Leveraging Accelerated Testing to Assess the Reliability of Two-Stage and Multi-Channel Drivers

J. Lynn Davis,[1] Curtis Perkins,[1] Aaron Smith,[2] Terry Clark,[2] and Karmann Mills[1]

[1]RTI International
3040 East Cornwallis Road; Research Triangle Park, NC 27709
Contact Information: ldavis@rti.org

[2]Finelite, Inc.
30500 Whipple Road; Union City, CA 94587

Abstract

The next wave of LED lighting technology is likely to be tunable white lighting (TWL) devices which can adjust the colour of the emitted light between warm white (~ 2700 K) and cool white (~ 6500 K). This type of lighting system uses LED assemblies of two or more colours each controlled by separate driver channels that independently adjust the current levels to achieve the desired lighting colour. Drivers used in TWL devices are inherently more complex than those found in simple SSL devices, due to the number of electrical components in the driver required to achieve this level of control. The reliability of such lighting systems can only be studied using accelerated stress tests (AST) that accelerate the aging process to time frames that can be accommodated in laboratory testing. This paper describes AST methods and findings developed from AST data that provide insights into the lifetime of the main components of one-channel and multi-channel LED devices. The use of AST protocols to confirm product reliability is necessary to ensure that the technology can meet the performance and lifetime requirements of the intended application.

1. Background

Solid-state lighting (SSL) technologies continue to evolve rapidly from the standpoint of the capabilities provided by SSL devices and the reliability of the lighting system. This has resulted in greater leverage of light-emitting diode (LED) technologies and improved electronics integration to provide new capabilities in lighting systems and greater reliability. Among the added features beginning to emerge are tunable white lighting (TWL) products with higher power factors. Advances in SSL driver technologies play a critical role in these new products.

Single-colour LED-based luminaires have made significant market penetration in many demanding lighting applications. With the additional functionality available with LEDs, the next wave of LED lighting technology is likely to be TWL products that can adjust the spectrum of the emitted light between a range of values. This capability allows the light system to produce white light of an appropriate spectrum for the task at hand. For example, a warmer light (i.e., lower correlated colour temperature (CCT)) could be used for more relaxed tasks, such as conversations, while a cooler light (i.e., higher CCT) could be used for tasks requiring greater concentration and higher visual acuity [1-2].

TWL is produced using a light engine composed of LED modules containing assemblies of different LED colours (i.e., emission spectra), and the chromaticity is tuned by adjusting the current supplied to each LED assembly. The simplest TWL light engine uses only two different LED assemblies of different CCT values. Generally, this two-chip TWL approach is implemented with separate warm white and cool white LED assemblies although other two-chip approaches are possible. By varying the current supplied to the different assemblies, CCT values in-between those of the two end points (e.g., warm white and cool white) can be produced. Two-chip TWL solutions have the advantage of being simple to implement but the emitted light does not follow the Blackbody Locus.

An alternative approach to achieving TWL is to utilize three or more different LED assemblies in the modules. For example, direct emitters can be used to provide red, green, and blue colours that are mixed to produce white light. Additional colours such as amber or cyan can be added to improve the tuning range, light quality, and colour rendering. Utilizing three or more LED assemblies for TWL has the advantage of providing greater flexibility in light colours, including the advantage of following the Blackbody Locus. However, such lighting also requires a more complicated control system, which increases costs.

Driver technology is a key enabler for TWL since the different LED assemblies must be controlled separately. TWL products can either use separate drivers for each LED assembly or a more complex driver with the controls and switching for all channels, integrated into one unit. In general, a controller integrated circuit (IC) provides the control signals to operate the LEDs. In switched-mode power supplies, this control signal is supplied to the gate of metal-oxide semiconducting field-effect transistors (MOSFET), which act as switches to rapidly turn the LED assemblies on and off [3]. The switch-mode power supply design increases the overall driver efficiency, especially compared with that typically obtained with a linear power supply, but also introduces flicker into the light output [4].

