Solid-State Lighting Lifetime and Reliability

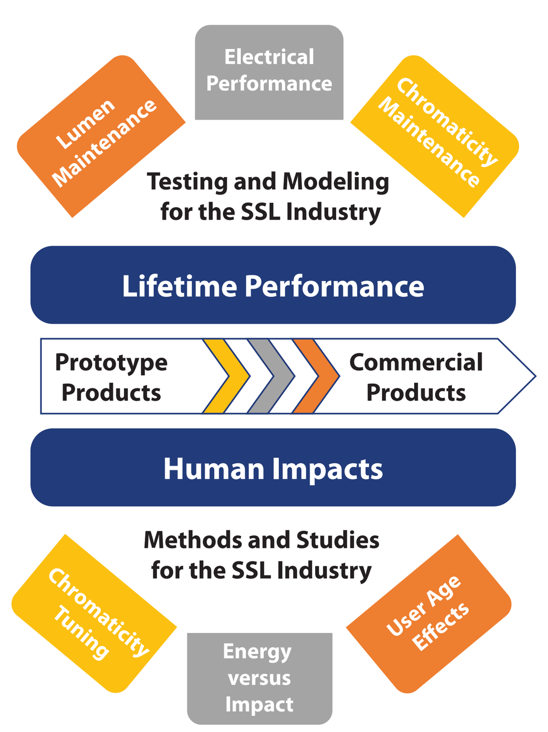
RTI International, Research Triangle Park, NC

Introduction

The objective of this effort is to understand and model lifetime and reliability concerns associated with solid-state lighting (SSL) technology. Endeavors are complicated by the cost and impracticality of real-time lifetime testing. This current work highlights the importance of understanding how SSL products fail and, subsequently, communicating failure modes and models to the SSL community. Our current work includes the following:

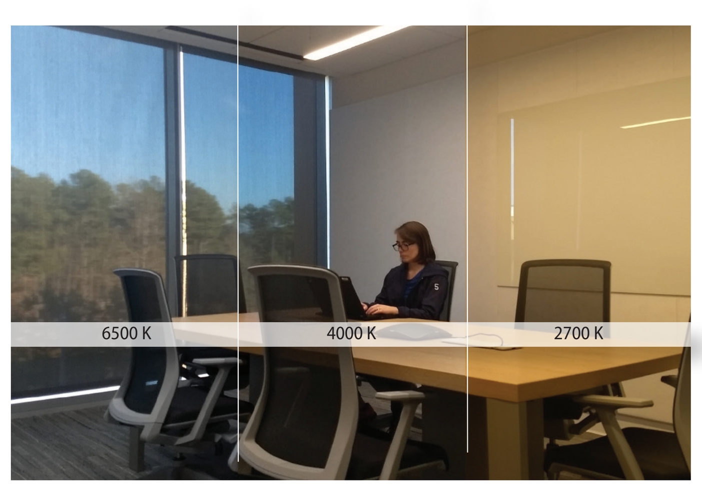
- Chromaticity and lumen maintenance of single-color and tunable-white light-emitting diode (LED) light sources.
- Accelerated Stress Test (AST) and health status indicators for SSL drivers.
- Organic light-emitting diode (OLED) panel reliability and luminaire performance.

SSL Program at RTI



RTI research efforts in the SSL lighting program span product performance and human effects, and study products ranging from prototype to commercial.

- The mission of the Solid-State Lighting Program at RTI is to advance the understanding of SSL luminaire design implications. Our findings are intended to aid the SSL industry in bringing ever-improved products to consumers in this significant, energy-saving product area.
- Our foundational work developed accelerated stress test (AST) methods for commercial LED luminaires and components. As the body of data grows, we continue to build models and methods for understanding product lifetimes based on material stability, electrical design, and chromaticity.
- RTI is also addressing the human-centric aspects of lighting, with a growing research effort to understand the impacts of lighting choice on human mood and activity.
- Our current work regarding tunable-white (TWL) lighting focuses on indoor applications, such as schools and offices. Using RTI's wealth of experience with monitoring human subject physiological factors, we are developing test methods for quantitative analysis of tunable lighting systems.



