Energy Efficient End-use Equipment
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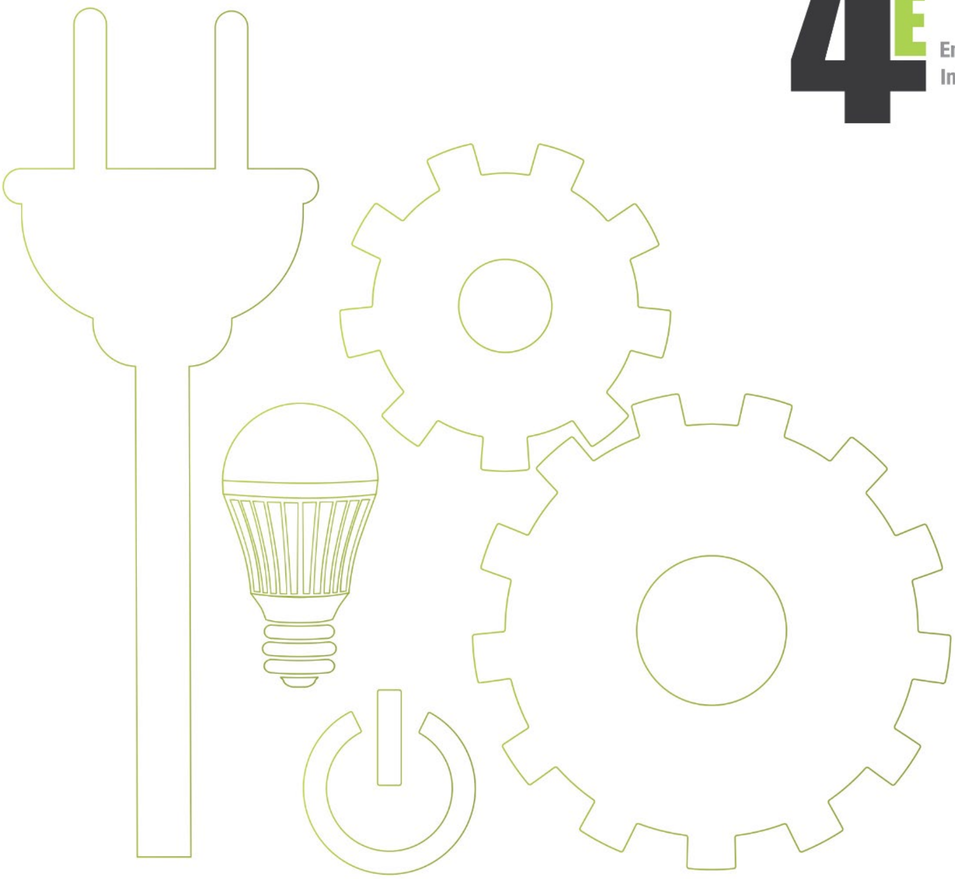

Literature Summary of Lifetime Testing of Light Emitting Diodes and LED Products

Prepared by the Lighting Research Center

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Authors: Nadarajah Narendran, PhD, Jean Paul Freyssinier, Indika Perera and Jennifer Taylor, Lighting Research Center, Rensselaer Polytechnic Institute

Foreword: This report was prepared for the IEA 4E SSL Annex by researchers and experts at the Lighting Research Center at the Rensselaer Polytechnic Institute in New York, USA. This report presents the latest research and findings on LED product lifetime testing and forecasting, based on a wide-ranging literature review from around the world.

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About the IEA 4E Solid State Lighting (SSL) Annex

The SSL Annex was established in 2010 under the framework of the International Energy Agency's Energy Efficient End-use Equipment (4E) Implementing Agreement to provide advice to its member countries seeking to promote energy efficient lighting and to implement quality assurance programmes for SSL lighting. This international collaboration currently consists of the governments of Australia, Canada, Denmark, France, the Republic of Korea, Sweden and the United Kingdom. Information on the 4E SSL Annex is available from: https://www.iea-4e.org/ssl/

About the International Energy Agency's Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E)

Fifteen countries from the Asia-Pacific, Europe and North America have joined together under the forum of 4E to share information and transfer experience in order to support good policy development in the field of energy efficient appliances and equipment.

4E focuses on appliances and equipment since this is one of the largest and most rapidly expanding areas of energy consumption. With the growth in global trade in these products, 4E members find that pooling expertise is not only an efficient use of available funds, but results in outcomes that are far more comprehensive and authoritative. Launched in 2008, in view of its achievements during the first and second five-year terms, the IEA endorsed 4E's application for a third term that will run to 2024. https://www.iea-4e.org/

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Acronyms, Abbreviations, and Terminology

Below are common terminology and abbreviations used throughout this report.

α	alpha, acceleration factor in degradation studies
A	arbitrary shape lamp type, as in A19
abrupt failure	failure of a LED product to operate or to produce luminous flux [IEC 62717:2014]; in this report catastrophic failure is used for the same purpose
ADT	accelerated degradation testing
AFV	abrupt failure value; the percentile of LED modules failing to operate at median useful life, L_x [IEC 62717:2014]
ALT	accelerated life testing
ANSI	American National Standards Institute
ASSIST	Alliance for Solid-State Illumination Systems and Technologies
β	beta, Weibull model's shape parameter
B_p, Bp	fraction "p" of products that have failed according to a given criterion, usually based on parametric changes; for example, B_{50} represents a point in time when 50 percent of the products have failed
BPA	Bonneville Power Administration
BR	bulge reflector lamp type, as in BR30
catastrophic failure	synonymous with abrupt failure; failure of an LED product to operate or to produce luminous flux
CCT	correlated color temperature
CIE	International Commission on Illumination (*Commission Internationale de l'Eclairage*)
CLASP	Collaborative Labeling and Appliance Standards Program
CLTC	California Lighting Technology Center
C_p, Cp	fraction "p" of products that have failed according to a given criterion, usually based on catastrophic failure
CPUP	California Public Utilities Commission
CRI	color rendering index
CTE	coefficient of thermal expansion
delta T, ΔT	delta temperature, the difference between the maximum operating temperature and the average room temperature during a power cycle
delta time-averaged LED temperature, ΔTavg	difference between the average temperature experienced by the during a power cycle and the average room temperature
dI/dV	differential conductance

EIA	Electronics Industry Association
EM	electromigration
EMI	electromagnetic interference
ESR	equivalent series resistance
EU	European Union
EUL	effective useful life
F_p, Fp	fraction “p” of products that have failed according to a combination of parametric (Bp) and catastrophic (Cp) failures
FR-4	flame retardant, a NEMA grade designation for glass-reinforced epoxy laminate material used in printed circuit boards
HADT	highly accelerated decay testing
HALT	highly accelerated life test
HASS	highly accelerated stress screen
HCI	hot carrier injection
IC	integrated circuit
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IES	Illuminating Engineering Society
IGBT	insulated-gate bipolar transistor
I-V	current vs. voltage relationship
JEDEC	Joint Electronic Devices Engineering Council
L_x, Lx	median useful life, defined as the length of operating time during which a total of 50% (B_{50}) of a population of operating LED modules of the same type have flux degraded to the luminous flux maintenance factor x [IEC 62717:2014/AMD2:2019]; for example, L_{70} represents 70 percent luminous flux maintenance of a given light source
LED	light-emitting diode
LED integrated lamp	LED lamp, incorporating control gear and any additional elements necessary for stable operation of the light source, designed for direct connection to the supply voltage [IEC IEV 845-27-055]. In this report LED integrated lamps are also referred to as LED products, LED lamps, or LED systems.
LED lamp	electric lamp based on LED technology [IEC IEV 845-27-054]
LED light source	electric light source based on LED technology [IEC IEV 845-27-053]
LED luminaire	luminaire designed to incorporate at least one LED light source [IEC IEV 845-30-056]. In this report LED luminaires are also referred to as LED products or LED systems.

LED package	single electrical component encapsulating principally one or more LEDs, possibly with optical elements and thermal, mechanical, and electrical interfaces (IEC IEV 426-08-28)
LED product	in this report, defined as a replacement lamp or a luminaire based on LED technology
LED system	same as LED product
life (of a lamp)	the total time (usually expressed in hours) for which a lamp has been operated before it becomes useless, or is considered to be so according to specified criteria [EC IEV 845-07-61]. For the purposes of this report, life is defined as the shorter period when estimated from parametric and catastrophic criteria.
life to X % failures	the length of time during which X % of the lamps subjected to a life test reach the end of their lives, the lamps being operated under specified conditions and the end of life judged according to specified criteria [IEC IEV 845-07-63].
lifetime	in this report, refers to the qualitative duration of an LED product's life
LRC	Lighting Research Center
luminous flux maintenance	ratio of the luminous flux of an electric light source at a given time in its operational life to its initial luminous flux, the electric light source being operated under specified conditions (IEC IEV 845-27-114). In this report luminous flux maintenance is also referred to as lumen maintenance.
mA	milliamp
min	minute
MOSFET	metal oxide silicon field emission transistor
MR	multifaceted reflector lamp type, as in MR16
MTBF	mean time between failures
MTTF	mean time to failure
NEMA	National Electrical Manufacturers Association
NYSERDA	New York State Energy Research and Development Authority
PAR	parabolic aluminized reflector lamp type, as in PAR20
parametric failure	change over time of light output, chromaticity, or other photometric measure related to the operation of the LED system beyond a set threshold value
PCB	printed circuit board
pc-LED	phosphor-converted LED
PoF	physics of failure
R^2	coefficient of determination
RC	resistor-capacitor circuit

reliability	the ability of a product or system to perform its intended function for a specified time under its expected operating conditions [IEEE, 2010]
RFI	radio frequency interference
RH	relative humidity
RPI	Rensselaer Polytechnic Institute
R_{theta}, RΘ	thermal resistance, defined as the quotient of the difference between the virtual temperature of the device and the temperature of a stated external reference point, by the steady-state power dissipation in the device [IEC IEV 521-05-13]
SDSADT	step-down stress accelerated degradation testing
SEA	Swedish Energy Agency
SSADT	step stress accelerated degradation testing
SSL	solid-state lighting
SUSADT	step-up stress accelerated degradation testing
T_j, Tj	temperature at the p-n junction of a light-emitting diode [IEC IEV 845-27-068]
T_{max}, Tmax	maximum temperature
UK	United Kingdom
US, U.S.	United States
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
V_f, Vf	LED forward voltage
W	watt

Summary

It was nearly two decades ago when white phosphor-converted LEDs became commercially available. Today, the white LED has transformed the lighting industry and is considered the preferred light source for most lighting applications. Even though many lighting standards have been published over this period, we still do not have a good standard defining LED system lifetime or a test method that can accurately estimate the lifetime of LED lighting products. Therefore, the objective of this report was to survey and summarize the literature on LED system lifetime definition, failure mechanisms of LED components and systems, parameters that accelerate failure, and available test methods for estimating LED system lifetime.

An LED product has many components, and failure of any one component will lead to whole system failure. According to the literature, the failure of an LED system can be broadly categorized as catastrophic or parametric.