Since control of the current supplied to each LED assembly is essential for colour tuning operation, separate MOSFETs and control signals, one for each assembly, are necessary. Schematically this can be represented by different signals from one controller IC, assuming the integrated multi-channel driver architecture, going to different MOSFETs which, in turn, feed the different LED assemblies, as shown in **Figure 1**. In practice, a single IC with separate channels for each LED assembly is used, and the MOSFETs are either integrated into the same package as the controller IC or are placed on the driver board as separate, discrete devices. Separate energy storage components (e.g., inductors and capacitors) are also part of the direct current (DC) output for each channel.

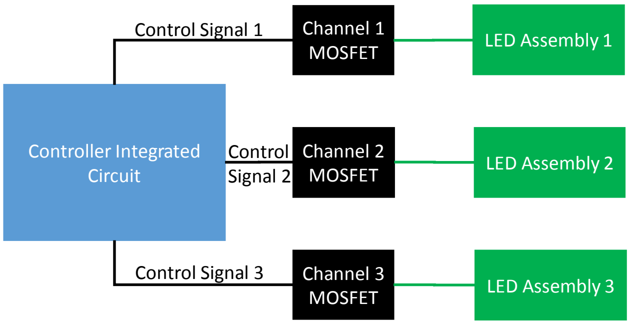

Figure 1: Schematic illustration of the driver structure for multi-channel TWL drivers.

As an additional consideration, it is often desirable to have high power factors in TWL drivers which is difficult to achieve in a single-stage design. Consequently, two-stage designs are becoming more common. In this approach, the first stage provides filtering/rectification of the alternating current (AC) input power as well as power factor correction (PFC). The output from the first stage is an intermediate DC signal that feeds the second stage which in-turn drives the LEDs. Perhaps the most common multi-stage driver design is a two-stage typology using a flyback circuit in the first stage and a buck circuit in the second. While multi-stage designs improve driver power factor, this approach introduces additional complexity that needs to be understood from a reliability standpoint.

In this paper, we report on findings to date on accelerated stress testing (AST) of one-stage and two-stage SSL drivers that could be used for TWL devices. All the testing has been performed using wet high-temperature operational lifetime (WHTOL) protocols which have been shown to help identify failure modes in SSL devices [5]. To help understand the characteristics of accelerated testing on multi-stage, multi-channel drivers, we first examined a single-channel multi-stage driver used in a 6” downlights and then proceeded to study more complex single-channel and multi-channel devices. In general, AST protocols are needed for this type of study due to the long lifetimes of electronic drivers. Information from these tests can help determine the critical areas in these devices where failures may occur and provide guidance on potential limitations of such devices.

2. Experimental

During this work, accelerated aging testing of commercial LED drivers was performed using an experimental chamber set to either 75˚C and 75% relative humidity (7575) or 65˚C and 90% relative humidity (6590). These environments were chosen as the WHTOL protocol since we have previously shown that these conditions accelerate failure modes in a wide variety of components used in SSL devices [5]. Most drivers were placed inside the environmental chamber and connected to external electrical loads (i.e., in the form of LED modules) that were placed outside the chamber as shown in **Figure 2**. In most cases, the operational load was chosen to be roughly 90% of the maximum power rating for the tested driver. However, for the extended tests on two-stage single-channel devices, a 6” downlight was used as the test samples so the LEDs and the driver were subjected to 7575 together.

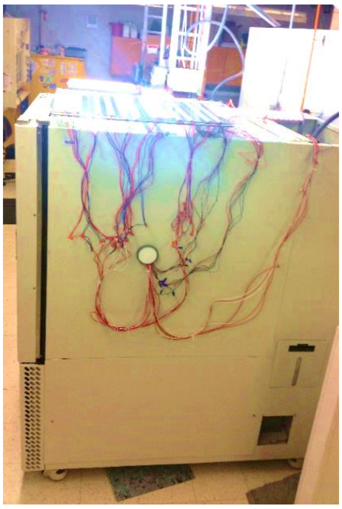

Figure 2: Picture of the test setup with the electrical loads (i.e., LED modules) external to the environmental chamber and wires running to the drivers.

