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Accelerated Stress Testing on Multichannel Drivers—Updated Test Results

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U.S. Department of Energy
3610 Collins Ferry Road
Morgantown, WV 26505

Prepared by

RTI Authors: Kelley Rountree, Lynn Davis, and Karmann Mills
RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

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Disclaimer

List of Acronyms

°C	degree Celsius
β	Weibull shape parameter
η	Weibull scale parameter
A	Ampere
ac	alternating current
AST	accelerated stress testing
CCT	correlated color temperature
Ch. 1	Channel 1
Ch. 3	Channel 3
dc	direct current
DMX	digital multiplex
DOE	U.S. Department of Energy
DUT	device under test
ESR	equivalent series resistance
F(t)	cumulative distribution function of a population
g	gram
HALT	highly accelerated lifetime testing
Hr	hour
Hz	hertz
IC	integrated circuit
IP	ingress protection
lux	illuminance
K	Kelvin
kV	kilovolt
LED	light-emitting diode
LLC	inductor–inductor capacitor
LSRC	LED Systems Reliability Consortium
mA	milliampere
MOSFET	metal-oxide-semiconductor field-effect transistor
ms	millisecond

nF	nanoFarad
PF	power factor
PFC	power factor correction
RTOL	room temperature operational lifetime
SPD	spectral power distribution
SSL	solid-state lighting
t	time
TC	thermocouple
THD	total harmonic distortion
TWL	tunable-white lighting
V	volt
W	watt

Executive Summary

The primary function of a solid-state lighting (SSL) driver is to convert the alternating current (ac) from the electrical mains power to a suitable direct current (dc) that can operate the light-emitting diodes (LEDs) in an illumination source. To complete the conversion from ac to dc, the driver uses a series of circuits that are often set up in two stages (i.e., a two-stage driver) where ac is converted to an intermediate dc signal and then later converted to a final dc output. The reliability and efficiency of the SSL driver is dependent upon the reliability of every component located in the electrical circuits. Therefore, components that are more susceptible to failure during driver operation are likely to cause abrupt failure of the entire SSL device.

As LEDs impart new capabilities to SSLs, including the ability to incorporate multiple LED primaries into a single light source to provide a tunable spectral power distribution, control over the power (current) delivered to each LED primary is necessary. The power provided to each LED primary is controlled by either assigning individual, single-channel drivers to each LED primary or using one driver with separate power control channels for each LED primary (i.e., a multichannel driver). The robustness and system complexity of SSL drivers capable of controlling multiple LED primaries is examined in this study.

This report is the second in a series of studies about accelerated stress testing (AST) of drivers used for SSL luminaires. Two-stage drivers intended for use in downlights, troffers and street lights were selected to undergo exposure to an AST environment consisting of 75°C and 75% relative humidity (7575). The 7575 AST environment was chosen for this study because a previous study demonstrated that 38% of a sample population of 6-inch downlights failed in less than 2,500 hours in these conditions. A mixture of single-channel (i.e., one output current channel designed for use with one LED primary) and multichannel (i.e., separate output current channels designed for use with multiple for LED primaries) two-stage drivers were exposed to the 7575 environment. This report provides updated AST test results for only the multichannel driver products. The multichannel driver population consisted of three products (with two-stage architecture) and a total of five samples. In addition to AST results, the product life distribution (Weibull analysis) of two-stage driver Hammer Test samples is reported.

Through 4,000 hours of exposure to the 7575 environment, three of the five tested multichannel drivers (60%) failed. The first device to fail was a single sample of one product that failed relatively quickly into testing (1,250 hours). The device failed abruptly in the inductor–inductor capacitor (LLC) converter circuits. In addition, both samples of another product failed after cumulative ageing in the 7575 environment exceeded 3,000 hours. For the samples of this second product, photometric flicker and incorrect correlated color temperature readings (for a given control signal) were produced by the drivers just prior to failure. Before that time, only normal operation was observed. Upon inspection, both of these failed samples showed signs of excessive heat near the metal-oxide semiconducting field effect transistor (MOSFET) and transformer of the intermediate dc circuit, though only one experienced MOSFET failure at this position, whereas the other experienced capacitor and fuse failure in the filter and condition circuit.

The two samples of the third product remained operational through 4,000 hours of exposure to the 7575 environment and exhibited minimal changes in electrical and photometric properties. The most notable electrical change was an increase in power factor (PF) at low dimming levels that led to efficiency increases up to 5%. Additionally, a change in the harmonic components of the Fourier transform of the illuminance at low dimming levels was also observed during photometric flicker testing as ageing increased. The slight increase in electrical efficiency and the change in photometric flicker waveform described for these samples was not significant enough to be noticed by the end user.

The findings in this report continue to support that many of the drivers used in SSL devices are highly robust. The extreme conditions of the 7575 environment produced minimal changes until failure was imminent. In addition, these findings suggest that degradation of SSL drivers may be monitored through changes in parameters such as PF, inrush current, and photometric flicker of attached LED loads at low dimming levels.

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1 Introduction

The widespread use of two or more different light-emitting diodes (LEDs) as light sources imparts a new capability to solid-state lighting (SSL) luminaires—the ability to tune the lighting spectrum to a particular spectral power distribution (SPD).[1] This ability has potential advantages in office spaces, schools, and healthcare facilities, arising from the physiological effects on humans caused by light.[2*] Achieving this level of performance places greater requirements on the drivers used in such products. First, the drivers should provide higher power factors (PFs), which are usually achieved with two-stage architectures. The driver converts the input alternating current (ac) to an intermediate direct current (dc) voltage with power factor correction (PFC) in Stage 1. Then, the driver converts the intermediate dc to a final dc output voltage for operating the LEDs in Stage 2. The second requirement is that the drivers used in tunable-white lighting (TWL) systems must have two or more control channels – one for each LED primary.[1] The cumulative effects of ageing that occur within an SSL driver over its operational life can lead to changes in current delivery to the LED primaries or failure of the entire luminaire, producing abrupt failures, reduced luminous flux failures, and even excess flicker failures.

The greater complexity, additional cost, and unknown reliability of two-stage, multichannel drivers have motivated this work to better understand the reliability and failure modes and to possibly provide early indicators of degradation for the drivers used in common luminaires such as downlights, troffers, and street lights. To study product robustness, a representative group of single-channel and two-stage multichannel commercial driver products were exposed to an accelerated stress testing (AST) environment of 75 degrees Celsius (°C) and 75% relative humidity (7575). Complete descriptions of this test and the chosen SSL drivers are provided in the Initial Results report.[3] The current report is an update on the findings from this study based on additional testing.

The previous report provided detailed descriptions of two-stage drivers, including common electronic circuitry, topologies, and configuration.[3] The findings in that report demonstrated good reliability of stand-alone single-channel and two-stage multichannel drivers through 2,500 hours of ageing in an AST environment of 7575. This follow-up report includes new ageing data from 7575 testing of multichannel drivers through 4,000 hours. This report also provides a more detailed life data analysis, drawing on the previous Hammer Test results,[4] but does not consider room temperature operational lifetime (RTOL) tests.

This current report is part of a planned series that documents AST findings for single-channel and multichannel drivers used for SSL luminaires. A final report is expected to be produced at the end of driver robustness testing to summarize overall results. Upon completion, the reports in this series will include information about the following items:

- **Initial Results of Accelerated Stress Testing on Single-Channel and Multichannel Drivers (Status: Completed[3]).** This report describes the electronics used in two-stage drivers and the performance of commercial driver products exposed to 7575. This report also provides electrical characterization of the drivers and photometric characterization of LED loads operated by the test drivers after 2,500 hours of ageing in 7575. A comparison of the Hammer Test results on select 6-inch downlights with RTOL test results is also provided.
- **Accelerated Stress Testing on Multichannel Drivers—Interim Update (Status: Current report).** This report updates the ageing data of multichannel drivers exposed to 7575 AST environment to 4,000 hours and identifies potential indicators of degradation in driver performance. An updated understanding

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[*] In tunable lighting products, the correlated color temperature (CCT) is often used as a indication of the spectra changes: higher CCT values generally denote higher blue content in the illumination, whereas lower CCT values generally denote higher red content.[1] There are several limitations to referring to the spectrum of a tunable source solely by its CCT value. However, for the linear TWL sources that are the general focus of this report, CCT is an adequate indicator of the lighting spectrum and will be used to indicate the control setting of the TWL device.

of SSL driver lifetime reliability is given by using Weibull analysis to compare the 7575 AST environment to previously studied Hammer Tests.

