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WHITE PAPER

Achieving Optimal Color Rendition with LEDs

A Review of Various Models for Classifying Light Source Color Rendition and Guide to Using LEDs to Achieve Fidelity Color Rendering for Retail and Other Indoor Environments

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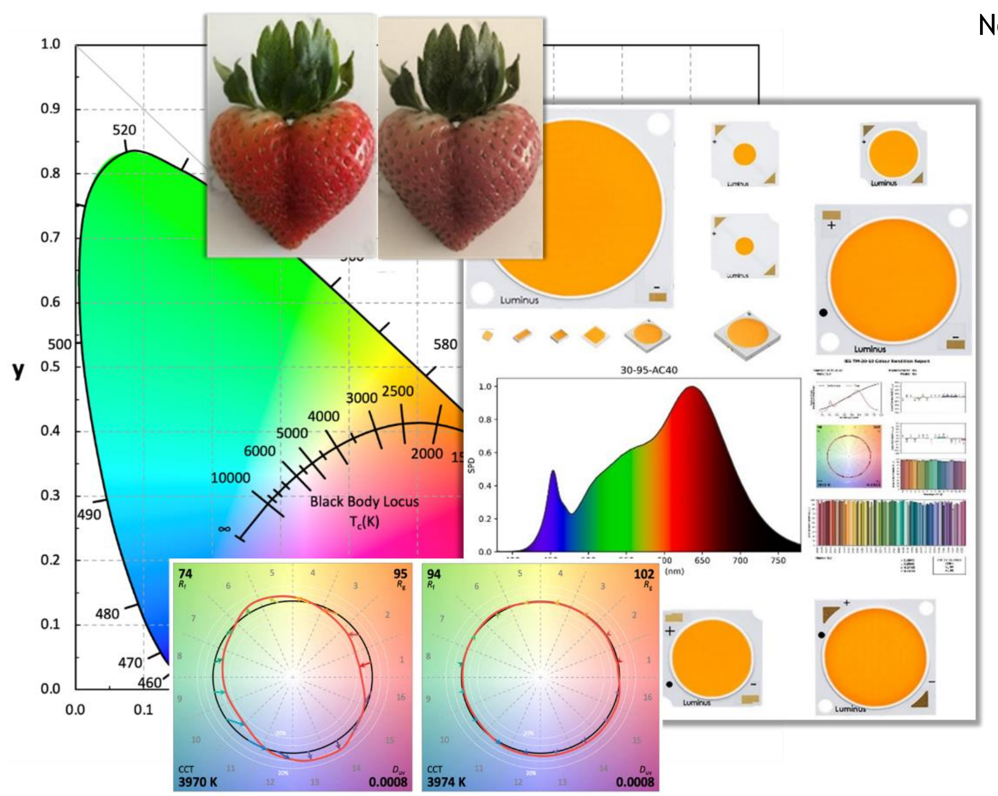

Overview

One of the essential functions of human vision is perceiving color, which is an important source of information about our world. For example, the bright red color of a ripe strawberry tells us it is ready to eat. Humans see color as a function of reflectance—specific wavelengths of light reflected into our eyes. Lighting profoundly affects how we see color by either accentuating or altering how various wavelengths appear.

This White Paper explains color rendering—how light affects the appearance of the colors we see. It describes the various systems used for measuring the color rendition capability of light sources, such as the Color Rendering Index (CRI), Gamut Area Index (GAI), TM-30, and more. We compare these methods and discuss how they have evolved to provide more accurate assessment of LEDs for different lighting needs.

By properly applying these indices, you can create the right lighting scheme for virtually every type of environment—from retail stores to surgical operating rooms. We describe the superior color rendition capabilities of Luminus LED products, including Standard LEDs, Sensus™, PerfectWhite™, Hospitality COB Series™, and Salud™, and how they help architects and lighting designers to meet specific functional lighting objectives.

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1.0 Color Rendition

LEDs serve many specialized purposes. They appear in retail displays and illumination for stage entertainment. They create ambiance in homes and hospitality venues and provide task lighting for industrial and commercial production. LEDs lighting influences plant growth in horticulture and illuminates medical procedures in clinical settings.

But not all light is the same. The visible spectrum of light (a small portion of the full electromagnetic spectrum) encompasses wavelengths of approximately 380-740 nanometers (nm), as shown in Figure 1. What we typically perceive as “white” light is actually a blend of many wavelengths in the visible spectrum. Different light sources may have more or less of certain wavelengths. The wavelength profile of a light source (called its spectral power distribution, SPD*) can have considerable effect on the appearance of our environment, the objects in it, and our visual experience.

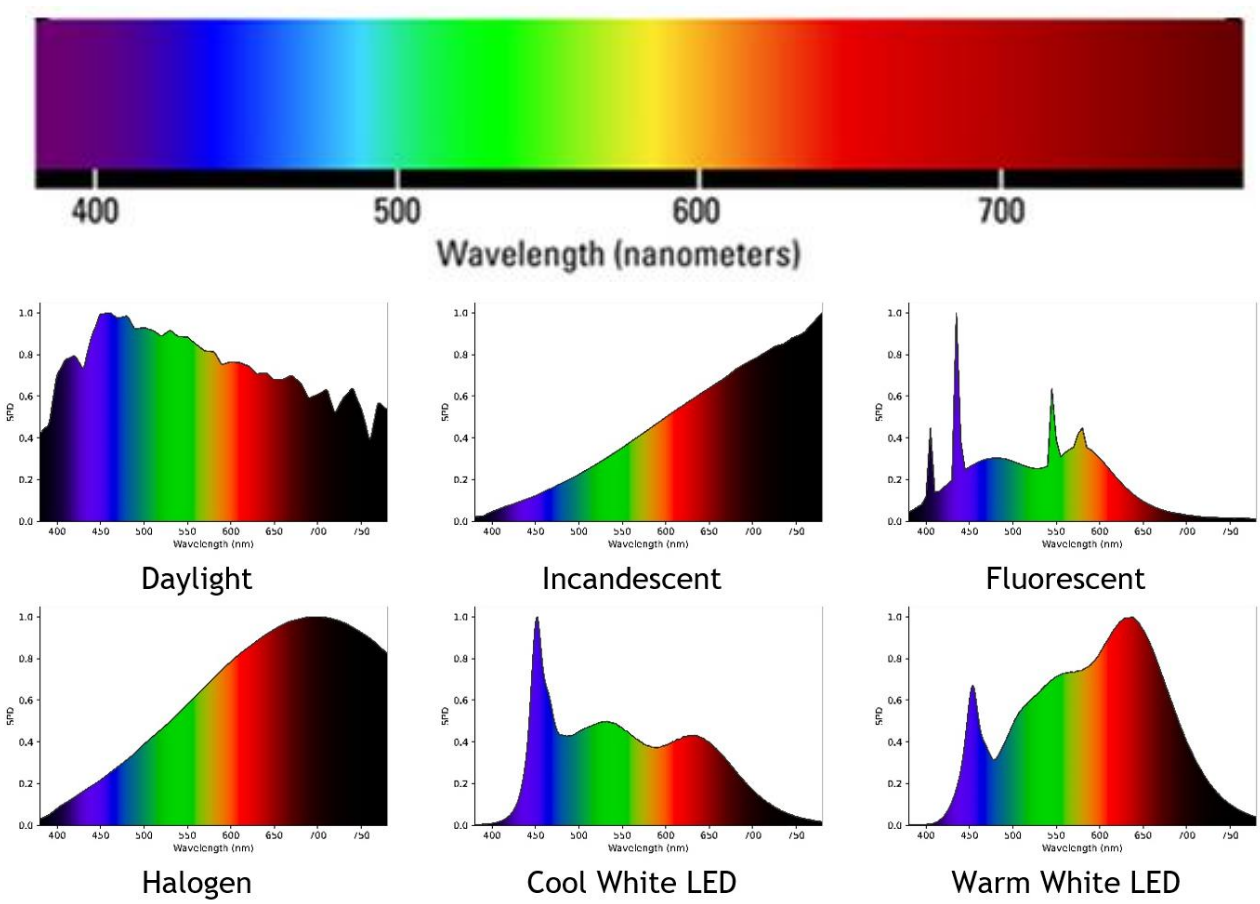

Figure 1 – The spectrum of light that is visible to humans, from roughly 380-740 nm (top), and examples of the spectral power distribution (SPD) of several light sources, where the y-axis represents relative intensity of the light at each wavelength on the x-axis.

*For more explanation and discussion of spectral power distribution and other quantitative aspects of light, refer to the Luminus Help Center article “*What does CCT, CIE, and SPD mean in LED lighting?*”

1.1 How Humans Perceive Color

Humans see color when light in the visible spectrum enters the eye through the pupil and strikes the retina at the back of the eye. The retina includes color-sensitive cones. When photons with certain wavelengths hit matching cones, the cones fire a chemical reaction. The chemical reaction communicates along the optic nerve to the cerebral cortex of the brain, where it is interpreted as a specific color.

Lighting affects how our eyes perceive color via reflectance. Most light sources contain a mix of different wavelengths. As light strikes an object, some wavelengths are absorbed and some of the wavelengths are reflected into our eyes. For example, a red strawberry appears red to us because all other wavelengths of light (green, yellow, indigo, etc.) are absorbed while only the red spectrum of wavelengths are reflected off the fruit into our eyes (Figure 2).

But the reflected color of an object is not absolute. As a light source's SPD changes (for example, from bright daylight to early evening twilight) different wavelengths shine on an object with different intensities, which alters the reflectance of that object—an object can only reflect wavelengths that are present in the light source—thus altering human perception of its color.

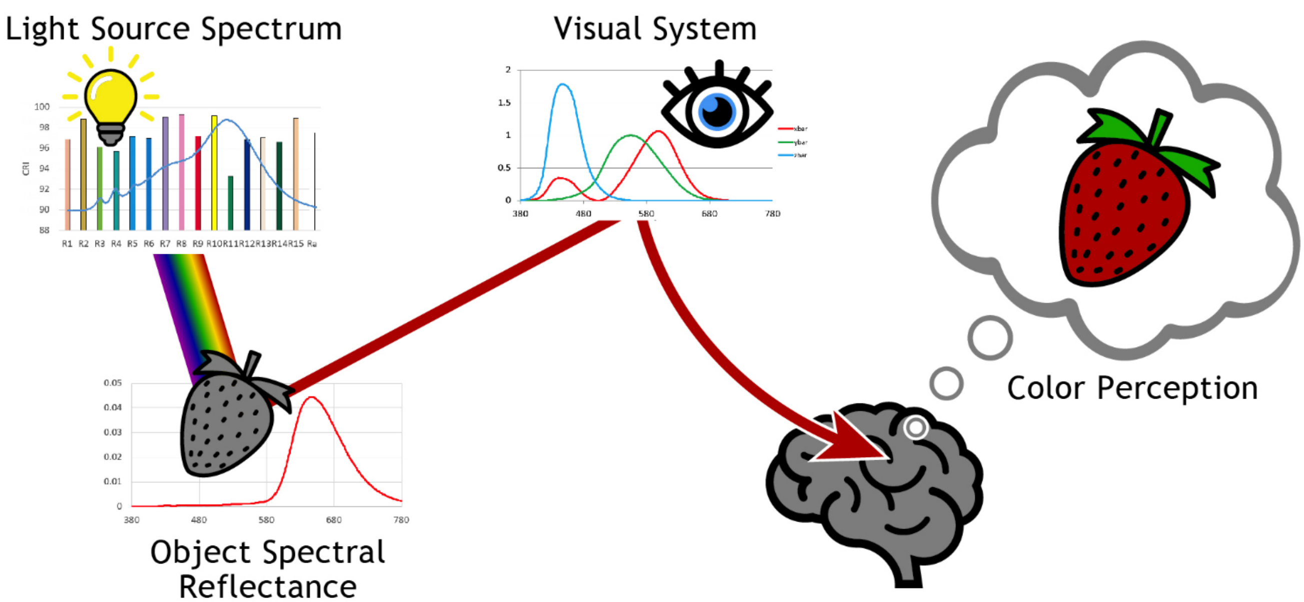

Figure 2 -A ripe strawberry reflects long-wavelength light (in the red spectrum) while absorbing most middle- and short-wavelength light (in the yellow, green, blue, and violet spectra). The reflected light is received by the retina and processed by the human visual system resulting in our perception of a red strawberry.

Due to their different SPDs, even white light sources can have a different appearance with a reddish or orange tint (described as warm) or a blue cast (described as cool). The tint of a white light source is characterized by its Correlated Color Temperature (CCT). Measured in degrees Kelvin (K), CCT values are a standard metric used to describe white light sources.

For example, candlelight (quite warm) is rated around 1850K, while bright daylight typically exceeds 5000K. The CCT of a light source affects how our eyes perceive the color of objects it illuminates, referred to as color rendering. Although, a light source's CCT is not the only factor that determines how colors appear; additional factors will be discussed in the following sections. (Further information about SPDs, CCT, and other lighting concepts is available in the Luminus Help Center.)

1.2 The CIE Color Space

In 1931 the CIE defined a mathematical system to quantify all the colors that can be perceived by the average human eye—based on experiments performed with human observers.

Human perception is represented by tristimulus curves that graph the response of each of the three cone types in the human eye as a function of wavelength—thus the "tri" in tristimulus (Figure 3). Humans do not perceive individual wavelengths but a blend of red, green, and blue in varying proportions, thus the space under the curves encompasses the range of human color perception.

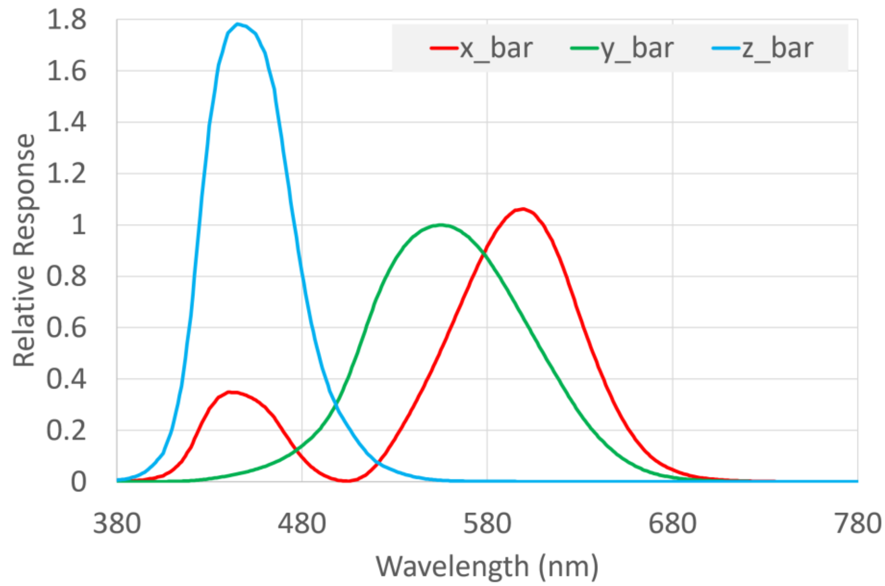

Figure 3 –The CIE 1931 tristimulus curves are labeled $\bar{x}$, $\bar{y}$, $\bar{z}$ and are standardized mathematical functions developed to represent human S, M, and L cone responses. The process of calculating CIEx and CIEy from an SPD is discussed in the Help Center article How do I calculate CIEx and CIEy from an SPD?

The CIE "color space" is a horseshoe-shaped diagram that also represents the entire range of human color perception based on luminance and chromaticity (Figure 4). The outer curved boundary of the color space is called the spectral locus. It is defined by monochromatic points representing a pure hue of a single wavelength. For a complete description of the CIE 1931 (x, y) color space, 1976 color space (u', v') and their refinements, refer to the Luminus Help Center article What is the CIE Color Space? What's the Difference Between CIE 1931 and CIE 1976?.

Commonly, the chromaticity coordinates x,y are used to identify a specific color in the diagram. However, because the human eye sees only a blend of wavelengths, there can be many different light source SPDs that share a single chromaticity point—a virtually infinite number of SPDs.

SPDs that share a chromaticity point in the CIE color space are called metameric. Metamerism is a significant concept for color rendering. It is the phenomenon where different light sources with widely different SPDs can nevertheless result in the same perception of an object's color to a human observer. [1] The comparison of different SPDs with matching CCTs on the black body curve is an example of metamerism (e.g., halogen vs LED at 3000 K).

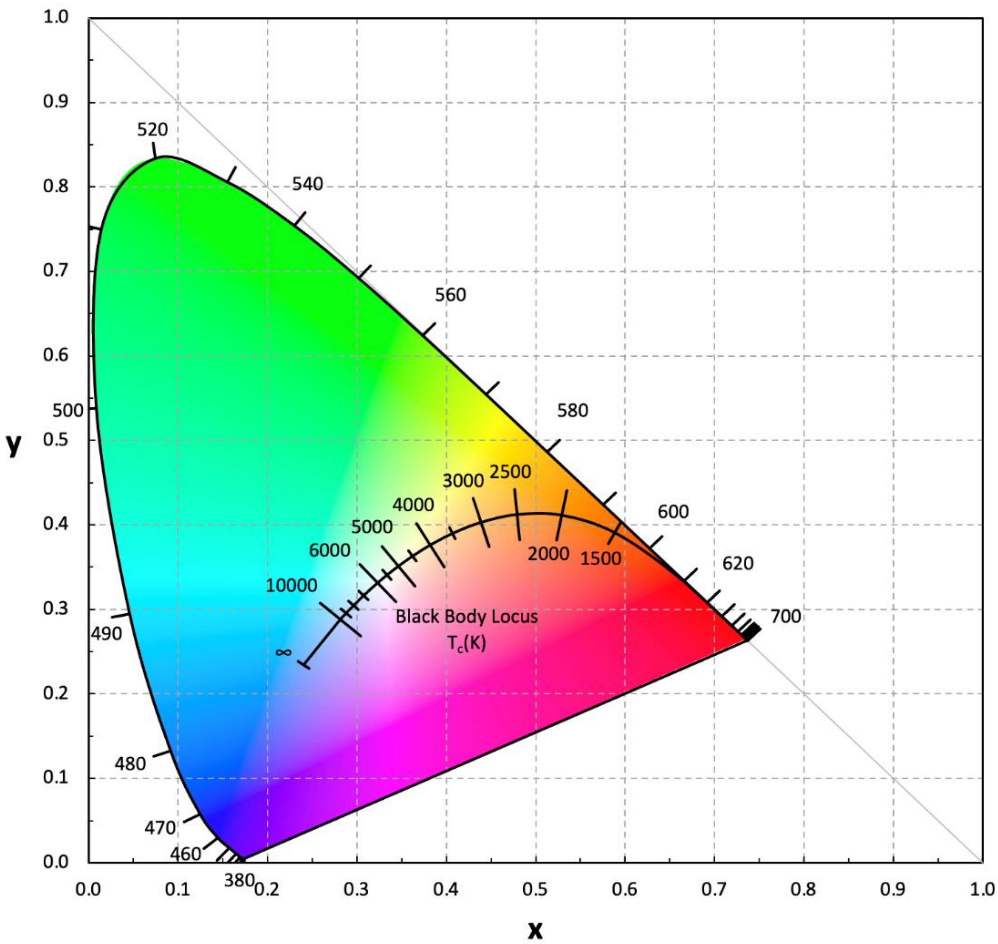

Figure 4 – The CIE 1931 chromaticity diagram (color space) representing a mathematical mapping for all colors visible to the human eye. The Black Body line represents the points in the color space where light appears "white" to our eyes, even though it may have a mixture of multiple hues. (For more information about the Black Body Locus refer to the Help Center article What does CCT, CIE and SPD mean in LED lighting.)