- *Catastrophic failure:* A change that leads to a sudden cessation of light output of the LED system (e.g., the solder connecting the LED package electrical pads and the printed circuit board separating due to a physical crack formed in the solder).
- *Parametric failure:* A change in light output, color, CCT, or other photometric measure related to the operation of the LED system over time beyond a set threshold value (e.g., the light output of an LED system decreases 30 percent compared to its initial light output, known as L70). It should be noted that after parametric failure, a light source could still have some functionality and it may be difficult for a consumer to distinguish between a failed and a non-failed lamp.

Most lifetime test method standards in use presently consider only parametric failure; that is light output maintenance of the LED product. Importantly, the tests and predictions are based only on measurements of the LED packages in the system. Even when an entire system is considered, studies have shown that lighting products in applications can fail parametrically or catastrophically. The literature suggests that LED system lifetime depends on both the application environment and the use pattern. Together, these conditions cause high LED junction temperature (which degrades the components surrounding the chip and leads to parametric failure) and thermal stress at the interconnects (which results in broken connections and leads to catastrophic failure). Therefore, to accurately estimate the life of LED lighting systems, the test method and the experiment setup must have the ability to change the environmental conditions and the on-off switching pattern.

Furthermore, past studies show that the differences in operating temperatures during on/off cycling have an inverse linear relationship with the number of cycles to failure (for varying median life). Likewise, the median lamp life, based on lumen depreciation and the maximum operating temperature, have an inverse linear relationship. Therefore, life testing of LED products must consider both types of failure and conclude the shorter of the two times as the product lifetime. One study has shown that it is possible to estimate the lifetime of an LED lighting product in any application if the expected application environment temperature and the use pattern (switching on and off) are known.

This report recommends two potentially successful life test methods for LED lighting systems.

- The test method proposed in the European Union is one of the two most promising that can be adopted for estimating LED system lifetime [European Union, 2019]. However, this test method is not predictive because the test only includes one environmental parameter (temperature, but not the relative humidity) and one use pattern (power cycling), and it is thus not possible to estimate lifetime under different application conditions. To achieve this goal, it would be necessary to conduct the test under different environmental conditions and use patterns (e.g., three temperatures and three dwell times).

- The second most promising test method for estimating LED system lifetime is the one proposed by the Lighting Research Center [LRC, 2016] and formalized by the Alliance for Solid-State Illumination Systems and Technologies [ASSIST, 2020]. This method has the capability to predict LED system lifetime based on specified or expected environmental conditions and use pattern. However, this method does not consider the influence of relative humidity as an independent variable.

Additional research that would enhance the above methods include: collecting data from large field installations of replacement lamps and luminaires; conducting a laboratory study at different off-times of the endurance test cycles; conducting a laboratory study at different humidity levels; and verifying the accuracy in the predictions of LED driver lifetime based on the models in the Telcordia SR332 standard and the Military Handbook 217F.

Literature Review Methodology

The goal of this project was for the Lighting Research Center (LRC) to conduct a comprehensive literature review that synthesizes available information on the latest research and findings on lifetime testing of LEDs and LED products. Specifically, the LRC was asked to conduct the following tasks, as outlined in the project's Statement of Work:

- Compile research on all aspects of lifetime definitions in Annex member states and elsewhere (review of existing research / literature);
- Review and summarize studies and research into the identification and analysis of potential failure mechanisms in LED lamps and luminaires;
- Look for similarities in the identified failure mechanisms including which ones introduce the greatest vulnerability (e.g., humidity, voltage surge/sag, etc.);
- Review the studies and published papers on accelerated lifetime testing of LED products, including lamps, luminaires, packaged LEDs and drivers;
- Summarize the findings in a document, following the outline provided in the Tender for Consulting Services;
- Discuss the strengths and weaknesses of characterizing LED product lifetime; and
- Make recommendations on best practice for defining and measuring lifetime of LED products.

Beyond the Statement of Work, the SSL Annex staff set forth the following objective: "The SSL Annex is concerned about the quality of products, and this study is intended to give regulators the tools they need to set lifetime requirements to protect consumers. The study should help governments know what kind of tests and associated metrics are required to ensure good products are placed on the market that meet or exceed their claimed lifetime." Further guidance was provided in an email to the principal investigator on April 8, 2020, which was used to guide the LRC's literature search with the understanding that this study was intended to contribute to the literature by preparing a meta-study that looked at the opportunities to formulate a test method for predicting lifetime and provide guidance to conduct testing to assess the effectiveness of the lifetime test procedures reported in the literature. The lifetime testing guidance should take into consideration both parametric and catastrophic failure modes.

As stated, the key purpose for this study is to help governments ensure quality LED lighting products and give regulators the tools they need to set lifetime requirements to protect consumers. Therefore, a reliable indicator of system level performance, such as a system level lifetime test method that can accurately predict a product's lifetime, is necessary. Example LED lighting products include replacement lamps (e.g., A, MR, PAR, linear) and complete luminaires (e.g., table lamps, downlights, surface-mounted ceiling fixtures, street and parking lot light fixtures).

Based upon the SSL Annex's input, during the course of the literature search, review, and analysis, LRC staff used the following methods and criteria:

- We identified papers and reports published worldwide, written in English, and published in international journals, conference proceedings, government sites, and white papers since 2011 highlighting test methods that looked applicable to this study and compiled them in a spreadsheet. The first level selection of literature was based on the publication title and the next level selection was based on the abstract. The Excel spreadsheet contains columns that include abstracts, year of publication, authors' names, affiliations, countries of authors, and notes about why a particular publication was selected or not selected for reference in this literature review. For example, if the paper addressed failure of the semiconductor die and not the LED package, it was considered not relevant because such information is useful for semiconductor chip manufacturers and not to the government agencies concerned about lighting product quality.

- As indicated in the project's scope, we focused primarily on system level test methods and system level failure mechanisms. LED device, package, and driver test methods and failure mechanisms were also reviewed but used only to inform our understanding of system level testing and failure.
- We selected primarily research-informed publications, where testing had been conducted to validate hypotheses on system performance and failure.
- The majority of papers referenced are from 2015 or later, as most system level testing has taken place during the past five years. Prior to 2015, most test methods and studies investigated individual LED packages, arrays, and drivers, rather than complete systems.

Many existing LED lighting standards consider only the luminous flux maintenance aspect and ignore the possibility of catastrophic failure. As a result, many published studies on system level testing also consider only the luminous flux maintenance failure of an LED product. Therefore, in our analysis we chose studies that took catastrophic failure into consideration as well, because having an understanding of what causes each type of failure provides a more accurate representation of system performance and reliability.

1 Introduction

Undoubtedly, LED technology has advanced significantly in the last decade. Today, LEDs are the primary electric light sources used in new designs for virtually all general and specialty lighting applications, both indoors and outdoors. LEDs have been successfully used in applications ranging from pathway lighting, where small amounts of light are needed, to stadium lighting, where large amounts of light with precise optical control are required. Similarly, successful indoor applications for LEDs range from under cabinet lighting in residences to high bay lighting in industrial settings (Table 1.1). For purposes of this report, the focus is on white light for general illumination, and consequently the focus is on phosphor-converted white LEDs as this is the predominant technology in the marketplace.

Table 1.1. Brief list of applications where LEDs have been successfully used in the past few years.

Indoors

- Residential and hospitality lighting, decorative and functional
- Commercial applications, from school and office to retail lighting to hospital evaluation and ER lighting
- Hospital and other applications where short-wavelength disinfection is desirable
- Industrial low and high bay, hazardous locations, in-ground mining
- Agricultural applications from growing to harvest timing control to pest control
- Transportation
- Daytime running, standard low and high beam, and advanced car headlights
- Signal and indoor lighting in all types of transportation vehicles

Outdoors

- Pathway lighting
- Area and parking lot lighting
- Street and roadway lighting
- Stadium lighting
- Construction zone lighting
- Façade lighting for building, monuments, bridges and temporary events
- Signage
- Traffic signals
- Taxiway, touch down, center line, and other airfield side applications in airports
- Search, beacons, and other safety and security applications

All of these applications and more had been dominated for decades by legacy light sources, including incandescent, fluorescent (linear and compact), and all forms of discharge lamps because each technology used to offer an advantage over the others depending on the priorities of each application. However, now LEDs offer an advantage over practically all light sources in all aspects, including energy efficiency, spectral characteristics, temporal and optical control, dimming, life, and overall system cost.

Although LED sources have the potential for the longest useful life of all lighting technologies, this is not an inherent property of LED systems and as such, they need to be designed carefully, considering the conditions under which they will be operating. It is important to emphasize that LED systems are also subject to the same mechanical, thermal, and electrical stresses that any other lighting system would experience in real-life applications and thus require careful design and installation to realize all of their benefits. Logically, understanding the lifetime of LED systems under realistic conditions of operation is key to determining their overall cost, that is, the cost to own (design, install, commission), operate (energy, repair, replacement), and decommission (disposal, recycling) the system. In turn, these costs are needed to inform decisions that are based on payback and return on investment of the project. There are, however, more implications to knowing the lifetime of a lighting system, including the ability to plan for maintenance, anticipate and prevent potential safety and security concerns (impact of lighting not being available), change the aesthetics of the ambiance in the space, and set clear expectations to end users and consumers. With traditional technologies, experience informed these and other design decisions because the lifetime of legacy light sources was better understood. With LEDs, the information needed is not yet available for many applications.

The objective of this report was to survey and summarize the literature on LED system lifetime definition, failure mechanisms of LED components and systems, parameters that accelerate failure, and available test methods for estimating LED system lifetime. The report starts with an overview of failure, reliability and existing rated life definitions, and continues with a review of failure mechanisms, test methods, and standards as they apply to LED components and systems. At the end, two methods are recommended for consideration to estimate LED system lifetime.

2 Overview of failure, reliability, and rated life

2.1 Failure and reliability

The concept of failure can be best related to the definition of reliability, a concept generally defined as "the ability of a product or system to perform its intended function for a specified time under its expected operating conditions" [IEEE, 2010]. For lighting applications, this means that any lighting characteristic that is expected or needed in the application and that is not met would result in the lack of reliability of the system, and thus could be considered to have reached the end of its useful lifetime, or rated life. For general illumination, these characteristics can include the light output, the color appearance of the light, temporal or spatial light distribution, among others.

A *failure mode* arises from the direct effect of a *failure mechanism*; that is, the failure mechanism is the cause of a failure mode [Collins et al., 2013]. For example, the browning or discoloration of the LED package lens material over time is one failure mechanism that manifests as lumen depreciation (the failure mode). When the failure mode occurs systematically over time, it is described as a parametric failure. Failure modes that result in abrupt and permanent disruption of the operation of the device under consideration are described as catastrophic. Further, both failure modes are associated with LED systems and their components.

Generally, LED systems are composed of a number of subsystems and elements, including:

- LED(s) and printed circuit boards
- LED driver and power regulation source
- Electrical contacts, interconnections, and standardized bases
- Optical elements, including primary, secondary and tertiary lenses, optical guides, reflectors, and diffusers
- Thermal management components
- Mechanical housing

Assuming a system series configuration, the failure of any of these components or subsystems could result in the malfunction or failure of the entire system [Goel and Graves, 2006].