- **Accelerated Stress Testing on Single-Channel and Multichannel Drivers—Final Report (Status: Pending).** This report will summarize the failure analysis from the single-channel and multichannel drivers operated in AST environments.

2 Background Information

2.1 Types of Accelerated Stress Testing

As the capability and market opportunity for SSL luminaires broadens (e.g., color-tunability is possible when using at least two LED primaries), the complexity and uniqueness of drivers to fulfill lighting-specific applications also increases. Several reports have shown that even one component failure (or a cascade of small changes because of ageing) in the SSL driver can lead to lower device performance, excessive flicker, or even abrupt lights-out failure.[3–10] Because SSL luminaires are expected to be more reliable and efficient than conventional lighting sources, ASTs consisting of elevated environmental stresses are used to produce conditions that increase the failure rate so that device failures occur in a timeframe conducive to laboratory testing.

2.1.1 Accelerated Stress Testing

Many conditions and/or processes are known to accelerate the ageing of SSL luminaires. Some of these conditions and/or processes include operation in elevated temperatures, elevated humidity, environments with a large number of airborne particulates, increased current densities supplied to the LED primaries, and thermal or power cycling of the device. In AST protocols, devices are controllably subjected to one or more of these stress factors for an extended period. An ideal AST expedites the ageing process to induce failures of a similar nature to those that would be encountered during normal operation and does not induce new failure mechanisms. Therefore, to maintain realistic temperature or humidity environments, AST environments often use a modest ramp to change environmental exposure settings (e.g., temperature, humidity) as opposed to rapid shock changes. When appropriate AST conditions are chosen, manufacturers are provided with a sense of what components in a device might fail without needing to operate the device for a lengthy and costly period of time. The identification of possible failure modes allows a more quantitative study of the failed component and failure mechanisms to improve device reliability.

Previous studies identified an acceptable ALT for integrated SSL drivers within a sample population of 6-inch downlights. The demonstrated work showed that an AST environment with nominal conditions of 75°C and 75% relative humidity (7575) led to electrical failure of 38% of the 6-inch downlight population in less than 2,500 hours of exposure to 7575.[10] A 1-hour on and 1-hour off power cycle was used in this test and produced some thermal cycling in the devices above the chamber temperature. The 6-inch downlights examined during this previous study contained a mix of single-stage and two-stage drivers and at least one tested product used a multichannel driver for control of a hybrid LED light source. Although the end application of the two-stage multichannel drivers studied in this current report is different than the 6-inch downlights previously studied (troffer and street lighting for the drivers versus residential and low-level office lighting for the downlights), the similarities between the drivers used during both instances motivated this current report.

2.1.2 Highly Accelerated Lifetime Testing

Highly accelerated lifetime testing (HALT) is a more accelerated version of AST and is not intended to be a universal reliability test for luminaires.[4] HALT is a screening protocol designed to provide feedback about the potential failure modes of luminaires in a quick timeframe (less than 2,000 hours). The identified failures from HALT provide qualitative information that can be further quantified by less aggressive ASTs. One of the earliest reported HALT testing methods was the Hammer Test initiated by the LED Systems Reliability

Consortium (LSRC).[4] The U.S. Department of Energy (DOE) has funded other HALT studies that include testing of the Philips L-Prize lamps[11] and stress testing of PAR38 lamps.[12]

The Hammer Test as conducted under guidance from the LSRC consisted of multiple loops (or cycles) of different ASTs, applied sequentially to the same luminaires. Each loop of the tests lasted for 42 hours and included four stages of environmental stress tests that were modeled after common methods used in ASTs in the electronics industry.[4] The four stages are described as follows:

- **Stage 1** lasts for 6 hours. The environmental chamber is first changed from room conditions and set to 85°C and 85% relative humidity. Power is applied to the devices under test (DUTs) on a 1-hour on and 1-hour off cycle.
- **Stage 2** lasts for 15 hours. DUTs are subject to temperature shock, consisting of −50°C and 125°C (air-to-air). The dwell time at each extreme is 30 minutes.
- **Stage 3** lasts for 6 hours. The environmental chamber is set to 85°C and 85% relative humidity, and power is applied to the devices on a 1-hour cycle.
- **Stage 4** lasts for 15 hours. DUTs are subject to high-temperature operational lifetime, consisting of a bake at 120°C. Power to the devices is cycled on and off hourly.

2.2 Weibull Analysis

The Weibull distribution is commonly used in reliability engineering and life data analysis to model a wide range of life behaviors. The cumulative distribution function of a population, *F(t)*, assuming a failure distribution that can be described by two-parameter Weibull function, describes the total fraction of the population, which has failed by time, *t*, which is calculated as shown in Equation 1, as follows:

$$F(t) = 1 - \exp\left(-\frac{t}{\eta}\right)\beta \qquad \text{(Eq. 1)}$$

Where

η = The Weibull scale parameter (also known as the characteristic life)
β = The Weibull shape parameter.

The Weibull scale parameter, η ($\eta > 0$), is also known as the characteristic life and describes the time for 63.2% of the population to fail. Small values of η suggests that the samples within the population failed quickly and in relatively close time proximity to each other, whereas larger values of η indicate a larger distribution in failure time. The Weibull shape parameter, β ($\beta > 0$ [also known as the Weibull slope]) describes the probability of failure over time. Weibull distributions with $\beta < 1$ are indicative of populations with early life failures and the failure rate decreases over time, whereas Weibull distributions with $\beta > 1$ are indicative of populations with wear-out failures (i.e., the failure rate increases with time). Weibull distributions with $\beta \approx 1$ indicate that the failure rate is constant with time.

The Weibull equation (i.e., Equation 1) can also be reformatted into a linear equation and plotted as a line.[13] The linear form of the Weibull equation is shown in Equation 2, as follows:

$$\ln\{-\ln[1 - \mathrm{F}(t)]\} = -\beta\ln(\eta) + \beta\ln(t) \qquad \text{(Eq. 2)}$$

From this form, the values of the η and β can be easily determined from a Weibull probability graph, which is made by plotting the double logarithm of the fraction of population failure (i.e., $\ln\{-\ln[1 - \mathrm{F}(t)]\}$) against the logarithm of time. In the Weibull probability graph, β and η are the slope and *y*-value at 63.2%, respectively.

3 Test Samples

Full descriptions of the DUTs discussed in this current report were provided in our previous report.[3] Briefly, all DUTs in this current report were subjected to accelerated aging in a 7575 environment to minimize the test time. All DUTs were two-stage drivers, and the current report includes updated results from the multichannel drivers (three products). All tested drivers were separate devices that are often bolted to luminaire frames and connected to LED primaries through external wiring. A list of the samples examined is provided in **Appendix A** of this report. The multichannel drivers in this current report were previously assigned numbers (i.e., DUT-M1, DUT-M2, and DUT-M3), and the sample terminology is used here for consistency. Two samples of each driver were tested in this study (except only one sample was tested for DUT-M1). A separate sample of each was maintained as a control.