1.3 What Is Color Rendition?

Color rendition (also commonly referred to as color rendering) is the effect of light on the color perception of objects. The International Commission on Illumination (CIE) publishes an International Lighting Vocabulary that defines color rendering as the "effect of an illuminant [light source] on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant." [2]. Put more simply, the color rendition characteristics of a light source (which can be measured) determine how accurately the color of an object appears to our eyes under that light source.

To determine accuracy, the light source is compared to a standard source, called the reference illuminant.* Each CCT has a defined reference illuminant; the light source under evaluation (test light source) is compared to the reference that matches its CCT.

* Reference illuminants are a set of standardized SPD data sets that represent real light sources such as incandescent light, sunlight, fluorescent light, etc. The reference illuminants—also called standard illuminants—provide common comparison points for light sources of all kinds. For more information refer to the Help Center article What is a Standard Illuminant (Reference Illuminant)?

There are various methods of measuring and specifying the color rendition capability of a light source; a commonly used metric was created by CIE in 1965, called the Color Rendering Index (CRI). The CRI measures a light source's ability to reveal the intrinsic colors of the objects it illuminates, referred to as its accuracy, or *color fidelity*. CRI is based on the average fidelity of how a light source renders eight color samples.

CRI is measured on a scale of 100* with values at higher end of the scale indicating more accurate color rendering (Figure 5). For example, Figure 6 illustrates the difference between color appearance at CRI of 95 (very accurate), compared to a CRI of 70, where colors appear washed out and not as "true to life." To determine a light source's CRI, it is tested using eight color chips (numbered R1 to R8), compared against a reference source with the same CCT. Typically, test values are measured by a spectrometer and calculated using the SPD.

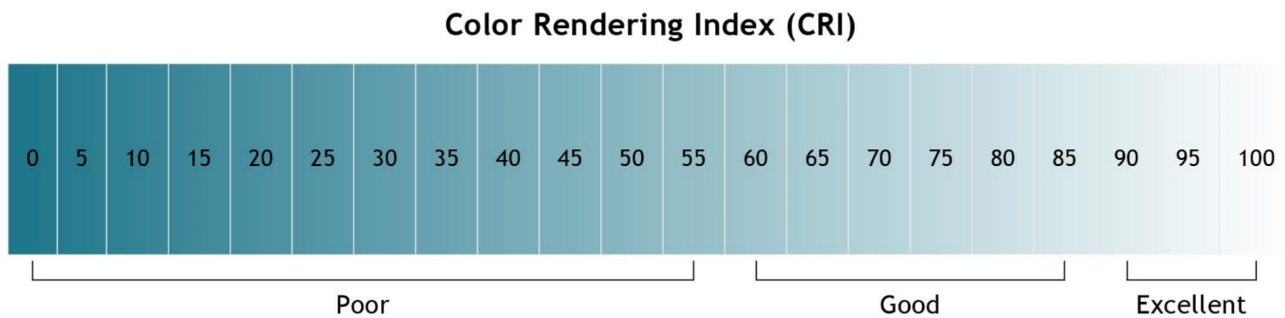

Figure 5 – The Color Rendering Index (CRI) scale, where higher values indicate more accurate color appearance.

In certain lighting applications a light source with a low CRI value can be preferable. LEDs with high CRI values typically contain more red content in their SPD, providing more accurate color rendition. Red light requires more energy consumption per lumen due to low eye response in that wavelength region. Thus, high-CRI LEDs operate at a lower efficiency—they produce fewer lumens (a measure of brightness) per Watt (LPW). In environments where accurate color rendition is less important than energy efficiency and reducing cost, LEDs with a lower CRI value may be the best choice.

* It is possible for light sources to have negative CRI values. For example, low-pressure sodium lights can have a CRI of -47. They render all colors in a muddy yellowish tone. Mathematically, the CRI (the R_a) is linearly scaled to indicate the amount of chromatic variation from the color of the object under the reference illuminant. The reference illuminance has a score of 100, and the distance from 100 indicates the accuracy of other light sources. Thus, a CRI value of 100 means no variation (perfect rendition); an R_a value of 60 means that there is four times the average color shift than is the case with an R_a value of 90.

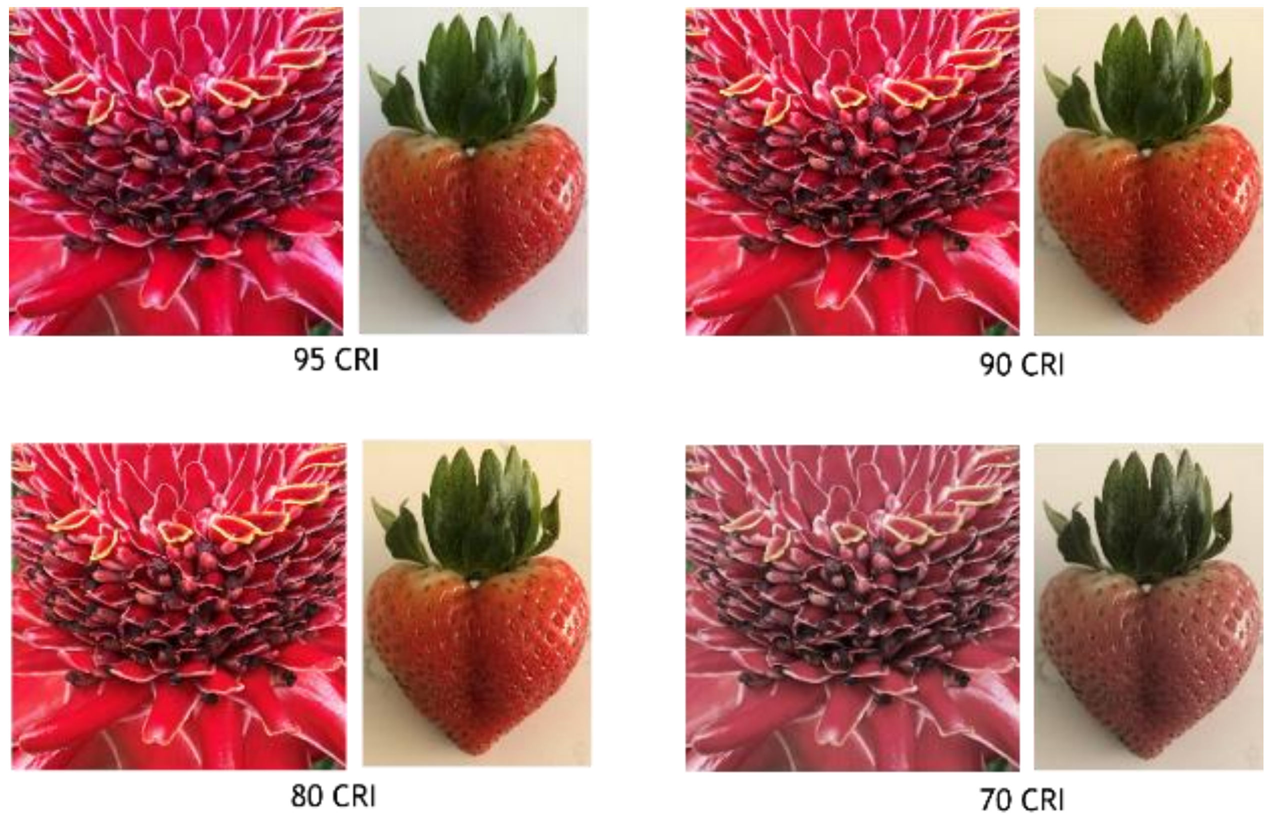

Figure 6 – Comparison of color rendering with different CRI values. With poor color rendering (lower CRI), reds typically appear more "orange" and other colors appear generally washed out or dull. Light sources with good color rendering (high CRI) typically show vibrant colors and rich "cherry reds."

1.4 Color Attributes

There are some additional core concepts and terminology needed to understand color rendition and how to design lighting that is optimal for different applications, including: saturation, hue, chroma (illustrated in Figure 7), chromaticity, gamut, fidelity, value, color preference, and chromatic fidelity.

- *Hue* refers to the specific color, for example, red, red-orange, and orange are three hues.
- *Value* refers to how light or dark a color a color is—how much gray is incorporated. Black has a low value (dark), white has a high value.
- *Chroma* refers to the intensity of a color, how pure its hue is. Also referred as saturation—highly saturated colors are vivid; low-saturation colors appear more washed out or dull. The colors along the edge of the CIE color space can be said to be fully saturated, as they are pure wavelengths of their respective colors. Highly saturated colors can also be described as high chroma.
- *Fidelity*. The color fidelity of a light source refers to how accurately it renders the color of an item compared to a reference source. The CRI (discussed below in Section 3) is a measure of fidelity.
- *Chromaticity* describes the coordinates of a light source SPD on a diagram such as the CIE 1931. It represents a combination of wavelength and purity.

Figure 7 – illustration of hue, value, and chroma (saturation).

The terms defined above are all objective measures of light and color; they can be quantified based on physical properties such as wavelength distribution. The next two concepts describe subjective characteristics that relate to human perception:

- *Color preference* refers to the aesthetic qualities of a light source. Research demonstrates that human observers prefer colors that appear both "natural" and "vivid". Color preference is explored more in the discussion of color gamut in Section 3.2
- *Chromatic adaptation* is an aspect of human perception, where our visual system partially adapts to slight differences in the color and amount of light. For example, as light transitions from bluish daylight at noon to more amber in the afternoon, our eyes adjust so the color of objects will nevertheless appear constant. Similarly, artificial light that is slightly off-white will be perceived as a true white after some time lapse.

Color preference is just one of several subjective attributes of lighting. Even though CRI is referenced to human visual perception (the CIE color space), it is an objective metric. When designing lighting for human-occupied spaces, subjective attributes of color are also an important consideration. Based on various studies of human psychological response, we prefer lighting that renders objects and the environment with attributes such as *naturalness* and *vividness*. Other variants include normalness, acceptability, vibrancy, and appreciation. [3]

2. The Importance of Color Rendering Accuracy in Selected Application Areas

Accurate color rendering matters in many industries and applications. Poor color rendering can make objects look unappealing. The wrong color can detract from an environment's ambiance. It can even make performing tasks difficult, inaccurate, or unpleasant. Proper color rendering is key for interior design to create an inviting or invigorating ambiance. It is particularly critical for retail settings where vivid colors can make foods seem fresh and appetizing, clothes and other display objects look more exciting, and generate feelings of comfort and opulence. LED technology has revolutionized the possibilities of enhancing experiences with lighting design due to increasingly affordable high-CRI options.

Color quality is not the only consideration when designing a lighting system. A holistic system level approach is needed to make the best decision. Factors to consider include:

- Color quality
- Cost of ownership
- Reliability/lumen maintenance
- Regulatory and NGO requirements
- Energy efficiency
- Safety
- Optics (light targeting requirements)
- Application-specific requirements

Incandescent light sources are dead. Why? They have excellent CRI. The reason that incandescent lighting is being "legislated out of existence" (per the U.S. Department of Energy) is the low energy efficiency, or lumens per watt (LPW), of this technology. A typical incandescent light provides only about 14 LPW, while modern LEDs have exceeded 200 LPW at the fixture level. The cost of ownership for a 60 W-equivalent LED bulb is about 87% lower than an incandescent bulb.

2.1 Application-Specific Color Rendition Considerations

2.1.1 Indoor Spaces

Indoor lighting is an application area where good color rendering provides value. We spend the majority of our indoor time in workspaces and living spaces with excursions to display spaces such as retail shops, lobby areas, event venues, and sales offices. Understanding the principles of color rendering allows us to improve the comfort and utility of these areas.

- **Office Spaces** – in the workplace, people need comfortable light that is bright enough to promote alertness and support productivity. In the U.S., the Well Building Standard has defined desirable indoor lighting for workplaces. [4].
- **Home** – at home we need comfortable light that is attuned to human circadian functioning (wakefulness and sleep cycles), called Human-Centric Lighting. This typically means relatively bright light containing blue/cyan wavelengths during the morning and daytime, more amber- and red-spectrum lighting in the evening. Avoiding blue wavelengths in the evening and at night is important for health; the European Union has adopted standards for blue light content in lighting products. [5]. To learn more about human centric lighting, read the White Paper, *Lighting for Health: Human-Centric Lighting*.
- **Task Lighting** –various applications from diamond grading to visual inspection of paint surfaces have specific requirements. Lighting needs to be suitable for performing the visual task and there can be some instrumentation-specific needs for color fidelity.
- **Manufacturing Environments** – lighting in industrial and manufacturing environments must provide sufficient illumination for workers to see fine details, read small print, and work

safely. In the U.S., the Occupational Safety and Health Administration (OSHA) mandates lighting standards. At the same time, lighting should be comfortable enough for humans working in the environment, not overly bright or harsh. Standards such as Well Certified provide guidance on how to balance these considerations. [4]

2.1.2 Outdoor Lighting

Outdoor lighting is another application area where good color rendering provides value. Streetlights, stadium lights, and architectural lighting are three examples.

- **Streetlights & Light Pollution** – Illuminating streets and parking lots requires light that is bright enough to ensure safety of pedestrians and visibility for drivers, yet not so bright that it wastes energy or contributes to light pollution (refer to the Dark Sky initiative for more information on the harmful effects).

  Color temperature is an important consideration for street lighting (Figure 8); the American Medical Association has recommended that nighttime street lighting should have a color temperature no higher than 3000K to avoid too much blue light that can interfere with human and animal circadian cycles.

  For exterior applications, LEDs have an optical design advantage because they emit focused, directional light without excess illumination diffused in all directions, and can provide brighter light (higher luminance) on target at the appropriate CCT, using less energy than previous technologies.

Figure 8 – Replacing HPS streetlights, which have poor color rendering and higher energy costs, with LEDs has a significant impact. For example, LED implementation has resulted in 64% energy savings for the City of Los Angeles, while still meeting the LABSL standard of 3000 K and > 70 CRI for LED installations. Photo credit.

- **Stadium Lighting –** for stadiums, a color temperature of 4000K-6500K is recommended. This provides light that is bright enough for attendees to easily see sporting play or other event action. It is also important for stadium lighting to provide good color rendering because much of the activity is filmed for television broadcast. Many stadiums have adopted the TCLI (refer to Video Lighting, below). Efficiency and cost are also important considerations, given the number of light fixtures needed for large venues.
- **National Parks** – when out in nature, an excess of artificial light can spoil the experience, reducing visibility of stars and the night sky and interfering with natural animal nocturnal activity. The objective is to provide the least amount of light to ensure safety, at appropriate color temperatures, with minimal stray light and low energy use.

2.1.3 Specialty Environments

- **Food Safety Lighting –** Many countries have regulations to ensure food safety. In the US, the Department of Agriculture (USDA) regulations include lighting specifications for facilities such as meat processing plants to ensure that employees can clearly see and remove contaminants. The ability of a light source to render red wavelengths (the R9 CRI sample) is critical for viewing animal tissues for health and safety inspection.
- **Gallery/Museum –** Color fidelity is a key requirement for lighting in museums and galleries, ensuring that the contents can be seen as the artists intended. However, natural daylight and some artificial lighting includes UV wavelengths that can cause damage to pigments and artwork materials over time. Museums have often used light around 3500K, but research is ongoing [6] to determine the optimal balance of art preservation, fidelity, color rendering, viewer preferences, and account for chromatic adaptation.
- **Medical Environments** – One example of how important it is for LEDs to provide accurate color rendering is in medical facilities. Light in a surgical operating room must be ensure that surgeons can discern fine gradations of red tones to differentiate tissues, blood, and bodily structures. Lighting for this environment requires a balance of color temperature and CRI considerations. To learn more, refer to the Help Center article How is Color Rendition (CRI) Applicable in Medical Environments and What is the Cyanosis Observation Index (COI)?
- **Hospitality** – Hospitality venues such as hotels, restaurants, and bars often have complex lighting needs. In a hotel, there are multiple spaces, from lobby to meeting and event rooms, hallways and guest rooms, all with unique lighting needs. For example, lobby lighting should create a warm and welcoming feeling for guests, with sufficient light for specific activities, such as at the check-in desk. Restaurants also want to create an inviting space for patrons and can use light to create atmosphere, whether bright light to evoke a fresh and natural feeling, or dimmer light to provide a sophisticated, romantic ambiance. But in any type of restaurant, color rendition of foods is paramount, ensuring customer meals look appealing. Decorative lighting can also be a part of the mix in hospitality spaces, for example to spotlight high ceilings or artwork.
- **Stage Lighting** – Lighting color in theatrical productions can be used to for emotional effect, to enhance the skin tones of actors, enliven the fabrics of costumes, or to change the appearance of the scenery to support on-stage action. Stage lighting designers use color mixing—adding or subtracting colors/wavelengths of light to alter its appearance. Traditionally this was done using “gels”—colored filters places at the front of stage light fixtures. Today, LEDs have added new options to the toolbox for stage lighting design.

