by Al Near

The industry faces a color quality challenge with the advent of LEDs

"Beauty is in the eye of the beholder": This subjective approach may be suitable for fine art, but it proves much less effective in engineering-rooted disciplines like lighting.

And yet, with the emergence of high brightness LEDs and other SSL technologies, subjectivity is often the only basis available for designers to gauge the color quality of projected light sources. Current metrics such as the International Commission on Illumination (CIE)'s Color Rendering Index (CRI)—introduced more than 40 years ago—do not completely account for how the human eye sees color under LED lighting or comprehensively compare this lighting to traditional sources.

As lighting technologies continue to grow and refine, it is clear that balanced lighting standards need to follow closely behind this evolution to ensure both beauty and a quantifiable color quality metric.

WHY COLOR QUALITY MATTERS

The average individual may not recognize it, but the various wavelengths and colors that electric lighting provides greatly impact our physiological and psychological levels. Consider, for example, the feeling rendered after entering a dimly lit room with older, 4,000K, halophosphate, cool-white fluorescent lamps versus the feeling of being outside in daylight for 20 minutes. People typically respond better to an environment when they experience full-spectrum color quality.

The health benefits that lighting with good color quality offers is not exclusive to one industry; it is relevant for employers who want more productive workers, retailers who want to showcase their products in the best light, interior designers who want their full color palette to shine through and caregivers who want to ensure optimal patient healing.

Although overall color perception can vary depending on age, visual acuity and, as some couples may have already suspected, even gender, a defined color quality metric for light solutions provides manufacturers and end-users the mutual benefit of seeing eye-to-eye on color consistent results.

GOOD IS NO LONGER GOOD ENOUGH

While a CRI in the 90s for an LED light source is still a decent relative gauge of color performance, it does not tell the entire story. The current CRI is essentially a measure of only the first eight (R1 to R8) CIE color reference samples, which are naturally more pastel colored. LEDs produce a spectral power distribution that enhances the perception of saturated colors in the lighting application, in some cases, even at a lower CRI. The CRI metric does not cover more saturated colors, such as the strong reds that are prevalent in skin tones, art work, clothing and grocery store produce. Thus, many LED specifiers are beginning to evaluate specific R9 reference sample values in addition to CRI.

But even with that, how high does an R9 value really need to be to render good color quality? While an R9 in the teens or low 20s is somewhat noticeable to the human eye, how perceptible to most people's vision is the difference between an R9 of 65 to 75 versus an R9 of 95?

Add to that the fact that engineering a high-CRI or color-enhanced LED array or module requires the application of additional specific phosphors to achieve the targeted effect, which lowers lumen output. This, in turn, lowers the overall efficacy (lumens per watt) of the array or module. **Figure 1** shows two representative LED modules and their lumens per watt performance at both 80-plus CRI and 90-plus CRI. LED module B has additional phosphors added to enhance color. At both 80-plus and 90-plus CRI, module B has a lower efficacy than module A, and it is significantly less efficacious at the higher CRI value. As illustrated, the "lumen penalty" for high CRI can range from 20 to 30 percent, depending upon the amount of color enhancement that is undertaken (**Figure 2**).