The 7575 test was an operational test so power was supplied to the drivers with a one-hour on and one-hour off duty cycle. Several measurements were used to track the aging of the drivers before and during 7575 testing. Electrical measurements such as power consumption and power factor were made using a Kill-A-Watt meter.

Since most of the LED loads were placed external to the environmental chamber during 7575 testing, flicker measurements were performed periodically as part of the driver characterization. These flicker measurements were taken with a small integrating sphere, containing a highly diffuse reflecting interior coating, placed over a portion of the appropriate LED module [6]. Photometric flicker readings were obtained at a measurement port on the integrating sphere using a hand-held flicker meter (GigaHertz, Model BTS-256-EF). Flicker readings were taken at 20 μsec intervals for a duration of 40.94 ms (2048 samples).

The drivers examined in this study were commercially available SSL devices with power consumptions ranging from 10 W to 140 W. Additional characteristics of these products are given in **Table 1**. Although most drivers had dimmer capability, this study was performed without any dimming applied. Product A was a 6” downlight with the two-stage driver integrated into the housing, and both the drivers and LEDs were placed in the environmental chamber. A total of 10 samples were tested for this product. Only one sample of Product E was tested due to its high power output. Two samples of each of the remaining drivers were tested and these devices allowed the electrical load (i.e., LED modules) to be placed outside the environmental. Product-F was the only device that used MOSFETs integrated into the controller IC package, and there were separate MOSFETs for each channel integrated into the IC package. The other devices utilized a design in which separate, discrete MOSFET components were used for each channel and the controller IC was packaged separately.

Table 1. Characteristics of the DUTs examined in this study.

Product No.	Initial Power Consumption and Power Factor	Number of Channels
Driver-A	10.2 W, PF = 0.93	1
Driver-B	53.0 W, PF = 0.99	1
Driver-C	42.7 W, PF = 0.99	1
Driver-D	56.2 W, PF = 0.99	1
Driver-E	140 W, PF = 0.99	2
Driver-F	38.2 W, PF = 0.99	4
Driver-G	48.0 W, PF = 0.99	4

3. Results

Benchmarks of 6" Downlights with Two-Stage Drivers

An examination of the performance of the single-channel, two-stage downlight product provides insights into the aging characteristics of multi-stage drivers. Figure 3 shows the switching signals for the MOSFET from a downlight device used as a control. The gate control signal originates from the controller IC and determines the MOSFET switching characteristics. The source and drain signals demonstrate the actual MOSFET operation. Similar graphs are provided in **Figure 4** and **Figure 5** for devices exposed to 7575 (4,000 hours) and 6590 (2,250 hours), respectively.

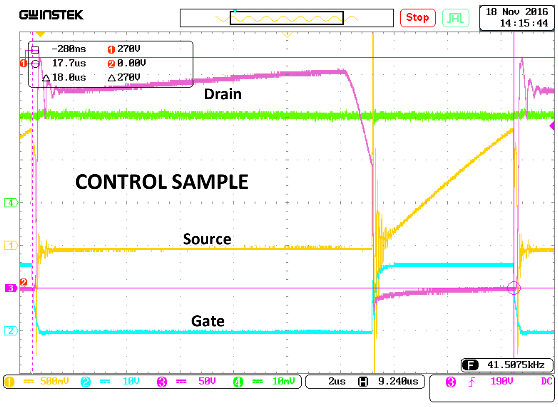

Figure 3: MOSFET switching signals for the control downlight using two-stage driver.