- **Video Lighting** – Video and film recording presents a unique challenge. It must account for how objects, actors, and scenery are lit to be captured by a camera sensor, and then how that recorded footage will appear to human audiences. A standard called TCLI (television lighting consistency index) has been introduced for industry use. Like the CRI, TCLI scores how a light source renders a set of sample colors. Only instead of referencing human responses, TCLI uses software to calculate how the samples will be "seen" by a camera. [7]

2.2 Retail Lighting

Retailers have unique lighting and color rendition needs. In a retail setting such a grocery or clothing stores, lighting considerations often include not only color accuracy, but also enhancement. The goal is not necessarily "perfect" color rendition but creating an "exciting" visual appearance with vivid colors that draw consumers' attention and increase product appeal.

The optimal lighting is accurate (high fidelity) to present products with natural color, comfortable for shoppers to remain in the store for longer periods of time and that also makes colors "pop". Using LED lights to increase certain wavelengths of light (sometimes called "color pumping") can make objects appear more vibrant.

Textile manufacturers may even include optical brightening agents (OBAs) in fabrics that help the whites and colors appear more vivid. OBAs use the phenomenon of fluorescence, absorbing invisible near-ultraviolet (UV) wavelengths and re-emitting them as visible blue light. It is the emitted blue light that makes the fabrics appear brighter to our eyes. The replacement of florescent lighting (which has a significant UV output) with LEDs has resulted in LED products that deliberately have UV content to activate OBAs.

Many LED products intended for retail settings incorporate near-UV wavelengths to enhance the effect of OBAs. However, some customers have concerns about using near-UV light around humans (although the wavelengths used in these lighting applications is not the harmful UVB, UVC, or even the least hazardous UVA (315-400 nm)). It is most accurately categorized as "near-UV".

Figure 9 – An example of retail lighting that is bright and naturalistic.

3. Models for Color Rendition Accuracy

Various models exist to describe these various color rendition capabilities of light sources. Each measure attempts to accurately describe what the human eye will perceive. These models typically characterize one of three key aspects color rendition: “the accurate rendition of colors so that they appear as they would under familiar reference illuminants; rendition of objects such that they appear pleasant, vivid, or flattering; and the capability of an illuminant to allow an observer to distinguish between colors when viewed simultaneously. These dimensions of color rendition are respectively referred to as *color fidelity*, *color preference*, and *color discrimination*.” [8]

Lighting source developers and manufacturers use evaluation systems to rate light output. Designers, architects, and others use models to specify the desired lighting for a setting. All color rendition models are voluntary, with no prescribed standards for use. An early and still commonly used model is the CRI, developed by the CIE as a measure of color fidelity. The CRI standard was first introduced in 1965 and has been improved over the years, most recently in 1995. It is this version, the *CIE 13.3-1995 General Color Rendering Index* R_a (commonly referred to as the CRI), that is in use today.

Other models to measure color rendition include the gamut area index (GAI), which measures color saturation, and the ANSI/IES TM-30 which measures both fidelity and gamut. There are various rendition classification models; we will discuss several of the most common methods below.

3.1 Color Rendering Index Ra (CRI)

The CRI attempts to measure how accurately a light source can reveal color. The CRI gauges each lighting source based on the average of eight defined Test Color Samples (TCS), labeled in Figure 10. It compares the appearance of the samples under a real light source against how they would look under a reference illuminant* (an established standard light source).

This color match is rated on a scale with a maximum of 100, with 100 meaning there is no difference in color rendition of any of the TCS samples between the measured light source and the reference illuminant. Light sources with a CRI score of 50+ are considered usable for most general applications. Top-grade LEDs, such as those from Luminus, boast CRIs with minimums of 80, 90, and 95 CRI.

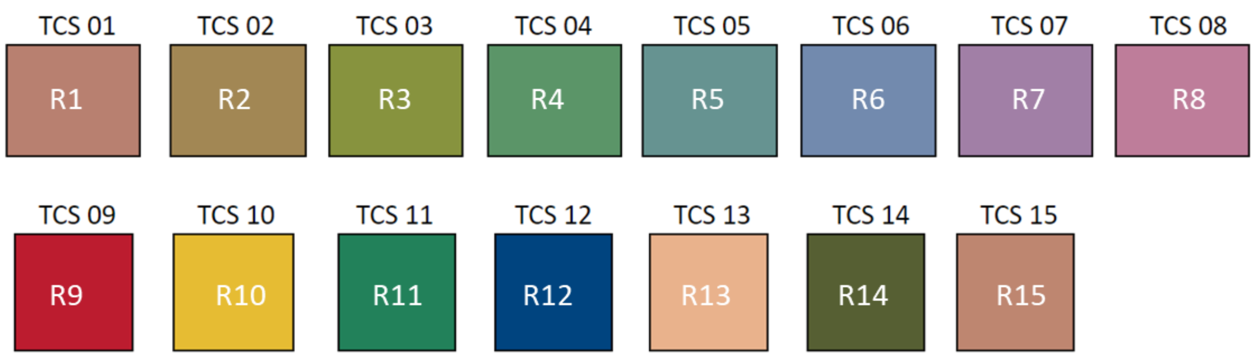

Figure 10 – The 15 Test Color Samples (TCS) samples. The eight indices used to calculate CRI R_a are labeled R1 to R8. The supplemental seven TCS samples are R9 to R15.

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* The reference illuminants, defined by standards committees, are full-spectrum SPDs that match the CCT of the artificial light source being measured. CCTs <5000K are compared to a Planckian black body and those >5000K are compared to the D-series, a mathematical representation of an ideal light source that resembles sunlight. In some color rendering models the black body SPD and the D-series SPD are blended in the CCT region between 4000K and 5000K. Reference illuminants are explained further in the Help Center article What is a Standard Illuminant (Reference Illuminant)?

Each result is expressed as an R_n value labeled R1 to R15. For example, R9 is a deep red—a critical reference color for many applications such as lighting in butcher shops, grocery stores, and medical settings. The CRI value of a light source is reported as the average value, R_a, of samples R1 – R8, which are the original eight TCS samples; the additional seven, R9 – R15 were added later.

While useful for some applications, there are many criticisms of using CRI for all color rendering determinations. Many have considered the eight CRI reference color samples to be limited, inaccurate, and too pastel to represent the vividness of the real world. Consequently, the seven additional reference colors were added, including the saturated red, R9. In addition, two skin tones and a vivid green make up the supplemental samples. However, only the original eight samples factor into CRI Ra calculations. Thus, with the additional reference colors, under sampling can still lead to inaccuracy.

With CRI, scoring also tends to be inconsistent between devices. We saw above (Section 1.2) that two metameric light sources with the same chromaticity coordinates can have very different SPDs. Similarly, two sources with the same CRI can render light differently because of the differences in their spectral power distribution (SPD). Gaps in the mathematical models and issues such as under sampling (with just eight CRI reference colors) mean that light sources with similar R_a values can nevertheless produce very different color rendering effects (Figure 10).

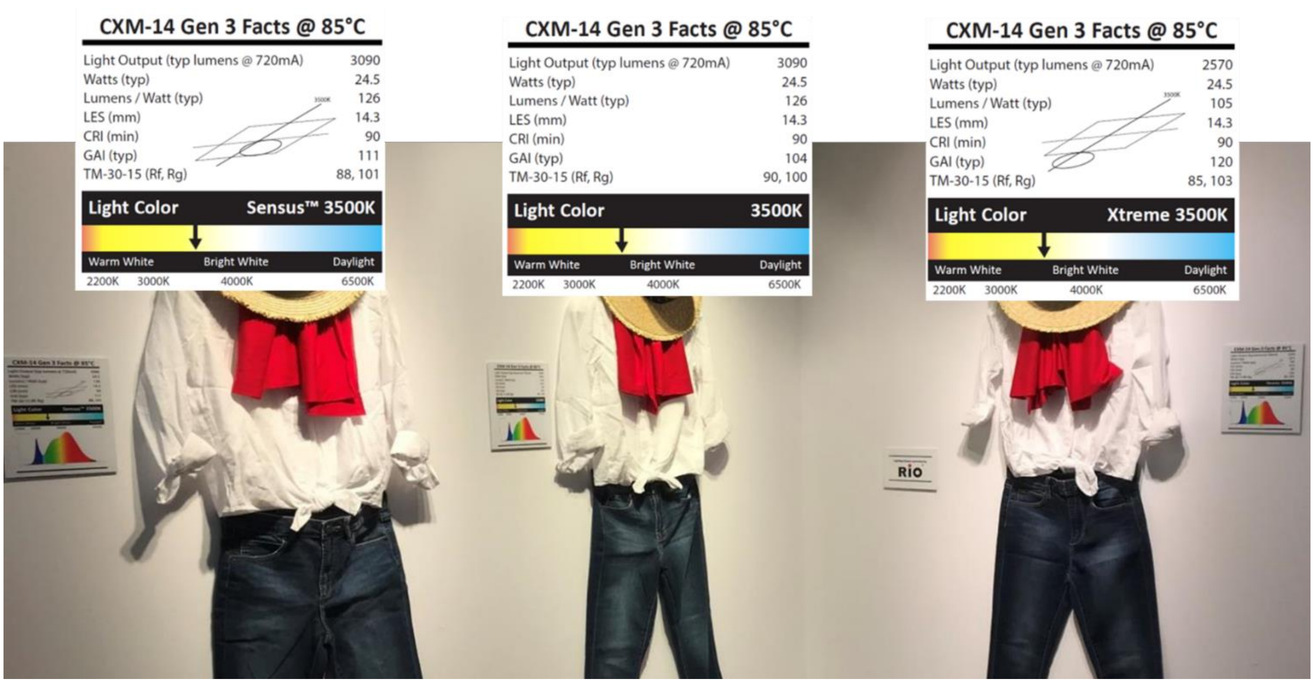

Figure 11 – Three LED bulbs with the same CCT (3500K) and an identical CRI (90) nevertheless render colors differently. The white shirt and the red scarf on the right and left appear visibly brighter; the shirt in the middle has a slightly yellow cast and the red scarf is a cooler tone (less orange, more blue).

Figure 11 demonstrates the differences between three LED sources. They have the same CCT value (3500K) and excellent (90+) CRI values, yet there is a visible difference to the human eye. All three are Luminus LED products, yet each is produced for a different use case.

Current research shows that the vibrancy of red tones is a determining factor in how humans perceive the quality of light sources. Thus, in many lighting applications such as retail environments, increasing the saturation of red wavelengths in a light is desirable. Yet the CRI, which is based on “outdated models of vision and color that underlie the calculation," [9] does not account for this perceptual preference. In fact, increasing the vibrancy of red in a light source is "penalized" in the CRI metric.

This issue—and the variation evidenced in Figure 11—both point to the need for more precise methods to quantify color rendition of light sources. In recent decades, new methods include the Gamut Area Index (GAI), Color Quality Scale (CQS), and TM-30, which are described in the following sections.

3.2 Gamut Area Index (GAI)

The CRI R_a metric was developed before the commercialization of LED lighting, and some experts do not consider it the most accurate method to characterize LEDs. A new metric, the Gamut Area Index (GAI) was developed in the early 1970s as a simple measure of hue saturation under an illumination source. GAI presents an alternative option for determining how a viewer will perceive color under LED lighting, which can be used in combination with CRI.

3.2.1 Understanding Gamut for Color Rendition

The term "gamut" is used with somewhat different definitions in the LED, architectural lighting, printing, and electronic display industries, which can lead to confusion. In the printing and display industries, gamut refers to the range (number of) of colors than can be created, for example by inks or by the color filters of liquid crystal displays. In architectural lighting, gamut may refer to the colors of light that can be created with a color-tunable fixture. In all of these cases, the number of colors created is less than all colors perceived by the human eye—the gamut is a subset of the CIE color space. For example, various display gamut areas are often shown overlaid on the CIE diagram for reference.

In the context of color rendition, however, gamut area is defined as "the area enclosed by a set of test color samples illuminated by a light source, in a two-dimensional chromaticity diagram or a plane of color space." [10] Within a defined color space, a "gamut" describes the subset of colors that can be perceived under specific lighting conditions. The TM-30 system uses Rg as a measure of gamut.

The gamut area characterizes color saturation (or chroma): the gamut of a light source designates the overall change in the chroma of object from how it appears under a reference light source. When the Rg value of a light source = 100, it means that, on average, the light source does not change the chroma of test samples when compared to their chroma under a reference light source. When Rg<100 it means that, on average, the light source renders colors as less saturated than the reference source, and Rg>100 means that, on average, the light source renders colors as more saturated than the reference source. We say "on average" because the light source's rendering of individual test samples may vary; Rg averages the overall chroma differences.

3.2.2 Color Rendition Gamut Area Index

The Gamut Area Index (GAI) is an early extension of this concept. The color coordinates of the reflection spectra of a set of TCS samples illuminated by the test light source define a gamut that is compared to a reference gamut and the result is called GAI_x where "x" defines the sample set and the type of reference source used.

A high GAI reveals greater color saturation and differentiation. GAI values can exceed 100 (a perfect match), but higher-valued colors may appear oversaturated. Architects, industrial designers, and theatrical designers tend to favor lighting with a GAI value between 85 and 100. Using light sources with a GAI greater than 100 can result in more vivid colors, a strategy employed in our Sensus product line (refer to Section 4.3).

The GAI definition has evolved over time. Originally GAI was a simple model using the equal energy* Illuminant E as a reference and eight color samples (GAI_{E8}). Since Illuminant E is constant and has a fixed gamut area which is then compared to all test sources the results are distorted as we move away from 5455K (the calculated CCT of Illuminant E).

Later GAI was refined to change the reference to a black body (BB) SPD matching the CCT of the light source and the same eight TCS samples as CRI R_a (GAI_{BB8}). The GAI has been further refined to use the same BB reference strategy but with 15 TCS samples (GAI_{BB15}). Each subsequent version of the GAI has been computationally more complex than the previous definition, but all are easily calculated using common software tools.

Plotting the gamut area encompassed by the reference black body along with the gamut area encompassed by the test light source reveals how accurately the two gamut areas match. Calculating the difference in area between the two gamuts provides an indication of saturation range (refer to the polygon outlines in the left image of Figure 12, which uses GAI_{BB8}.)

Luminus typically prefers the GAI_{BB15} measure, which we have found to be more accurate at characterizing the comparative color rendition capability of light sources with different color temperatures (different CCT). Refer to the polygon outlines in the right image of Figure 12, which uses GAI_{BB15}. Instead of a smooth "average" shape, individual point variations can be seen.)

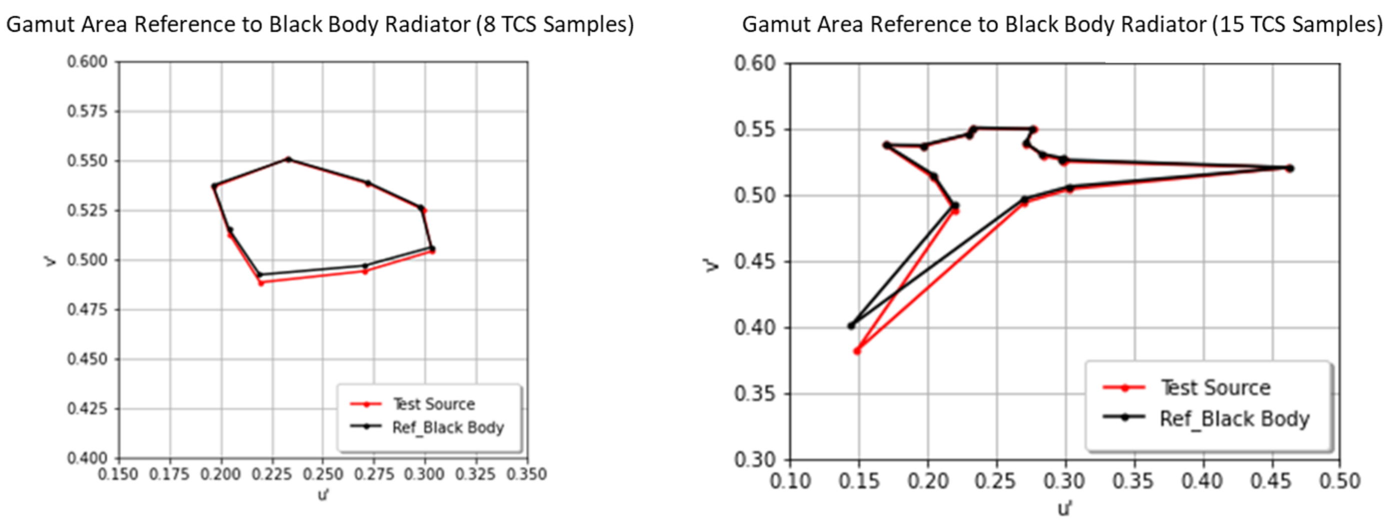

Figure 12 – Comparison of GAI_{BB8} (left) and GAI_{BB15} (right).

Experts suggest that GAI, by characterizing a light source's rendition of saturation/intensity, and CRI, by characterizing chromatic accuracy, complement each other. Used together they can provide a more complete method of evaluating a light source.[11] Lights with both high GAI and high CRI will offer perceived color quality (a subjective characteristic) in color rendition. Many psychophysical experiments have demonstrated the breakdown in the ability of Ra—or any measure of average color fidelity alone—to predict perceived color quality, which relies on attributes such as naturalness, vividness, preference, or acceptability.

* Equal energy Illuminant E has a constant value, usually 1.0 W/nm, at all wavelengths. It is a useful reference point in a number of colorimetric calculations. Illuminant E is not used in real room-lighting situations.