Several 6-inch downlights, each containing a driver, were also addressed in the Hammer Test report.[4] Product life distribution (Weibull analysis) of these products was previously performed to provide qualitative data regarding life expectancy of hybrid 6-inch downlights under the strenuous test conditions used during the Hammer Test. This current report regroups the products to evaluate the Weibull distribution of only the two-stage, multichannel drivers that underwent Hammer testing. A review of the Hammer Test samples revealed that five different products (accounting for a total of 12 samples) included in the test had two-stage drivers. In addition, two of these products, accounting for six samples and five failures, were multichannel drivers. Details about these products are also included in Appendix A of this current report.

Results from a Weibull data analysis previously presented with the Hammer Test[4] showed that the characteristic life (η) of the full population of Hammer Test samples (i.e., products with either single-stage or multi-stage drivers) was 996.9 hours, and the Weibull scale parameter (β) for this population was 1.935. The RTI International Team reclassified the Hammer Test data by driver type; only the data for the products with two-stage drivers are presented in this current report. These revised Weibull results are presented in **Figure 3-1**. By excluding the data from products with single-stage drivers, η increased to 1,040 and β increased to 4.66, indicating that the products reach the wear-out stage of product life sooner. These findings suggest that the two-stage drivers exhibited greater robustness in the Hammer Test than the single-stage drivers.

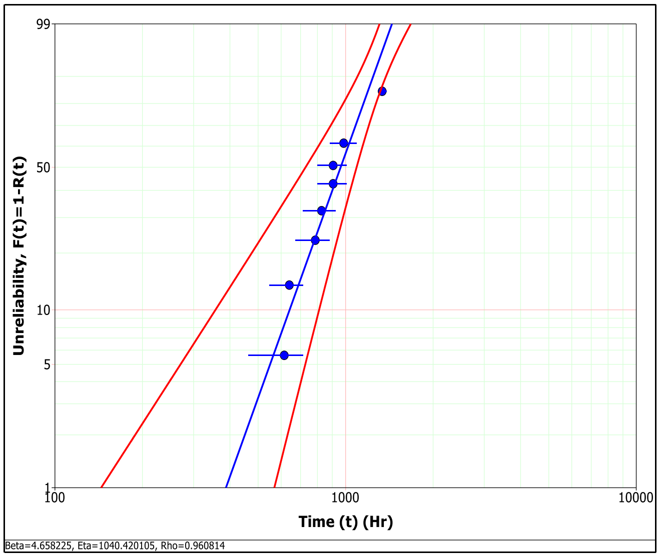

Figure 3-1. Weibull analysis data for the Hammer Test[4] were revised to include only products with two-stage drivers. The red lines show the 90% confidence interval

A similar analysis was also conducted for the five driver samples examined during this study, and the results are presented in **Figure 3-2**. Only three out of five (60%) of the samples subjected to 7575 failed at this interim stage; therefore, it is difficult to interpret the results. However, for the two-stage drivers examined during this test, β was only 1.41. This value is similar to the β value (1.18) measured previously for 6-inch downlights.[10] The values indicate that the failure rate during 7575 is accelerated slightly with time, but is not accelerated as much as the Hammer Test. This finding is not surprising because the Hammer Test uses more stressful conditions that those encountered during 7575.

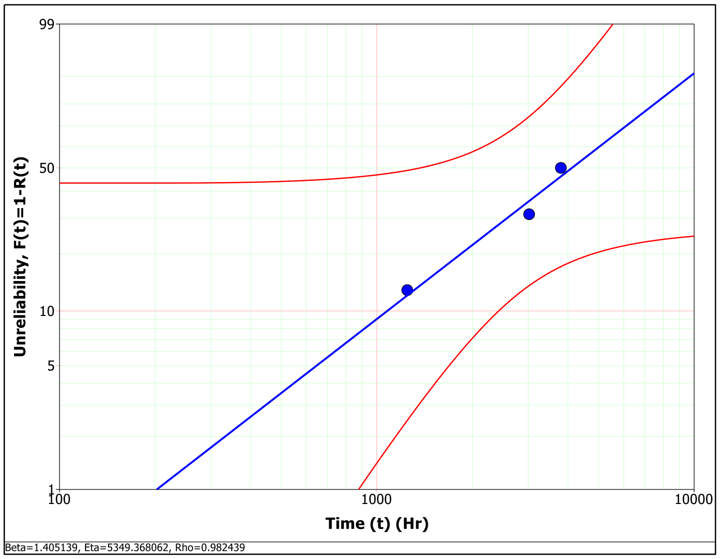

Figure 3-2. Weibull analysis data for the two-stage drivers examined during this study. The red lines show the 90% confidence interval

4 Experimental Procedures

This current report builds from our previous report, using the same AST and measurement methods. Complete experimental details were previously provided,[3] and updated and abridged experimental methods for this current report are provided here for clarity.

4.1 Accelerated Stress Tests

The two-stage multichannel drivers examined in this current study were subjected to AST testing at nominal conditions of 75°C and 75% relative humidity (7575) for a total of 4,000 hours. For all AST exposure, the DUTs were placed inside a temperature and relative humidity chamber, as shown in **Figure 4-1**. In this current report, a metal dome was added and placed over the devices to minimize the cooling effects caused by the air circulation in the chamber, thereby creating a larger thermal gradient between on and off states. As previously described, the LED loads were placed external to the chamber (in ambient room environment) to ensure that only the drivers were experiencing the 7575 environment.

In the initial report, environmental exposure was performed in increments of 500 hours until cumulative exposure reached 2,500 hours, and power cycling was performed to the DUTs on a 2-hour (DUT-M1) or 1-hour (DUT-M2 and DUT-M3) duty cycle.[3] Subsequent environmental exposures between 2,500 hours and 4,000 hours detailed in this report were performed in 250-hour increments, and power was supplied to all operational DUTs (DUT-M2 and DUT-M3) on a 1-hour duty cycle (current report). Sample degradation was measured during AST exposure by thermal tracking, and photometric measurements of LED loads operated by the DUTs were taken at the end of each 250-hour exposure cycle. Electrical measurements were taken at 4,000 hours or after device failure.

Figure 4-1. A metal dome was added around the DUTs during AST exposure

4.2 Measurement Methods

4.2.1 Temperature

Chromel alumel thermocouples (TCs) were attached to the case of the drivers near to the flyback transformer in the PFC circuit and the switching metal-oxide semiconducting field-effect transistor (MOSFET) in the dc–dc converter during 7575 AST exposure. The TC locations were chosen based on their identification as hot spots in our previous report.[3]

4.2.2 Electrical

The power characteristics of the multichannel drivers (DUT-M2 and DUT-M3) examined in this study were tested after 4,000 cumulative hours of 7575 exposure. Specifically, a Xitron 2802 two-channel power analyzer was used, and then compared with an unexposed control driver of the same product and, if applicable, compared with previous measurements made after 2,500 cumulative hours of 7575 exposure. The connections to the Xitron power analyzer were described in our previous report.[3] Peak inrush current data, PF, total harmonic distortion (THD), ripple, and other ac and dc voltages and currents reported herein were measured with the correlated color temperature (CCT) of the LED loads set to 3,500 Kelvin (K) unless otherwise noted. This value was chosen as an intermediate value between the two LED primaries (2,700 K and 6,500 K) in the TWL modules that were used as LED loads.

4.2.3 Photometric

In general, common photometric properties (e.g., illuminance levels, flicker waveform, SPD, chromaticity coordinates) of the LED loads connected to the sample drivers were obtained at the end of each 250-hour AST exposure time at three CCT settings: 6,500 K, 3,500 K, and 2,700 K. Details about measurement and instrumentation (hand-held spectral flicker meter: GigaHertz-Optik BTS256-EF) were provided in our previous report.[3]

5 Findings

Three different multichannel driver products—all capable of being used with TWL luminaires—were exposed to elevated temperature and relative humidity environments for an extended time. All three products were Class 2 devices that can operate at input ac voltages between 120 volts (V) and 277 V; however, during this work, they were only operated at 120 V during 7575 exposure. The three products were rated for surge protection of 2 kV.