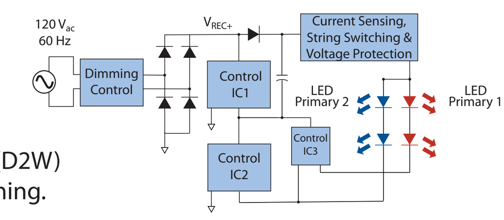
RTI is currently developing methods for testing effects of TWL systems.

Electrical Reliability Testing of Dynamic White Lighting

Driver Configurations for TWL Systems

Two major types of tunable-white products are as follows

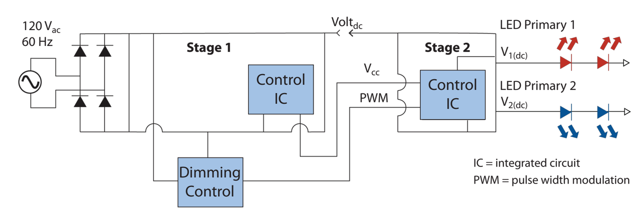
- Dim to warm (D2W) or warm dimming.
- TWL products.



Schematic representation of a driver for operating a D2W product.

Typically, a two-channel driver is used for both products, with differences lying in method of control:

- D2W has a single control input for both LED primaries (power).
- TWL uses separate control signals for each LED primary.

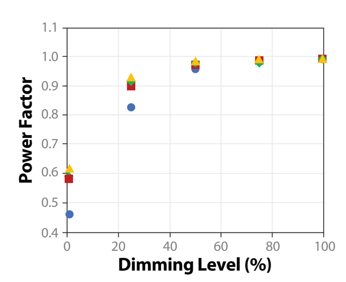


Schematic representation of a two-stage dual-channel driver for operating a TWL system with two LED primaries.

Degradation Processes

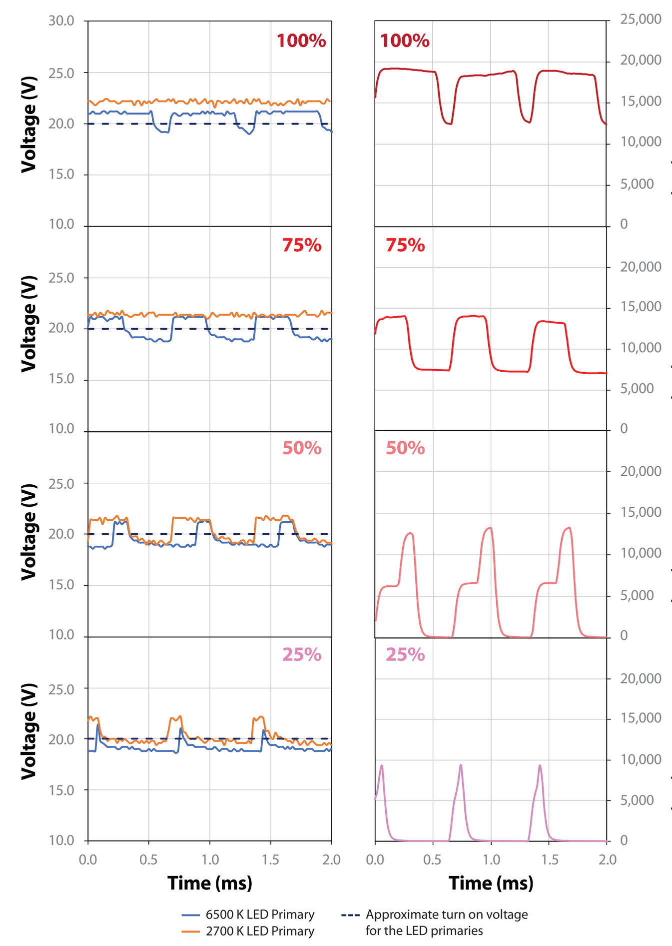
Gauging driver performance with dimming level provides a good health status monitor:

- The film capacitors degrade faster than other components, and the impacts of their degradation are observed at low dimming levels.
- Photometric flicker, efficiency, and other parameters are also impacted when dimming.