Color preference studies validate this approach. [12] For example, the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute (RPI) found that “when given a visual choice, people often prefer ‘white’ or minimally tinted sources that provide good color rendering.” [13] They proposed a new designation called "Class A" lighting to help simplify these technical concepts for consumers. Class A Color Lighting sources have chromaticity at or near the line of minimum tint (discussed in more detail below in Section 4.4), good color rendering (CRI>80 and 80<GAI<100), and consistent chromaticity.

3.3 Color Quality Scale (CQS)

Another alternative to CRI is the Color Quality Scale (CQS), developed by the National Institute of Standards and Technology (NIST). The CQS was developed to provide more accurate measurement of the color fidelity rendering capabilities of solid-state lighting sources. “Instead of only eight unsaturated, pastel colors, the CQS evaluates 15 colors that more accurately span the range of normal object colors across an expanded gamut. In addition, it considers factors including color discrimination and human preference.” [14]

The CQI samples are considered “high chroma,” meaning they have a high saturation of their hue (sometimes also characterized as high purity or high intensity), as shown in Figure 13. CQI values are calculated on a scale of 0-100, making them easily understood alongside the CRI.

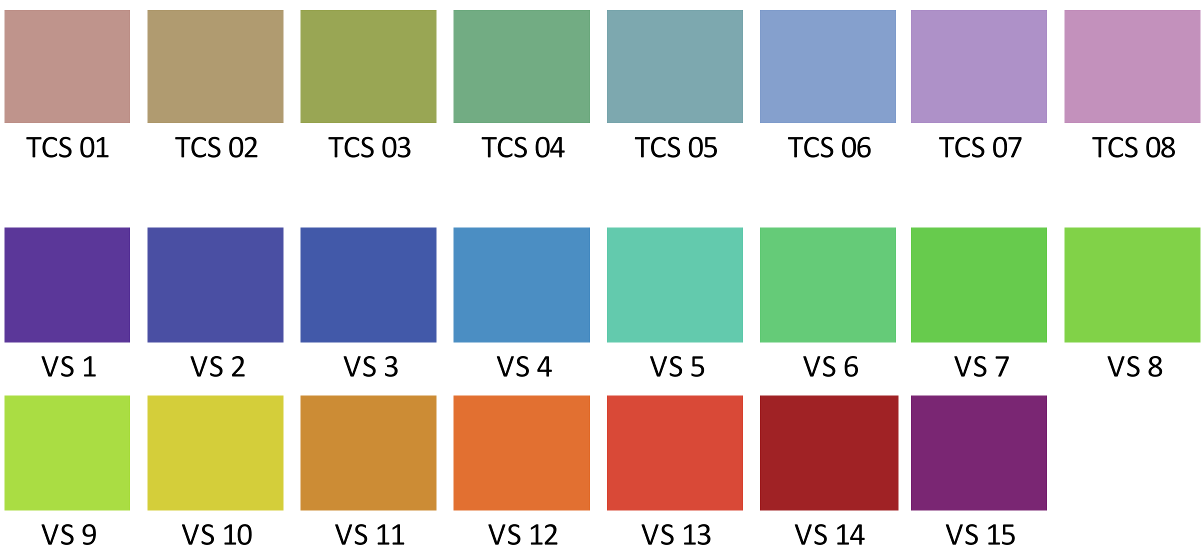

Figure 13 – The core CRI color samples (top) compared to the more saturated 15 CQS color samples (bottom) based on the Munsell color system (a three-dimensional representation of color by hue, chroma, and value).

3.4 ANSI/IES TM-30

Even with the CRI, GAI and CQS indices, many experts still found the measurement and characterization of light source color rendition to be insufficient. In 2014, the Color Metrics Task Force of the Illuminating Engineering Society (IES) developed a new method for characterizing light sources. This new system, called TM-30, provides a set of measures for describing color rendering capabilities that are closer to the range of colors humans perceive.

The new standard system was released in 2015 as ANSI/IES TM-30; the IES Method for Evaluating Light Source Color Rendition, Technical Memorandum 30-15 [15]. It established the TM-30 method for measuring light source color rendering capabilities and set out some standard formats for lighting manufacturers to report this information (Figure 15 and Figure 16). Subsequent updates and refinements have been released in 2018 as TM-30-18, and in 2020 as TM-30-20.

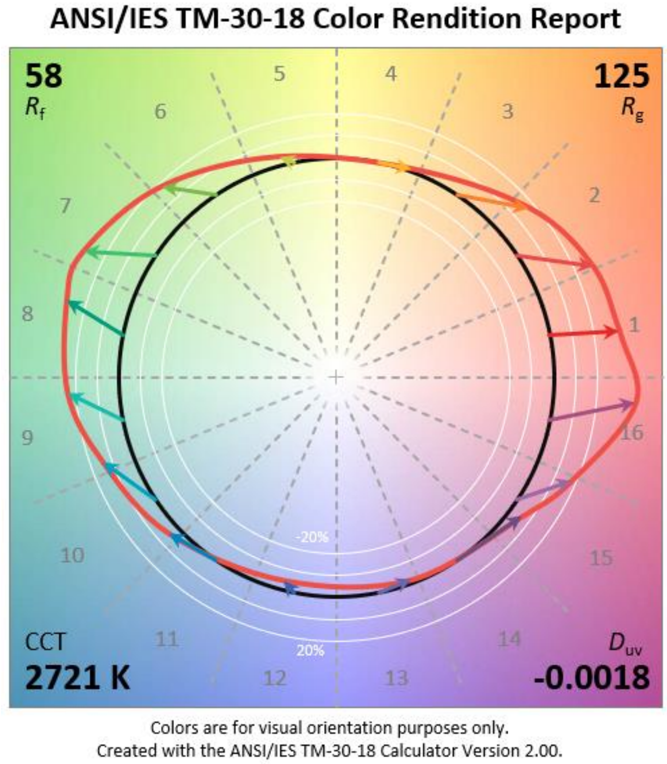

Figure 14 – Color vector graphic (sample 111 RGB). The black circle is the reference illuminant; the red circle charts the light source under test to compare to the reference source.

The TM-30 system represents the latest method for evaluating color rendering of LED light fixtures. A key differentiator for TM-30 is that it uses 99 color samples (CES) instead of the CRI base of 8 TCS. For ease of use, these CES samples are categorized into groups—called bins—and shown as a color vector graphic (Figure 14).

For a given LED fixture, its TM-30 scores can be reported numerically and represented graphically as a color vector graphic. The vector graphic shows one circle (black line), representing the reference sample colors, overlaid with a second circle (red line) representing the color rendition of those samples by the test light source. Variance of the red circle from the reference black circle indicates the color fidelity of the light source.

Light sources are scored based on two metrics, Fidelity (Rf, analogous to the CRI value) and Gamut (Rg, analogous to the GAI value). However, TM-30 uses the CAM02-UCS (a', b') color space rather than the 1931 (x, y) or 1976 (u', v') CIE color spaces. The rationale for this change in discussed in the standard.

Although it is sometimes mischaracterized as a two-measure system, TM-30 goes beyond reporting just these two average values, and also incorporates additional concepts such as gamut shape (defined as the average pattern of color shifts across different hues) and chroma shift. As a result, "the TM-30 Color Vector Graphic and Local Chroma Shift values capture information about color rendition that's impossible to describe with global average measures but is pertinent to more completely quantifying color rendition and understanding human evaluations of color quality in the built environment." [16]

For a full list of color characterization concepts incorporated into the TM-30 system, refer to **Appendix A.**

The TM-30 provides three approaches to analyzing color rendering:

- **R_f, color fidelity, or hue:** R_f gauges how similar or dissimilar a color is to the reference. For example, is something deep red or pink? Scores range from 0 to 100, with 100 indicating an exact match. R_f is a calculation that considers both chromaticity and saturation under the test source and reference illuminant, then determining the arithmetic mean of those color differences.

- **R_g, gamut, or saturation:** R_g describes how much color is there. The R_g scale ranges beyond 100, which indicates oversaturation. Scores below 100 indicate less saturation than the reference. R_g is a measure of the area spanned by the average coordinates of the CES in each hue-angle bin.

- **Color vector graphic:** TM-30 creates a graphical report that plots color averages for 16 hue bins and Rf and Rg scores for the 99 color samples.

Although TM-30 and CRI both use fidelity as an attribute, you cannot compare or swap TM-30 and CRI scores.

3.4.1 Understanding TM-30-15

The TM-30-15 report format (Figure 15) provides a range of information and metrics on a test light source. The report includes the Color Vector Graphic in the lower left. This first iteration of the TM-30 did not include hue angle bins (which were developed in 2018).

Color fidelity is represented by the V-shaped scatterplot on the right. This graph plots the average fidelity index (Rf) and gamut index (Rg) of multiple light sources with known color rendering performance, drawn from an IES “library”. It includes all types of light sources including incandescent, LED, halogen, and more. The red dot shows the test light source, demonstrating its fidelity relative to the landscape of artificial lighting.

The report shown in Figure 15 is for a Luminus LED product. It exhibits excellent color rendering performance, as demonstrated by the Color Vector Graphic, where the red circle almost completely matches the reference black circle, and the Fidelity Index (R_g vs R_f plot), where the red dot is located close to the peak of the V. By contrast, Figure 16 shows the TM-30-15 report for a sample light source with poor color rendition performance.

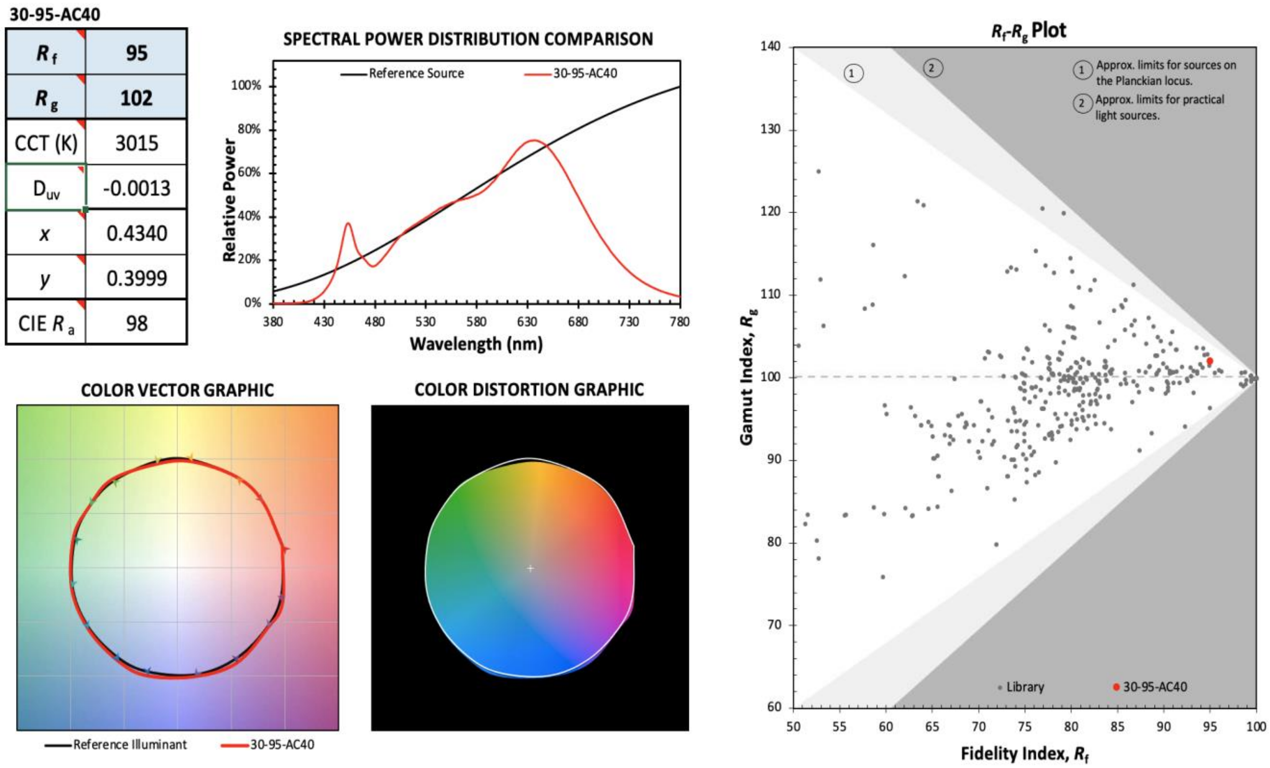

Figure 15 – Example of the TM-30-15 report format which includes the color vector graphic (lower left, prior to the creation of hue angle bins), along with the fidelity index and gamut index shown as a scatter plot and other light source performance metrics (shown here for Luminus Product 30-95-AC40).

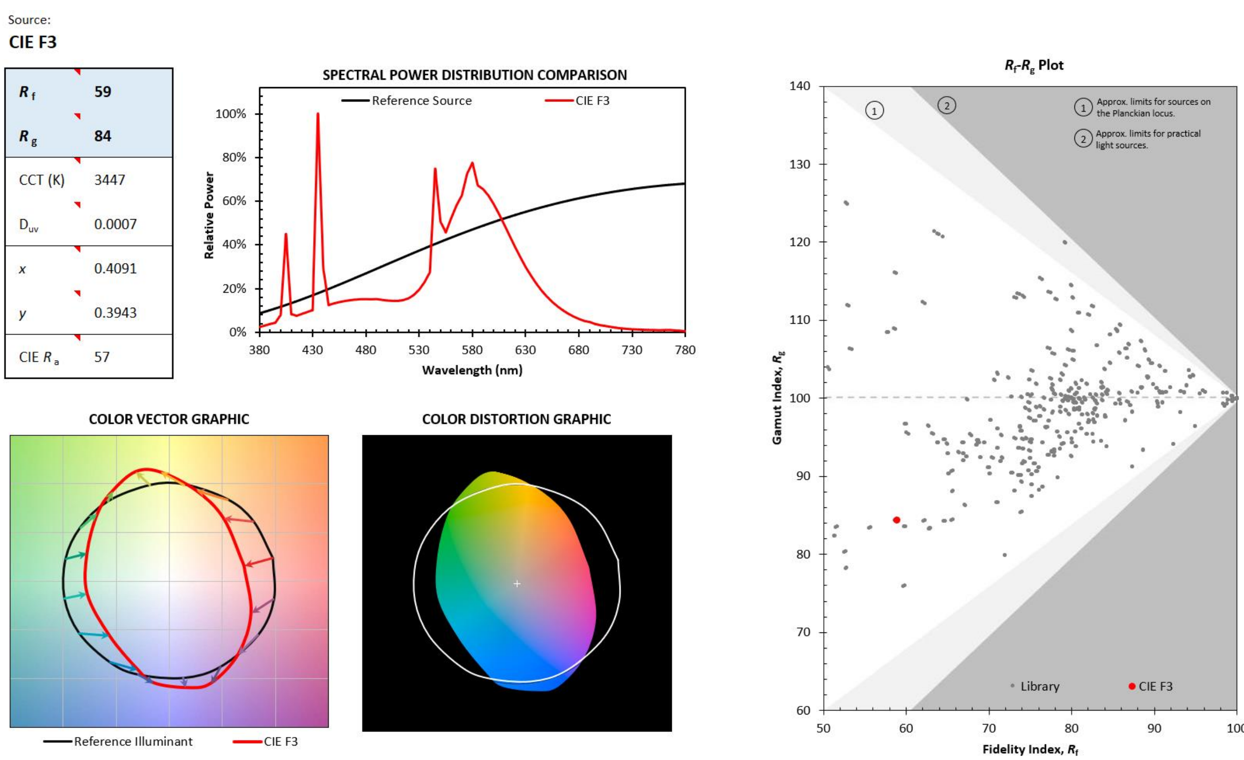

Figure 16 – Examples of a light source with poor color rendering. This example is from the TM-30-15 calculator example database.

3.4.2 Refinements in TM-30-18

In 2018, IES issued an update to the TM-30: TM-30-18, which expanded on TM-30-15 to offer more comprehensive evaluation on color quality of new light sources especially for the Solid-state Lighting (SSL) [17]. TM-30-18 is now widely accepted as the solid-state lighting color rendition standard and reporting format (Figure 17). The more recent TM-30-20 standard provides detailed guidance on the calculations to be used for objective characterization of light sources but retains the TM-30-18 report format.

In place of the V-shaped Fidelity Index chart in the TM-30-15 reports, TM-30-18 introduced Hue-Angle Bins (Figure 17). Notice that the circle image in the lower left shows 16 segments separated by dotted lines. Instead of just displaying data points for all 99 individual TM-30 samples around the perimeter of the circle, samples have been grouped together in "bins", and their average fidelity score is reported on the color vector graphic as R_f (in the upper left corner).

The TM-30 hue angle bins are shown as a histogram with the average fidelity (local color fidelity, R_f, h_j) score of each bin shown above each column (Figure 17, lower right). Additional histograms were also added:

- Local Hue Shift - the % of difference in hue (color) of the test source from the reference source for each bin
- Local Chroma Shift – the % of difference in chroma (saturation) of the test source from the reference source for each bin.