DUT-M1 is equipped with 0- to-10 V dimming and specified by the manufacturer to provide ingress protection (IP) equivalent to IP66. This driver has four channels, but only two were operated during these tests. The interior of DUT-M1 was fully encapsulated with a hard, black plastic. The LED loads used on the two channels of this driver were warm-white and cool-white LED modules, and the current required to operate these LEDs was approximately 90% of the specified load for each channel (maximum of 37 Watts per channel). The loads were mounted on aluminum heat sinks with separate dedicated warm-white and cool-white LED modules placed side by side on the heat sink. The same loads were used during the 7575 testing and all post-testing electrical and photometric characterizations.

The DUT-M2 and DUT-M3 products are both dimmable with digital multiplex (DMX) controls, and both are rated for use in dry and damp locations. The interiors of both products were unencapsulated, thereby allowing easy access to the interior components. Both products also had four output channels; however, only two channels were used for product DUT-M2, whereas all four were used for DUT-M3. Equivalent loads were used for DUT-M2 and DUT-M3, although the load was distributed equally between two channels for DUT-M2 and four channels for DUT-M3. The warm-white and cool-white LED modules were housed on the same printed circuit board with separate connections to the driver. Additional specifications for these products are provided in **Table 5-1**.

Table 5-1. Manufacturers' specifications for the multichannel drivers examined in this study

Driver Number	Output Voltage Range (V)	Output Current Range (mA)	Maximum Output Power (W)	Driver Efficiency	PF	THD at Maximum Load	Maximum Case Temperature (°C)
DUT-M1	30–54	700 typical	150	87%	> 0.92	< 20%	85
DUT-M2	2–55	200–1,050	50	89%	> 0.9	< 20%	85
DUT-M3	24	350–700	40	80%	> 0.9	<20%	90

Note: Values are given for 120-V operation only; mA = milliampere; W = watt.

5.1 DUT-M1

DUT-M1 is a two-stage, four-channel driver. In Stage 1, intermediate dc power is produced from the ac input power through a combination of PFC and inductor–inductor capacitor (LLC) converter circuits. In Stage 2, the dc power produced by Stage 1 is sent to separate buck circuits under the control of an integrated circuit (IC) to regulate dc output power for each LED primary.

Only one sample of DUT-M1 was tested in 7575, and its failure was documented in our previous report.[3] A brief summary of the failure analysis of DUT-M1 is provided herein because the results were used in the Weibull analysis found in Section 3. DUT-M1 failed in the resonant circuit of the LLC converter after 1,250 hours of 7575 exposure: two film capacitors and the MOSFET in this circuit failed. Photometric flicker and electrical output waveforms indicated minimal observable changes in the device prior to catastrophic failure.

5.2 DUT-M2

DUT-M2 is a two-stage driver that uses PFC and LLC converter circuits during Stage 1 to produce the intermediate dc voltage. The dc power from Stage 1 is then fed to separate buck circuits (one for each of its four channels) in Stage 2, under the regulation of a controller IC, to produce dc output for color tuning and dimming. Although DUT-M2 is a four-channel driver, only two of the channels were used in this study: Channel 1 (Ch. 1) provided dc power to the warm-white LED modules (2700 K), and Channel 3 (Ch. 3) provided dc power to the cool-white LED modules (6500 K).

Two samples of DUT-M2 (i.e., Sample 1 and Sample 2) were subjected to AST at nominal conditions of 7575 for a total of 4,000 hours; both samples are still operational after this level of exposure. After 4,000 hours of operation in the 7575 test conditions, the electrical characteristics (i.e., input volts, current, wattage, and inrush current; output volts, current, and wattage; and PF) of the samples were measured at room temperature at five different dimming levels (i.e., 100% [full on], 75%, 50%, 25%, and 1%). Overall, the test devices continue to have good electrical stability.

The input and output current and voltage have remained mostly stable for the DUT-M2 samples through 4,000 hours of exposure, with increases in input power being accompanied by increases in output power as shown in **Table 5-2**. The slight increase in input power consumption observed for the test devices can be traced to increases in impedance across the devices as the electrical components age. The PFs of the test devices were found to be significantly greater than the control at low dimming levels (**Figure 5-1**), a finding consistent with our previous report.[3] Within each device, the PF values at low dimming level were found to increase slightly as the devices aged from 2,500 hours to 4,000 hours, as shown for Sample 1 in **Figure 5-2**.

Table 5-2. Average input and output power of the test 7575 DUT-M2 devices after 4,000 hours exposure compared with the input and output power of the control DUT-M2 device

Dimming Level (%)	Input Power		Output Power	
	Control (Watts$_{ac}$)	Average 7575[a] (Watts$_{ac}$)	Control (Watts$_{dc}$)	Average 7575[a] (Watts$_{dc}$)
100	49.38	49.49	42.29	42.17
75	26.82	26.96	21.60	21.51
50	14.30	14.79	10.03	10.29
25	6.38	6.74	2.75	2.92
1	2.71	2.92	0.29	0.30

[a] These values are the average input and output watts of the DUT-M2 drivers after 4,000 hours of operation in the 7575 environment; watts$_{ac}$ = watts alternating current; watts$_{dc}$ = watts direct current.

As suggested in our previous report, we believe that the PFs of the test drivers operated at low dimming levels have increased because of degradation of the film capacitors in the filter and conditioning circuit. The degradation is likely to include increases in the equivalent series resistance (ESR) and possibly a reduction in capacitance. The capacitance values of the aged film capacitors are provided in **Table 5-3** and show degradation to almost half of the original capacitance values. In evaluation of stand-alone capacitor components, the failure threshold is set by the manufacturers' tolerances and is often given as a >20% change in capacitance and a >280% change in ESR.[14] The DUT-M2 devices have exceeded that threshold and are still operating properly, indicating that there is some compensation in the circuity for the ageing-induced degradation. However, there is likely a limit on the ability of the driver to compensate for these changes.

Table 5-3. Capacitance (in nanoFarads [nF]) of Sample 1 and Sample 2 film capacitors show degradation with ageing relative to the control

	After 2,500 Hours of 7575 Exposure		After 4,000 Hours of 7575 Exposure	
Device	**Capacitor C_5 (nF)**	**Capacitor C_6 (nF)**	**Capacitor C_5 (nF)**	**Capacitor C_6 (nF)**
Control	429.0	429.0	413.5	413.5
Sample 1	314.8	314.6	258.4	258.4
Sample 2	285.5	258.6	235.9	235.9

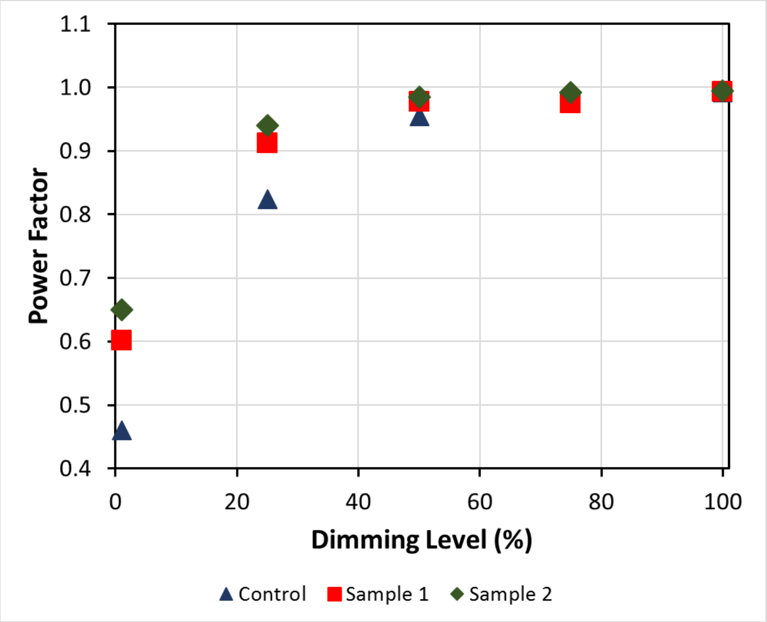

Figure 5-1. PF comparison of the control and post-4,000 hour exposure to 7575 DUT-M2 samples as a function of the dimming percentage.