2.2 Lamp Rated Life

For traditional light sources, lamp life is defined as the time that elapses until 50 percent of a large batch of lamps fails when operated under specified conditions, namely controlled laboratory conditions [ANSI/IES, 2017; CIE, 2011; IEC 60050-845]. In general terms, rated lamp life is the life value assigned to a particular type of lamp and is typically a statistically determined estimate of median operational life. Rated life is expressed in hours, applies to certain operating conditions and failure criteria, and is specified by the manufacturer. For example, a median life of 10,000 hours means that 50 percent of the tested products have lasted 10,000 hours without failure. Similarly, the definition applies to a large installation of lamps for which it is expected that at the end of the rated lamp life at least 50 percent would remain operational.

For electric lamps and luminaires, the definition of operational can be based on catastrophic failure modes (e.g., lamp burns out, as in incandescent lamps) and parametric failure modes (e.g., luminous flux depreciation, chromaticity shift). Generically, the International Electrotechnical Commission (IEC) addresses these possibilities in definition 845-07-63 "life to X % failures" as "the length of time during which X % of the lamps subjected to a life test reach the end of their lives, the lamps being operated under specified conditions and the end of life judged according to specified criteria."

Traditional light sources failed by different but known mechanisms, and their lifetime test conditions included on-off cycles that reflected this understanding. For example, incandescent lamps were tested under continuous operation, whereas fluorescent lamps were tested under 2:45 hour on, 15-minute off cycles (3-hour on, 20-minute off in the U.S.) [Rea, 2000]. However, in all cases these tests were conducted under controlled ambient temperature, typically 25°C. In addition to reporting light source lifetime defined this way, manufacturers also provided the expected lumen depreciation at 40 percent of the rated lamp life.

2.3 LED Rated Life

Unlike other electric light sources that depend on heating an element at high temperatures or radiation from excited mercury atoms, LEDs produce light directly from an electric current. This process is called electroluminescence, which can be very efficient at transforming electricity to light, hence the high energy efficiency from LEDs. Because of this, under favorable conditions the light output of LEDs typically degrades gradually over time rather than burning out. Following the recommendations from the Alliance for Solid-State Illumination Systems and Technologies [ASSIST, 2005], the lighting industry rates LED life as a function of a certain percentage of their initial light output value, typically 70%. This lumen maintenance criterion is typically referred to as “L70.” [IES LM-80, 2008a, 2015, 2020; IEC 62612, 2018]. However, other criteria can be used in addition or individually to define when an LED lighting system is no longer performing acceptably and is thus considered to have reached the end of its useful life. For example, IEC 62612 also considers 80% and 90% lumen maintenance categories as options to define useful lifetime.

Similarly, light source color shift has been used as a criterion to define the end of LED life [ASSIST, 2005; IEC 62612, 2018]. Light source color appearance is measured by the chromaticity (i.e., in the 1976 CIE u’,v’ chromaticity space) of the source [CIE, 2004, 2014]. Light source chromaticity consistency (initial among products of the same kind, and over time) is an important aspect of successful architectural lighting. Initial industry recommendations to consider light source chromaticity maintenance date to the early days of commercial phosphor-converted white LEDs and include varying criteria depending on the application. More recently, light source chromaticity maintenance has been used in standards and specifications for market transformation programs as one key aspect of lighting quality [e.g., IEC 62612, 2018; United States Environmental Protection Agency, 2020]. Chromaticity shift tolerance zones are typically specified as a function of the radius of a circle in the u’v’ chromaticity space, for example a 2-step u’v’ circle [CIE, 2014].

2.4 LED System Rated Life

2.4.1 Present practice

Briefly, the L70 value is determined by operating individual LEDs under a standard set of conditions (continuous operation; at least two different LED junction temperatures) for at least 6,000 hours [IES LM-80, 2020]. For lighting systems, the data obtained from this test, together with an estimate of the LED operating temperature in the lighting system, are then put into an exponential decay model which is used to predict the point at which the system is expected to reach 70% of its light output [IES TM-21, 2019]. Even though this procedure was intended for LEDs only, often this information is used by luminaire and replacement lamp manufacturers to determine the rated life of their products.

2.4.2 Limitations

Although LED lighting systems are claimed to have very long useful lifetimes when characterized by slow lumen depreciation, research has shown that catastrophic failure is common and can be the dominant failure mode in replacement lamps and luminaires [Narendran et al., 2007, 2015; Van Driel et al., 2018; Hathaway, 2020]. The most common catastrophic failure mechanisms in LED systems include solder joint, electrical interconnects, and driver component failures.

Using lumen maintenance as the primary, or only, definition of lifetime is based on the premise that the main failure mode in an LED product is gradual luminous flux decrease over time, and importantly, that power on and off cycling does not have a negative impact on LEDs or systems. However, research has demonstrated that power cycling has an impact on the life of LEDs, LED arrays, and LED systems [Wu, 2010; Jayawardena et al., 2013]. Thus, the useful life of an LED lighting system is dependent upon numerous factors and components, including operating temperature, humidity, on-off cycling, thermal management systems, luminaire housing, secondary optics, and driver components, and of course the LEDs themselves. The failure of any component can cause the whole system to fail.

Additionally, the problem with using this lumen depreciation metric as a life predictor for an LED product is that it only pertains to the LEDs themselves, and does not take into account the other components within an LED lamp or luminaire. In most applications the lifetime of the LED system is more important than just the LEDs' expected lifetime. This is because what matters to the end user is having the lighting system available when needed, and other components in the system are also subject to failure, most likely before the LED failure.

Thus, LED system lifetime should ideally be predicted in terms of both parametric and catastrophic failure. However, there is no complete agreement among published standards. In North America, standards only consider lumen depreciation of either LED packages [IES LM-80] or complete LED products [IES LM-84, 2014]. International standards, in addition, consider endurance tests to characterize initial catastrophic failures [IEC 62612, 2018; IEC 62717, 2019; European Union, 2019].

2.4.3 Additional considerations

If the factors such as temperature and humidity during operation and switching on and off have an effect on LED system life, then it follows that the specific conditions of operation in different applications need to be considered in any meaningful definition and test method of LED system lifetime.

As shown earlier in Table 1.1, there are multiple applications where LEDs are being used. These applications present varied operating conditions to the lighting systems in at least the following ways:

- ***Thermal environment.*** The operating temperature of the LED and other system components is determined by these factors:
  - Method of installation: e.g., fully ventilated (table lamps, street lights), semi-ventilated (recessed downlights, no ceiling insulation), enclosed (recessed downlights with ceiling insulation, in-ground outdoor fixtures)
  - Installation site: solar exposed vs sheltered
  - Geographical location: e.g., tropical vs. temperate locations
  - Seasonal variations: e.g., winter vs. summer
  - Total power dissipated by the system

- ***Relative humidity of the environment.*** The relative humidity of the environment where the LED and other system components is determined by these factors:
  - Method of sealing the luminaire (hermetic) to prevent water reaching the LED die and package components
  - Geographical location: e.g., tropical vs. temperate locations; seaside with high salt, and relative humidity
  - Seasonal variations: e.g., rainfall
- ***Pattern of use.*** The pattern of use includes the number and the duration of cycles and is determined primarily by the application itself, for example:
  - Residential: short but several on/off cycles per day
  - Commercial, industrial: long but few on/off cycles per day
  - Outdoor: long and typically single on/off cycle per day; failed daylight sensors (photocells) can result in the lights operating during the day at a higher than normal temperature because of the solar thermal gain.

The patterns of use can be a direct reflection of when the lighting in the space is needed and used, or the result of automatic controls (e.g., occupancy, vacancy, scheduling). Past studies have attempted to characterize the time of use of different light sources in common applications, including dimming [Leslie and Conway, 1996; United States Department of Energy, 2012; EN, 2015, 2017; NMF, 2019]. A sample of those findings are shown in Tables 2.1-2.5 and can be used as an initial step to determine test cycles for LED systems life testing.

Table 2.1. Sample average daily operating hours by residence type and room (abridged data from United States Department of Energy, 2012).

	Single family	*Multifamily*
Basement	1.6	1.4
Bathroom	1.6	1.6
Bedroom	1.6	1.6
Closet	1.4	1.3
Dining room	1.9	1.9
Exterior	2.6	2.7
Garage	1.5	1.5
Kitchen	2.3	2.3
Living/family room	2.0	2.0
Home office	1.9	1.8

Table 2.2. Sample average daily operating hours per lamp type by commercial building type (abridged data from United States Department of Energy, 2012).

	INC	*HAL*	*CFL*	*LFL*	*HID*
Education	10.5	12.4	10.4	11.0	11.1
Food service	10.2	12.0	10.3	11.1	10.5
Food store	10.5	12.3	10.4	11.3	11.2
Health case – inpatient	10.0	12.2	10.4	11.0	9.2
Lodging	10.3	12.2	10.3	11.0	11.2
Offices	10.1	12.3	10.4	11.0	11.1
Places of worship	10.0	12.1	10.4	11.0	10.5
Retail	10.6	12.5	10.4	11.0	11.1
Warehouses	10.3	12.4	10.4	11.0	11.2

Table 2.3. Sample average daily operating hours per lamp type by industrial building type (abridged data from United States Department of Energy, 2012).

	INC	*HAL*	*CFL*	*LFL*	*HID*
Apparel	12.6	11.7	13.0	12.5	16.9
Computer and electronic products	12.9	11.7	13.0	12.5	16.5
Metal products	13.0	11.7	13.0	12.6	16.7
Food	13.0	11.7	13.0	12.4	16.6
Furniture	-	11.7	13.0	12.4	16.6
Paper	-	11.7	13.0	12.4	18.3
Plastics	13.2	11.7	13.0	12.6	17.0
Printing	12.4	11.7	13.0	12.6	16.5
Miscellaneous	11.0	11.6	13.0	12.6	15.8

Table 2.4. Default annual operating hours and expected average installation life for sample indoor applications in European Standard EN 15193-1 [EN, 2017] (after Lighting Europe, 2018).

Indoor application	***Default annual operating hours***	***Average installation life***
Offices	2500	50,000
Education	200	50,000
Hospitals	5000	50,000
Hotels	5000	50,000
Restaurants	2500	25,000
Sports	4000	100,000
Retail	5000	50,000
Manufacturing	4000	100,000

Table 2.5. Default annual operating hours and expected average installation life for sample outdoor applications in European Standard EN 13201-5 [EN, 2015] (after Lighting Europe, 2018).

Indoor application	***Default annual operating hours***	***Average installation life***
Street	4000	100,000
Tunnel (entrance)	4000	100,000
Tunnel (interior)	8760	100,000
Sport (recreational)	1250	25,000
Area	4000	100,000

The operating temperature of LED systems can be characterized by instrumenting systems with thermocouples and measuring the thermal profiles as the systems are operated over several on/off cycles when installed in their intended (or a similar) application. This information can then be replicated in the laboratory during life testing. Especially for outdoor applications, official weather reports (e.g., European Environment Agency) could be used to establish a testing baseline for ambient temperature and relative humidity by geographical region and time of year as needed.

As it will be explained in the next sections, there are multiple failure mechanisms in LED components and systems, but the most relevant can be traced back to the effects of the environment (thermal, humidity) and power supply cycling. Therefore, it is important to emphasize that any definition of system useful lifetime and testing method take into account realistic worst case conditions as those found in the intended application for that system.