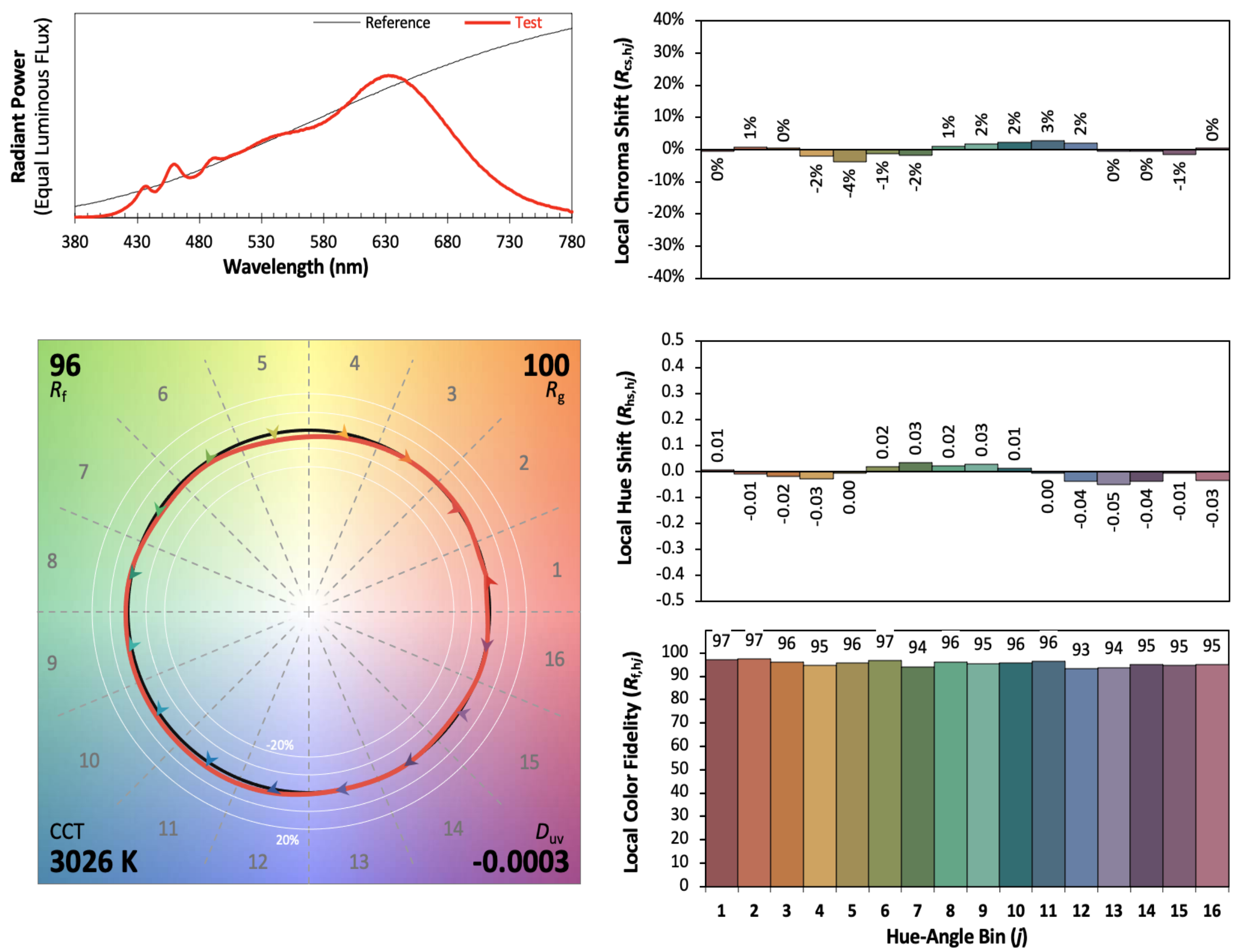

Figure 17 – TM-30-18 report. Shown: Luminus LED (30-95-AC40, 3000K) TM-30-18 report.

As the report in Figure 17 shows, high-CRI Luminus LEDs have extremely good color rendering. This will be discussed in more detail in Section 4. For comparison, Figure 18 shows examples both good (incandescent, right) and bad (fluorescent, left) results for the full TM-30-18 Report format for light sources near 3000K. These examples were created using the built-in calculator database example set. The appearance of 99 CES samples are compared for the test and the 99 reference sources in the bottom graphic. Differences are apparent for multiple samples illuminated by the CIE F4 spectrum. The Incandescent light source (right) is the definition for 100 CRI and therefore has excellent color fidelity.

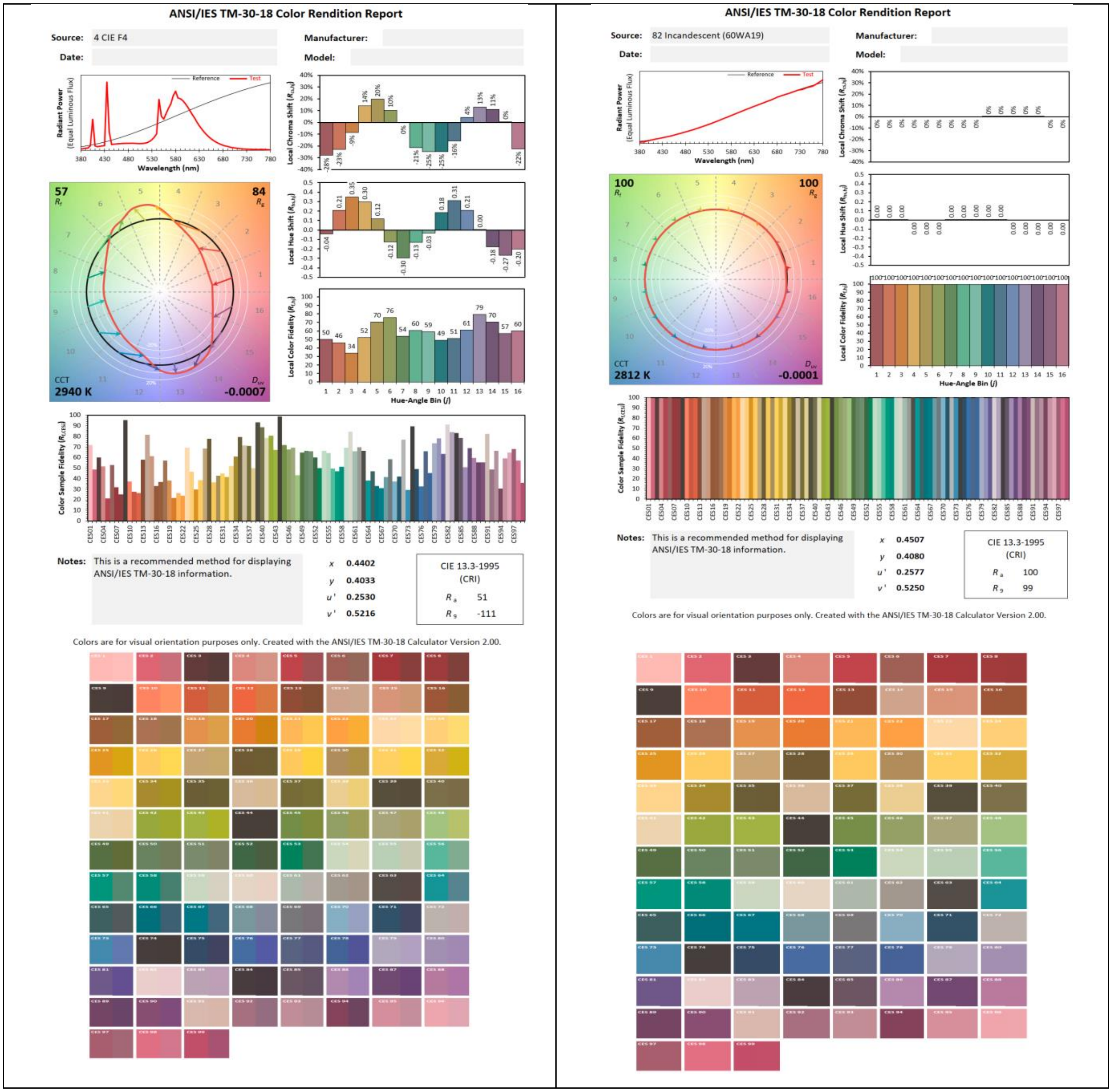

Figure 18 – Full TM-30-18 report format and color difference comparison of CES samples. The "bad" example is CIE F4, a standardized representation of a 2900K fluorescent light source. The "good" example is a 60-Watt incandescent light source (2800K) selected as a representative sample by the CIE.

3.4.3 TM-30-20 Guidance

TM-30-20 is the most recent version of this standard. It incorporates the TM-30-18 report format and calculator. When we reference TM-30-18 reports in this document, note that they conform to TM-30-20.

TM-30-20 introduced a new framework, called design "intents". When defining the requirements for any lighting application, TM-30-20 Annex E explains "a key element of setting color rendition criteria is deciding on the desired outcome, here called the ***intent***. Different intents may include promotion of:

- **Subjective qualities,** such as acceptability, naturalness, vividness, preference, or other aspects of aesthetics
- **Objective qualities,** such as color fidelity, gamut area, or any other specific measure in ANSI/IES TM-30-18
- **Task performance,** such as color discrimination, color matching, or object detection via color contrast."

To help lighting designers to balance these considerations, IES defined a new criteria framework with three intents as Preference, Vividness, and Fidelity, each of which can be ranked by priority for any specific application. This new framework is explained in sections added to the TM-30-20, Annex E and F, which provide useful guidance on how to interpret these metrics and apply them to different application intents. The design intents include:

- **Color Preference (P**): Intent to create a pleasing, natural-looking environment. Color Preference could be the dominant color rendition design intent in retail, office, hospitality, or residential lighting applications.
- **Color Vividness (V):** Intent to create a vibrant scene, regardless of whether that is natural-appearing or not. Color Vividness could be the dominant color rendition design intent in specific entertainment, display, or retail lighting applications.
- **Color Fidelity (F):** Intent to achieve similar color appearance, at equal illuminance levels, to the reference illuminant. Color Fidelity could be the dominant color rendition design intent in manufacturing, medical, color matching, or color reproduction lighting applications.

Each design intent includes three priority levels—Levels 1-3, with 1 being the highest or most restrictive—that indicate the stringency of the criteria. "Higher levels increase the likelihood of achieving the design intent while lower levels offer flexibility to account for other considerations, such as energy efficiency." [18]

The design intents provide a simple classification system (Table 1) to understand lighting source performance. The system is convenient shorthand to help users understand which lighting products align with their application needs. A two-character code combines the intent and the priority level, for example, a light source can be characterized as [P1 V- F1].

This means that for Preference (P) the light source meets specifications shown in the P1 box, for Vividness (V) the dash ("-") indicates that the light source does not address this intent, and for Fidelity (F), the F1 means the light source meets the specification of box F1. Therefore, this light source would be ideal for an application where human preference and fidelity (naturalness) are the priorities, such as in a home setting. As discussed above, a retail store, by contrast might place a higher priority on V to light merchandise to advantage.

Table 1 – Recommended Specification Criteria for design intent of Preference, Vividness and Fidelity (from Table E-2 in TM-30-20 Annex E). Note: all criteria assume a polychromatic environment with average horizontal illuminance between 200 and 700 lux and uniform chromaticity.

	Design Intent		
Priority Level (n)	**Preference (Pn)**	**Vividness (Vn)**	**Fidelity (Fn)**
1	Rf >=78 Rg >= 95 -1% <= Rcs,h1 <= 15%	Rg >= 118 Rcs,h1 >= 15%	Rf >= 95
2	Rf >=75 Rg >= 92 -1% <= Rcs,h1 <= 15%	Rg >= 110 Rcs,h1 >= 6%	Rf >= 90 Rf,h1 >= 90
3	Rf >=70 Rg >= 89 -12% <= Rcs,h1 <= 23%	Rg >= 100 Rcs,h1 >= 0%	Rf >= 85 Rf,h1 >= 85

This framework illustrates a nearly universal challenge faced by lighting designers and architects everywhere: every lighting choice has tradeoffs. Figure 19 illustrates this by overlapping the P, V, and F specifications to show how there is nowhere that the highest values of each intent coincide. For example, selecting the highest priority for vividness (the V1 box on the left) means sacrificing fidelity, as there is no overlap. If preference is the highest priority (P1 box), then high fidelity (F1) is also possible, but at the expense of vividness (V3).

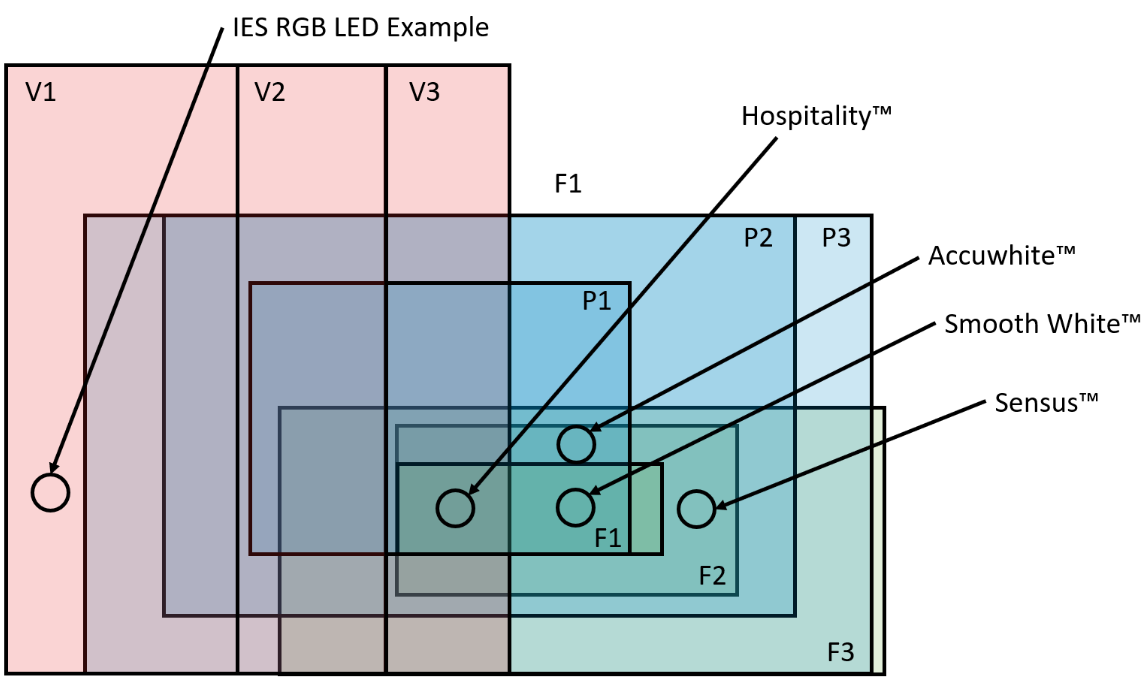

Figure 19 - Illustration of overlap between specifications. Overlapping areas represent possible combinations. The areas are not shown to scale (Figure E-1 from the TM-30-20 Annex E).

As a result of these Annex E changes, TM-30-20 reporting was changed only slightly from TM-30-18: the addition of the three optional attribute scores [P, V, F] was added.

The TM-30-20 Annex F mainly provides background and explanation for the development of the design intents, which were based on various studies [19] and as response to the rise of solid-state lighting sources. The TM-30-20 system is designed to have better orthogonality than previous systems. This and other improvements are discussed in Annex F.

3.4.4 Tradeoffs Between Energy Efficiency and Color Rendition

Among the tradeoffs sometimes required in lighting design, energy efficiency vs. color rendition performance is another one. It's an important topic for architects, lighting scheme designers, and building owners, as they try to provide optimal interior environments but at a reasonable cost. Color rendition is a factor in energy efficiency "because there is an intrinsic tradeoff between luminous efficacy of radiation and color rendition." [20] Typically, light sources with a higher CRI require more energy. TM-30-20 Annex F includes an examination of these tradeoffs.

Industry standards and various regulatory requirements have helped push the topic of color rendition to the forefront for architects and designers today. For example, the State of California instituted stringent standards for lighting in its Title 20 legislation which requires, among other things, that commercially available light fixtures meet a minimum CRI of 82. A summary of U.S and international regulations and standards (for example, Well Building Standards, IES, ANSI) is in **Appendix B.**

At the same time, the development of more multi-faceted color rendition models such as TM-30-18/20 is pointing the way towards new solutions. When criteria from TM-30-18 are used as a guide to improve color rendering (instead of using CRI/Ra/fidelity alone) there is less of an effect on the luminous efficacy of radiation (LER), i.e., color rendition can be improved without significant increase in energy use. [21] In fact, the US Department of Energy among other regulatory bodies has recognized the value of the TM-30 approach [22].

3.5 TM-30 vs. CRI

Although CRI is a familiar and long-standing color rendering metric, lighting experts have long noted its limitations. CRI was developed when incandescent and fluorescent light predominated, and concerns persist about CRI's ability to represent solid-state lighting. LEDs as a lighting technology did not start to become mainstream until roughly 2012. With today's high-quality LEDs a difference of just 4-5 points in the CRI (e.g., 80 CRI vs 85) is very noticeable.

CRI also represents only color fidelity, not the more subjective quality of perception—how well it looks to the human eye. CRI, therefore, can be particularly problematic for LEDs. LEDs can produce light that produces a poor CRI score, but that looks good to humans. In a Rensselaer Polytechnic study, participants were asked to rate fruit under different lighting sources. Participants found LED lighting vivid and the incandescent natural. The incandescent had a CRI rating of 100, the LED only 40 [23]. CRI combined with R9 has become a commonly used metric. While this is better than just CRI, the TM-30 system has much more detail than this simple approach.

IES asserts that the TM-30 scoring system is both more accurate due to its use of 99 samples, and more relevant for LEDs: "IES R_f uses a modern color space (CAM02-UCS)—with improved uniformity and a more accurate chromatic adaptation transformation—and an optimized set of color samples representative of real-world objects, making it especially relevant when average color fidelity is an important consideration". The IES recommends that lighting professionals transition to IES R_f and acknowledges the usefulness of publishing CIE R_a values alongside R_f [24].

4. Luminus Solutions for Accurate Color Rendering

Luminus LED products score well on both CRI and TM-30 rendering scales offering architects and designers multiple options for accurate color rendering for different settings. These solutions include the AccuWhite™, Sensus™, PerfectWhite™, Hospitality, CCT-tunable, and Salud™ LED families, along with many other LEDs in the Luminus product portfolio; color rendering data is available for all of our LEDs.

4.1 Standard LEDs (AccuWhite™)

The Luminus Standard LEDs (also sometimes called AccuWhite LED series) is one of the highest-fidelity color rendering products we offer, with consistent R_a = 97 CRI and a minimum of score of 93 across all hue angle bins. Referring to the TM-30-18 report (Figure 20), AccuWhite 3000K LED scores R_f of 96 and R_g of 100. Rich red tones are assured through R9 values above a 90+ score, The product is available with standard warm white (2700K and 3000K CCT), and Candle Warm options (2200K and 1800K CCT). Refer to **Appendix C** (Table 4 and Table 5) for complete color rendition data for these LEDs.