Dimming (%)	Efficiency (Control)	Efficiency (Post 7000 Hours – 7575 AST)
100	84.60%	84.0%
75	79.37%	78.0%
50	67.63%	66.0%
25	35.97%	37.9%
1	5.09%	6.3%

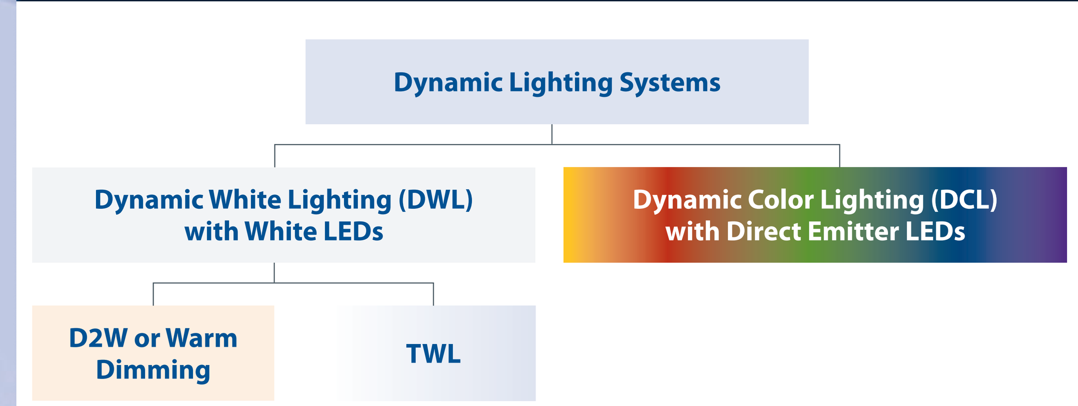
Understanding Photometric Flicker of TWL Systems



The LED voltage waveforms (left) and corresponding photometric flicker waveforms (right) are shown at various dimming levels (red hue percent labels) for a two-stage dual-channel driver for TWL systems with two LED primaries. The CCT is set to 3,500 K. At 100% (top graphs, maximum power), the two LED primaries operate at different times, but one of them is always on. At 50% dimming (third plots down), the LED primaries have different pulse widths.

- Many driver waveforms that can be used to modulate LED power for a TWL system. This choice will impact efficiency and photometric flicker.
- The human impacts of these switching waveforms are not well understood.

Tunable and Dim to Warm Products

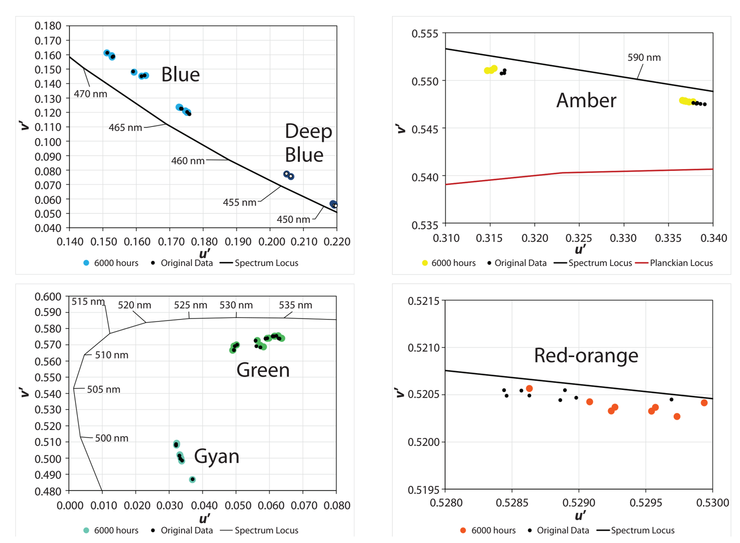


Advantages of Dynamic Lighting

- Can provide lighting flexibility for a space.
- Can be achieved with excellent luminous efficacy (>100 LPW) and color rendering.
- Can administer lighting to improve circadian entrainment or other benefits of human-lighting interactions.
- For DWL, presents a range of lighting options at colors around the black body locus.
- For DCL, presents a much larger color gamut for lighting environments, including the possibility of lighting on the black body locus.