3 LED Package Related Failure Mechanisms, Test Methods, and Standards

3.1 Introduction

Commercial white, phosphor-converted (pc-) LEDs were first introduced to the market during the mid-1990s. The semiconductor industry was very enthusiastic and initially claimed LEDs to have very long lifetimes, up to 100,000 hours. This claim was based on metrics such as Mean Time to Failure (MTTF) and Mean Time Between Failures (MTBF) commonly used in the electronics industry for rating the lifetime of electronic components.

3.2 Failure Mechanisms

Reliability and life research of gallium nitride (GaN) based LEDs and phosphor-converted (pc) white LEDs began during the late 1990s to early 2000s [Nakamura, 1998; Narendran et al., 2000, 2001; Steranka, 2002; Levada et al., 2005]. Soon after white pc-LEDs became available in 1999, the LRC began testing 5-mm type white LED devices, and it became obvious that lifetime claims based on MTTF or MTBF were not meaningful to the lighting industry. Initial laboratory test results of 5-mm type pc-LEDs showed that at nominal current (20 mA), these devices depreciated down to 50 percent light output in approximately 6000 hours [Narendran et al., 2000, 2001]. Based on the initial observations that LED light output depreciated before failing catastrophically (which might take a very large number of hours), the lifetime of white pc-LEDs was defined as the time it takes to reach 70 percent lumen maintenance [Narendran et al., 2001]. The early 5-mm type pc-white LEDs experienced rapid lumen depreciation due to browning of the encapsulant surrounding the GaN blue chip. In 2002, Steigerwald and colleagues at Lumileds published a paper that showed improved lumen maintenance for their Luxeon high-power white pc-LED compared to the initial commercial 5-mm pc-LEDs [Steigerwald et al., 2002]. After 2002, several researchers investigated GaN-based pc-white LED failure and reliability. Researchers from Padova University in Italy, including Levada and colleagues, started LED failure analysis and reliability testing in 2005. In their 2005 paper, the researchers analyzed accelerated life tests of GaN LEDs operated under direct current and discussed the related failure mechanisms from high current stress [Levada et al., 2005].

Lumen depreciation and changes in light chromaticity are considered parametric failure modes and can result from several mechanisms, including defect growth within the semiconductor chip, encapsulant and phosphor degradation (browning). In particular, lumen depreciation and chromaticity changes are the result of operation at high junction temperature [e.g., Narendran et al., 2000, 2001; Narendran, 2005; Narendran and Gu, 2005; Narendran et al., 2007; Cai et al., 2017]. The literature reports increased degradation when the LEDs operate under high temperature and high humidity conditions.

Operation in elevated humidity conditions results in defects in the active region at the chip level, leading to additional photometric and colorimetric changes [Law et al., 2016]. It is believed that elevated humidity also causes damage on the edge of the LED chip, which reduces light output [Tan et al., 2009]. Elevated temperature and humidity as well as short-wavelength irradiance have been observed to induce and lead to the deterioration of phosphor energy conversion and darkening of encapsulation materials at the package level [Lall and Zhang, 2013; Appaiah et al., 2015; Law et al., 2016; Mehr et al., 2014, 2016].

Additionally, volatile organic compounds (VOC) trapped within LED packages with silicone encapsulant can result in lumen depreciation and light color changes [Marcus, 2012]. The literature also reports parametric changes in thermal resistance characteristics, resulting in lower ability to transfer heat out of the junction [Tan et al., 2009; Lall and Zhang, 2013; Law et al. 2016].

The primary causes of LED chip-related catastrophic failure mechanisms include defects in the LED chip itself and electromigration of metals into the chip caused by metal contacts attached to the semiconductor (which results in short-circuit failure). These mechanisms are caused by electrical and/or thermal stresses [Meneghini et al., 2005; Lu et al., 2009]. One of the most common failures at the LED package level is due to solder joint (lead wire to LED semiconductor chip positive and negative terminals) failures that disrupt the electrical path and results in an open-circuit [Chang et al., 2010]. The literature also reports LED chip and package level interconnect corrosion caused by elevated temperature and humidity where silver can be removed by electromigration from underneath the LED contact with the connection pads on the circuit board. Corrosion results in increased series resistance [Tan and Singh, 2014]. Humidity was also found to reduce 40–60% of interfacial adhesion strength inside the LED package, which can lead to the delamination at different interfaces such as the LED chip's die attach interface, and between the LED chip and encapsulant interface [Hu et al., 2007; Zhou et al., 2009; Luo et al., 2010; Fan and Yuan, 2013].

3.3 Test Methods

The 70 percent lumen maintenance criterion (termed L70) selected by Narendran et al. in 2001, was based on a number of assumptions, including typical mean lumen values and economic life considerations of traditional light sources [Rea, 2000]. This proposed definition was supported by contemporary human factors research that showed that temporal changes of approximately 30 percent in ambient illumination were needed before observers reported noticeable changes in the illumination [Akashi and Neches, 2004].

Preliminary industry adoption followed by companies such as Cree, Lumileds, and Nichia who explored the feasibility of the L70 concept as a measure of LED life. Shortly thereafter, the Alliance for Solid-State Illumination Systems and Technologies (ASSIST), an industry alliance formed by Rensselaer's Lighting Research Center, formalized the recommendation of using L70 as well as a maximum chromaticity shift measured by a 4-step MacAdam ellipse as criteria for the definition of LED life [ASSIST, 2005]. This recommendation was made in the context of general illumination applications where these two parameters are meaningful for achieving successful applications.

The *ASSIST recommends* publication proposed a method to test LED lumen maintenance performance at three different LED junction temperatures (T_j) and determine L70 values for the corresponding T_j using an exponential decay function [ASSIST, 2005]. The *ASSIST recommends* publication states that the intended user of this information is the LED system manufacturers (not LED system users) so that they can properly design LED lighting systems. The testing methods in the ASSIST (2005) publication formed the basis for the industry standard published by the Illuminating Engineering Society (IES) in IES LM-80-08, *Approved method: Measuring lumen maintenance of LED light sources* [IES, 2008a].[1]

The ASSIST and IES LM-80 testing methods capture two common LED package failure modes, namely, lumen depreciation and chromaticity shift, but other failure modes are possible, such as increase in forward voltage (V_f) and thermal resistance (R_{theta}), as well as catastrophic failure. These failure modes are attributable to thermal, electrical, mechanical, environmental, chemical, and radiation stress factors and are important to be considered in lighting applications [Van Driel et al., 2018].

For many years, the IES LM-80 standard was used to test and report L70 values for new LED packages. With improved encapsulant materials and improvements in packaging methods, pc-LED lumen depreciation slowed significantly and required data projection methods to estimate the time for luminous flux to depreciate to the 70 percent value. With this in mind, the IES introduced TM-21, *Technical Memorandum: Projecting Long Term Lumen, Photon, and Radiant Flux Maintenance of LED Light Sources* [IES, 2011] to extrapolate lumen maintenance data obtained using LM-80 data to determine L70 for LED packages. However, in their most recent versions, IES LM-80 (2020) and TM-21 (2019) do not mention L70 as a criterion to define "rated lumen maintenance life" [IES, 2008a,

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[1] Latest version published in 2020

2011, 2015, 2019a]. Rather, IES TM-21-19 states that the extrapolation methods shall not be used to project lumen maintenance beyond L70 [IES, 2019a].

White LED lighting products for lighting applications started to emerge in the industry during the mid-2000s. For LED lighting systems to be used in applications, lighting specifiers needed lifetime information. In the absence of a standardized LED system (product) lifetime test method, the lighting industry continued to use IES LM-80, or modified versions of LED package lumen maintenance data, to rate LED system lifetime.

Globally, IEC standards describe test methods for LED modules, lamps, and luminaires that require stating the lumen depreciation at the end of the test and assign a lumen maintenance category accordingly [e.g., IEC 62612, 2018; IEC 62717, 2019; IEC 62722, 2014]. It is worth emphasizing that the IEC test methods are not intended to predict lifetime.

Additionally, some programs, including US EPA's Energy Star®, the European Union, and others, have used rapid cycle test data (such as 5-minutes on, 5-minutes off, 30-seconds on, 30-seconds off, etc.) together with lumen maintenance test data to assure the reliability of LED products [United States Environmental Protection Agency, 2020; IEC 62612, 2018].

3.4 Standards

For over a decade the industry practice to estimate LED system life has been to report lumen maintenance values according to the test procedure in IES LM-80 [IES, 2008a]. These values are further used as the basis for extrapolation of the time to reach L70 using the methodology outlined in publication IES TM-21 [IES, 2011, 2019a]. The methods in TM-21 should be used carefully as the uncertainty in the projection depends on the number of samples and test duration. One of the main aspects to remember is that lumen maintenance projections should be limited to a maximum of six times the duration of the LM-80 test. Importantly, LM-80 and TM-21 continue to be used as the basis for estimating LED system lifetime. This issue is discussed in detail in section 6.

To address color shift, ANSI/IES TM-35, *Technical Memorandum: Projecting Long-Term Chromaticity Coordinate Shift of LED Packages, Arrays, and Modules*, was recently published [ANSI/IES, 2019]. This standard provides, after years of research into the different color shift mechanisms of different types of LED packages, a method for projecting chromaticity shifts from data available in LM-80 reports for LED packages. The publication is based on the differential chromaticity analysis, which applies a curve-fit to the chromaticity over time and extrapolates relative changes in chromaticity in u' v' chromaticity space. Given how recent this standard is, there is not enough public information on its use.

4 LED Driver Failure Mechanisms, Test Methods, and Standards

4.1 Introduction

Reports in the literature show that as LED package technologies have matured, other components in the system are becoming the weak links. One of the most commonly cited studies reported that over 70 percent of the failure modes in one model of outdoor LED luminaire over several product generations and across a combined 212 million field operation hours were due to the driver. The most common causes of driver failure are related to solder joints, electrical connections, and circuit components, including MOSFETs, electrolytic capacitors, rectifying diodes, and opto-isolators [United States Department of Energy, 2011, 2014].

Research discussed in this section, based on literature on LED drivers, consistently shows that the correct operation of the following components has a direct and positive effect on the LED driver's lifetime:

- Input stage electrolytic capacitor
- Output stage electrolytic capacitor
- MOSFET
- Power diode
- Control integrated circuit

The failure of these components can be parametric [Han 2009; Han and Narendran, 2009; Sun et al., 2016; Zhang, 2017; Niu et al., 2018a, 2018b; Keil and Hofmann, 2019] as well as catastrophic [RTI International, 2013, 2019; Lall et al., 2015].

The literature discussed in this section attributes the following list of stressors as affecting the lifetime of LED driver components:

- Elevated operating temperature
- Elevated humidity
- Electrical overstressing (due to poor product design)

4.2 Electrolytic Capacitors

The parametric failure of electrolytic capacitors on the output stage of LED drivers has been studied in the past by Han (2009), Han and Narendran (2009), Sun et al. (2016), Zhang (2017), and Niu et al. (2018a,b).

In this type of capacitor, the failure mechanism is the evaporation and deterioration of the dielectric material, which results in a decrease of the capacitance as well as an increase of the equivalent series resistance (ESR). Operation at elevated temperature or an increase in capacitor internal temperature has been shown to be the main stressor for the dielectric dry out effect. The increase in ESR and the decrease in capacitance lead the electrolytic capacitor to degrade. Capacitor manufacturers typically use a 10% to 20% decrease in capacitance and a 200% increase in ESR (both measured at 120 Hz) as the criteria to define the parametric end-of-life of electrolytic capacitors [Han, 2009]. The results from Han (2009) showed that the LED driver output current ripple increases with an increase in ESR and a decrease in capacitance. Additionally, Han and Narendran (2011) proposed that driver output current ripple can be used to predict LED driver lifetime related to parametric failure.

