

Solid-State Lighting Lifetime and Reliability

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Introduction

The objective of this effort is to understand and model the 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 luminous flux maintenance of single-color and tunable-white light-emitting diode (LED) light sources, including dim-to-warm (D2W)
- Accelerated Stress Test (AST) and health status indicators for SSL drivers
- Organic light-emitting diode (OLED) lighting

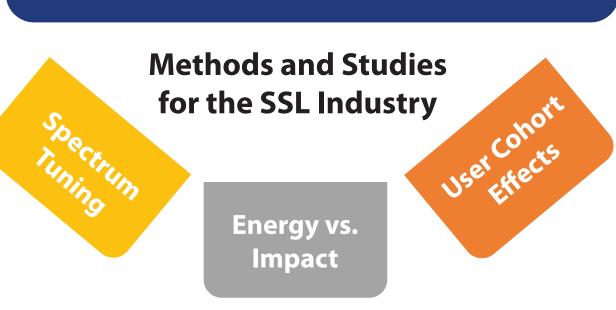
SSL Program at RTI



Lifetime Performance

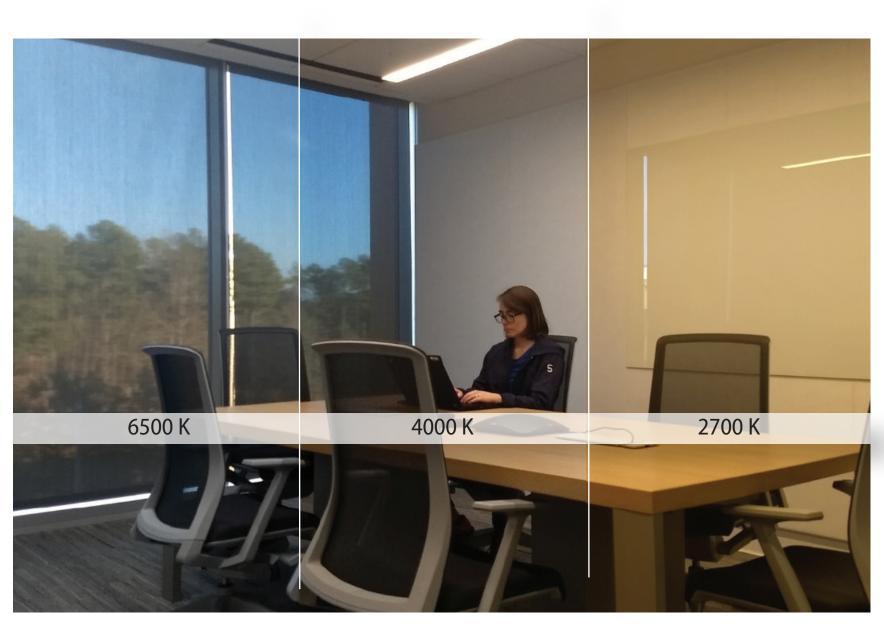
Commercial Products

Human Impacts of Light



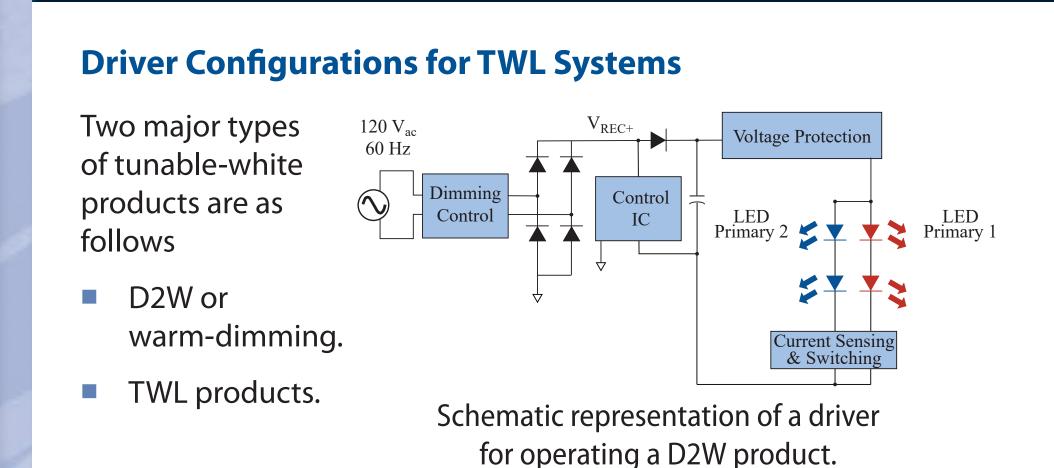
RTI research efforts in the SSL lighting program span product performance and human effects, and study products ranging from prototype to commercial.