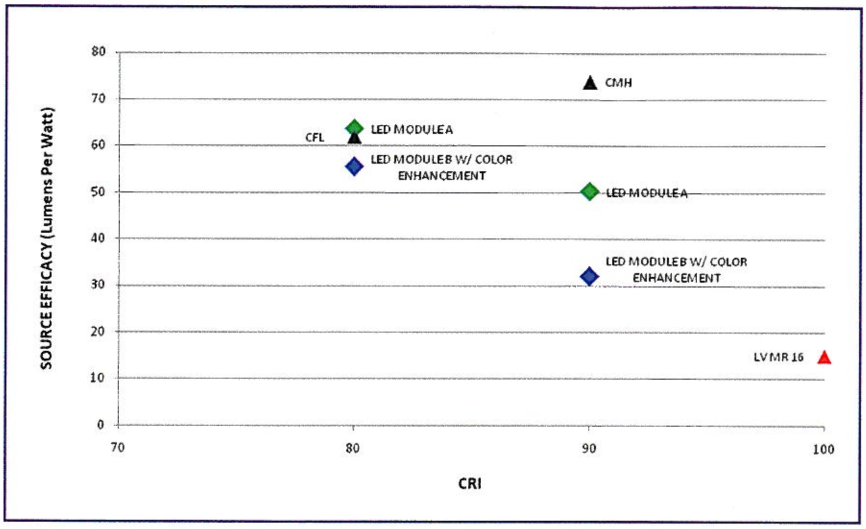


Figure 1. Lumens per watt performance of LED modules at 80-plus and 90-plus CRI.

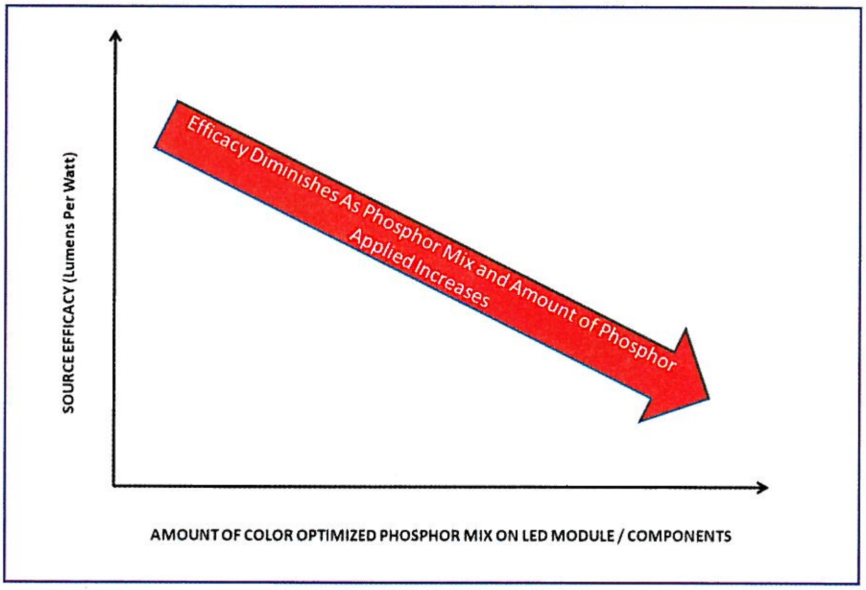


Figure 2. Lumen penalty for high CRI.

LIGHT DESIGN TRADE-OFFS

Specifiers continue to ask: "How important is color for the application that I am undertaking?"; "How good is good enough with respect to color?"; and "If the color quality of an LED lighting product is deemed acceptable, am I getting enough lumen output to do anything with it?"

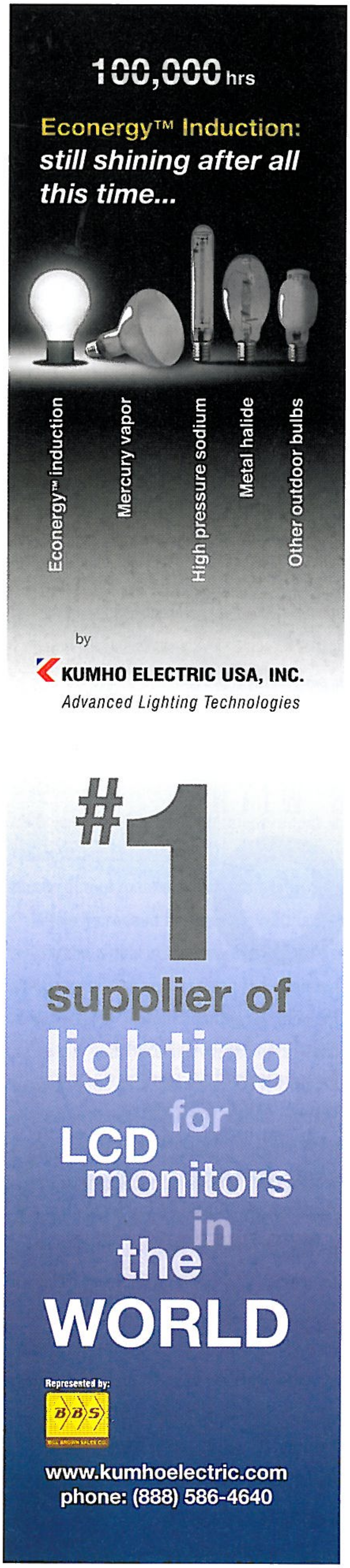
While increased lumens per watt is the overarching goal in the new age of energy-efficient lighting applications, the intended effect—from accent lighting to ambient lighting in commercial environments—will trigger trade-offs between CCT, CRI, R9, fixture efficacy, available beam distributions and, ultimately, cost.