In their studies, Han (2009) and Han and Narendran (2011) used constant elevated ambient temperature as the stressor ranging from 150°C to 205°C for each group of capacitor samples. The capacitor positive lead temperature was monitored as a surrogate for capacitor internal temperature, while capacitance, ESR, and output current ripple (i.e., the percent ratio between peak-to-peak current amplitude and mean current amplitude) were also monitored. Han and

Narendran (2011) used the second derivative of the current ripple change over the duration of test to estimate the lifetime of capacitors. The authors then used an exponential extrapolation to predict application lifetime (e.g., positive pin temperature 100°C) from plotting the lifetime of capacitors vs. positive pin temperature from the data from accelerated life tests.

Cracking or even melting of metallized film capacitors was another failure mechanism that was observed by Keil and Hofmann (2019), which was caused by elevated humidity and is another critical stressor in addition to the elevated temperature similar to the finding from Han (2009), Han and Narendran (2009), Sun et al. (2016), Zhang (2017), and Niu et al. (2018a,b). Although, not directly related to LED drivers, other literature such as Wang and Blaabjerg (2014) also observed humidity effects on metallized film capacitors in power electronic converters.

Liang et al. (2020) also observed parametric failures due to electrical stress in addition to temperature and humidity in LED drivers. In this study, Liang et al. (2020) used the failure criterion of output current ripple from the constant current driver as ≤10%, and the accelerated life testing was conducted on LED drivers under the following test conditions:

- Constant temperature
- Constant temperature (120°C) and humidity (75% and 95% RH)
- Constant temperature (120°C), humidity (85% RH), electrical stress (38 V)
- Constant humidity (85% RH) and temperature cycle (25°C to 85°C at a cooling or heating rate of 2°C/min, soak time 30 minutes, and cycle time 2 hours)

The authors claimed the output current decreases with the increase of temperature but showed no obvious attenuation or sudden failure of the LED driver. They also concluded that the high humidity temperature cycle had no obvious accelerated aging effect on the tested driver, but there is an obvious increase in LED driver degradation between the effective relative humidity range of 55% to 85%. Liang et al. also claim the change in the LED driver output current was caused by the decrease in ESR of the output filter capacitor with the increase of the temperature. Additionally, they observed the temperature rise of other devices causes the output current to decrease, indicating an interaction among devices in the LED driver and leading to failure based on a specified criterion.

Niu et al. in 2018 conducted elevated capacitor testing at an upper operational temperature of 85°C (2018a) and 100°C (2018b), and the normalized capacitance and ESR were regularly measured during the 3,000 testing hours. They used a 20% of capacitance decrement as the failure criterion since the capacitance decreases rapidly after the capacitance reaches 80% of initial value. Niu et al. (2018a, 2018b) concluded the ESR change has relatively higher impact on the electrical and thermal performance than capacitance change and is critical to estimating the lifetime (using Monte Carlo simulations) of the LED driver used in the study.

In a 2016 study by Sun et al., electrolytic capacitors in a RC linear driver were aged at a 125°C ambient temperature. The relative output power of these linear drivers connected to a stable LED load was measured as a function of time. The authors used a physics of failure (PoF) approach to predict lifetime based on Monte Carlo simulations performed to obtain a probability of failure for the output stage electrolytic capacitor.

Zhang (2017, 2018) tested quasi-flyback LED driver samples under temperature cycling with the low temperature at –40°C and the high temperature at 85°C in an accelerated life test. The ramping up or down temperature rates were 5°C/min and soak time of 2-hours at −40 °C and 22-hours at 85 °C. The authors used the change in the capacitance to quantify the degradation and assumed the time to reach a change of capacitance of ±25% of the initial value as the lifetime.

Zhang (2017, 2018) presented the improved part stress analysis (PSA) method as an effective way to predict the reliability and lifetime of LED drivers. Zhang showed that improved PSA and data obtained from accelerated life testing matched well in predicting lifetime estimates at 90% LED driver survival rate, whereas the results from the Military Handbook: Reliability prediction of electronic equipment (MIL-HDBK-217F) [United States Department of Defense, 1991] model were approximately two times higher. The improved PSA method uses the MIL-HDBK-217F exponential failure distribution with an improvement on the operating conditions for each of the critical components of the LED driver such as electrolytic capacitors. In the 2017 study, Zhang used data in existing literature from Chelminski (2016) for validating the predictability of the improved PSA model as well.

Lall et al. (2015) used high temperature storage life acceleration testing (at 135°C), constant temperature (at 85°C), and humidity test conditions (85% relative humidity) when testing LED drivers, monitoring ESR and capacitance at the output stage capacitor. Lall et al. observed no indication of parametric degradation in the monitored capacitance and ESR measurements under the 85°C and 85% relative humidity test, but observed 4 out of 10 catastrophic failures. The high temperature storage life acceleration testing produced measureable degradation of aluminum electrolytic capacitor ESR and capacitance.

Similarly, in 2013 RTI International observed 2 out of 17 catastrophic failures (both 6-inch downlights) in their Hammer testing of fifteen 6-inch downlights and two 2×2 troffers. A description of the Hammer test conditions are provided in Section 6 of this report.

RTI International in 2019 also conducted an accelerated life test using temperature (75°C) and humidity (75% RH) as stressors, with the LED drivers undergoing power cycling with a 50% duty cycle and a period of two hours (1-hour on and 1-hour off). In this study, 2 out of the 11 LED driver samples failed catastrophically due to capacitor failures ranging from 2,800 hours to 4,000 hours. There were a total of 7 driver failures (others due to MOSFETs and fuses). The capacitors in the EMI filter in Stage 1 seemed to be the most susceptible to failure according to the report [RTI International, 2019].

4.3 MOSFETs (Metal Oxide Semiconductor Field Effect Transistors)

According to Lan et al. (2012, 2014), parametric failure of MOSFETs can be caused by:

- Hot carrier injection (HCI) at the MOSFET
- Electromigration (EM) at the output of the MOSFET

Lan et al. concluded that these failure mechanisms are found to be accelerated by high output voltage and high operating temperature. In their studies, Lan et al. (2012, 2014) tested the LED drivers at 120°C with output voltage at the maximum of 17 Vdc and maximum output current of 45 mA. The I-V curves of the LED drivers were obtained every 24–48 hours. A thermoelectric cooling device was used to maintain the driver at 18.5°C during the I-V curve measurement. The authors observed changes in the current to voltage (dI/dV calculated based on I-V behavior) relationship of the MOSFETs used in linear mode LED drivers. Their results included a shift in the knee-point of the I-V curve over time, which the authors claim to be useful for predicting MOSFET failure.

Lan et al. (2012) concluded that the black box testing and degradation model can be used to explain the degradation phenomena of LED drivers without knowing the detailed circuitry, which is of significant importance to LED systems testing. Unfortunately, access to the critical parameter dI/dV linked to the degradation index identified to explain LED degradation has to be available. By identifying the degradation rate of dI/dV at different stages (i.e., with respect to time), the corresponding failure mechanism (i.e., HCI or EM) can be found.

Lall et al. (2015) observed that constant temperature and humidity testing at 85°C and 85% relative humidity caused short-circuit failures in the components, leading to catastrophic failure of the driver. They observed 3 out of 10 IGBT (insulated-gate bipolar transistor)/MOSFETs having the top blown off, causing catastrophic failure to the system and were likely due to an electrical surge from moisture seepage into the component.

In the RTI International study from 2019, two catastrophic failures related to MOSFETs occurred out of 7 total failures where 11 LED drivers were subjected to the same 75°C and 75% RH power cycled test that was described in the section 5.2.

4.4 Driver Printed Circuit Board (PCB)

Keil and Hofmann (2019) also identified ambient elevated humidity causing galvanic corrosion at the solder interconnects on the PCB assembly in a driver as another key parametric failure of LED drivers. The authors claim this galvanic corrosion can be reduced by cleaning the PCB assembly after soldering.

Vandevelde et al. (2018) found high power LEDs soldered on insulated metal substrates have a limited lifetime due to the fatigue fracturing of the solder connections when the assembly is subjected to temperature cycles. In addition, the authors also found the number of cycles to failure decreases with increasing temperature excursion, as expected, but also when increasing the maximum solder temperature and dwell time at the maximum temperature. Vandevelde et al. claimed that the number of cycles to failure follows a Weibull distribution, and that a common function shape could be applied to the different thermal cycling tests. According to the authors, this confirmed that solder joint failure existed regardless of the temperature profile.

Soltani et al. (2018) investigated the substrate and surface-mounted LED devices under two drive currents (75 mA and 100 mA), three ambient temperatures (25°C, 85°C, and 105°C), and three substrate materials (FR-4 and two other materials). The authors found that the coefficient of thermal expansion (CTE) mismatch of the materials in the LED package and between the LED package and substrate. This CTE mismatch caused mechanical failures (such as die attach delamination and lens cracking), leading to both catastrophic failure and parametric failure. Soltani et al. used L70 as the failure criterion in this study and employed an Arrhenius-type equation to estimate the lifetime of the samples under test.

In 2013, RTI International conducted a hammer test (described in section 6) and found that 6 out of 12 failures from a sample of 17 LED luminaires were caused by catastrophic failure of the PCB. They attributed the failures to the extreme cyclical thermal stress during the test conditions, given that the 6 failures were from two 6-inch downlight product families intended for indoor applications.

To the best of our knowledge, no further investigations have been undertaken to predict LED driver lifetime based on this failure mechanism.

4.5 Standards

In the absence of LED driver-specific standards, and given that most LED drivers presently are electronic in nature, manufacturers have used the Telcordia Reliability Prediction Procedure [Telcordia SR332, 2016] and the Military Handbook for reliability prediction of electronic equipment (MIL-HDBK-217F) [United States Department of Defense, 1991] as guidelines to estimate LED driver lifetime. Standard IEC 62384: *DC or AC Supplied Electronic Control Gear for LED Modules – Performance Requirements* includes guidance on how to quote product life and failure rate in Annex B for informative purposes [IEC, 2020]. In this publication, manufacturers are encouraged to provide the maximum temperature at the critical location in the product for which it can reach a 50,000 hour life. In addition, and for ease of comparison among products, manufacturers are encouraged to provide the number of failures over time when the product is operated continuously at the maximum temperature identified in the previous sentence.

5 LED System Reliability and Life Test Methods and Standards

5.1 Background

One of the widely claimed benefits of LED lighting products is the potential for long service life when used in their intended applications. However, the lighting industry needs an agreed upon standard to define LED system life and a corresponding test method to accurately estimate lifetime when used in different applications.

LED systems (or products) have many components, including LED package(s), printed circuit boards (PCBs), secondary optics, driver, heat sink, and mechanical housing (Fig. 5.1). The exact composition of components and subsystems depends on the product. Failure of any individual component or subsystem can lead to system failure.