- The mission of the Solid-State Lighting Program at RTI is to advance the understanding of SSL technologies. 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 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 lighting (TWL) 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



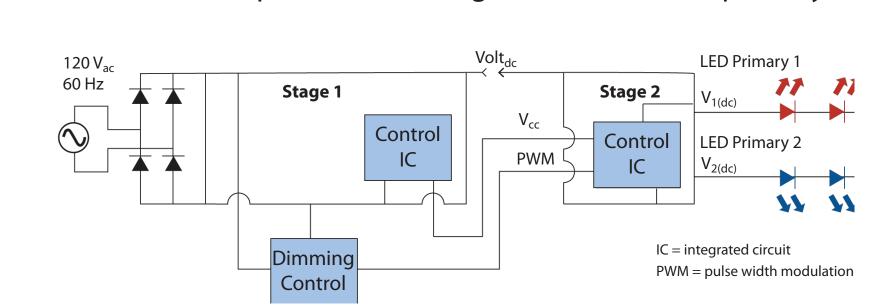
RTI is currently developing methods for testing effects of TWL systems.

Electrical Reliability Testing of Dynamic White Lighting



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.

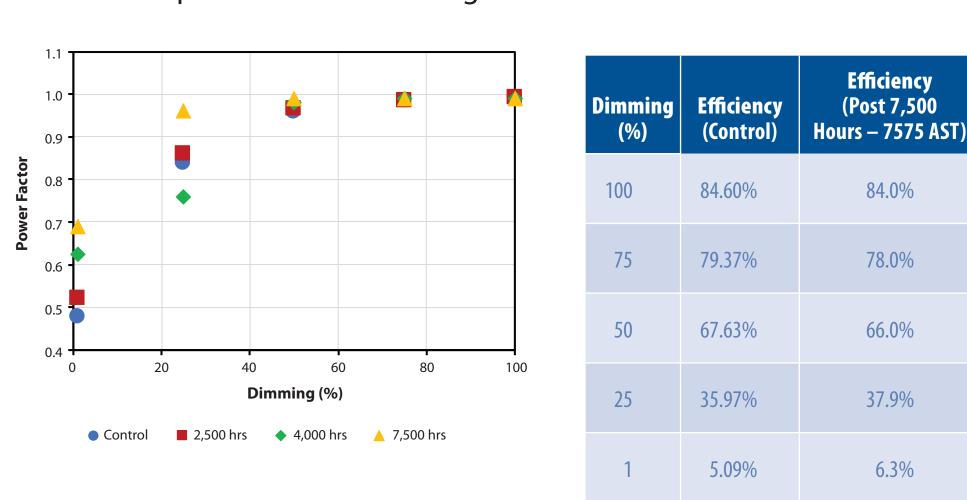


Schematic representation of a two-stage dual-channel driver for operating a TWL system with two LED primaries.