Reliability and Other Concerns

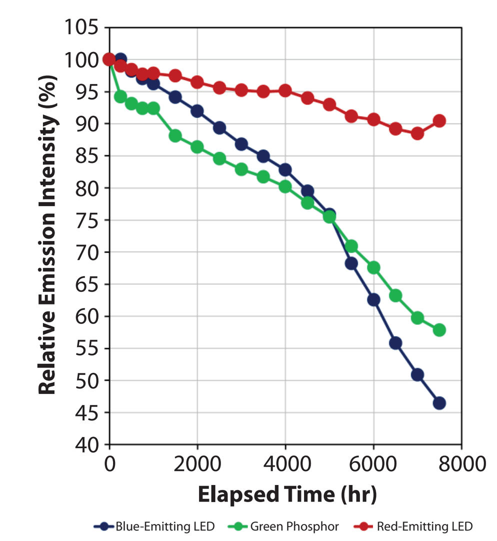
- How is chromaticity maintenance and luminous flux maintenance impacted by the use of multiple light sources? What if they behave differently?
- Are there new complications associated with having to maintain multi-channel control in the driver, especially as the driver ages?
- Testing procedures are not standardized. Should there be an expected setting profile?
- Initial purchase price is generally higher than fixed correlated color temperature (CCT) products but has been steadily declining.



Based on a limited analysis of LM-80-15 data, the luminous flux maintenance and chromaticity shift of direct emitters is dependent on the following:

- Current
- Temperature
- Base semiconductor material
- Doping levels—Deep blue very stable, amber is not as stable
- Phosphor shifts in phosphor-converted LED (pcLED) color devices

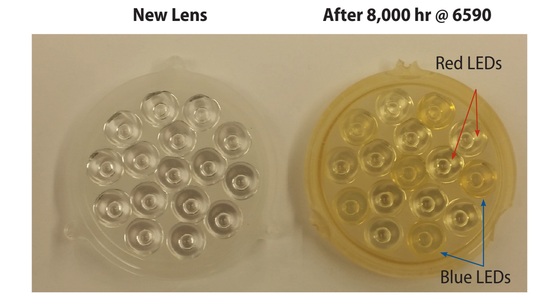
- The impact of lens "yellowing" can also be a significant factor in poor luminous flux maintenance and excessive chromaticity shift, especially in specific environments such as encountered in humid settings.
- Lens yellowing was more pronounced for LEDs with a blue pump, but minimal for direct-emitting red LEDs.



Horticulture lamp with direct-emitting red and pc-white LEDs in 6590.

	Total Light Loss	Loss Due to Lens	Other Losses
Blue	62%	49%	13%
Green	49%	18%	31%
Red	13%	3%	10%