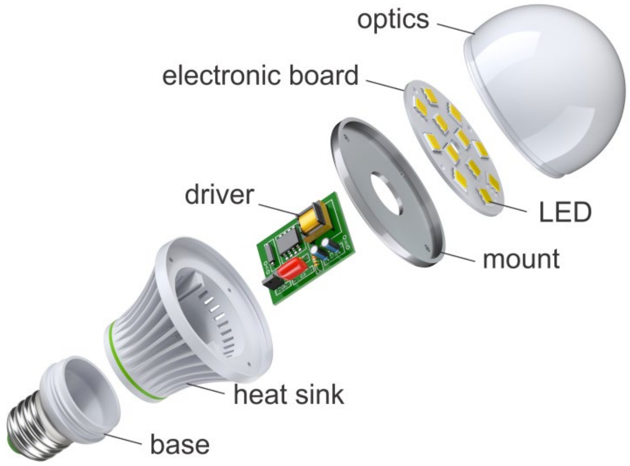


Figure 5.1. Anatomy of a sample LED product.

Until approximately 2007, most of the failure analysis studies in the literature reported findings on the failure mechanisms and expected lifetime of individual components such as LED packages, secondary transmissive optics, and drivers [see sections 4 and 5]. Since approximately 2007, the research community expanded their activities to study aspects of LED system reliability and life with the intent of identifying system level failure modes, frequency of failure of individual components, and the failure mechanisms. It is important to note here that one critical aspect of system level studies is that they include the interactions among individual components that are otherwise omitted in component level studies but are nevertheless critical in determining overall system reliability. In 2010, the United States Department of Energy published the report entitled *LED Luminaire Lifetime: Recommendations for Testing and Reporting* [United States Department of Energy, 2010]. This report put forward one very important clarification, namely that “reliability” and “lifetime” are not synonymous because up to that point publications addressing LED system life had been using these terms interchangeably. The DOE report pointed out that a luminaire or lamp includes a number of interdependent components and subsystems, each with different life and reliability values, and that the system has to be evaluated as a whole. In this DOE report, luminaire’s “lifetime” or “end of life” was defined by when there is no light emitted.

As LED products continued to be introduced into the marketplace, the need for system level reliability and life testing methods was initially filled by the methods that manufacturers had historically used for other electronic systems, including:

- Accelerated life testing (ALT)

- Highly accelerated life testing (HALT)
- Step stress accelerated degradation testing (SSADT)

Most accelerated life testing methods include test conditions conducive to identifying weak components in the system and infant mortality issues and thus, are considered pass-fail tests. Although these tests often are not conducted in conditions that are representative of those experienced by the systems in their intended applications, the expectation is that if a product can endure, for example, 1000 cycles under overstress, then it will perform reliably under normal use. Collectively, these research efforts have informed the development of short-period life testing methods that could accurately and reliably estimate LED system reliability when used in different applications.

The next section covers a summary of accelerated life test methods and is followed by a section on test methods intended to estimate LED system life in conditions similar to those found in general lighting applications.

5.2 LED System Reliability and Life Test Methods

5.2.1 Accelerated life test methods

This section describes four types of accelerated test methods that have been used for assessing LED lighting systems' reliability or lifetime.

5.2.1.1 Highly accelerated life testing (HALT)

HALT is a pass/fail type test used primarily to identify the upper thermal destruction limit of products including mechanical, electronic, and others (see Fig. 5.2). The objective of the HALT process is to subject the device under test to stress environments well above the expected application environments to determine its operating and destructing limits [Cai et al., 2012].

Formulated in the 1980s, HALT is an experimental testing scheme claimed to be best used during the product development phase to reveal the design weaknesses of electronic devices by subjecting them to stressors such as:

- vibration
- extreme constant temperature
- ramp temperature stresses

Because HALT does not provide information on degradation mechanisms, it is not suitable for testing systems for which that information is needed, as is the case in lifetime estimation of LED products (e.g., lumen maintenance and chromaticity shift over time is part of the information that defines their life). Therefore, HALT tests have been recommended as the first step before step-stress accelerated testing is conducted to identify the range of stressors that bound the upper and lower destruction limits of the device under test. As an example, Cai et al. recommend this approach for establishing LED system and subsystem (e.g., light engine, power supply) upper and lower destructive limits. In that study, three samples, including a golden sample, were stressed from 55°C to 135°C in 11-steps. The test included a 12-hour dwell time for each temperature stress step. The total light output of the samples was measured in an integrating sphere after 30 minutes stabilization at a 25°C ambient temperature. The junction temperature of the samples was measured using a pulsed current method [Cai et al., 2012].

Additionally, Cai et al. (2012) also used HALT test data to observe the presence of additional degradation mechanisms and modes within the range of the stressors to be used in succeeding tests. Using the light output and junction temperature measurements, the authors concluded that above 110°C temperature stress conditions the LED products tested showed irregular behavior compared to the data collected below 110°C, suggesting the LED product might have been subjected to stress conditions that might lead to additional degradation mechanisms.

5.2.1.2 Highly accelerated decay testing (HADT)

HADT is similar to HALT but is used to identify upper product operating limits, as illustrated in Fig. 5.2 [Cai et al., 2016a]. In this example, at each of the stress levels the sample device was subjected to a progressive increase while maintaining a dwell time of approximately 12 hours under stress level. Measurements of degradation parameters (e.g., estimated Tj or a surrogate, luminous flux, chromaticity) are carried out during discrete times during the dwell time; for example, after the end of the first hour and at the beginning of the last hour within the dwell time at a particular stress level similar to the HALT testing described by Cai et al. (2012).

Similar to HALT, HADT is also used to ensure consistency in the degradation mechanism, an estimate of goodness of step-fitness is made based on the predetermined degradation mechanism of the accelerated product (α) to maintain a value between 0 and 0.2. For example, in a related LED lifetime test study, Cai et al. (2016a) maintained Δα<0.1.

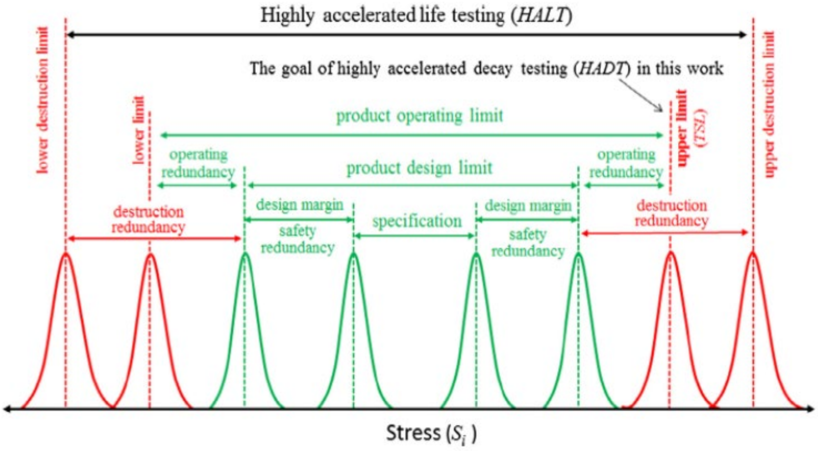


Figure 5.2. Comparison between HALT and HADT tests [Cai et al., 2016a].

The HADT methods are recommended as a first step to identify a product's upper operating limits as well as its output parameters under these conditions. This information can be then used to decide the stress limitation to be used in subsequent testing methods, such as SSADT, to assess LED system or subsystem lifetime [Cai et al., 2012, 2016a].

5.2.1.3 Step-stress accelerated degradation testing (SSADT)

Accelerated degradation testing (ADT) is an alternative approach to accelerated life testing used to assess the lifetime of devices. The ADT process assumes:

- Reliability is related to product quality characteristic degradation over time
- Collected degradation data at higher levels of stress can be used to predict a product's lifetime at a use-stress level

Step stress accelerated degradation testing (SSADT) is a version of ADT that is claimed to have short testing times and work with small sample sizes, which results in resource and overall cost savings [Tseng and Wen, 2000].

Initially introduced by Nelson (1980), SSADT uses experimental data and cumulative exposure modeling to predict product lifetime. In 2000, Tseng and Wen used SSADT methods to predict the useful lifetime of indicator LED packages. In the past decade, a number of successive research activities have developed two variants of the SSADT test [Cai et al., 2012, 2015, 2016a, 2016b, 2017; Hao et al., 2016, 2017; Gong et al., 2012; Ren et al., 2012; Yang et al., 2012]:

- Step-up stress accelerated degradation testing (SUSADT)
- Step-down stress accelerated degradation testing (SDSADT)

There are key assumptions in the formulation of the SSADT, including [Tseng and Wen, 2000; Cai et al., 2012, 2015, 2016a, 2016b, 2017; Tian and Yang, 2014; Hao et al., 2017]:

- The performance degradation of test samples is irreversible
- The failure mechanism and failure mode of test samples remain unchanged in each of the accelerated stress levels
- Under different stress levels, ADT data have the same distribution pattern and pseudo failure life, and these data should be subject to the same type of distribution
- Test samples have "no memory characteristics," i.e., they cannot be returned through any conditioning/processing to their initial performance characteristics
- Residual life is not affected by the damage accumulation method
- Residual life has nothing to do with the accumulation method; depending on the loaded stress level and accumulated partial failure
- The process of performance degradation can be described by a linear or linearized expression

In addition, others have introduced the use of multiple stressors (e.g., temperature and humidity) in order to accelerate the failure mechanism causing the failure mode [Cai et al., 2012, 2015, 2016a, 2016b, 2017; Hao et al., 2016, 2017]. For example, Cai (2016a) measured light output depreciation over time under a relative humidity of 85% while ambient temperature step-up from 65°C, 85°C, and 95°C in the SUSADT and step-down from 95°C, 85°C, and 65°C in the SDSADT. The authors of these research studies have noted the importance of ensuring that multi-stress conditions accelerate the expected typical degradation mechanism but do not introduce other non-typical degradation mechanisms.

It is worth emphasizing that prior to conducting the SSADT test, it is necessary to conduct HALT or HADT tests to determine the maximum stress level for each of the SSADT degradation conditions [Tseng and Wen, 2000; Cai et al., 2012, 2015, 2016a, 2016b, 2017; Hao et al., 2016, 2017].

5.2.1.4 Hammer test

The Hammer test was devised to serve as a HALT method for rapid screening, pass/fail type testing procedure to ensure reliability based on the extreme conditions that the device under test can endure [RTI International, 2013]. The test was intended to produce solid-state lighting luminaire failures during a test period of less than 2,000 hours. The Hammer test was designed solely to provide qualitative insights into potential failure modes of luminaires. Although the test designers claim that the Hammer test is not to be used as a universal accelerated life test, their report shows tested luminaires data can be fitted with a Weibull model that confirmed the Hammer test is an accelerated test based on the Weibull model's shape parameter (β).

The Hammer test consists of 42-hour loops with four stages of different environmental stresses modeled after common stress tests used in the electronics industry. The four stages include:

- Stage 1: 6-hour duration under steady-state environmental conditions at 85°C and 85% RH with 1-hour ON and 1-hour OFF power cycling. This stage was modeled after the Electronics Industry Association (EIA) and Joint Electronic Devices Engineering Council (JEDEC) standard EIA/JEDS22-A101-B.
- Stage 2: Cycling temperature shock consisting of 15 hours at -50°C to +125°C (air-to-air), 30-minute hold time at each temperature extreme under constant power ON operation and a temperature transition time of less than 5 minutes at a maintained 40% relative humidity (RH). The test stage was modeled after JEDEC standard JESD22-A104D.