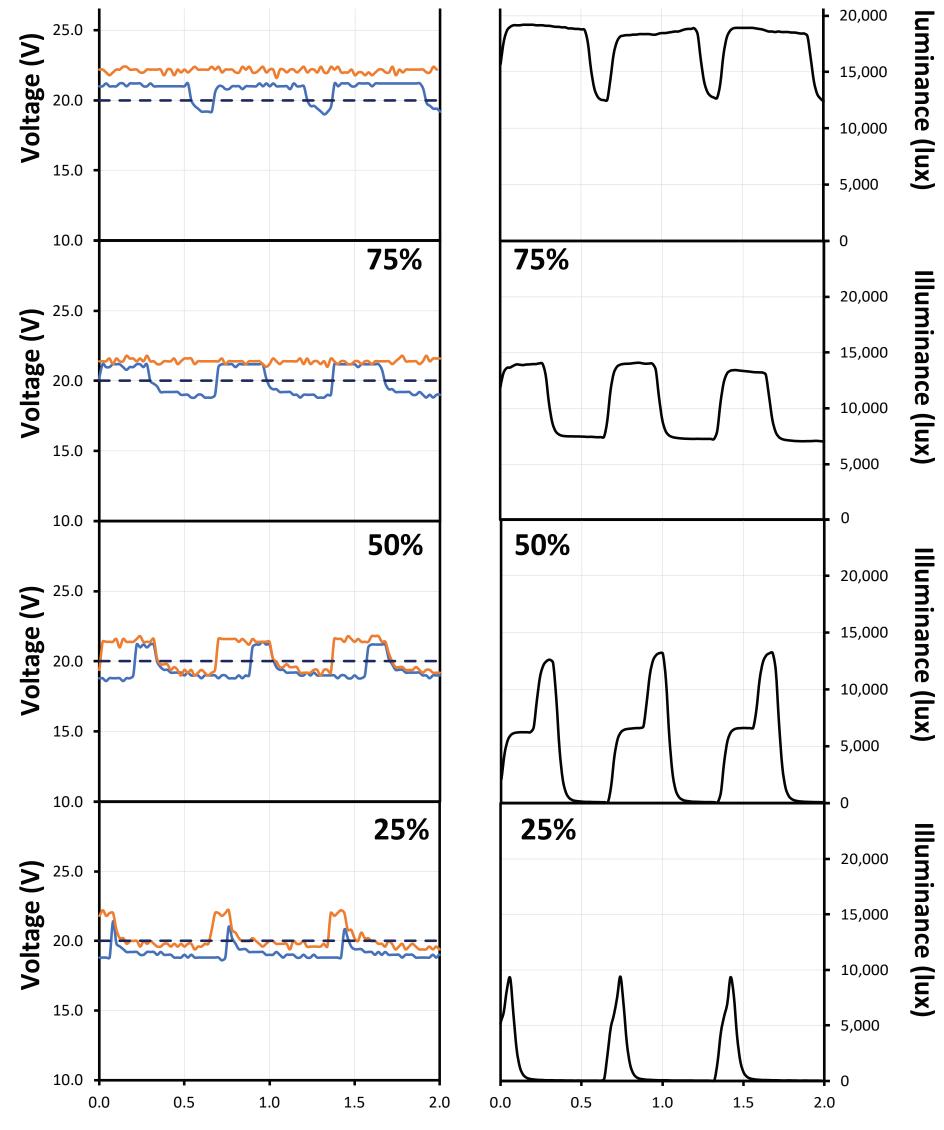
Degradation Processes

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.