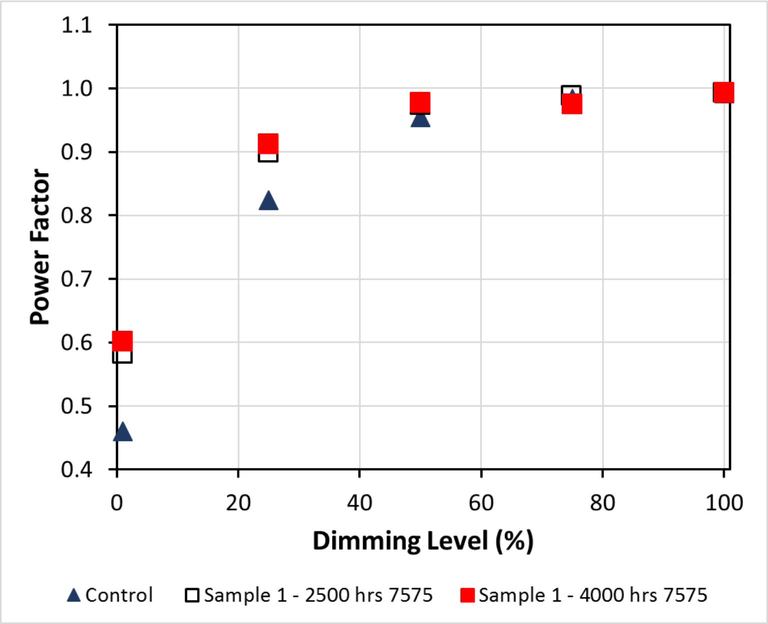

Figure 5-2. PF of Sample 1 continued to increase at low dimming level as cumulative exposure to the 7575 environment increased

From the electrical analyses, the driver efficiencies of the DUT-M2 samples were tabulated and compared with the control in **Table 5-4**. When the driver is supplying maximum power (no dimming, 100%) or slightly dimmed power (75% or 50%) to the LED modules, the efficiencies of Sample 1 and Sample 2 are comparable with—or slightly lower (< 1% difference) than—the control device. However, as the LED modules are dimmed even further and driver output decreases (e.g., dimming levels of 25% or 1%), Sample 1 and Sample 2 experience an increase in efficiency by up to 5%. The increase in efficiency at lower output results from the increased PF at lower dimming levels and minimal change in true power consumed by the load.

Table 5-4. Efficiencies of the control and sample 1 (after 4,000 hours of 7575 exposure) DUT-M2 drivers at various dimming levels.

Dimming Level (%)	Control Device	Sample 1	Sample 2
100	84.98%	84.80%	84.58%
75	79.20%	77.94%	79.00%
50	66.93%	68.25%	68.33%
25	35.49%	39.77%	40.47%
1	4.97%	6.24%	6.74%

Another notable electrical change with 7575 exposure is the magnitude of the inrush current for the sample devices exposed to 7575 test conditions compared with the control device. As shown in **Figure 5-3**, the Ch. 1 (warm-white LEDs) inrush currents of the devices exposed to the 7575 environment were lower than that of the control device across the dimming range. The Ch. 3 (cool-white LEDs) inrush currents were also collectively lower than the control device over all dimming ranges, though there was some instability in Ch. 3 for each sample that led to inrush currents that were higher than the control at some dimming levels. In addition, the average inrush current across both channels was found to decrease as exposure age increased; this result is shown for Sample 1 in **Figure 5-4**. It is likely that the lower inrush current stemmed from higher impedance within the device, possibly because of higher capacitor ESR and lower capacitance. This behavior, especially at low dimming levels, provides a potential indicator of driver degradation and may be a predictor of residual life of the driver. Additional work is needed to identify the level of degradation necessary for product failure.

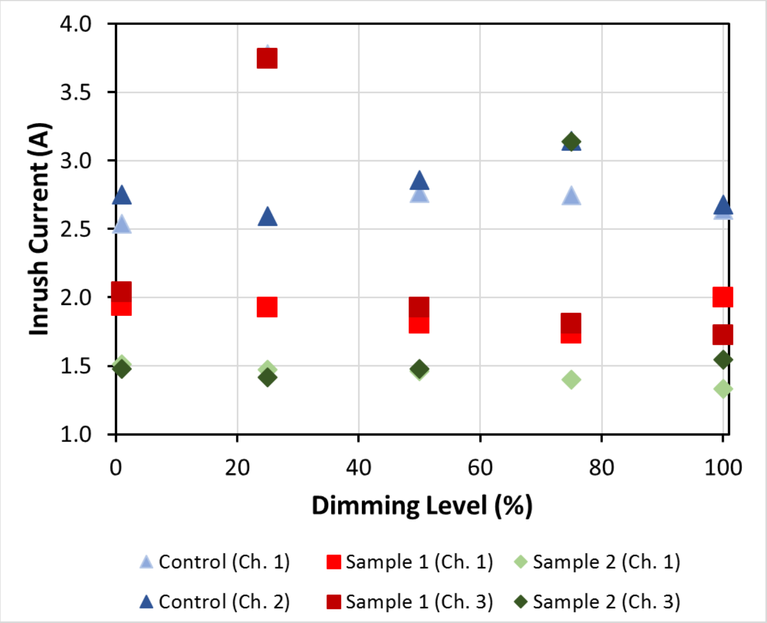

Figure 5-3. DUT-M2 devices after exposure to 4,000 hours of 7575 AST have overall lower inrush currents than the control device at all dimming levels

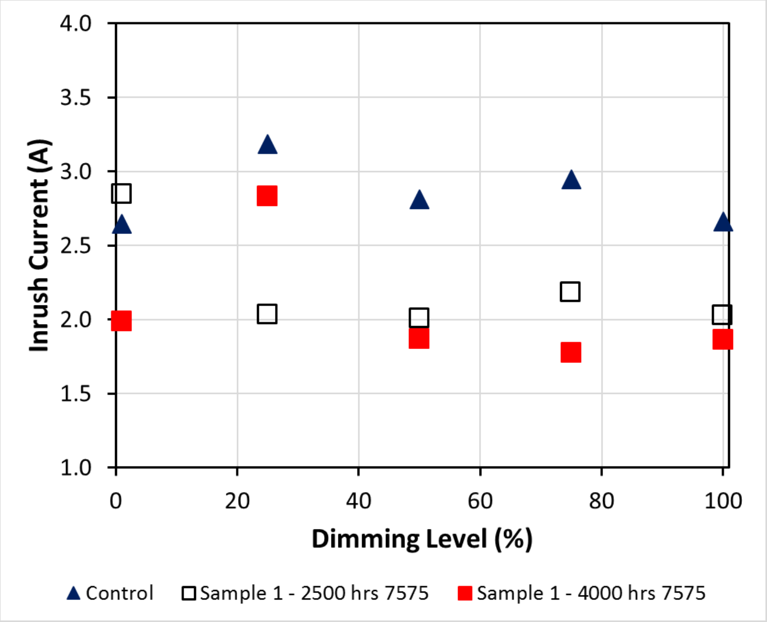

Figure 5-4. The inrush current of Sample 1 continues to drop as cumulative exposure to the 7575 environment increases

Flicker measurements were collected from the LED loads connected to the DUT-M2 samples following every 250 or 500 hours of exposure. DUT-M2 uses a hybrid drive waveform that dynamically adjusts its amplitude and shape to achieve optimal efficiency. As a result, the waveform of each driver is likely to be different at any point in time. Possible signs of degradation can be detected in the dynamic waveform of the driver at low dimming levels by examining the peak shape (i.e., the rise and decay of the photometric flicker signal). The photometric flicker of the LED load connected to the DUT-M2 samples after 4,000 hours of 7575 exposure were compared with that of an unexposed control sample, and a representative flicker waveform of Sample 1 (at low dimming level [1%] and with DMX control set to 3,500 K) is presented in **Figure 5-5**. The flicker waveform for LEDs connected to the driver exposed to 7575 environment had small, additional peaks compared to LEDs connected to the control driver, a possible sign of driver degradation. The flicker waveform of the sample and control drivers were transformed to the frequency domain by Fourier transformation (Figure 5-5.). For the drivers exposed to 7575 environment, the Fourier transformations indicated that there were no harmonic series associated with the fundamental frequency of 910 Hz. However, the control sample had a harmonic series associated with the fundamental frequency of 910 Hz. The additional peaks in the flicker waveform and change in harmonic components found in the Fourier transform of the photometric flicker waveform for DUT-M2 devices had little, if any, impacts on the flicker percentage and flicker index as shown in **Table 5-5**.