- Stage 3: Repeat of stage 1 for a 6-hour duration with 1-hour ON and 1-hour OFF power cycling under steady-state at 85°C and 85% RH.
- Stage 4: High-temperature soak test with a duration of 15 hours at 120°C with operating cycle 1-hour ON and 1-hour OFF. Relative humidity maintained at 40%. This testing stage was modeled after the JEDEC standard JESD22-A103C, test condition A. The test time used was only 15 hours compared to the minimum recommended 1,000 hours in the JEDEC standard.

At the end of each 42-hour loop, the test luminaires are screened visually for physical defects and relative light output and color and a go/no-go decision is made. Complete electrical and photometric measurements of the sample luminaire are conducted based on the IES LM-79 test method [IES, 2019b] using an integrating sphere every 5 loops (210 hours). In this study, the pass/fail criterion was based on 50% of the samples reaching greater than 30% lumen depreciation ($L_{70}B_{50}$).

RTI International (2013) observed the following failure modes after using the Hammer test protocol on one 2×2 troffer and six 6-inch downlight luminaries:

- Driver circuit failure
- Failure of PCBs and solder interconnects
- LED and optical component degradation

5.2.1.5 Summary of accelerated test methods

Life test methods should provide a means to predict LED system lifetime. Due to the cost and restriction of time available to conduct life testing, there is constant pressure from industry stakeholders on researchers and standards organizations to define test methods and protocols that are not only able to predict system lifetime, but do so in a short test duration (e.g., test methods requiring less than 3,000 hours to predict lifetime of over 25,000 hours). Accelerated life testing (ALT) and accelerated degradation testing (ADT) are testing methods that accelerate the degradation of the product by subjecting it to temperature, humidity, vibration, power cycling, thermal cycling, mechanical loading, and other stress conditions that often deviate from the product's normal operating conditions. The results of this accelerated testing are then used in conjunction with statistical models to identify acceleration factors to estimate the product's lifetime under normal stress conditions but in a shorter time period [Nelson, 1990, 2005a, 2005b].

The main difference between ALT and ADT is that in ALT, the product under test is subjected to various environmental conditions and the data are collected until the product fails or until the end of the test duration. In contrast, ADT measures the actual physical failure mechanism that is causing the product to degrade with time, leading to a failure. A failure is then defined as either a catastrophic failure, or a parametric failure, when the degradation reaches some defined threshold value [Collins et al., 2013].

Additional tests methods are categorized as "highly accelerated," including for example, highly accelerated life testing (HALT), highly accelerated stress screening (HASS), and highly accelerate stress testing (HAST). These test methods are conducted for the sole purpose of qualitatively identifying or discovering potential weak components or sub-systems at the design or development stages. These highly accelerated test methods are not intended to be used to estimate system lifetime [Nelson, 2005a; Hobbs, 2008; General Motors Company, 2011; Gullo, 2012; Collins et al., 2013].

In a step-stress accelerated degradation testing (SSADT) method, the concept of ADT is used with the added advantage of reducing required resources such as the number of products subjected to testing and environmental chambers and setups used to provide environmental stressors.

As described, the SSADT testing method has a set of key assumptions embedded in its formulation that have not been fully verified in the literature. The key assumptions include (a) the failure mechanism remains unchanged under the stress levels, (b) the products under test have “no memory characteristic,” and (c) the failure distributions of the products do not change under the different stress levels. Additionally, research that has been proposed for lighting systems has not investigated directly how systems and subsystems could fail due to interactions from the degradation of components or subsystems [Cai et al., 2012, 2015, 2016a, 2016b, 2017; Hao et al., 2016, 2017].

A number of variants of SSADT have been proposed in the past, including [Tseng and Wen, 2000; Cai et al., 2012, 2015, 2016a, 2016b, 2017; Hao et al., 2016, 2017]:

- subjecting the products to a single environmental stressor in subsequent ascending level of stress value (SUSADT)
- a single environmental stressor in subsequent descending level of stress value (SDSADT)
- utilizing more than a single environmental stressor, only ascending or descending the level of stress value of a selected single stressor and maintaining other stressors constant

By reducing test time and its ability to predict system life, SSADT shows promise, provided that additional research work clearly shows that the critical assumptions, which are at the foundation of SSADT test program, are verified. Additionally, the SSADT testing has not been validated for power-cycling, which has been shown in other studies to be a critical factor in determining system lifetime due to catastrophic failure modes.

5.2.2 Predictive life test methods

As mentioned in the background, the lighting industry is in need of a definition and test method to estimate life of LED systems when used in different applications. Broadly, such a test method should consider testing the whole system under conditions that are representative of the conditions found in the intended applications (environment and power switching patterns), and include the predominant failure modes (catastrophic and parametric) as suggested by LRC research findings [Lighting Research Center, 2012; Narendran and Liu 2015]. The accelerated life test methods described in the previous section have served a limited purpose in achieving this objective. Similarly, and following the lead from the IES LM-80 method to measure LED package lumen maintenance, most of the initial system level research investigated lumen maintenance tests as a way to quantify LED system lifetime (e.g., IES LM-84 plus TM-28; LM-80 plus TM-21). With this in mind and all the knowledge gained from LED package lifetime studies up to that point, in 2006 the LRC began a multi-year study on behalf of the Alliance for Solid-State Illumination Systems and Technologies (ASSIST) to develop a recommendation for an LED system life definition and testing methods (beyond lumen depreciation) to estimate LED system life. As part of this effort, the earliest LED lighting system long-term performance data, including lifetime estimates, was published in 2007 [Narendran et al., 2007]. This study included parametric failures (lumen maintenance and color shift) for LED systems operating under different thermal conditions (open air, recessed with and without insulation). A key lesson from this study was that testing LED products such as downlights in open air at room temperature (i.e., 25°C) may not represent the actual light level and lifetime when used in realistic application conditions [Narendran et al., 2007]. Partially based on these results, the authors also pointed out that the increasing trend to report estimated LED system life based on lumen maintenance projections from IES LM-80 test data would not yield accurate predictions. The reasons for the discrepancy are rooted in the use of only one component of the system (LED package), the use of only one failure mode (lumen depreciation), and the fact that lumen depreciation at the system level is determined by several factors in addition to LED package degradation, including optical degradation of the LED package and electrical degradation of the driver [Lighting Research Center, 2013; Narendran and Liu 2015].

In 2009, Sari and colleagues from Singapore, Netherlands, and UK working together, studied LED systems, specifically the testing and modelling of flux degradation with time [Sari et al., 2009]. This team of researchers pointed out that it is possible that more than one degradation mechanism could dominate system lifetime. They proposed and verified a degradation model that could result in better system lifetime estimates based on parametric failure [Sari et al., 2009]. In 2010, Luo et al. studied the effects of moisture in the environments on LED module reliability [Luo et al., 2010]. Through reliability experiments in mild and extreme conditions, Luo et al. found that moisture diffuses into the interfaces of packaging material, not only causing a decrease in light output but also increasing the potential for a LED module to become disabled through electronic failure. The main lesson learned in this study is that moisture can cause lumen depreciation, too [Luo et al., 2010]. Thus, parametric failure in LED systems (e.g., lumen depreciation) can be due to multiple factors, as suggested by Sari and colleagues in 2009.

Another important step in system level research was the introduction of power cycling. The need to introduce this factor for life testing was based on the research by Wu (2010) which showed that when the difference between maximum and minimum temperatures (ΔT) experienced by the LEDs during power cycling increased, the cycles to failure of an LED array decreased. In other words, higher ΔT shortens lifetime due to catastrophic failure caused by weakening and failing solder interconnects between the LED and the printed circuit board. In a follow-up study where high-power LEDs were tested under power cycling conditions, ΔT showed strong correlation with cycles to failure [Wu, 2010]. Collectively, these studies showed that very rapid power cycling does not cause sufficient damage to the LED systems to cause failure because the very fast power cycles result in small temperature changes at the LED-to-PCB interface, and the resulting thermal stress due to the mismatch in thermal expansion coefficients is small as well [Lighting Research Center, 2010]. In these studies, the maximum junction temperature (T_j) of the LED showed very little effect on the number of cycles to failure when T_j was below the LED's breakdown temperature. However, the maximum junction temperature correlated well to lumen depreciation [Lighting Research Center, 2010]. This was an important contribution to the literature relevant to systems because it showed the importance of power cycling, a condition experienced by lighting products in most lighting applications, to elicit catastrophic failure mechanisms that otherwise are not captured in lumen maintenance tests, including IES LM-80 and LM-84.

Follow-up studies investigated the LED junction temperature changes when an LED A-lamp is switched on and off. The results showed that the junction temperature ramps up to a maximum reaching stability after about 60 minutes when switched on, and cools down to room temperature and reaches stability after about 60 minutes (Fig. 5.3, left) [Lighting Research Center, 2010]. Additionally, the experiment results showed that the rapid cycling of LED A-lamps (e.g., 2-minutes on, 2-minutes off) introduces very small temperature change during a cycle (Fig. 5.3, right), and thus the thermal stress caused to the LED system during a cycle is small and will not introduce damage to the LED system components [Lighting Research Center, 2010]. In the same study, it became evident that a slower cycling test, one that reaches stabilization at the upper and lower ends of the temperature range, was needed to mimic real-life applications and cause failure modes that would be seen during applications. The results from this LRC study discouraged the use of very fast cycles and proposed that to predict LED system lifetime accurately, products must be power cycled with slow cycles such that the LED systems will experience maximum ΔT (the difference between stabilized maximum operating temperate and the average room temperature). Results from the LRC studies until 2010 indicated that LED system lifetime can be reduced if switched on and off at slower rate such that during a power cycle the LED junction temperature experiences maximum temperature change and as a result solder joints (e.g., at the LED-PCB interface) experience thermal stress. These conditions will then result in catastrophic failure due to thermal stresses [Lighting Research Center, 2010]. The need for slow thermal cycles has been corroborated in several LED life test studies in the past decade [e.g., Narendran and Liu, 2015; Lighting Research Center, 2016; Itron and Erik Page & Associates, 2017; Swedish Energy Agency, 2018].

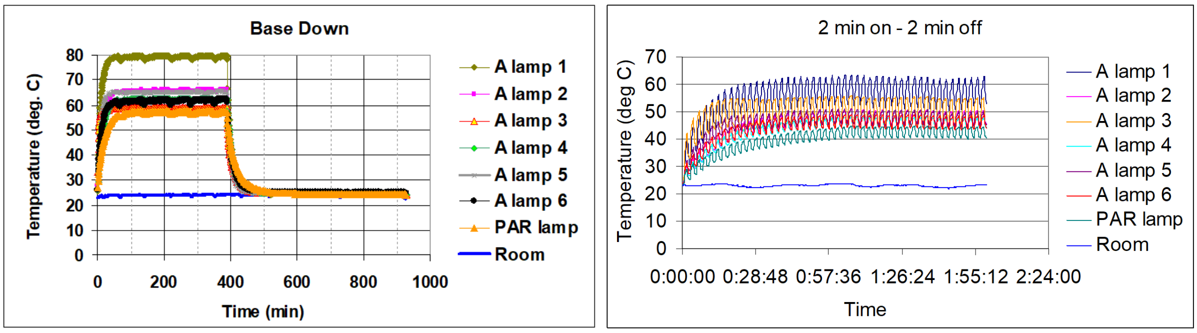


Figure 5.3. Left figure illustrates temperature profile experienced by the LED A lamp when switching on and off; right figure illustrates the temperature profile experienced by the LED A-Lamp when switched on and off rapidly (2 min on – 2 min off) [Lighting Research Center, 2010].

