LED Color Stability

Lumen maintenance has dominated discussions about LED lifetime, but color shift is another important performance attribute that can cause an LED lamp or luminaire to fail. The color stability of LEDs varies from product to product, and potentially for the same product used in different applications. Properly communicating about color shift, understanding why and when it can occur, and appropriately monitoring performance can help lead to a successful, long-lived installation.

Why and where is color stability important?

The importance of color stability—and the tolerances for how much change is allowable—vary by application. For example, maintaining constant color over time is very important for light sources in a museum or retail store, but less important for street lighting. Color stability is also important where multiple lamps or luminaires are being used to wash a wall, or where objects are being evaluated based on color—such as in a hospital or factory.

Color stability should not be confused with color consistency. Color stability refers to the ability of a product to maintain constant color (chromaticity ⓘ) over its lifetime, whereas color consistency refers to the product-to-product variation within a lamp or luminaire type.

What metrics are used to describe color shift/color stability?

Several metrics are used to describe the color of a light source; for more information, see the DOE fact sheet, *LED Color Characteristics*.[1] Color shift is best communicated using Δu'v', which describes the magnitude of chromaticity shift in the CIE 1976 chromaticity diagram (u', v'). That diagram is the most perceptually uniform for light sources, so comparing the amount of shift for sources with different starting chromaticities is possible. Importantly, Δu'v' encompasses shifts in correlated color temperature (CCT) ⓘ and D_{uv} ⓘ—considering the change in either of those metrics alone would give an incomplete characterization of the color difference. Also noteworthy is that Δu'v' does not capture the direction of the shift, only the magnitude.

MacAdam ellipses are another metric that is sometime used to report color stability or color difference. The ellipses, which are often described in terms of a "step size"—or multiple of the original ellipse—are the result of a color matching experiment intended to test the sensitivity of human color vision. They were derived under very specific conditions, but have proven useful in many applications. In fact, the CIE 1976 chromaticity diagram (u', v') was developed so that in the area encompassing nominally white light sources, the MacAdam ellipses are actually approximately circles. That means that the difference tolerances that were derived can be communicated using Δu'v', because a one step change in any direction is approximately equal to a Δu'v' of 0.001.

1 Available at: http://www1.eere.energy.gov/buildings/ssl/factsheets.html

When does color shift become noticeable?

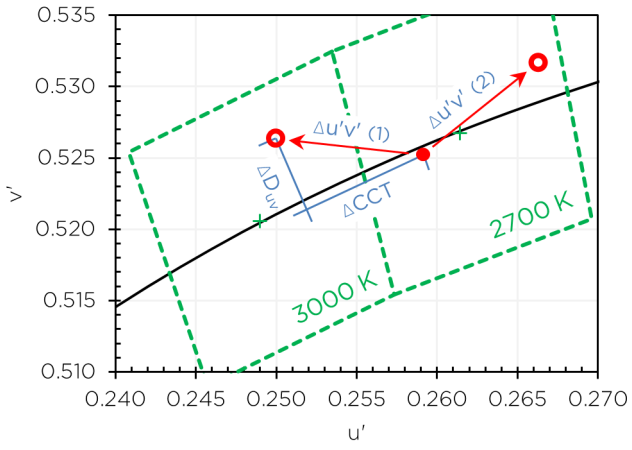
Exactly when color shift becomes noticeable—a just noticeable difference—depends on the application. In MacAdam's experiment, a trained observer could spot small differences in the small field of view showing two colors. In a room with lights at either end, the detectable difference would be much larger. Further, time may mask changes that occur slowly; that is, depending on the rate of change and the acceptability of the new color, changes that occur over a very long period (e.g., 25,000 hours) may not be objectionable if all of the light sources shift in the same magnitude and direction.

Are there established tolerances for color shift?

Like many other metrics, there are no official standards limiting the amount of acceptable color shift. Rather, a specification may be established on a project-by-project basis if it is necessary. To qualify for ENERGY STAR®, the measured Δu'v' of 9 out of 10 samples of a lamp must be less than 0.007 over the first 6,000 hours of lamp operation—a level that may or may not be acceptable for a given application.

What standards apply to the measurement of color stability?

Color stability refers to performance over time; therefore, it is not addressed by basic photometric testing according to IES LM-79-08. Rather, the chromaticity of LED packages over time is measured as part of IES LM-80-08. This procedure requires measurements of lumen output and chromaticity for a sample of products to be taken at least every 1,000 hours, for a minimum of 6,000 hours. Measurements may be made at finer intervals, and the duration may be extended.