Similar differences in photometric flicker were observed for both DUT-M2 samples at multiple dimming and CCT levels. Further investigation and testing are needed to conclude whether these additional peaks in the flicker waveform and the absence of some frequencies in the frequency domain are indicative of driver degradation.

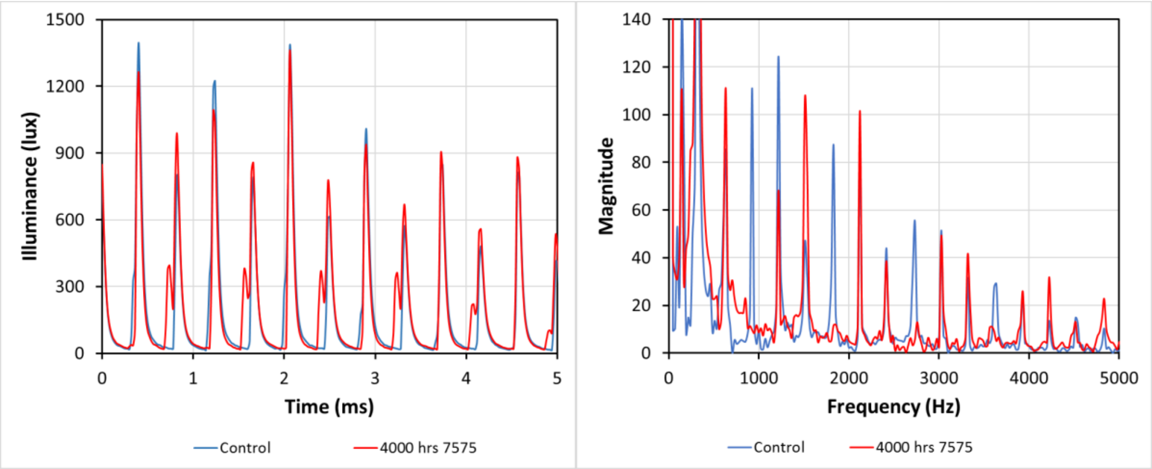

Figure 5-5. Comparison of photometric flicker waveform (left) and the Fourier transform of the flicker waveform (right) of the control device and Sample 1 after 4,000 hours of 7575 exposure. (Note: The flicker waveform was acquired with the DMX controller set to 3,500 K and 1% dimming.)

Table 5-5. Photometric flicker properties after 4,000 hours of 7575 exposure at the 1% dimming level

DUT-M3 Device	Percent Flicker (%)	Flicker Index	CCT (K)
Control	97.8	0.5150	3,227.0
Sample 1	98.1	0.4839	3,232.4

5.3 DUT-M3

DUT-M3 is a two stage four-channel driver with a flyback PFC converter for Stage 1 and separate buck circuits for each channel in Stage 2. In our previous report, we described the reliability of DUT-M3 through 2,500 hours of exposure to a 7575 environment. We reported minimal changes in electrical characteristics – although an increase in PF was observed at low dimming levels due to ageing of film capacitors in the filter and conditioning circuit. Additionally, the driver continued to provide stable power to its LED load through 2,500 hours of 7575 exposure as measured by photometric flicker.

In this current Phase 2 report, testing in the 7575 environment continued until both DUT-M3 devices failed to produce light from their respective LED module loads. To determine the exact time to failure and other transient events, TCs were placed on the transformer and MOSFET of each DUT. The selected transformer and MOSFET were located in the flyback PFC converter of Stage 1 and the buck circuits for Stage 2, respectively. TC data provides time to failure by tracking changes in component temperature. Properly functioning components produce electrical heat (i.e., the total component temperature is larger than the chamber ambient temperature), and therefore the temperature of the device rises and falls when it is power cycled. Non-functional components do not produce electrical heat, so component temperature tends to follow the chamber background. Components in partially functioning circuits generally have temperatures between the chamber background and the maximum temperature when powered on. Both DUT-M3 devices (i.e., DUT 347 and DUT 346) failed during operation in the 7575 environment, and the TC data for their respective failure times are shown in **Figure 5-6**.

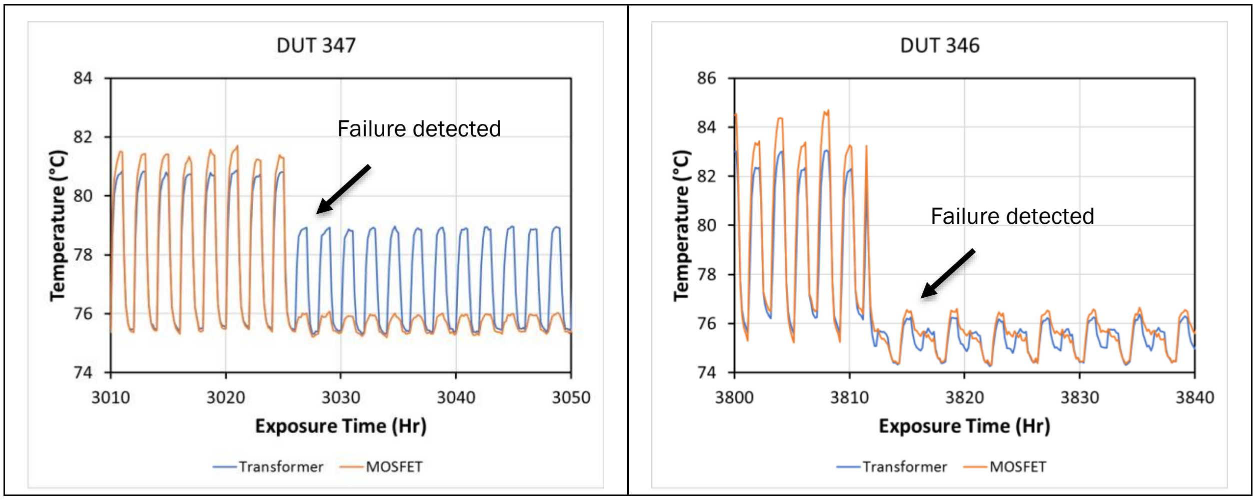

Figure 5-6. Temperature profiles of the DUT-M3 samples detect failure in situ

DUT 347 (Figure 5-6, left) failed first after 3,027 hours of exposure to the 7575 AST environment, as evidenced by temperature reductions in both the transformer and MOSFET components. A closer inspection of the temperature profile suggests that failure occurred immediately after the device was powered on because there was no rapid rise in component temperature, as occurred when the device functioned normally. Instead, after failure, the temperature of the MOSFET for DUT 347 was greatly reduced, fluctuating near ambient chamber temperature (75 or 76°C). However, the temperature of the transformer for DUT 347 was less reduced (75 to 79°C), suggesting that there was still some functionality of the transformer component. With the difference in temperatures observed between the transformer and MOSFET, it can be assumed that failure occurred somewhere in the circuit between the transformer in Stage 1 and the MOSFET of Stage 2.