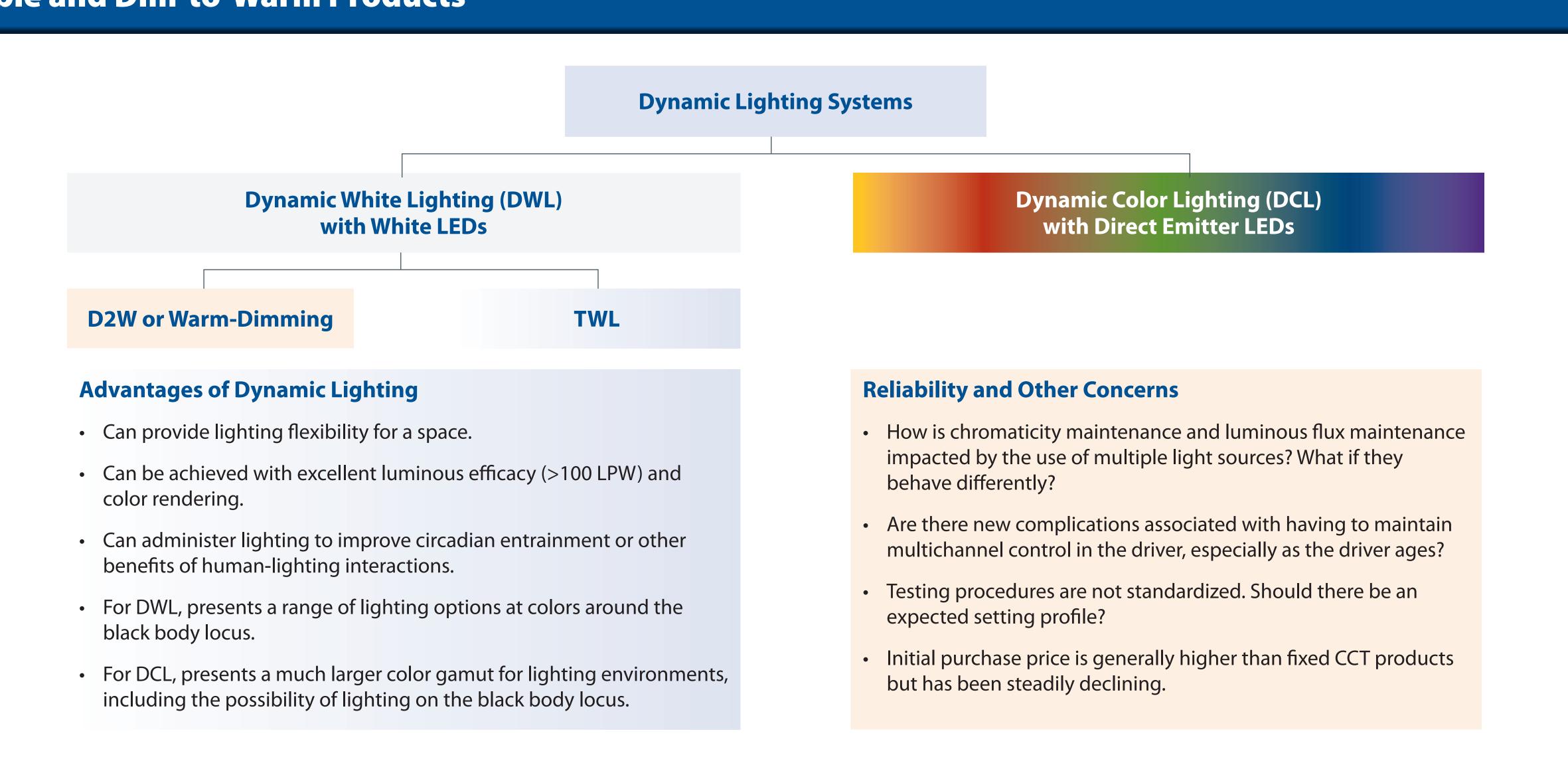


Understanding Photometric Flicker of TWL Systems



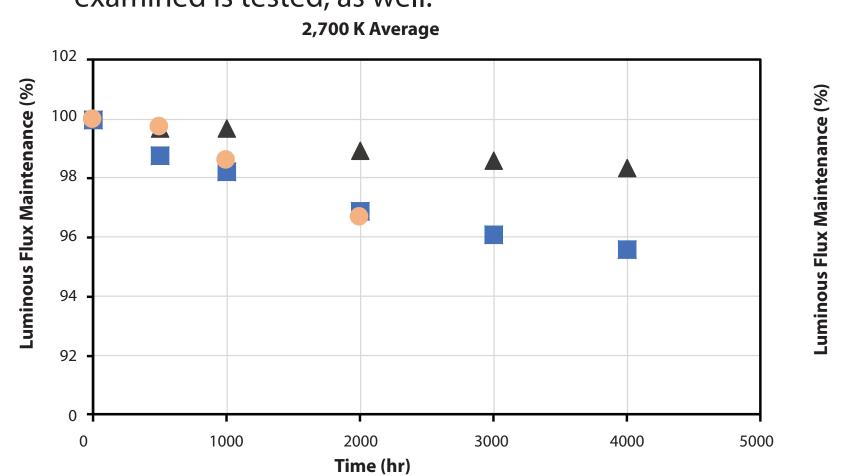
- The LED voltage waveforms (above left) and corresponding photometric flicker waveforms (above right) are shown at various dimming levels (red hue percent labels) for a two-stage dual-channel driver for TWL systems with two LED primaries. The correlated color temperature (CCT) is set to 3500 K. At 100% (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 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.