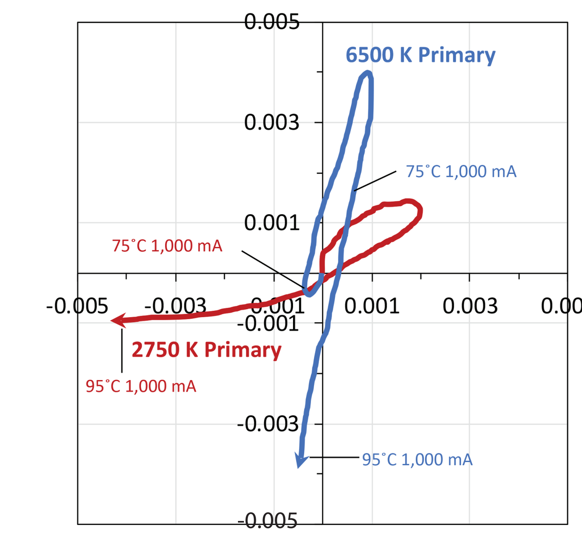
New Lens　After 8,000 hr @ 6590



Modeling Chromaticity Shift—An Example

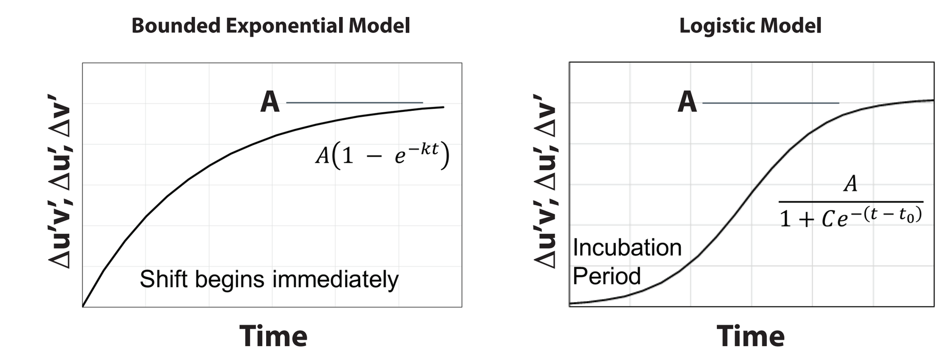
- Chromaticity shifts of dynamic light sources can produce a significant change in the color and quality of the light over the expected lifetime of any lighting product.
  - Sources rarely shift in the same direction and at the same rate, creating a change in chromaticity of the LED primaries in dynamic systems.
- Chromaticity shift impacts the system tuning range as well as a change in luminous flux.
- Shifting can be corrected with an additional feedback loop but that adds complexity.
- However, the ability to adjust the intensity of LED primaries is impacted by the head room available in the driver, which can change with age.

Shift after 20,000 hours



Chromaticity shift can be modeled with different analytic functions to describe the following:

- **Fast,** asymptotically limited change: Bounded exponential function.
- **Slow,** asymptotically limited change: Logistic function.