DUT 346 (Figure 5-6, right) failed second at 3,812 hours of exposure to the 7575 AST environment. However, just before failure, the temperature of both components in DUT 346 increased rapidly, suggesting normal operation initially, and then decreased rapidly, which is indicative of failure. With no electrical power being dissipated in the device, the component temperatures dropped quickly to their new levels. Hereafter, the temperature profiles of the transformer and MOSFET components for DUT 346 showed small thermal oscillations around the ambient chamber temperature (75°C). This finding indicates that both components ceased to function at approximately 3,812 hours, limiting failure to a location before the PFC converter of Stage 1.

Electrical measurements and failure analysis of the DUT-M3 devices support the TC data. When device failure occurred, power consumption and PF of both samples dropped significantly compared with the control device as shown in **Table 5-6**. DUT 347 continued to draw power after failure, consuming approximately 1% of the initial power necessary to operate the LED modules. The continuation of power consumption observed in DUT 347 indicated the presence of functional circuits in the driver, supporting the TC data that the transformer (or a component near the transformer) was still functional. Further electrical analysis of DUT 347 identified multiple failed components in the PFC converter of Stage 1: two resistors were found to be open near the transformer, the gate of the MOSFET nearest the flyback transformer was open, and other components (diode bridge and MOSFET) partially failed (**Figure 5-7**). A similar heat surge was observed for DUT 346 near the transformer in the PFC converter stage (**Figure 5-8**), but the components near the heat surge were still functional at the end of testing. Additionally, DUT 346 completely stopped drawing power after failure occurred, unlike DUT 347. Further electrical analysis of DUT 346 limited failure to the filter and conditioning circuit, where a cascade of events led to device failure. Specifically, two film capacitors and one inductor responsible for filtering electromagnetic interference were found open, which may have led to the blown fuse that completely stopped ac power draw.

Table 5-6. Electrical properties of the failed DUT-M3 samples compared with the control DUT-M3 sample

DUT-M3 Device	Input Current (A)	Input Power (W)	PF
Control	0.33	39.47	0.99
DUT 346	0.00	0.00	0.01
DUT 347	0.01	0.32	0.27

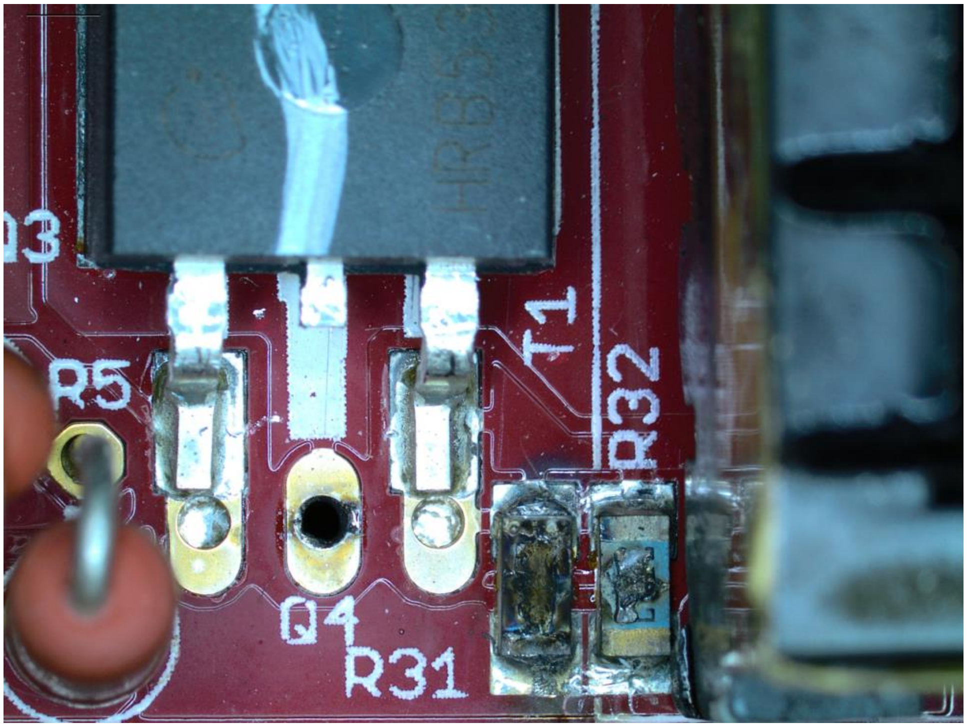

Figure 5-7. Failed components of DUT 347 include two open resistors (R31 and R32) and a MOSFET Q4

The DUT-M3 drivers had an LED module load that consisted of warm-white (2,700 K) and cool-white (6,500 K) LEDs, each operated by its own channel. Photometric flicker measurements were acquired at three CCT settings (i.e., 2,700 K, 3,500 K, and 6,500 K) to test the operation of each channel independently (2,700 K and 6,500 K) and to test the operation of the channels together (3,500 K). The CCT of the LED module was set by the driver's power control center, which delivers remote DMX control over spectral color and dimming.

Photometric flicker measurements of the loads connected to the DUT-M3 drivers were taken prior to DUT-M3 failure at regular intervals of 250 or 500 hours of exposure to 7575. At the end of the AST exposure interval, just prior to complete device failure (3,000 hours for DUT 347 and 3,750 hours for DUT 346), noticeable signs of intermittent or pending failure were detected on both drivers when the CCT value was set to 6,500 K by the

DMX controller. For DUT 347, a warm-up period was needed before any light output began from the 6,500 K LEDs. For DUT 346, photometric flicker produced a CCT value (5,034 K) that does not align with the control setting. This "incorrect" value persisted for a couple minutes until the device fully warmed up. As shown in **Figure 5-9**, there was a drastic change in flicker waveform produced by the LEDs during this warm-up period compared to the associated photometric flicker waveform from LEDs operated by the control driver. The change in flicker waveform was observed with no dimming (100%) and with partial dimming (50%). Finally, it should be noted that the change in flicker waveform was only observed when the CCT value was set to 6,500 K, and no change in flicker waveform was observed at 3,500 K or 2,700 K for both DUT 346 and DUT 347. This finding might indicate greater susceptibility to ageing for channels that provide power to cool-white LEDs. Additional data is needed to validate the susceptibility of cool-white channels.