Close up of the CIE 1976 chromaticity diagram (u', v') illustrating the difference between Δu'v', ΔD_{uv}, and ΔCCT. ΔD_{uv} and ΔCCT are insufficient for characterizing color difference. Only Δu'v' describes the total color difference that might be observed, although it does not describe the direction of the shift. As such, Δu'v' (1) and Δu'v' (2) would have the same value, despite shifting in different directions.

LM-80 measurements are taken with the packages operating continuously in a temperature-controlled environment, where the solder point and ambient air temperature are at equilibrium. This does not necessarily simulate real-world operating conditions, so laboratory test results for LED packages and experiences with complete lamps and luminaires in the field may not perfectly match.

Do color stability measurement standards apply to complete products?

The LM-80 data for LED packages, in conjunction with in situ temperature measurement test (ISTMT) data, can be used to estimate the performance of a complete lamp or luminaire. For color shift, this accounts for the stability or instability of the LED package, not any other components in the system, such as the lens, louvers, or driver. As previously noted, differences between the test conditions and real-world operating conditions should be understood when evaluating the predictive ability of the results.

Are there methods and/or standards for projecting color shift in the future using measured data?

Unlike for lumen maintenance, there is currently no available standard method for projecting future color stability using LM-80 measurements. Likewise, there are no established methods for accelerated testing. Some manufacturers may have internal algorithms. An IES committee is currently working on this issue.

What affects the color stability of LEDs?

Changing operating conditions can have short-term, reversible effects and long-term, irreversible effects. Ambient air temperature, drive current, and the design of a lamp or luminaire's thermal management system can all influence the junction temperature of the LED, which in turn can affect its output characteristics. This is apparent in the 30 minutes or more that many LED products take to reach thermal equilibrium—although often the changes are not as noticeable as they are with compact fluorescent lamps, for example.

Of greater concern for long-term color stability is the effect that high temperatures can have on materials. Even without excessively high ambient temperatures, the phosphors used to convert narrow-band LED emission to a broader range of wavelengths may settle, curl, delaminate, or otherwise change the amount of photons that are converted. This action varies based on the design of the package. Likewise, other materials in the optical path, like plastics, glues, or epoxies, may discolor over time. Temperature fluctuations, which are not included in standardized test procedures, may exacerbate degradation for some LED products.

More information on the causes and process of color shift can be found in the DOE SSL Program GATEWAY report, *Color Maintenance of LEDs in Laboratory and Field Applications.*[2]

2 Available at: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_results.html

How do LEDs compare to other technologies?

The color stability of LEDs can vary greatly. At least one product type (200 samples) monitored by the DOE SSL program maintained a $\Delta u'v'$ for all samples of less than 0.003 over 25,000 hours of continuous operation, with the mean less than 0.001. In contrast, testing of a different product using the same methods resulted in all five samples exceeding a $\Delta u'v'$ of 0.007 in less than 6,000 hours. There are certainly many products with excellent color stability, but it may be difficult for consumers or specifiers to identify them.

Many types of light sources have some color instability over time. The most pronounced is generally metal halide, but fluorescent lamps can also shift. Given the diversity of LED product performance, it is difficult to generalize them as better or worse than conventional technologies.

Are warranties that cover color shift available?

Only a small number of manufacturers offer a warranty for color shift, likely because there are many complications, including:

- Lack of a standard test method for determining and/or projecting future color shift.
- Difficulty in determining the baseline chromaticity—is it the specified chromaticity, the chromaticity of an individual product, or the chromaticity of a group of products? Under what conditions is that chromaticity measured?
- Difficulty in determining the final chromaticity—is an LM-79 test required? Handheld measurements cannot control for ambient conditions.
- No standardized definition of the specific circumstance—does the allowable color difference refer to the lamp(s) in their original condition, or to other lamps of the same type in the same installation?
- Trouble assigning responsibility—if an LED package degrades, it may be the fault of the lamp or luminaire designers for providing insufficient thermal management. Likewise, multiple components could contribute to color shift of a complete product.

Best Practices

Differentiating between products with excellent color stability and those that may pose a problem is difficult. In situations where color stability is important, specifiers should carefully review LM-80 data for LED packages and ISTMT test data for the lamp or luminaire. If an integral LED lamp is intended to be used in a conventional luminaire, all manufacturer guidelines should be followed—and specific discussions with the manufacturer may be necessary. For the most critical applications, specifiers may wish to work with manufacturers to include a product warranty that addresses the concerns previously listed, if one is not already available.

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