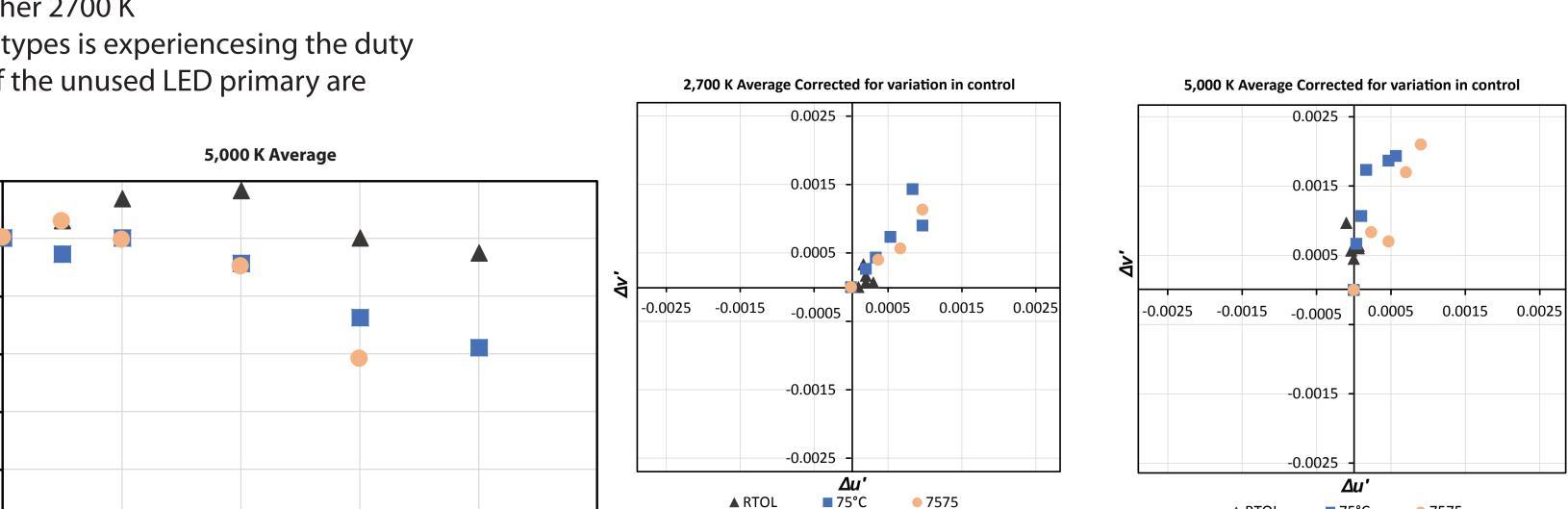
Tunable and Dim-to-Warm Products



Adjustable Color Recessed Lighting

- Recessed lighting with adjustable color is a recent addition to the household lighting market. These devices have two LED CCT sources, 2,700 K and 5,000 K, but are manually tunable with a switch on the back, before installation.
- Our experimental design (1-hour duty cycle and at either 75°C elevated ambient temperature bake or 75°C/75% RH) uses two populations in each AST setting. Each luminaire was assigned to be set at either 2700 K or 5,000 K. This ensures that so only one of the LED primaries types is experiencesing the duty cycle in AST. Every 3,000 hours, the photometric properties of the unused LED primary are examined is tested, as well.





Summary

- Testing of multiple generations of OLED panels and luminaires has shown consistent improvement in luminous flux maintenance lifetime. The best products are projected to operate for >36,000 hrs at room temperature before decaying to 70% of the original luminous flux level. Luminous flux maintenance is impacted by the overall stability of the organic emitters as weighted by the photopic sensitivity curve $(V(\lambda))$.
- Chromaticity maintenance in OLEDS has also shown consistent improvement and is within industry expectation. Chromaticity shift is also affected by the relative degradation rates of the organic emitters.
- In general, neutral white OLEDs exhibited better luminous flux maintenance than warm white OLEDs. However, warm white OLEDs typically exhibit better chromaticity
- Drivers remain a critical component of the reliability of SSL devices, and the multichannel drivers used in tunable sources places even greater demands on system reliability. The EMI filtering and surge suppression circuits in a typical driver are susceptible to degradation from environmental and electrical factors which can impact overall driver reliability.
- Many new tunable lighting technologies are becoming available in the market and the different LED technologies used in these devices are presenting new challenges to understanding SSL device reliability.