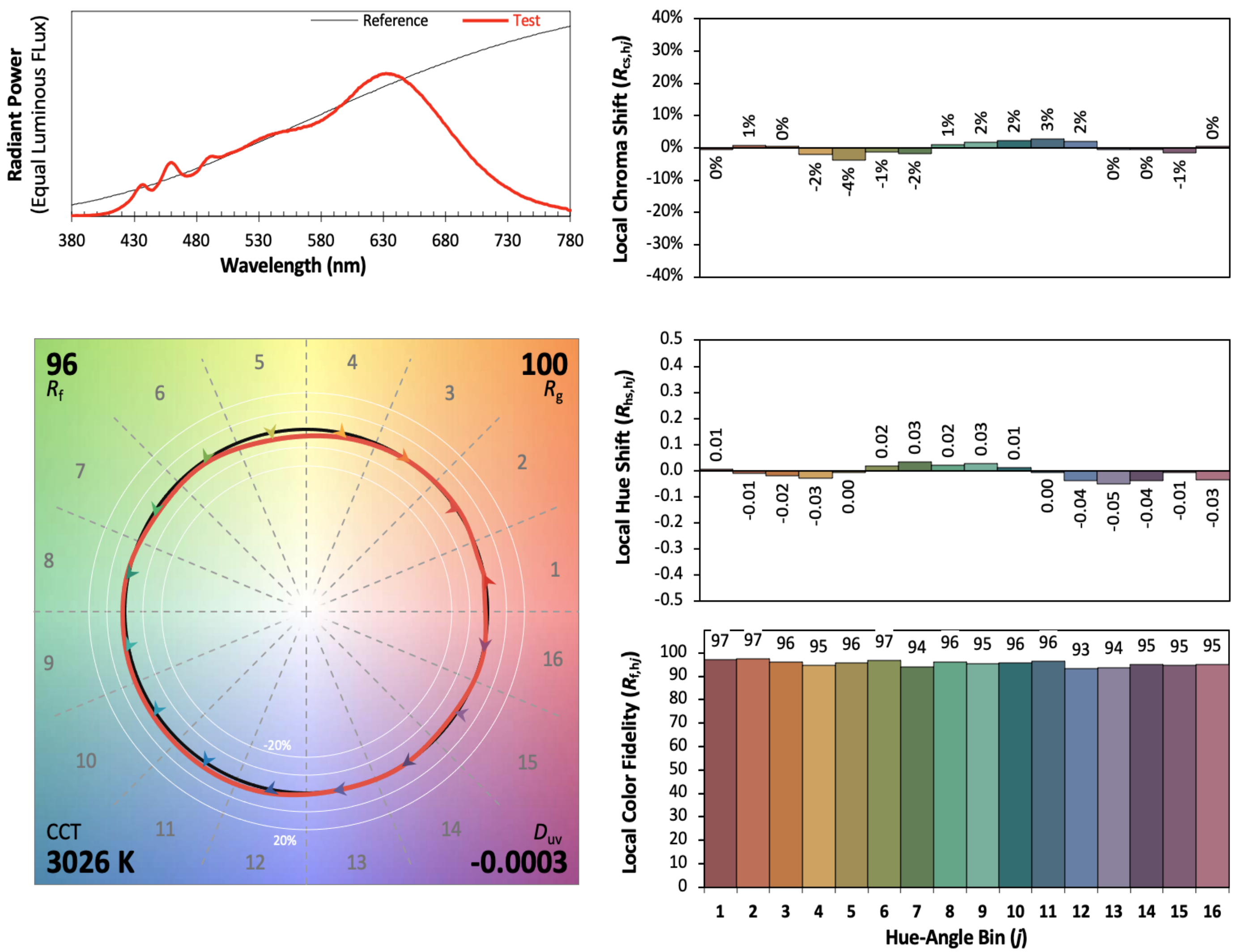

Figure 20 - Color rendering accuracy of Luminus AccuWhite 3000K LED (30-95-AC40) shown in TM-30-18 report format. TM-30-20 intent ratings for this product are [P1, V-, F1].

4.2 Color Mix Tunable LEDs

Tunable LEDs are a recent development in the industry. They are LED bulbs that can be adjusted by the user to vary the amount and characteristics of light emitted. Luminus provides a line of tunable Color Mix LEDs (the CDM Series) that can be adjusted across a range of SPDs to provide either cool white or warm white lighting (Figure 21).

Tunable LEDs offer greater flexibility and occupant satisfaction; researchers are studying their effects on well-being, alertness, and mood. [25] For example, Pacific Northwest National Laboratory conducted an experiment using color-tunable lighting in a nursing home. The facility was filled with bright blue-white light in the mornings then adjusted to warmer light in the afternoon. The lighting become progressively more amber and less intense into the evening hours, and finally reaching its lowest intensity just before bedtime. The result was that residents experienced improved sleep quality, slept longer, and showed reduced "agitation" in their behavior. [26]

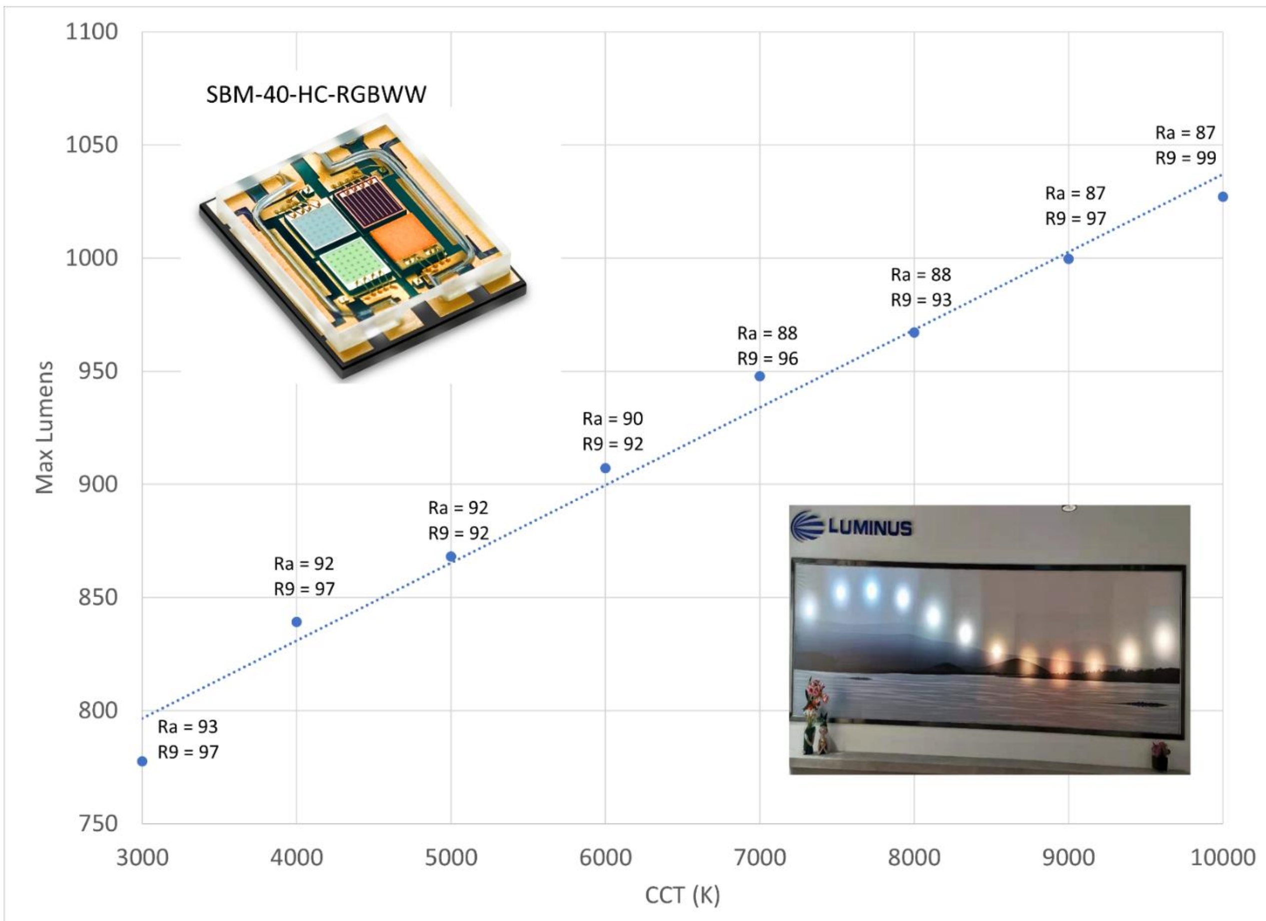

Figure 21 – The Luminus line of SBM-40 LEDs is offered in both RGB-cool white and RGB-warm white versions, what's notable about the WW version is the consistently excellent color rendition (high CRI values, Ra) across a wide range of CCTs—from Ra = 93 at 3000K to Ra=87 at 10,000K

We also provide CCT Tunable COB (chip on board) modules with two independent channels (warm and cool) to assist luminaire makers with designing human-centric lighting applications. While human comfort is a key objective of tunable LEDs, these products should also provide good color rendering. For example, Luminus CCT Tunable Modules offer CRI of 95 with both channels powered on.

These LEDs (the CTM series) are available in a wide range of sizes and CCT ranges, all of which have high quality of light with 90 CRI minimum. The 4000K to 1800K CCT range is ideal for applications such as residential and hospitality where warmer CCTs are preferred, while the 6500K to 2700K range is popular in commercial applications. There is also a 5000K to 2200K CCT range leveraging Salud technology in the 5000K channel for high melanopic ratios for healthy daytime lighting, up to 0.95, while the 2200K channel provides relaxing warm light with a melanopic ratio of 0.33. Since Salud technology brings a unique combination of high melanopic ratios, high CRI (90+) and high R9 (~85), the quality of light of these particular CTMs is quite remarkable.

All of these tunable products enable full control of each channel independently, so the user can control the intensity and CCT of the light using a two-channel driver and a user interface such as dual dimmers or an integrated controller, such as the Cuvee Systems two channel driver and dimmer switch, which is available from Luminus. Luminus also offers dim-to-warm technology where an on-board IC automatically shifts the light output from cool CCTs to warm CCTs as the light source is dimmed. This enables a very simple system using a standard LED driver and dimmer switch.

The warm-dimming CDM-series products also come in a range of sizes, CCT options, and dimming curve options where the dimming can look similar to a halogen bulb with 95 CRI minimum and a steep drop from 3000K to 1800K at low dim levels. Alternatively, it can be a more gradual CCT shift over the entire dimming range, so the effect is a "linear" warming effect.

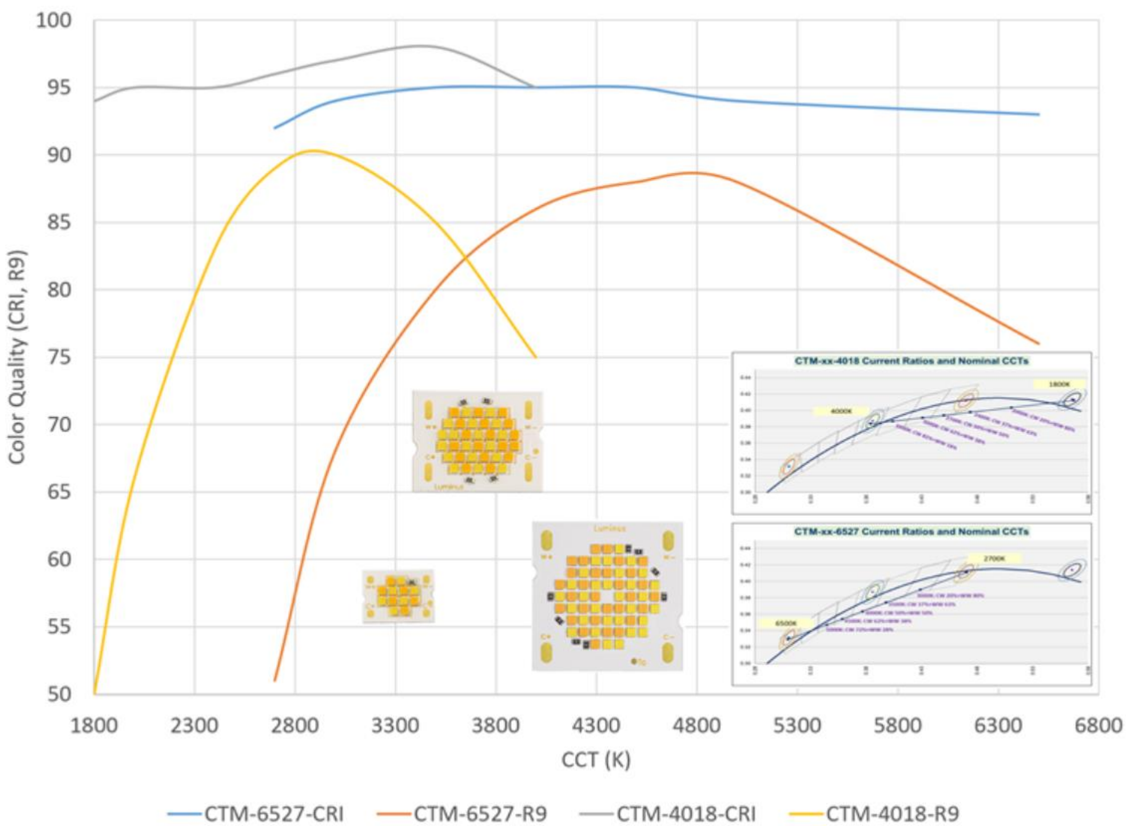

Figure 22 – The Luminus CTM (CCT tunable modules CTM-4018, CTM-6527) together offer very high CRI performance (92+) across a full range of CCTs (the gray line and blue line in the graph). The CTM series LEDs provide light to emphasize the red spectrum, which means the LEDs are well suited to applications where R9 is important.

4.3 Sensus™ for Superior Retail Lighting

Luminus Sensus LEDs provide consistent bright whites and pure colors, with 90+ CRI, R_f of 93 and R_g of 102 at 3000K (Figure 23). Unlike most LEDs intended for retail lighting, Sensus and Xtreme Sensus LEDs from Luminus are designed to provide bright vivid whites and colors without using any near-UV wavelengths to excite brightening agents. Instead, we reference the latest research about human color preference and visual perception of “pure white” light.

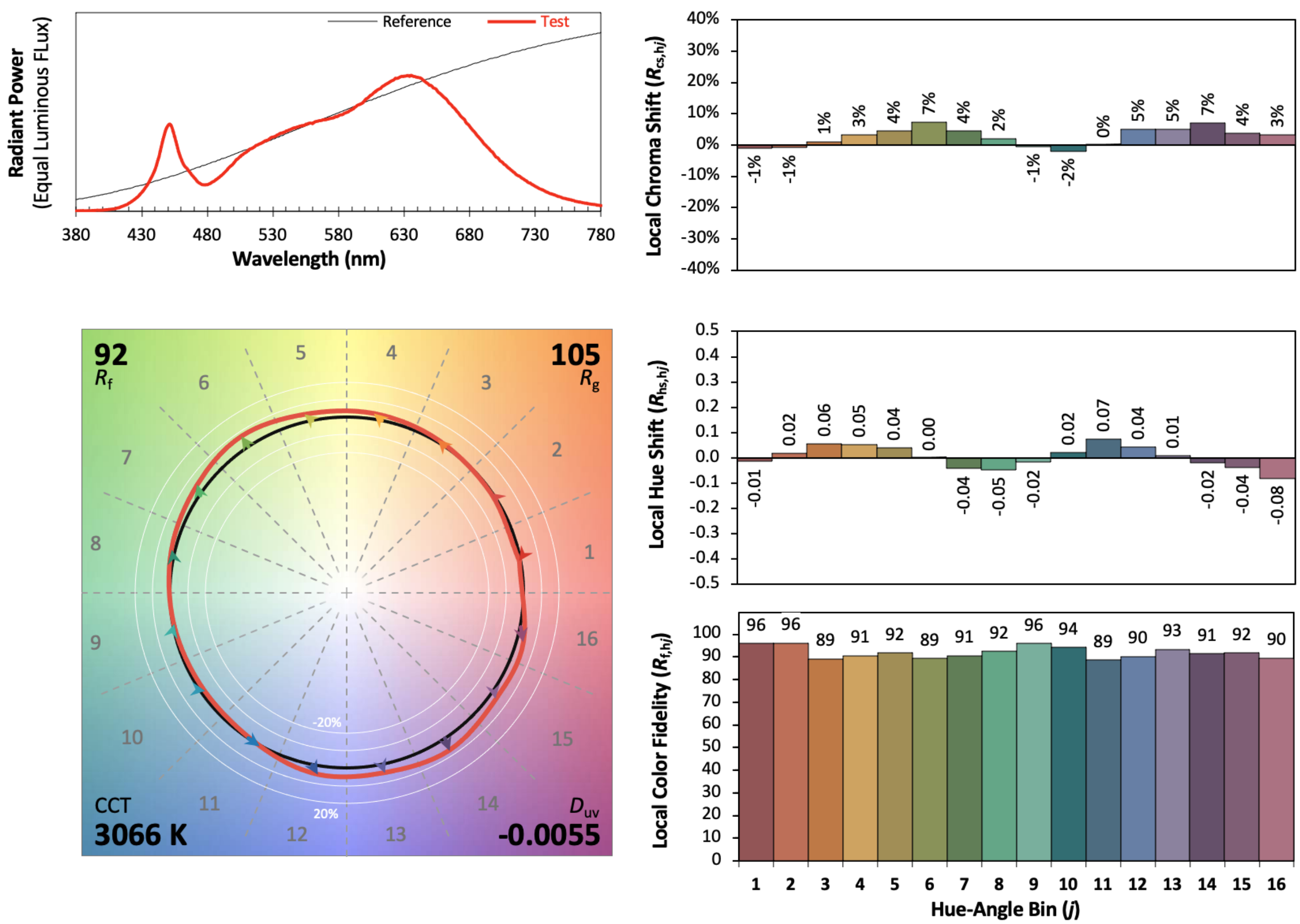

Figure 23 – Sensus 3000K (30-95-AC42) LED color rendering performance, in TM-30-18 report format. TM-30-20 Intent ratings for this product are [P1, V-, F2].*

4.4 Color Preference and Human Perception

An additional concept that factors into considerations of what is “good” color rendering is color preference: the human subjective response to qualities of light. As mentioned above (Section 3.2.2), the LRC conducted a series of studies to understand how observers perceive white light sources and what they prefer in terms of object color rendering and the hue or tint of a light source.