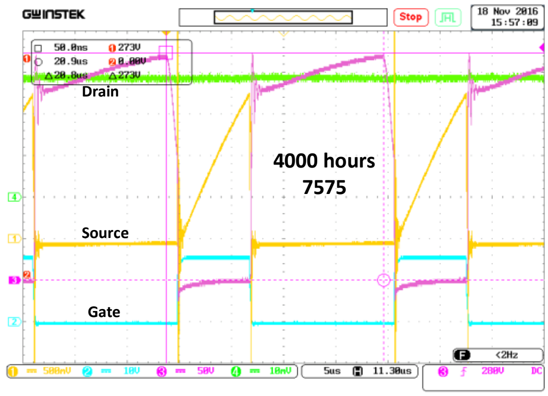

Figure 4: MOSFET switching signals after 4,000 hours of 7575 testing for a 6" downlight with a two-stage driver.

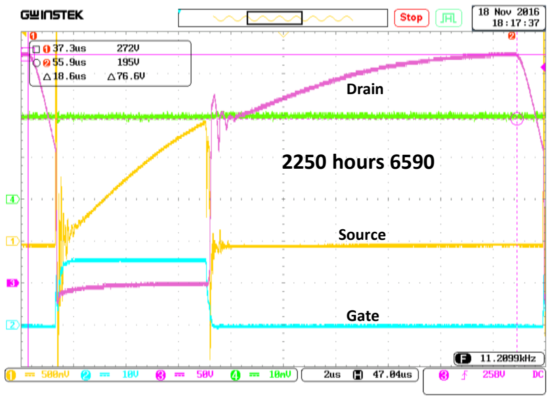

Figure 5: MOSFET switching signals after 2,250 hours of 6590 testing for a 6" downlight with a two-stage driver.

A closer examination of Figure 4 and Figure 5 reveals the emergence of a parasitic capacitance on the drain waveform after WHTOL testing as evidenced by the slow rise in drain voltage after switching compared to the control. This finding suggests some degradation of the drain in the MOSFET during operation in WHTOL. There is also come capacitance on the source side of the MOSFET as shown by the slow voltage rise, but this level of capacitance changes little during testing. The net result of the increase in parasitic capacitance on the drain is a reduction in driver efficiency that varied from 1% to 5% depending on the sample and testing protocol. The net result of the lower driver efficiency is an increase in dissipated power within the driver resulting in increased component and board temperatures. This outcome was confirmed using thermal imaging.

In addition, measurement of the power consumption of the downlights indicated that this parameter increased with exposure time in WHTOL testing as shown in **Figure 6**. The power consumption in both WHTOL environments was virtually unchanged for the first 1,000 to 1,500 hours, but then began to steadily increase. The increase occurred sooner and increased rapidly for the 6590 environment than in 7575. This finding is consistent with the generally lower efficiency that was measured for the downlight sample subjected to 6590 than those subjected to 7575.

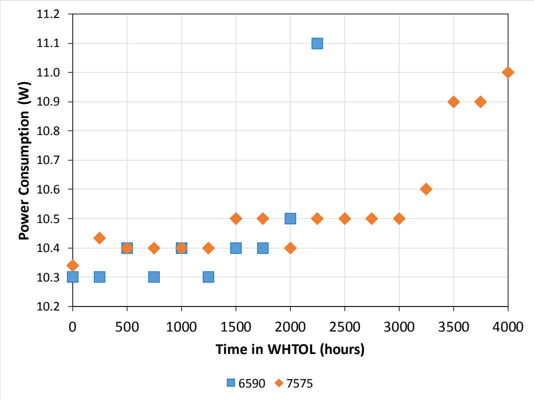

Figure 6: Power consumption of 6” downlights during 6590 (blue squares) and 7575 exposures (orange diamonds).

Despite the increased parasitic capacitance, all devices were fully operational at the end of testing, although the luminous efficacy (combined lumen maintenance and driver efficiency inputs) of the devices in WHTOL had decreased below 60% of the initial value. Thermal management of the MOSFET is clearly important in minimizing the growth of parasitic capacitances on both the source and drain and in achieving desired reliability levels [7-9]. This outcome clearly demonstrates that designs with good MOSFET thermal management will likely have good reliability.