Recent Reports:

- Round 3 Update of Stress Testing Results for Organic Light-Emitting Diode Panels and Luminaires (pending)
- Part 3: Accelerated Stress Testing Results on Single-Channel and Multichannel Drivers: Final Report (February 2019)
- Accelerated Stress Testing of Multi-Source LED Products: Round 2 (July 2019)
- Dim-to-Warm LED Lighting: Initial Benchmarks (July 2019)
- Current findings can always be found at the DOE website: https://www.energy.gov/eere/ssl/technical-reports-briefs



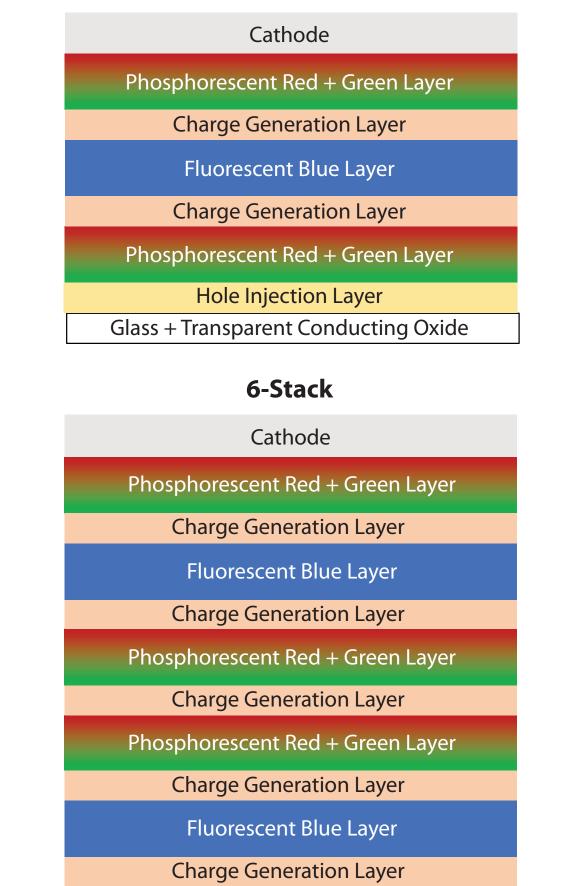
OLEDs

- OLEDs are an emerging technology often used for applications that require diffuse lighting sources in comparison to the more directional nature of traditional LED sources often OLED operational voltage increases over time with operation.
- A lack of low-voltage drivers has been identified as a key problem in device efficiency and robustness for OLED technologies.
- Widespread use of OLEDs has also been limited by the stability of organic emitters. Relative emitter stability of organic emitters can be tracked through chromaticity shift.
- RTI has tracked the aging of 3-stack configuration OLED luminaires over three product generations and 6-stack configuration OLED panels over two product generations, with separate populations tested in 25°C, 35°C and 45°C. The newest generation of 6-stack OLED panels was also tested in 65°C and 90% relative humidity due to new encapsulation

Key Findings

- Luminous flux maintenance of OLEDs depends on the overall stability of the organic emitters (weighted by $V(\lambda)$).
- The luminous flux maintenance of OLED panels and luminaires has improved significantly. Rated luminous flux maintenance lifetimes > 36,000 hrs are possible for room temperature
- Rated luminous flux maintenance lifetimes are typically shorter at higher temperatures and for warm white OLEDs.
- Improvements still needed in luminous efficacy.
- Chromaticity stability of OLED panels depends on the relative stability of the different organic emitters. Uneven degradation of organic emitters produces chromaticity shift.
- The chromaticity maintenance of OLEDs has also improved in the last 5 years and can be $\Delta u'v' = 0.004$ after 12,000 hrs at 45°C.
- The blue fluorescent emitter remains a challenge to efficiency and lifetime and is, likely, the reason why luminous flux maintenance is lower for warm white OLEDs than neutral white OLEDs.