Researchers found that humans consistently preferred minimally tinted white illumination sources that they perceived as pure white. For light sources with CCT>4000K, preferred lighting chromaticity lies above the blackbody locus. For light sources with CCT<4000K, human preference is associated

* The Sensus component shown here is designed to enhance vividness but has a V- score. This is because the saturation increase is rotated slightly towards the blue hue bins and the Rcs,h1 value is slightly below zero.

with chromaticity below the blackbody locus. Represented graphically (Figure 24) this group of light sources preferred by human observers is sometimes referred to as a "line of minimum tint."

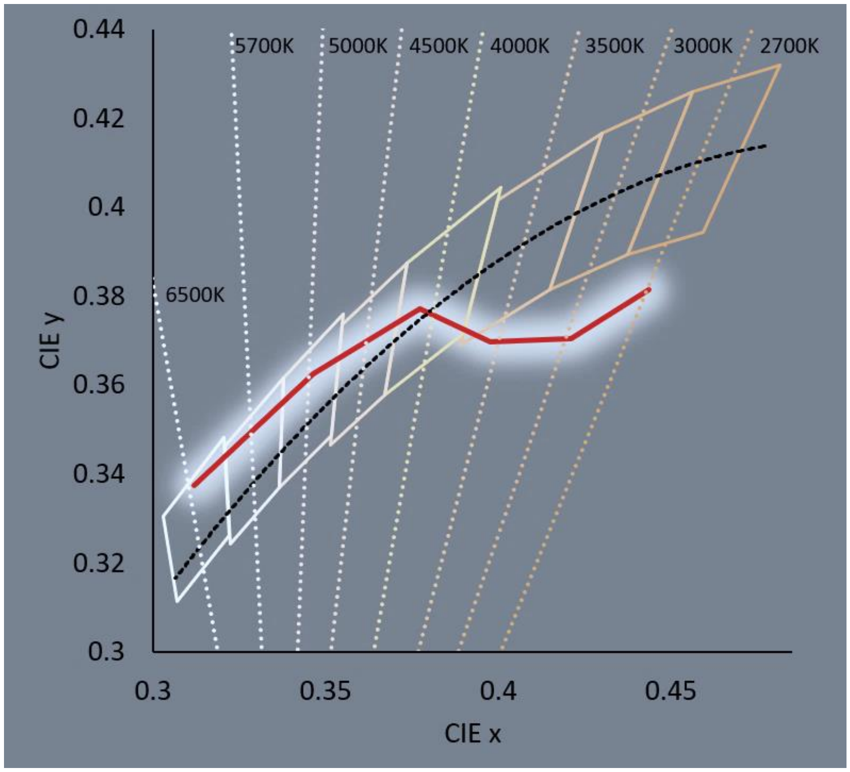

Figure 24 – ANSI 7-Step Quadrangles and the blackbody locus compared to the red line which charts the light sources that humans perceive as pure white light, also called the line of minimum tint. At cooler CCT values (>4000K) where light appears more "blue" to our eyes, the pure white perception line lies slightly above the black body curve. At 4000K the perception line crosses below the BBC. In this warmer CCT region (values <4000K) light on the curve appears more "yellowish" to our eyes, thus perception of a pure white light is further away from the curve.

Two primary considerations emerged from research studies: the "vividness" and the "naturalness" of object colors. But no single rendition metric encompasses both. As a result, LRC recommended combining GAI and CRI to achieve high satisfaction of observers. Light sources that score high on both GAI and CRI are called Class A sources. [27] These Class A sources are also the same that lie on or near the line of minimum tint.

The Luminus Sensus LED line is designed based on these white light preferences as applied in retail environments. Figure 25 shows how Sensus LEDs provide bright (CCT<4000K) light with chromaticity that lies below the blackbody curve. Xtreme Sensus LEDs provide chromaticity that lies right on the line of minimum tint, which creates bright, pure whites and rich saturated color in textiles without the need for UV wavelengths in the light source to stimulate fluorescent brighteners.

By optimizing LED design based on the latest science of human perception and preference, Sensus products are also more efficient (higher lumens per watt) than other types of retail bulbs that use near-UV light. Refer to **Appendix C** (Tables 6-9), for complete color rendition data for Sensus LEDs.

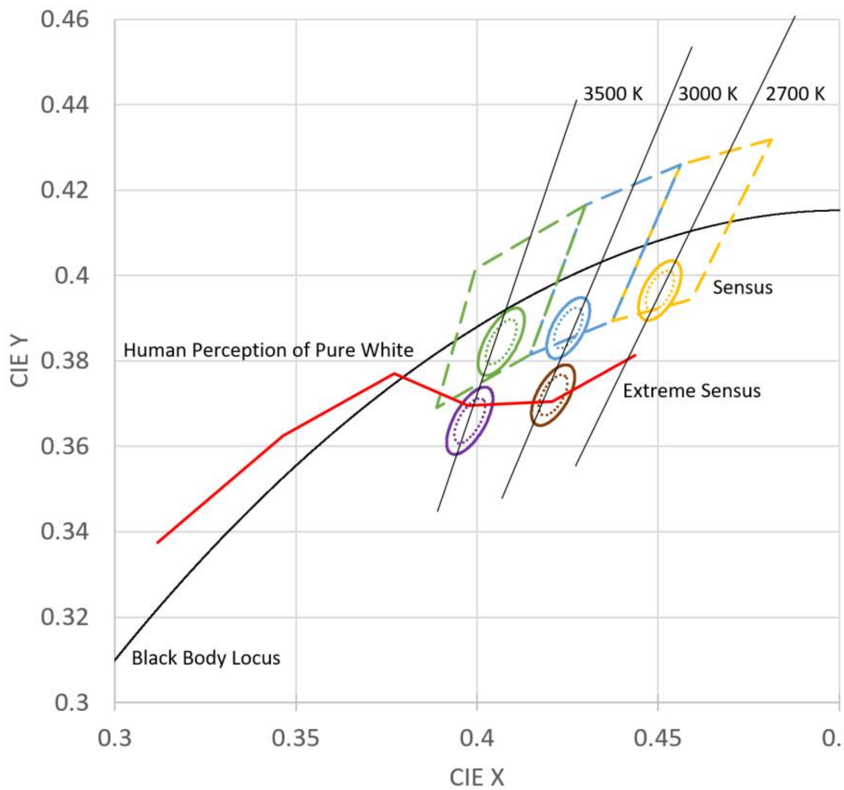

Figure 25 – The red line marks human visual perception of a pure white light. This figure plots Luminus Sensus products, which lie close to the pure white line, and Xtreme Sensus products, which lie right on the line providing light that renders colors accurately and with maximum appeal.

Figure 26 – typical warm LED (left) compared to the vivid illumination of Sensus LED (right).

4.5 PerfectWhite™ LEDs

Luminus PerfectWhite LEDs deliver near-perfect color rendering (Figure 27, Figure 28). Ideal for specialty retail, luxury hospitality, museum, and art gallery applications, PerfectWhite bulbs provide an average (Ra) of 93 across the 15 CRI samples, and TM-30 scores of R_f = 92, R_g = 100. Refer to **Appendix C** (Table 14) for complete color rendition data for PerfectWhite LEDs.

Perfect White	Ra	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
	94	94	94	96	96	93	90	95	97	96	88	95	82	93	99	95

TM-30-15 R_f	TM-30-15 R_g	TM-30-18 R_f	TM-30-18 R_g
92	100	93	100

Figure 27 – A PerfectWhite LED provides excellent color rendering according to all the measurement methods including CRI (top table), and TM-30. Revision to the Rf calculation in TM-30-18 resulted in a slight change in the Rf values for this product (lower table) from Rf = 92 to Rf = 93.

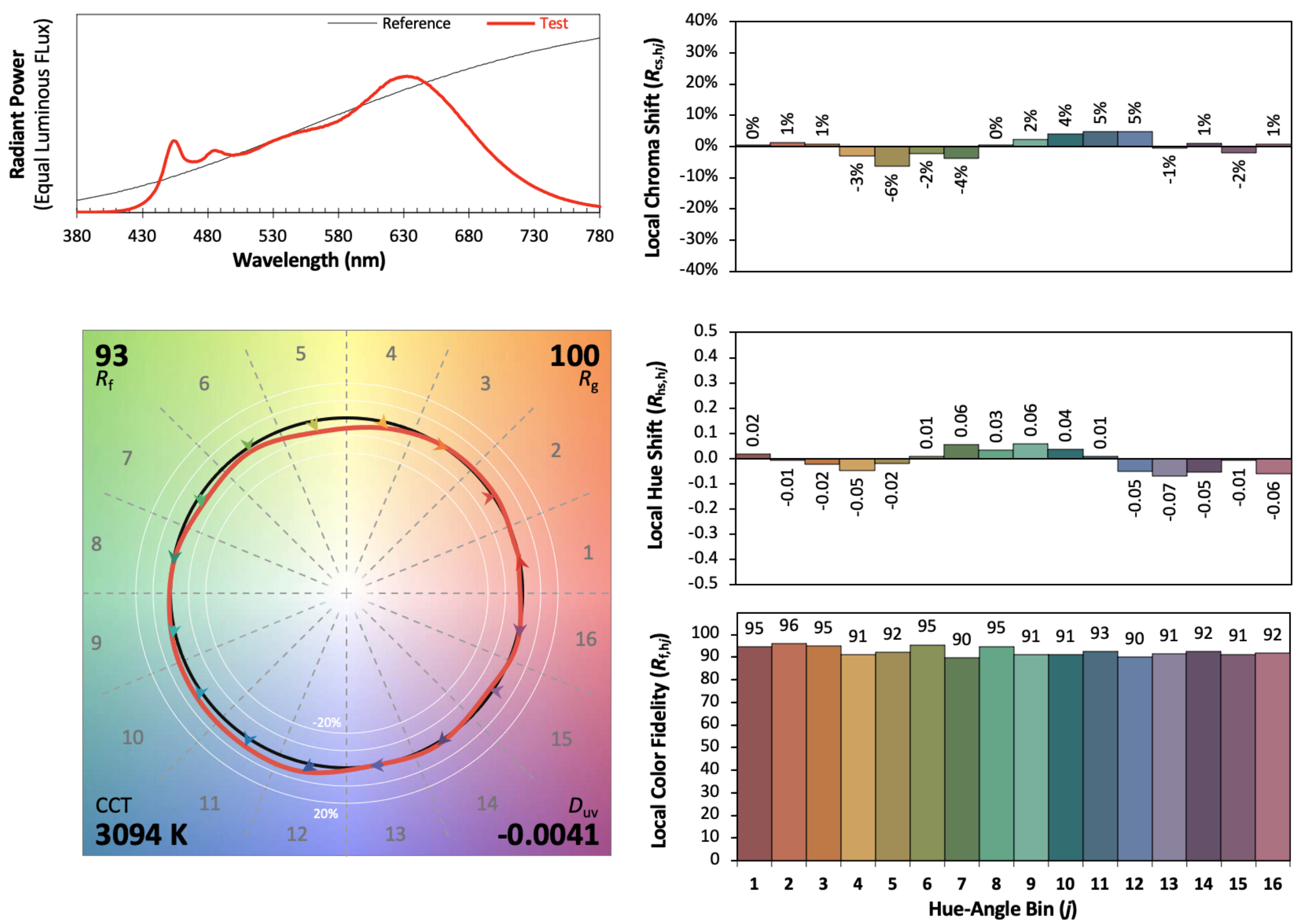

Figure 28 – PerfectWhite 3000K (30-90-AC32) demonstrates superior LED color rendering performance with intent ratings of [P2, V-, F1].

4.6 Salud™ LEDs

A recent addition to the Luminus product portfolio is the Salud line of LEDs. Designed to achieve human=centric (circadian) lighting design objectives, Salud also provides the benefit of exceptional color rendering accuracy. They achieve CRI Ra 90+ with high R9 reds (Figure 29). Refer to **Appendix C** (Table 15) for complete color rendition data for Salud LEDs.

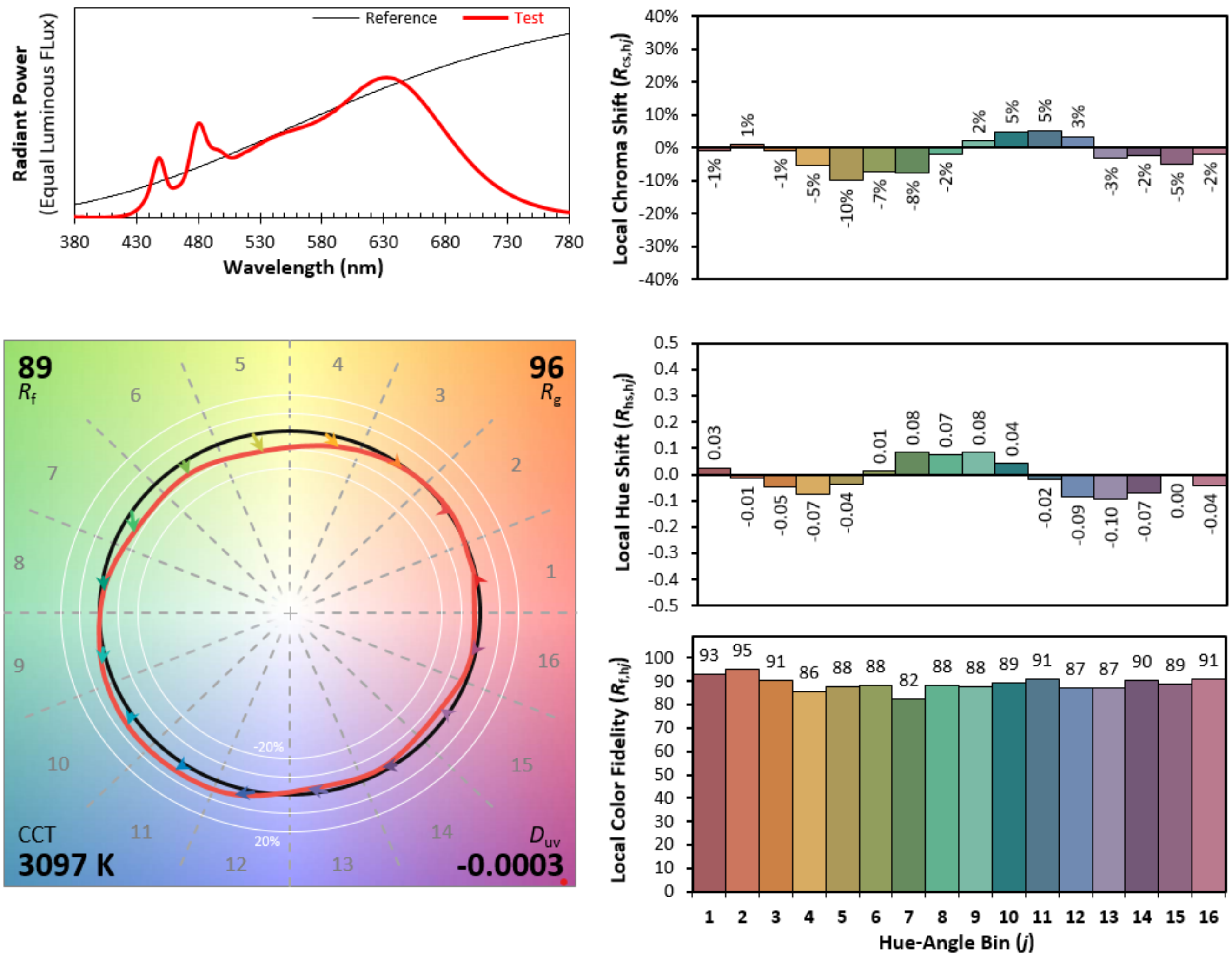

Figure 29 – As shown in this TM-30-18 report for Luminus 3000K Salud LED, color fidelity is high (Rf = 89), while also supporting the objectives of human-centric lighting.

4.7 Hospitality COB Series™ LEDs

Luminus provides multiple LED products that are used by hospitality lighting designers, including our Hospitality COB Series (Figure 30). These LEDs provide a warm, welcoming glow with pure whitening for high-fidelity color rendering (CRI of 90 and above), ideal for hotels, restaurants, and other hospitality venues. Refer to **Appendix C** (Table 10) for complete color rendition data for Luminus Hospitality COB Series LEDs.