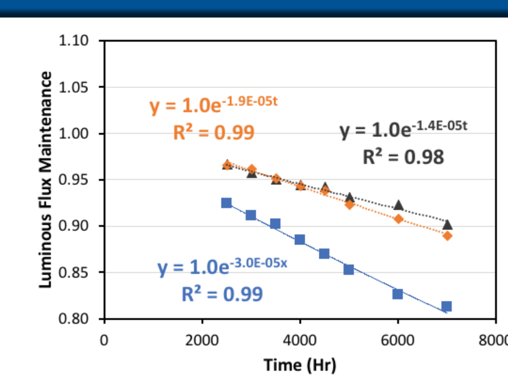


Summary

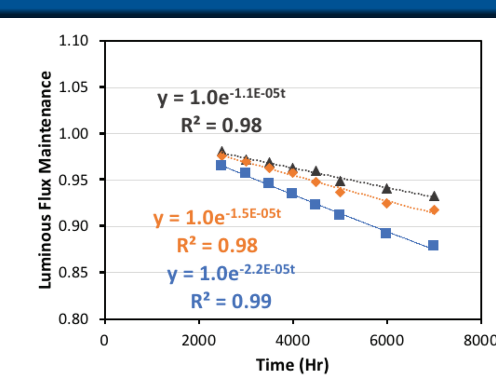
- RTI is developing lifetime models and ASTs to address a need for reliability research regarding dynamic lighting systems including TWL and DCL technologies.
- AST is the accepted method for studying failure modes and robustness of LED technologies. Developing meaningful AST methods for dynamic lighting systems is complicated by the large number of potential settings and the different effects that a given setting will have on a dynamic lighting system because the cumulative effects of current, junction temperature, and use time of each LED primary will impact total system reliability.
  - Overcoming this limitation requires a knowledge of the expected performance of the dynamic lighting system.
- Both chromaticity maintenance and luminous flux maintenance are important parametric failure modes for dynamic lighting systems.
  - For TWL lighting, chromaticity shift direction and magnitude will depend upon both materials (e.g., polymers, phosphors) and LED package format. These factors will also impact luminous flux performance along with other factors, such as current and temperature.
  - For DCL lighting, the doping levels of the LED primaries will have an impact on chromaticity maintenance, but other effects related to temperature, current, and use time may also be important in overall parametric performance.
- The dynamic response of the LED drivers used in dynamic lighting systems also varies widely depending on design, method of control, and settings during use. Testing to date has indicated that changes in power factor and/or overall efficiency at low dimming levels may be a potential health status indicator in multichannel drivers used in dynamic lighting systems.
  - OLED technologies continue to improve during performance testing for robustness, chromaticity maintenance and luminous flux maintenance.

OLEDs

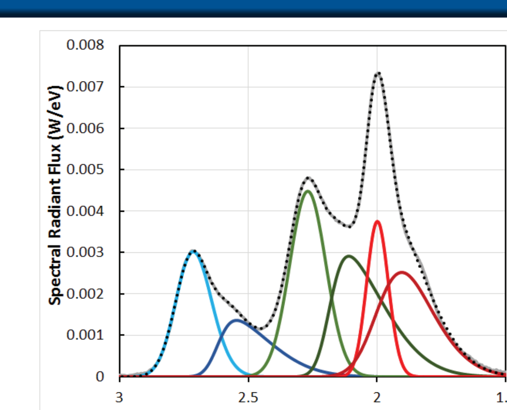
- OLEDs are an emerging technology that can be used for applications that require diffuse light. The OLED forward voltage generally increases over time with operation.
- Abrupt failure of the OLED panels generally occurs through a shorting mechanism that may be caused by the formation and growth of organic particles. The tendency for panels to fail abruptly is reduced in later products, and abrupt failures are less likely, but dark spots still tend to occur over time.
- Mildly accelerated conditions were found to provide meaningful acceleration of OLED failure modes and can reproduce field failures in greatly reduced time periods. Luminous flux degradation in such testing can be modeled by using standing lighting industry methods such as a single-exponential decay function after an initial period.
- RTI has tracked the aging of Acuity Chalina luminaires over three product generations (AST tests consist of 35°C and 45°C elevated ambient bakes) and OLEDWorks Amber and Lumiblade Brite 2 and Brite 3 panels (also AST 35°C and 45°C).
- The luminous flux maintenance of the current OLED products is improving but still remains lower than that of some inorganic LEDs using mid-power LED packages made during the 2011 timeframe.
- Improvements in the thermal management of OLED panels tended to produce gains in the luminous flux and the chromaticity maintenance of the panels.
- Widespread use of OLEDs has also been limited by the stability of organic emitters. Relative emitter stability can be tracked through chromaticity shift.
- Differential loss of light emission from the blue, green, and red light-emitting molecules that comprise the OLEDs produced chromaticity shifts that were significant in early products but have improved in later products that use more stable materials and have better thermal management.
- A steady increase in power provided by the driver was measured in most cases. A concomitant decrease in efficiency also occurred.
- A lack of low-voltage drivers has been identified as a key problem in device efficiency and robustness for OLED technologies.