Single-Channel Two-Stage Drivers

As part of this evaluation, three different commercial single-channel, two-stage driver products were tested in 7575. The drivers were connected to LED modules that served as electrical loads during *in situ* operational testing. Single-channel drivers can be used in TWL devices if a separate driver is used for each LED assemblies. The performance of these devices as a function of exposure time in 7575 was monitored using photometric flicker and power measurements and a summary of findings is given in **Table 2**. In general, minimal changes in both electrical characteristics and flicker performance were found with these drivers after 2,250 hours of 7575.

Table 2. Change in electrical and photometric properties for two-stage, one-channel drivers.*

	Driver B	Driver C	Driver D
Initial Power	53.0 W	42.7 W	56.2 W
Power @ 2,250 hr	53.0 W	42.6 W	56.8 W
Initial Flicker %	0.6%	0.2%	0.6%
Flicker % @ 2,250 hr	0.6%	0.2%	0.6%
Initial Flicker Frequency	1971 Hz	Not detected	122 Hz
Flicker Frequency @ 2,250 hr	1971 Hz	Not detected	122 Hz

* Two samples of each product was tested.

Multi-channel and multi-stage drivers

In the final phase of this evaluation, three different commercial multi-channel, two-stage driver products were tested in 7575. Two samples of Driver F and Driver G were tested, but only one sample of Driver E due to its higher output power. For simplicity, only two channels on each driver were tested and approximately equal currents were supplied to each channel. This setting corresponds to roughly a mid-point CCT value in a TWL system. Separate LED assemblies were used for each channel with one driver channel connected to warm white LED assemblies and the second driver connected to cool white LED assemblies. LED modules, consisting of cool white and warm white LED assemblies, were used as electrical loads during testing. These loads were placed external to the environmental chamber which enabled monitoring of the devices during 7575.

The performance of these four-channel multi-stage drivers during WHTOL testing was monitored using photometric flicker and power measurements, and a summary of initial and final values of key parameters is given in **Table 3**.

Table 3. Change in electrical and photometric properties for multi-stage, four-channel drivers.

	Driver E	Driver F	Driver G
Initial Power	140 W	38.2 W	48.0 W
Power @ 2,250 hr	Failed	40.0 W	48.2 W
Initial Flicker %	0.6%	23.9%	3.9%
Flicker % @ 2,250 hr	Failed	23.9%	3.7%
Initial Flicker Frequency	434 Hz	1440 Hz	300 Hz
FI @ 2,250 hr	Failed	1453 Hz	300 Hz

* One sample of Driver E was tested and two samples of both Driver F and Driver G were tested.

In general, the performance of the multi-channel drivers changed more than the single-channel drivers in 7575. The lone sample of Driver E failed after 1,750 hours of 7575, and electrical examination of the failed part indicated that the first stage of the driver was operating correctly (i.e., the stage containing AC rectification, conditioning, and PFC) and the point of failure was likely in the second stage. Since the driver was potted, a more detailed failure analysis was not possible; however, based on our previous findings, it is possible that the failure of the device involved the MOSFET in Stage 2 [5].

Drivers F and G exhibited minimal change in photometric flicker performance, in line with the behavior found with the single channel drivers. However, there was an increase in power consumption, especially with Driver F samples, as 7575 exposure progressed. Based on our study on two-stage drivers in 6” downlights, we believe that this increase in power consumption arises from increased capacitance in the device, potentially caused in part by parasitic capacitance in the switching MOSFETs. For Driver-F, there was also some evidence of the driver output being reduced by the controller chip during 7575 testing due to high temperatures. The integration of the switching MOSFETs into the same package as the controller IC resulted in a higher temperature at the controller chip package during 7575 than was found for other parts of the circuit. As a result of more limited thermal performance of the integrated device, the integrated control chip scaled back the output power during 7575 for Driver-F to avoid overheating. The other driver products utilized separate controller ICs and MOSFETs so the thermal limitations were not a great and the devices operated at full power during 7575 testing.

