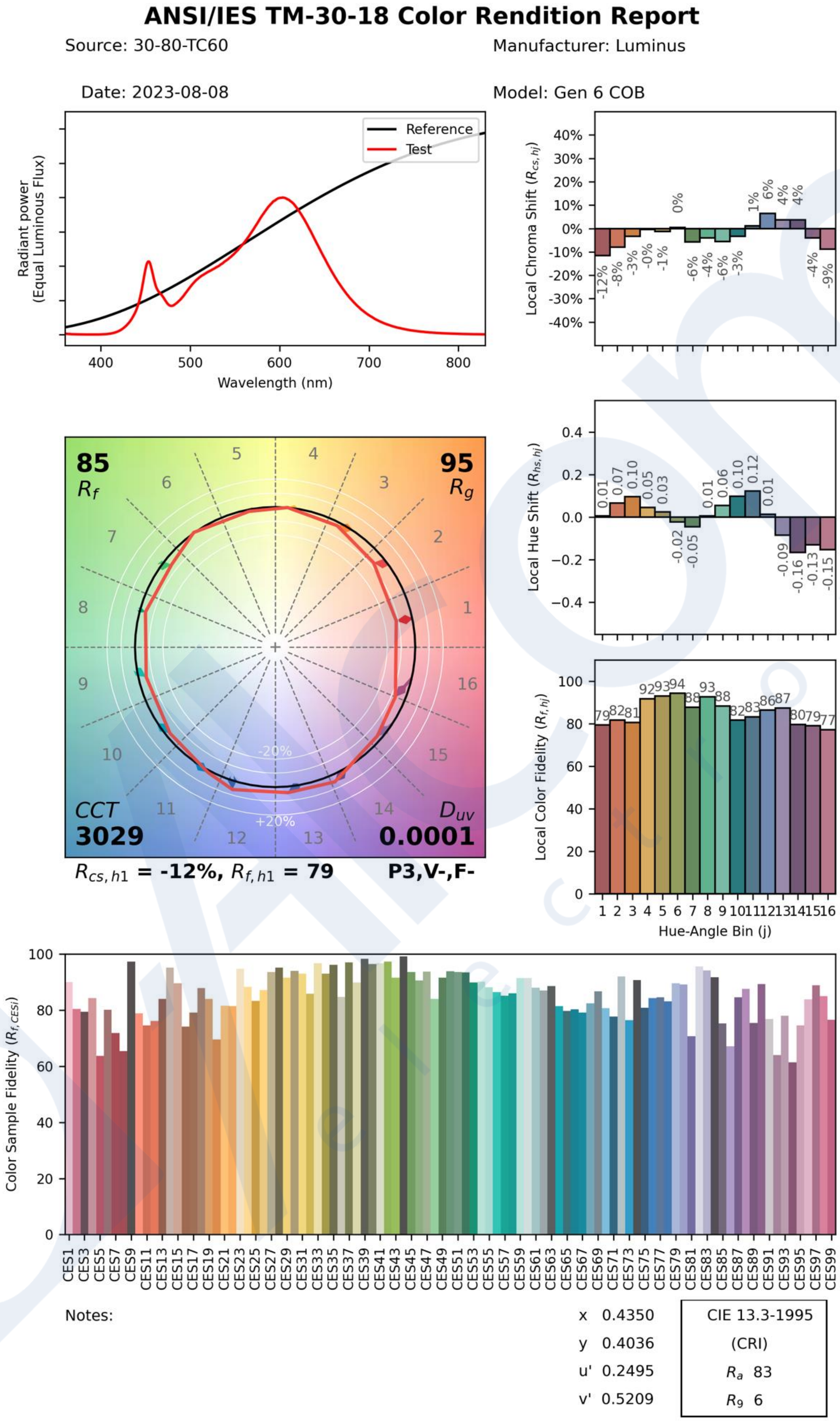
P2,V-,F2

Notes:

x 0.4333
y 0.4037
u' 0.2484
v' 0.5207

CIE 13.3-1995
(CRI)
R_a 91
R_9 55

Figure 18. Full TM-30-18 report for the 30-90-TC60 Gen 6 COB component.



ANSI/IES TM-30-18 Color Rendition Report

Source: 30-80-TC60

Manufacturer: Luminus

Date: 2023-08-08

Model: Gen 6 COB

$R_{cs,h1}$ = -12%, $R_{f,h1}$ = 79

P3,V-,F-

Notes:

x 0.4350
y 0.4036
u' 0.2495
v' 0.5209

CIE 13.3-1995
(CRI)
R_a 83
R_9 6

Figure 19. Full TM-30-18 report for the 30-80-TC60 Gen 6 COB component.