For example, if exceptional color quality is the ultimate goal for the intended lighting application, one might initially consider high-CRI level LEDs. However, implementing such technology may entail costs unrelated to the project's overall color quality goals, such as potentially more expensive dimmers and LED dimming drivers.

The aforementioned 20 to 30 percent lumen penalty incurred by the use of higher CRI LEDs may not yield enough usable lumens. As a result, the designer could trade-off by lowering his or her CRI requirement for the LEDs in return for more delivered lumens. In fact, the lower CRI LED may still yield more than adequate color quality for the application, especially if it has a good R9. Another possible trade-off would be to utilize 80-plus CRI LED products for all the ambient lighting to lower the space's overall watts per sq ft and then deploy more cost-effective, yet exceptional color rendering, low-voltage MR16 or ceramic metal halide solutions for color-sensitive areas.

FULL COLOR QUALITY: NEXT STEPS

Manufacturers must discover the balance between energy efficiency and color



quality in order for emerging technologies such as LEDs to improve. This is a goal that can be sooner and more effectively realized if current light sources are ranked by a standard, yet accurate, color metric as well as lumens per watt.

The metric gaining the most traction within the industry is the National Institute of Standards and Technology's Color Quality Scale (CQS), which was created to better address the shortcomings of CRI to describe the color quality of white light. The CQS implements a scale of 15 higher chroma colors as opposed to CRI's eight-color scale.

Until CQS or an alternative solution is adopted to resolve the color quality metric issue, however, subjectivity in the LED lighting product evaluation process will still play a significant part. That said, to ensure apples-to-apples comparisons between manufacturers, the following criteria should be considered collectively, with technological trade-offs additionally considered depending upon the application:

- **Source efficacy** (lumens per watt): Performance of the module or LED array
- **Delivered efficacy** (lumens per watt): "True" LM-79 fixture performance (not just a reference to the module/array LPW)
- **CCT** (Correlated Color Temperature): The cooler the LED CCTs, the higher the efficacy, so the color temperature at which LM-79 data is derived is a critical point of consideration when making sure that a fair comparison is taking place
- **Fixture-to-Fixture Color Consistency:** A good metric for determining this with LED is to refer to Standard Deviation of Color Matching (SDCM) data, commonly referred to as "MacAdam Ellipses," which are named after light and color studies conducted by David Lewis MacAdam. Those studies concluded that the average human eye's color discrimination threshold is approximately three times the standard deviation (SDCM) for a specific chromaticity value.

  Therefore, a target value for extremely color sensitive applications would be between < 3 SDCM (3-step MacAdam) initially and then potentially ranging up to 5 SDCM sustained over lifetime to L_{70}. For less color sensitive applications such as ambient lighting, an initial range from 5 to 7 SDCM (5 to 7-step MacAdam) may prove acceptable
- **CRI**
- **R9**

As warm-white LEDs become more powerful and efficacious, remote and local phosphor LED approaches become more refined, and as other SSL technologies emerge, manufacturers will be able to create mainstream lighting solutions that feature both energy efficiency and color quality, without as much of a technological trade-off as we are seeing today. The key is to define as an industry what the color quality standard metric should be and capture its effect to eliminate confusion.

After all, every bright idea to evolve lighting technology and meet consistent color quality not only improves lighting professionals' outlook, but directly impacts the perspective and health of individuals who work and live under these light sources.

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