4. Discussion

Electronic drivers play a key role in SSL devices employing tunable white technologies. The driver not only must meet the reliability standards established by existing SSL technologies, but must also deliver adjustable current levels to each of the different LED modules in order to tune the colour of the white light. This capability can be achieved in two different ways. Either separate drivers can be used for each LED assembly in the tunable light engine or all the controls and electronics can be assembled into a single driver and distributed to the appropriate LED assemblies. The integrated driver solution offers the possibility of thinner product profiles but adds complexity into the driver that could affect reliability. The multi-driver approach for TWL devices enables existing optimized single-channel driver technology to be used but can also increases product size.

As demonstrated by the extended aging study on the two-stage single-channel driver in the 6" downlight, driver performance will degrade during use in 7575 and increased parasitic capacitance in the MOSFET is responsible for at least part for the increase in power consumption. While the point of failure of SSL drivers will depend upon many factors including driver design, thermal management, component derating, and input power quality, we have found that components in Stage 2 of the driver including MOSFETs and capacitors are especially prone to degradation in WHTOL. Although the power consumption of the 6" downlights increased, indicating some level of degradation in the electronics, the overall performance of the driver generally stayed within parametric limits through 4,000 hours of testing under 7575 conditions. Given that WHTOL testing creates a highly accelerated lifetime, achieving this level of performance in a commercial downlight product is significant. Testing of these devices was eventually halted at the 4,000-hour mark due to an issue with the LEDs – the exposed lead frame in the mid-power LEDs darkened during testing causing luminous flux maintenance to drop below the 0.5 level. It is important to note that this outcome was the result of the LED used in this product and not the driver [10, 11].

The larger single-channel, two-stage drivers (Drivers B, C, and D) exhibited excellent performance in 7575 with minimal changes in power consumption, driver efficiency, and device flicker through 2,250 hours of testing. This finding indicates that traditional one-channel driver technology can provide excellent reliability in many applications including tunable white lighting.

There was some level of change in performance of the multi-channel drivers in 7575. The lone sample of Driver E experienced abrupt failure following 1,750 of exposure. The full cause of the failure is not known but likely resides in the Stage 2 electronics, possible involving the MOSFET. The two-channel product Driver F demonstrated an increase in power consumption after 7575 testing, which suggests that there may be some level of electronics degradation in the products. However, the photometric properties of the LED modules attached to these samples of this product did not show any changes. This finding indicates that while some degradation of the product may have occurred during accelerated testing, device operation has been minimally affected and the expected lifetime is still excellent. The two-channel product Driver G also exhibited minimal change in electrical and photometric flicker performance even after 2,250 hours of exposure to 7575. This finding provides additional support that two-channel drivers can provide high reliability in TWL applications if designed properly.

Conclusions

TWL lighting devices is likely the next wave of LED technologies, and the performance of the driver is especially key in these devices. We have demonstrated that single-channel drivers can be used in TWL products and provide high reliability. This conclusion was based on the finding that no failures were observed and virtually no changes in power consumption, driver efficiency, and photometric flicker properties were measured during the WHTOL tests. However, using single-channel drivers in WTL devices requires a separate driver for each LED module.

Multi-channel drivers allow a single driver to control all tunable white settings. However, this study demonstrates that care must be taken in choosing the driver and operational conditions to achieve high product reliability. The high-powered Driver E failed abruptly at 1,750 hours of testing. While there was an increase in power consumption for both of the Driver F samples, the photometric flicker properties of the LED modules powered by these devices were unchanged after 2,270 hours of exposure which is an indication that the increased power consumption is having a minimal impact on driver performance.

In summary, driver performance is key to the overall reliability of WTL devices and excellent performance can be achieved in multi-channel, two-stage drivers, as demonstrated by Driver G and to some extent by Driver F. This work suggests that the added complexity of multi-channel drivers could impact reliability so additional research is needed to understand the potential impacts.

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