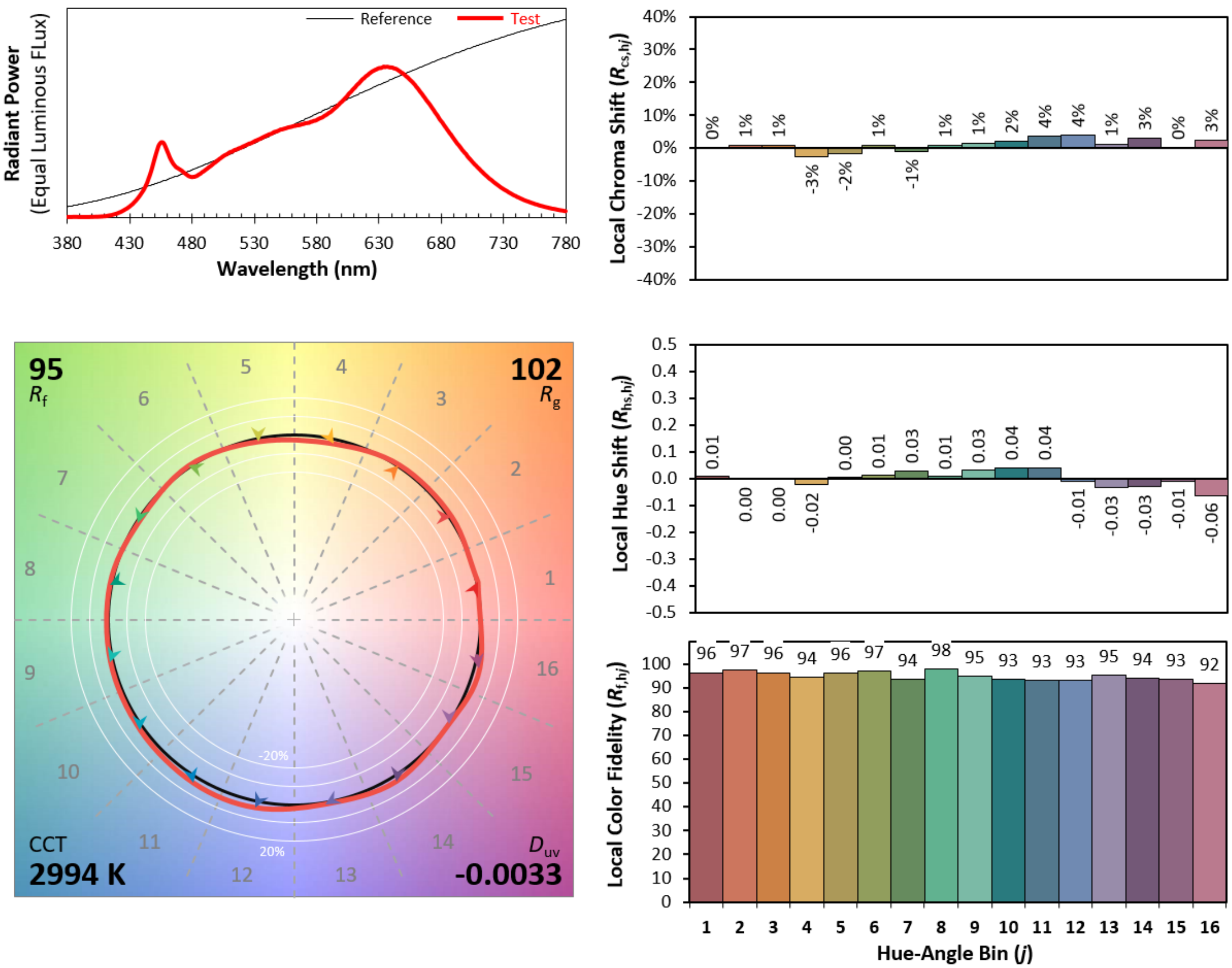

Figure 30 – The TM-30-18 report for Luminus COB Hospitality Series LEDs (30-95-TC41), demonstrating excellent color rendition performance with close match of the circles in the color vector graphic and average of Hue-Angle bins show color fidelity (R_f) of 95 [P1, V3, F1].

With the wide range of LEDs in the Luminus product portfolio, we can meet the lighting and color rendition needs of most customers. Additionally, tailored lighting solutions can be developed to meet unique specifications.

5. Conclusion

The color rendition performance of artificial light sources such as LEDs determines how well humans can perceive the world indoors and at night. Light sources with good color rendition are said to have high *fidelity*—they render people, objects, and environments accurately to our eyes.

For some lighting applications, fidelity is the most important quality of a lighting scheme. For other applications, considerations such as saturation, hue, or efficiency may also be important. By understanding and applying the various models of color rendition, we can determine which light sources create the optimal viewing conditions for different applications—from retail stores to food processing plants, living rooms to hospital operating rooms.

While each of the various mathematical color rendition models offer valid means of evaluating characteristics of LEDs and artificial lighting sources, combining several of the methods—such as CRI plus TM-30—can provide the most complete reference point for architects and lighting designers.

With their consistently high performance across all measures of color rendition and efficacy, Luminus LEDs offer a solution for virtually any color-sensitive lighting application. Learn more about each of these LED products and their color rendition capabilities by visiting our website: Luminus.com.

6. Resources

For additional information on color rendition concepts and applications, or about Luminus LED products, we recommend the following resources:

Luminus Application Notes: luminus.com/resource/application-notes.

Luminus Help Center articles on relevant topics such as CCT, SPDs, Reference Illuminants, TM-30-20 Intent, and more: Luminus Help Center

Datasheets with detailed specifications can be found on the Product pages of the Luminus website: www.luminus.com

Additional Resources

CIE guide to International Lighting Vocabulary: https://cie.co.at/eilvterm/17-22-107

The latest ANSI/IES TM-30-20 standards: https://store.ies.org/product/tm-30-20-ies-method-for-evaluating-light-source-color-rendition/

7. Contact Customer Support

For assistance with your color rendition questions, please contact: techsupport@luminus.com.

8. References

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Appendix A: Measures and Graphics Included in ANSI/IES TM-30-18 Reports

Table 2 – Summary of Measures and Graphics included in ANSI/IES TM-30-18.

Measure	What it Characterizes	Interpretation	Possible Values	Typical Values
Fidelity Index Rf	Average similarity for all colors	Values closer to 100 indicate greater similarity to the reference	1 to 100	70 to 100
Gamut Index	Approximation of the average change in chroma for color	Values above 100 increase in chroma; values below 100 decrease in chroma	0 to 150	80 to 100
Color Vector Graphic	Visual representation of hue and chroma changes for all colors (i.e., gamut shape)	Radial arrows for chroma shift, tangential arrows for hue shift	NA	NA
Local Chroma Shift	Average relative change in chroma for colors within 1 of 16 hue angle bins (j)	Values above 0% for increased chroma, values below 0% for decreased chroma	Approx. -100% to 100% (varies by hue)	Approx. -20% to 20% (varies by hue)
Local Hue Shift	Average change in hue angle (in radians) for colors within 1 of 16 hue angle bins (j)	Positive values for counterclockwise shift (e.g., red to orange), negative values for clockwise shift	Approx. -1 to 1 (varies by hue)	Approx. -0.2 to 0.2 (varies by hue)
Local Color Fidelity	Average similarity for color within 1 of 16 hue angle bins (j)	Values closer to 100 indicate greater similarity to the reference	0 to 100	60 to 100
Sample Color Fidelity	Average similarity for a specific color sample (i)	Values closer to 100 indicate greater similarity to the reference	0 to 100	60 to 100

SOURCE: ANSI/IES TM-30-20, Annex E, Table E-1.

Appendix B: Color Rendition Specifications

Table 3 – Summary of color rendition specifications and recommended practices.

Type	Name	Criteria
Voluntary (Energy Efficiency Rebate)	DesignLights Consortium Qualified Products List, Technical Requirements V4.4, Indoor Luminaires	$R_a \geq 80$
Voluntary (Energy Efficiency Rebate)	ENERGY STAR Certified Light Bulbs V2.0	$R_a \geq 80$, $R_9 \geq 0$
Voluntary (Building Certification)	WELL Building Standard V1	$R_a \geq 80$, $R_9 \geq 50$
Voluntary (Building Certification)	WELL Building Standard V2 All Spaces Except Circulation Circulation Areas	 $R_a \geq 90$ OR $R_a \geq 80$, $R_9 \geq 50$, OR $R_f \geq 78$, $R_g \geq 98$, $-1\% \leq R_{cs,h1} \leq 15\%$ $R_a \geq 80$ OR $R_f \geq 78$, $R_g \geq 95$, $-7\% \leq$ Rcs,h1 $\leq 15\%$
Mandatory (for sale in state)	California Appliance Efficiency Regulations (Title 20)	$R_a \geq 82$
Mandatory (residential new constr)	California Building Efficiency Standards (Title 24 JA8)	$R_a \geq 90$, $R_9 \geq 50$
Mandatory (military medical facilities)	U.S. DOD UFC 4-510-01: Design Military Medical Facilities	$R_f \geq 80$*, $R_g \geq 97$, $R_g \leq 110$, $-9\% \leq R_{cs,h1} \leq 9\%$ (with exceptions)
Proposal	Class A [20-22]	$R_a \geq 80$, $80 \leq$ GAI ≤ 100
Proposal	Royer et al. *Color Preference* [10, 23, 24] Tier A (Best) Tier B (Good) Tier C (Acceptable)	 $R_f \geq 78$, $R_g \geq 95$, $-1\% \leq R_{cs,h1} \leq 15\%$ $R_f \geq 74$, $R_g \geq 92$, $-7\% \leq R_{cs,h1} \leq 19\%$ $R_f \geq 70$, $R_g \geq 89$, $-12\% \leq R_{cs,h1} \leq 23\%$
Recommendation	IES Lighting Handbook, 10th Ed. General Interior Color Appraisal Color Matching & Reproduction	 $R_a \geq 80$ $R_a \geq 85$ $R_a \geq 90$
American National Standard Recommended Practice	ANSI/IES RP-1-12: Office Lighting General Color Matching/Discrimination	 $R_a \geq 80$ $R_a \geq 90$
American National Standard Recommended Practice	ANSI/IES RP-3-13: Educational Facilities General Color Discrimination	 $R_a \geq 80$ $R_a \geq 90$
Recommended Practice	IES RP-4-13: Lbiraries Meeting Rooms	 $R_a \geq 85$
Recommended Practice	IES RP-7-01: Industrial Important Critical	 $R_a \geq 70$ $R_a \geq 85$
American National Standard Rec. Practice	ANSI/IES RP-28-16: for Seniors and the Low Vision Population	$R_a \geq 80$

*IES TM-30-15 value. Equivalent to $R_f = 82$ for IES TM-30-18. Other values are equivalent for 2018 and 2015 versions.

SOURCE: U.S. Department of Energy, Pacific Northwest National Laboratory, published as Table 1 in: Royer, M. "Analysis of color rendition specification criteria." Light-Emitting Devices, Materials, and Applications. Vol. 10940. International Society for Optics and Photonics, 2019. Available online.

Appendix C: Luminus Products Color Rendering Data

Complete color rendering data for many of the Luminus LED product lines* is shown in the Tables below, including CRI, TM-30, GAI, and R9 values. The far-right column in each table shows the melanopic ratio (MR), a measure used for creating human-centric lighting (HCL) designs: lighting that supports human circadian function. In calculating MR values, Luminus uses Illuminant E (not D65) as recommended in the Well Building Standards and by IES.** For more information about HCL refer to the white paper "Lighting for Health: Human-Centric Lighting."

Table 4 - Luminus Standard AC40 LEDs (Gen 4)

Standard (AC40)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	Rg	P	V	F			
22-70	72	-21	69	98	73	98	P-	V-	F-	98	103	0.27
22-90	92	55	90	101	91	101	P2	V-	F3	97	99	0.35
24-90	92	59	91	101	92	101	P2	V-	F2	102	105	0.42
27-80	81	0	80	97	83	97	P-	V-	F-	97	101	0.43
27-90	92	62	90	100	91	100	P2	V-	F2	101	105	0.48
27-95	98	97	95	100	95	100	P1	V-	F1	100	103	0.51
30-80	82	5	82	97	84	97	P3	V-	F-	95	99	0.50
30-90	93	66	91	100	92	100	P2	V-	F2	102	105	0.55
30-95	98	99	95	102	96	102	P1	V-	F1	106	108	0.58
35-80	82	7	81	97	83	97	P-	V-	F-	95	99	0.57
35-90	93	65	89	98	90	98	P2	V-	F3	96	100	0.63
35-95	99	98	94	101	95	101	P1	V-	F2	101	103	0.66
40-70	73	-15	71	95	74	95	P-	V-	F-	90	96	0.57
40-80	82	8	81	97	83	97	P3	V-	F-	93	97	0.65
40-90	93	66	89	98	90	98	P2	V-	F2	97	100	0.74
40-95	96	92	94	102	94	102	P2	V-	F2	100	103	0.73
50-70	73	-19	70	94	73	95	P-	V-	F-	88	94	0.72
50-80	83	10	80	94	82	95	P-	V-	F-	90	94	0.82
50-90	92	65	86	95	88	96	P2	V-	F3	93	97	0.91
50-95	96	97	90	98	92	99	P2	V-	F2	97	100	0.92
57-80	84	17	80	94	82	94	P-	V-	F-	93	96	0.91
65-80	82	8	80	96	82	96	P-	V-	F-	92	95	0.95

* For additional product details, refer to Luminus Help Center article "How to figure out the COB product information from the customer part number."
** Wood, J. "M/P ratios – Can we agree on how to calculate them?" Illuminating Engineering Society, November 27, 2019.

Table 5 – Luminus Standard AC30 LEDs (Gen 3)

Standard (AC30)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
24-90	92	65	91	101	92	101	P2	V-	F2	95	100	0.40
27-80	81	8	82	94	84	94	P3	V-	F-	90	97	0.44
27-90	92	65	89	101	91	101	P2	V-	F2	99	103	0.45
27-95	98	86	95	102	95	102	P2	V-	F1	104	107	0.49
30-80	82	8	81	96	83	95	P-	V-	F-	94	99	0.59
30-90	92	67	89	101	90	101	P2	V-	F2	101	105	0.52
30-95	97	85	94	101	95	101	P2	V-	F2	101	104	0.57
35-80	82	8	81	95	83	95	P-	V-	F-	94	99	0.59
35-90	93	73	89	100	90	100	P2	V-	F2	104	107	0.62
35-95	96	83	92	100	93	100	P2	V-	F2	99	103	0.65
40-80	82	10	81	95	83	95	P3	V-	F-	92	96	0.68
40-90	92	69	89	99	90	99	P2	V-	F3	97	101	0.71
40-95	98	94	93	100	93	100	P2	V-	F2	100	103	0.76
50-70	72	-17	69	95	72	96	P1	V3	F2	89	95	0.69
50-80	83	12	81	95	83	96	P-	V-	F-	91	95	0.82
50-90	92	73	89	99	90	100	P2	V-	F2	97	101	0.86
50-95	97	95	93	100	94	101	P2	V-	F2	98	100	0.89
65-80	83	16	81	95	83	95	P1	V3	F2	93	96	0.96

Table 6 – Sensus (AC42) LEDs (Gen 4)

Sensus (AC42)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
27-90	93	63	88	103	90	103	P2	V-	F3	119	121	0.48
30-80	81	6	79	99	81	99	P3	V-	F-	107	110	0.51
30-90	92	64	87	104	88	104	P2	V-	F3	117	118	0.55
35-90	94	72	90	101	91	101	P2	V-	F2	108	110	0.64
31-90	93	67	89	102	90	102	P2	V-	F2	112	114	0.58

Table 7 – Sensus (AC32) LEDs (Gen 3)

Sensus (AC32)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
30-80	83	10	81	97	83	97	P3	V-	F-	103	107	0.55
35-80	83	12	82	96	84	96	P1	V3	F2	97	101	0.60
30-95	97	93	93	104	94	104	P1	V-	F2	115	115	0.60
35-90	93	73	89	100	90	100	P2	V-	F2	104	107	0.62

Table 8 – Xtreme Sensus (AC44) LEDs (Gen 4)

Xtreme Sensus (AC44)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
30-90	93	71	86	105	88	105	P2	V-	F3	134	133	0.58
35-90	93	69	87	102	88	102	P2	V-	F3	120	121	0.64

Table 9 – Xtreme Sensus (AC34) LEDs. (Gen 3)

Xtreme Sensus (AC43)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
30-90	93	82	85	105	87	105	P1	V3	F2	133	133	0.56
35-90	92	79	85	103	86	103	P1	V3	F2	120	122	0.63

Table 10 – Hospitality COB Series LEDs (TC41)

Hospitality	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
27-90	93	64	90	101	91	101	P2	V-	F2	115	117	0.50
27-95	96	96	95	103	95	103	P1	V3	F1	117	117	0.55
30-90	93	65	90	100	91	100	P2	V-	F2	108	111	0.56
30-95	97	94	94	102	95	102	P1	V3	F1	112	113	0.60
35-90	92	62	88	98	90	98	P2	V-	F3	103	107	0.63
35-95	97	93	93	100	93	100	P1	V3	F2	106	108	0.70
40-90	94	71	88	98	90	98	P2	V-	F3	103	106	0.76
40-95	98	98	93	101	94	101	P1	V-	F2	104	106	0.76

Table 11 – Special Purpose (AC48) LEDs.

Special Purpose (AC48)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
18-70	77	80	75	123	77	123	P2	V3	F-	403	334	0.48
30-70	76	27	87	111	88	111	P1	V2	F-	178	164	0.85

Table 12 – Special Purpose (AC38) LEDs.

Special Purpose (AC38)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
18-70	78	80	77	121	79	121	P1	V3	F-	353	297	0.49
30-70	76	26	87	111	88	111	P1	V2	F-	179	165	0.84

Table 13 – Smooth White Series (TS31) LEDs.

Smooth (TS31)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
27-95	97	91	95	99	96	99	P1	V-	F1	97	98	0.51
30-95	97	98	95	100	96	100	P1	V-	F1	101	102	0.60
35-95	98	89	96	99	96	99	P2	V-	F1	95	97	0.68
40-95	98	94	94	98	94	98	P1	V-	F2	97	98	0.78
50-95	98	94	96	100	97	101	P2	V-	F1	98	100	0.90

Table 14 – PerfectWhite Series (PC32) LEDs.

PerfectWhite (PC32)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
30-90	94	96	92	100	93	100	P1	V-	F2	111	111	0.66

Table 15 – Salud Human-Centric Lighting (MP-3030-21C2) LEDs.

Salud (MP-3030-21C2)	CRI	R9	TM-30-15		TM-30-18		TM-30-20			GAI_{BB8}	GAI_{BB15}	MR
			R_f	R_g	R_f	R_g	P	V	F			
30-90	94	96	88	96	89	96	P1	V3	F2	97	98	0.66
35-90	94	80	88	94	89	94	P1	V3	F2	94	96	0.72
40-90	92	69	86	93	87	93	P1	V3	F2	90	93	0.79
50-90	92	83	87	95	90	96	P1	V3	F2	91	92	0.98

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