Commercial OLED Sample Description



3-Stacks. Testing was performed on luminaires from three different generations.

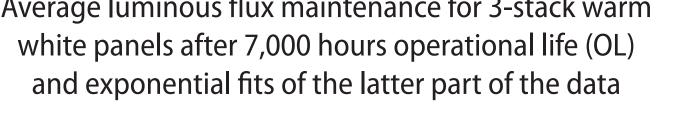
6-Stacks. Testing was performed on panels from two different generations. All tests performed on two CCT values.

Phosphorescent Red + Green Layer

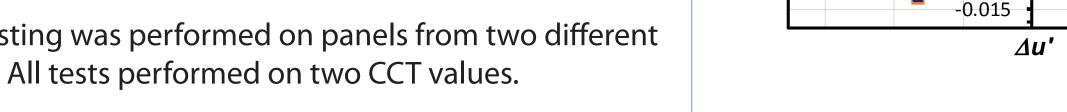
Glass + Transparent Conducting Oxide

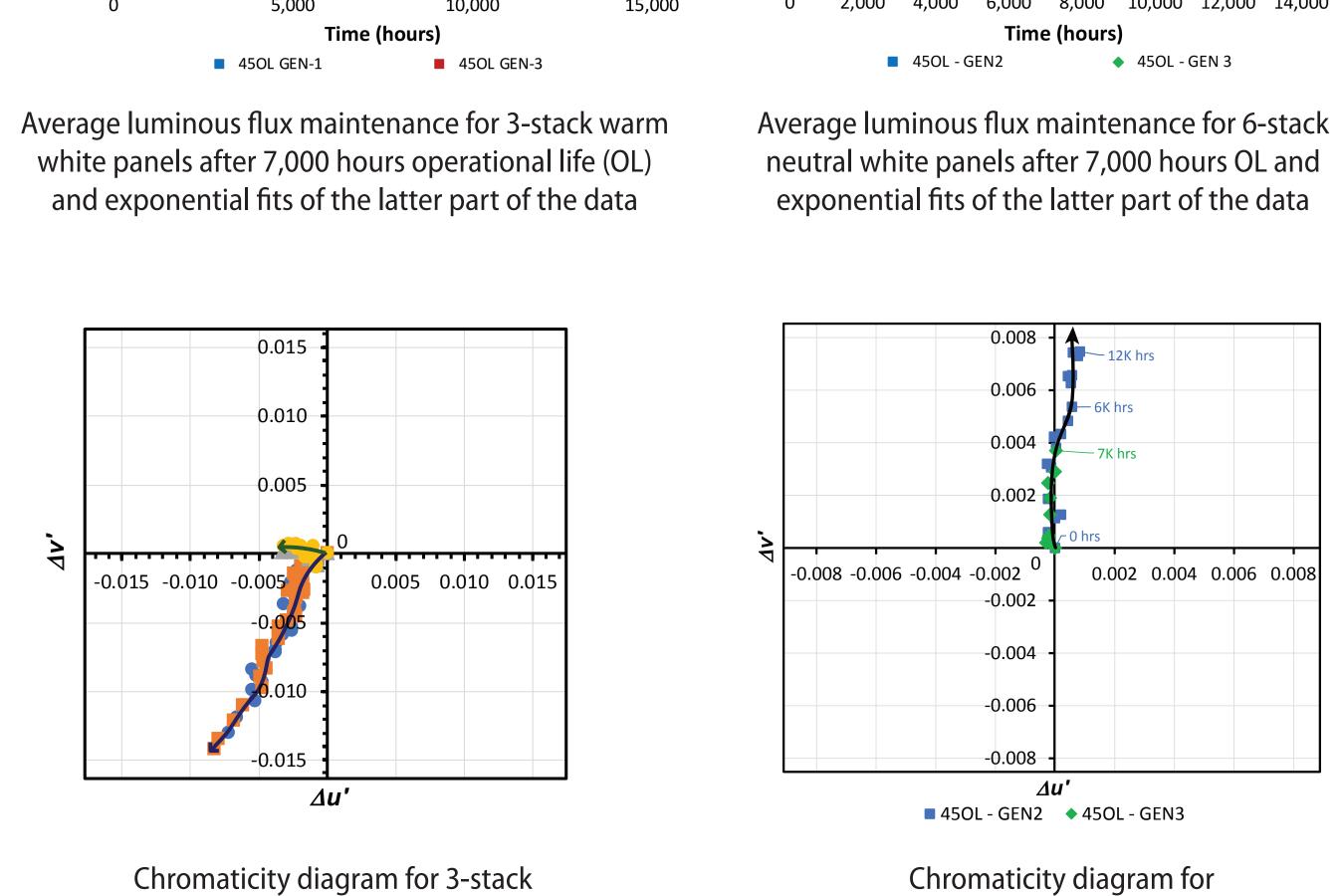
Manufacturer-supplied drivers included in test.