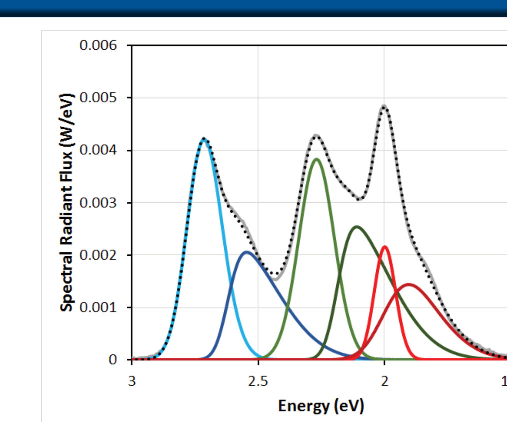
Average luminous flux maintenance for Brite 2 warm white panels after 7000 hours operational life (OL) and exponential fits of the latter part of the data.



Average luminous flux maintenance for Brite 2 neutral white panels after 7000 hours OL and exponential fits of the latter part of the data.



Spectral emission deconvolution of the Brite 2 warm white panels with two skewed Gaussian used to model each blue, green, and red emitter.



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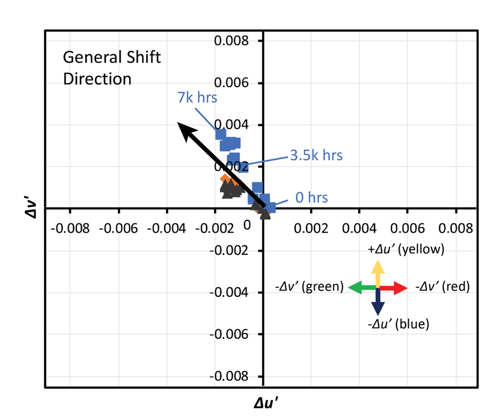
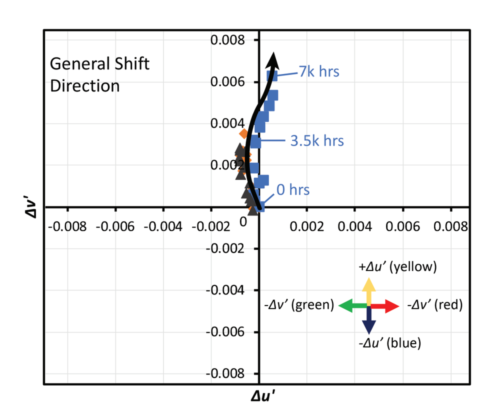


Chromaticity diagram for Brite 2 warm white panels.



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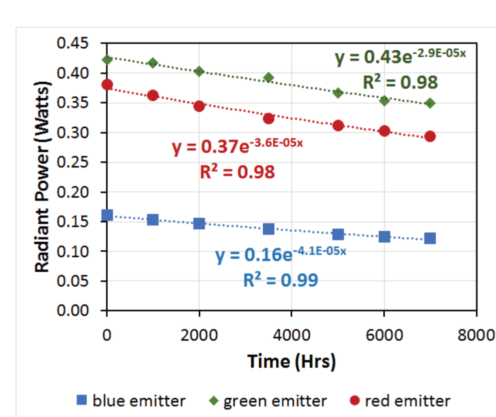
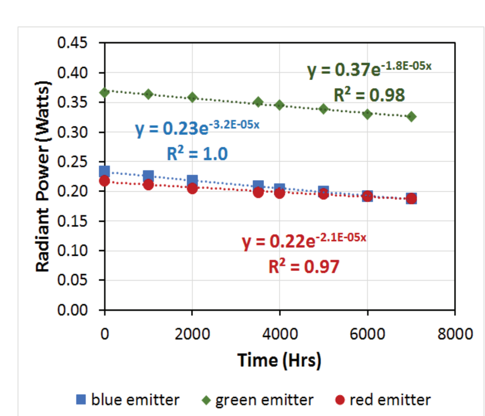


Radiant power determined from the skewed Gaussian curve fits of each spectral emission component of Brite 2 warm white panels in 45OL.



Radiant power determined from the skewed Gaussian curve fits of each spectral emission component of Brite 2 neutral white panels in 45OL.

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www.rti.org

More Information

RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

*Lynn Davis, Fellow
919.316.3325
ldavis@rti.org