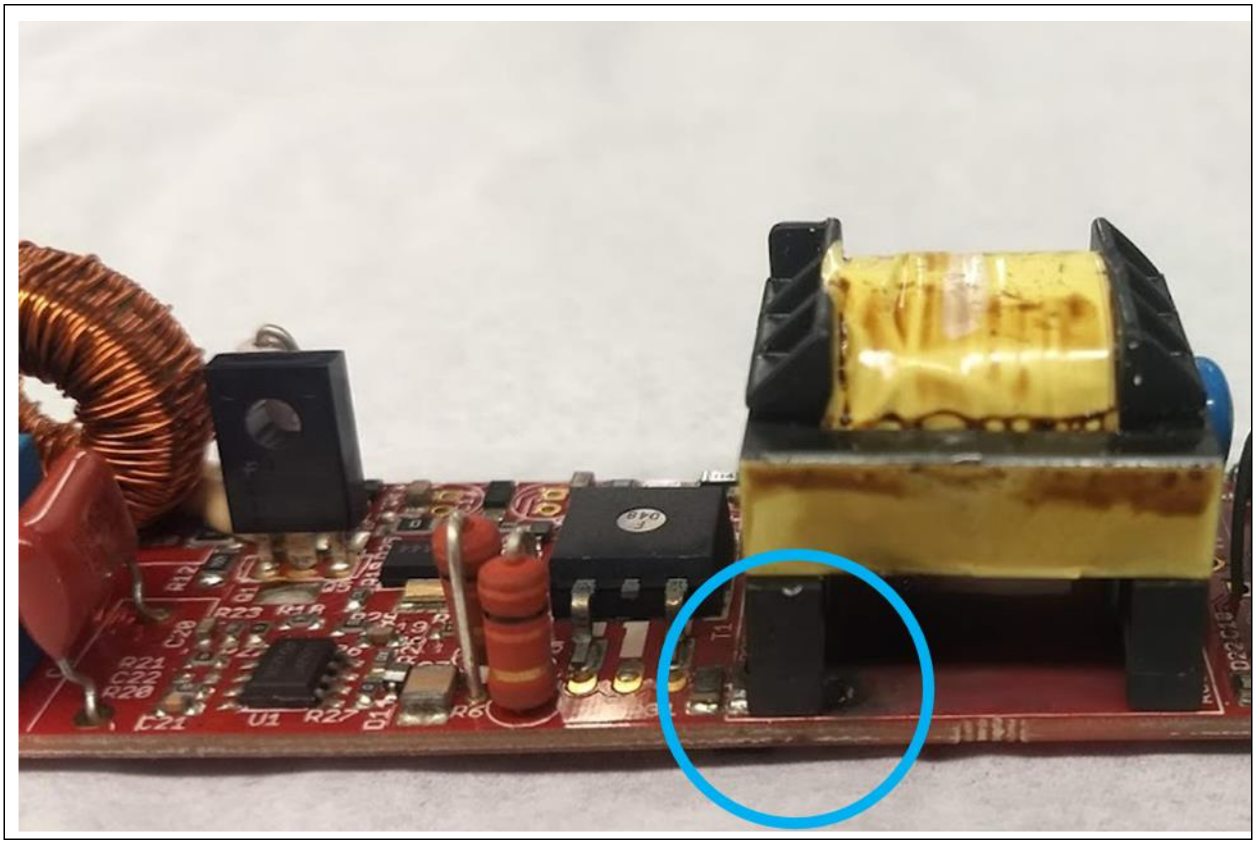

Figure 5-8. Evidence of excess heat is observed for DUT 346 around the transformer and MOSFET of the PFC stage

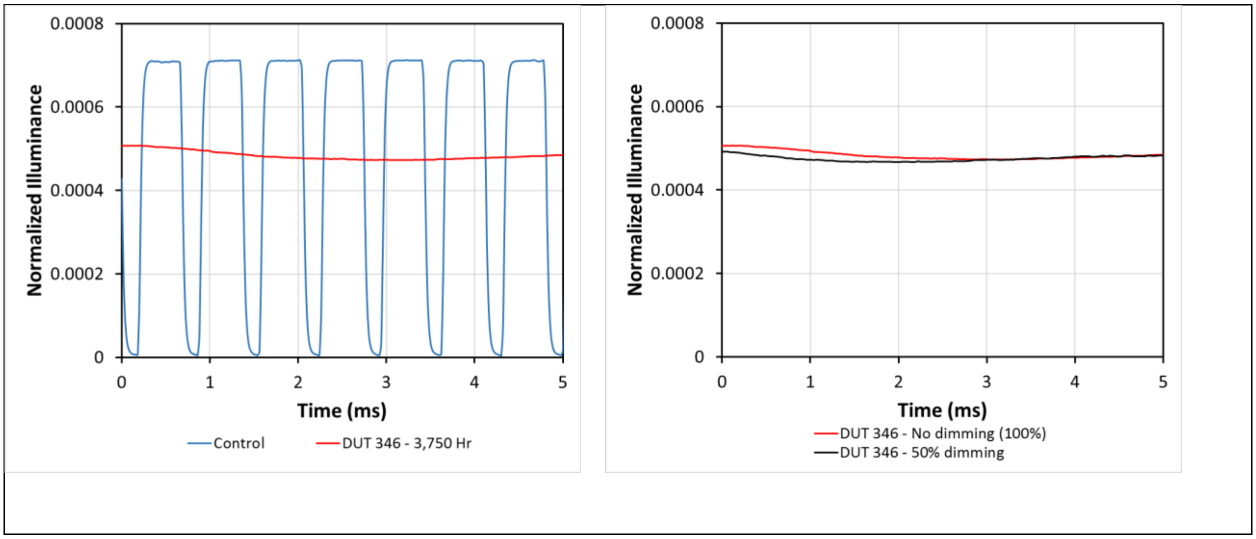

Figure 5-9. Flicker waveform of DUT 346 (no dimming) recorded at 6,500 K for the measurement time interval just prior to device failure compared with the control (left) and with partial dimming (50%, right)

6 Conclusions

Advanced lighting fixtures such as TWL luminaires were made economically possible by incorporating multiple LED primaries into a single lighting fixture. Because each LED primary requires separate dc control, manufacturers produced sophisticated, multichannel drivers that are capable of regulating dc power to each LED primary through separate channels. In many cases where a multichannel driver is required, a two-stage driver architecture is used to increase PF and minimize THD. This updated study examined the robustness of two-stage multichannel drivers and investigated whether degradation in the front end of the circuit would impact the quality of light produced by the LED load.

AST exposure studies, performed in a 7575 environment, were conducted on three different two-stage multichannel LED driver products, labeled DUT-M1, DUT-M2, and DUT-M3. There were five total samples: one sample of DUT-M1 and two samples each of the other two products. All of the tested drivers were compatible with TWL luminaires. During 4,000 hours of testing, three out of the five test samples (60%) failed. One failed sample was a DUT-M1 product and the other two failed samples were both DUT-M3 products. Two of the samples (these samples were not from the same product) failed in the PFC circuit and the third sample failed during the filter and condition circuit. The DUT-M1 sample did not exhibit any changes in its electrical or photometric properties before abrupt failure. In contrast, the photometric properties of the LEDs driven by the DUT-M3 samples changed just before failure possibly signaling the onset of the wear-out phase of device life. For these samples, noticeable changes in photometric flicker and a CCT value that differed from that set by the control signal were found for the driver. The changes in photometric flicker waveform were abrupt and easily observed with the human eye.

At the end of this study, only one of the three products (DUT-M2) remained operational for a total of two operational samples. The surviving samples were thoroughly characterized both electrically and photometrically to understand any changes that have occurred to the driver during the AST. The electrical study indicated an increase in driver efficiency at low dimming level likely caused by increased capacitor ESR, which produces a higher PF. In addition, a decrease in inrush current was also found with driver degradation. The photometric study did not reveal significant changes in the readings for flicker or luminous flux, but it did show a change in flicker waveform peak characteristics, including the absence of a harmonic series in the Fourier transform of the output photometric flicker waveform. These changes in photometric flicker cannot be perceived by the human eye, and it is unclear at this time whether the flicker waveform changes can be used to predict device failure. However, the data suggest that PF, inrush current, and driver efficiency at low dimming levels (e.g., 1%, 25%) are potential early indicators of driver degradation, particularly as the device transitions to the wear-out stage of product life. Indeed, a method to predict time to failure before systems failures are observed visually is still needed for end users of TWL systems.

7 References

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8 Appendix A

Table A-1. Identifying information for the samples included in this report

Identification Number	Brand	Model	Type	Power Rating [a]
DUT-M1	LG	LLP 150W 0.7 A	Multichannel driver	150 W
DUT-M2	eldoLED	POWERdrive 561/M	Multichannel driver	50 W
DUT-M3	Finelite	89661	Multichannel driver	40 W
Luminaire A	Cree	LR6-DR1000	6-inch downlight with an integrated, multichannel driver	12.5 W
Luminaire B	Cree	CR6 499485	6-inch downlight with an integrated, multichannel driver	9.5 W
Luminaire C	Philips	Lightolier Calculite C6L15 20 DL 30 KW CC DW	6-inch downlight with an external driver	28 W
Luminaire F	Lunera	22-Ge	2-foot × 2-foot troffer with an external driver	40 W
Luminaire G	BetaLED	Essentia ESA-ADR-628-C	6-inch downlight with an external driver	55 W

[a] The power rating for each driver is the maximum power rating of the driver. The power rating for the Hammer Test samples is the nominal power rating for the complete SSL device.

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