$y = 1.00e^{-1.4E-05t}$ $y = 0.98e^{-3.9E-05t}$ $y = 0.98e^{-1.6E-05t}$ $R^2 = 0.95$ $y = 1.13e^{-5.4E-05t}$ 4.000 6.000 8.000 10.000 12.000 14.000 Time (hours) 450L GEN-1 ■ 450L GEN-3



warm white panels





6-stack neutral white panels

Chromaticity of 3-Stack and 6-Stack OLED Panels Wavelength (nm)

→ 3-Stack WW → 6-Stack WW → 6-Stack NW

▲ RTOL ■ 75°C ● 7575

Through 4,000 hours, the affects of AST are most significantly seen in

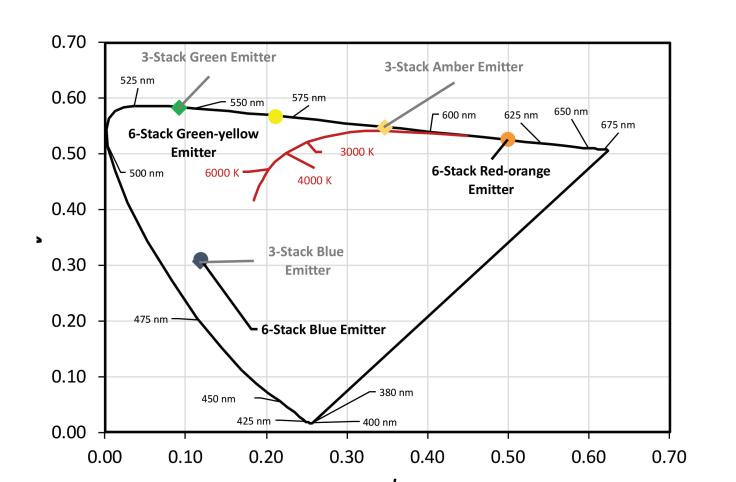
Both sources, in general, have chromaticity shift in the yellow-green

direction. However, the cool white, 5,000 K LEDs are shifting more

the cool white, 5,000 K LEDs.

rapidly in this direction.

- Blue is a fluorescent emitter.
- Red + Green are phosphorescent emitters.



- Luminous flux maintenance = stability of all emitters $V(\lambda)$ weighting.
- Chromaticity maintenance = relative stability of the emitters.

Acknowledgments

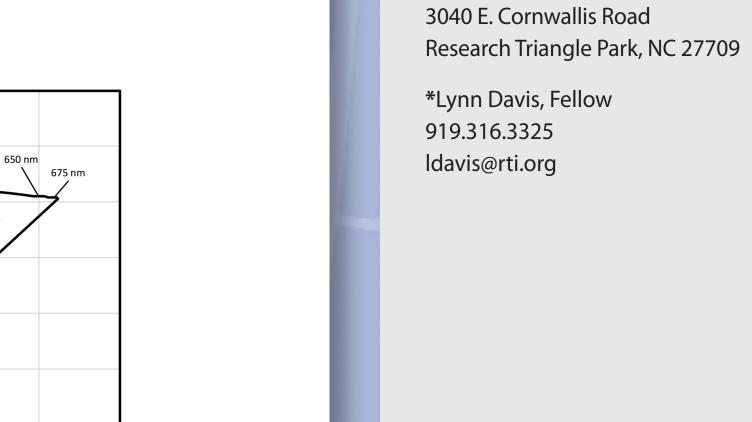
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