In 2011, the LRC began a study with the objective to develop a shorter time test method that can predict the failure of LED luminaires under real-world operating conditions, specifically targeting catastrophic and parametric failures. This study considered that in real life, lighting systems are switched on and off. For example, the patterns may be 6 am to 6 pm (12 hours on, 12 hours off) in offices, and 6 am to 10 am and 6 pm to 10 pm (4 hours on, 8 hours off) in home applications. Even though the common belief at that time was that LED products do not fail catastrophically, LRC studies showed that when power cycled, LED systems can fail catastrophically. Therefore, when life testing LED systems to project lifetime in applications, it is important to include power cycling (slow not very fast) since in real-life applications, products are switched on and off.

Also in 2011, Li et al. (Philips Lighting, Shanghai, China) published the results of LED systems testing, including a proposed reliability prediction model by considering failure of each subsystem including mechanical, optical, and electronic components [Li et al., 2011]. The authors pointed out that each subsystem has multiple failure modes, in which each failure mode has its own failure distribution and the system reliability test should include stresses for each failure mode [Li et al., 2011]. This paper is very comprehensive with respect to testing and analyzing failure modes of different subsystems in an LED system, including parametric and catastrophic failures. However, in one section the authors stated, "*The failure rates of electronic components are well known and several standards are already available, including, MIL-STD-217 and Telcordia SR332, to estimate driver lifetime as long as components' case temperature, current, voltage and power are known. Here each components' failure rate is calculated and the total failure rate of the whole driver is estimated by summing the failure rates of each component*" [Li et al., 2011]. However, we must point out that recent unpublished LRC results have shown that the lifetime estimates of LED drivers using MIL-STD-217 [United States Department of Defense, 1991] and Telcordia SR332 [Telcordia SR332, 2016] methods are not accurate in terms of elapsed time to failure or the type of component that fails. Therefore, we suggest that testing the complete driver in an environment similar to the application environment and use pattern will yield more accurate LED driver lifetime estimates.

During the period of 2012 to 2015, many researchers analyzed LED system lumen depreciation and attempted to develop models to project data to determine L70. In 2012, Meneghini and colleagues (University of Padova, Italy) studied and analyzed the degradation of state-of-the-art high power LEDs. The results of their studies showed that LEDs go through significant degradation of their electrical and optical characteristics when they are operated close to their current and temperature limits [Meneghini et al., 2012]. This study showed that LED lumen depreciation can be related to optical and electrical issues. Thus, when developing extrapolation models to project lumen depreciation it is important to consider multiple degradation functions and rates, and that the degradation could happen at different times in the LED operation time.

In 2013, Koh et al. attempted to shorten the 6,000 hours testing time that is used in many industry standards by using L95 instead of the more commonly used L70 criterion [Koh et al., 2013]. A shortcoming of using the L95 criterion is that it assumes a constant depreciation rate after that point in time, which is contrary to the evidence presented by Koh et al. This assumption, if adopted, can yield erroneous lifetime projections. More importantly, in spite of previous studies that had demonstrated catastrophic failures, Koh et al. only considered lumen depreciation in their study. As such, the authors overlooked the fact that shortening the test time may not provide an opportunity for catastrophic failures to appear during the test period. However, there is a possibility that catastrophic failures can happen beyond the short test period, resulting again in erroneous lifetime projections.

Shailesh et al. (2018) published a paper titled “Understanding the reliability of LED luminaires” to educate manufacturers and end users on what constitutes the overall reliability of an LED luminaire and the reliability of individual subsystems. According to the authors, the different subsystems in an LED luminaire introduce many reliability issues that are critical in deciding overall system lifetime. The authors discussed a general theory of assessing the reliability of the optical, electrical, and thermal subsystems of an LED luminaire. According to the authors, the theory explained in this paper is useful in designing experiments to express the reliability of an LED luminaire and its subsystems in terms of remaining life. In addition, the authors summarized and discussed the research conducted by several groups around the world, including Philips Lighting in China and Netherlands, the Chinese Academy of Sciences, the Lighting Research Center in the U.S., and Guilin University of Electronic Technology in China [Shailesh et al., 2018]. This publication is useful for those interested in understanding different test methods.

5.2.3 Laboratory validation studies

This section describes recent and relevant studies that aimed at validating a life test method for LED systems by comparing test results from large sample sets to expected life values.

5.2.3.1 LRC large scale laboratory validation study of a lifetime test method

With funding from the Bonneville Power Administration (BPA), New York State Energy Research and Development Authority (NYSERDA), and ASSIST, in 2013 the LRC started a long-term study to develop an accelerated test method that allows for accurate prediction of LED system life in any lighting application if the LED junction temperature and the on-off switching pattern are known. The method tests the whole system, includes on-off power cycling with sufficient dwell time, and considers both catastrophic and parametric failure (L70). Commercially available LED A-lamps, MR-16 lamps, and integrated LED downlights (a total of 287 samples) were subjected to different test conditions of delta temperature and dwell time [Lighting Research Center, 2016; Narendran et al., 2016, 2017; Narendran, 2017]. Appendix A describes this study in greater detail.

Products selected for long-term life testing: The following types of LED products were tested in the three stages of this study:

- Commercially available, Energy Star® rated LED A-lamp product, rated as a 75 W incandescent replacement (90 samples tested)
- Commercially available, Energy Star rated LED MR-16 lamp product, marketed as a 50 W incandescent replacement (90 samples tested)
- Two commercially available, Energy Star rated LED downlight luminaires: Downlight 1 was 14 W and marketed as a 75 W incandescent replacement (80 samples tested), and Downlight 2 was 11 W and marketed as 60 W replacement (27 samples tested)

Samples of each of the product types were installed in luminaires under conditions similar to those as intended under normal operation. Thermal sensors were attached to the LED products and the thermal profiles were measured. This way, lower and upper LED junction temperatures (T_j) values that can be found in most applications using these LED products, as well as the time required for the system to reach maximum temperature (full stabilization) after switching on, and the time required for the system to cool down to room temperature (full stabilization) after switching off, were determined. Based upon these findings, three delta temperatures (ΔT) and three dwell times were selected as independent variables for the long-term study.

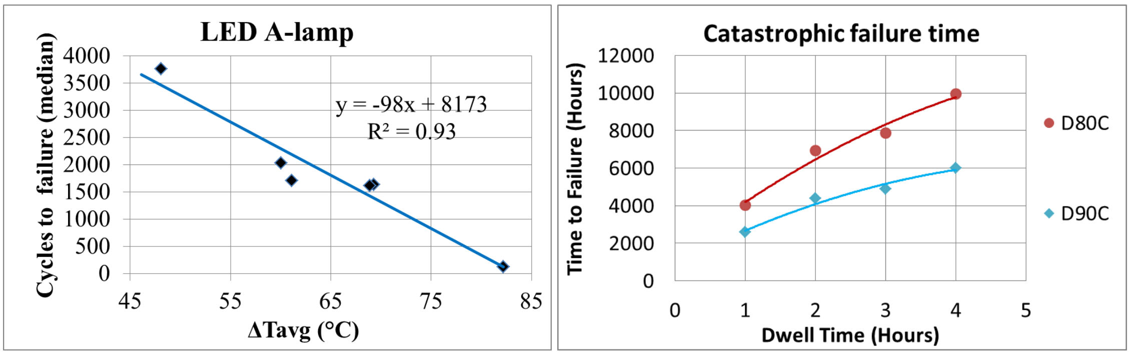
Following is a summary of the results for the A-lamp products tested. Similar analyses were completed for the other two systems and were reported in the full project publication [Lighting Research Center, 2016].

LED A-lamp catastrophic failure results: Table 5.1 shows the results summary for catastrophic failure of the LED A-lamps for the different test conditions. The average time between the 5th and the 6th lamp failures was used to denote the median life. As seen in the table, higher ΔT conditions result in shorter time to failure for both dwell time conditions. Also, shorter dwell times result in shorter time to failure for 80°C and 90°C, except for the median time to failure for ΔT at 100°C. For that condition, the median life for the 4-hour dwell time was shorter than for the 2-hour dwell time. This is because the failure takes place due to cumulative damages caused at each transition that are also dependent on the temperature change during the transition. Further analysis showed that 84% of the failures were due to solder joints breaking between the LED and the PCB, and 16% were due to driver failure.

Table 5.1. LED A-lamp catastrophic failure times for each test condition (ΔT and dwell time).

	Delta time-averaged temperature (°C)		**Time to failure (median life) (hours)**	
ΔT/Dwell Condition	**2 hours**	**4 hours**	**2 hours**	**4 hours**
80°C	48	60	7,516	8,801
90°C	61	69	3,411	7,091
100°C	69	82	3,225	521

Figures 5.4 (a) and (b) clearly show that the life of an LED system is affected by switching it on and off. The panel on the left shows that the number of cycles to failure (median life) and delta time-averaged temperature have an inverse linear relationship with goodness-of-fit $R^2 > 0.9$. From this relationship, the cycles to failure were inferred for 1-hour and 3-hour dwell times. Knowing the total cycle time for each dwell time, the cycles to failure were converted to time to failure, as shown in the right figure. The panel on the right (Figure 5.4(b)), clearly shows that with shorter dwell times, more frequent on-off switching will cause LED systems to fail faster. For the continuous-on case, the lamps were not switched on and off and therefore the cycles for all cases were only one. The times to catastrophic failure were zero failures for 80°C, 7,000 hours for 90°C, and 1,100 hours for 100°C. These results emphasize the need to include power cycling as an independent variable in LED system life tests. The number of cycles to failure is not a relevant parameter in this case.



(a) (b)

Figure 5.4. (a) Cycles to failure as a function delta time-averaged temperature (ΔTavg); (b) Time to failure as a function of dwell time for the different ΔT values.

LED A-lamp lumen depreciation results: Most of the lamp samples failed catastrophically before the light output reached L70, meaning that catastrophic failure times were shorter than parametric failure times. To understand parametric life, L70 values for each condition were determined by extrapolating the lumen depreciation data that was available before the lamps failed catastrophically. The median lamp life, L70 in hours, is shown in Table 5.2. Figure 5.5 shows that failure (median life) as a function of maximum operating temperature has an inverse linear relationship with goodness-of-fit, $R^2 > 0.9$. The estimated L70 values decreased when the maximum operating temperature increased. The projected L70 values for the different test conditions are similar, indicating that temperature cycling for this relatively short test duration has minimum effect on lumen depreciation, as opposed to the strong correlation with the maximum operating temperature achieved at each ΔT.

Table 5.2. Maximum operating temperature (ΔTavg) values and time to failure values for the different ΔT and dwell time conditions.

ΔT/Dwell Condition	Maximum operating temperature (°C)			Time to L70 (hours)		
	2 hours	4 hours	Continuous-on	2 hours	4 hours	Continuous-on
80°C	106	108	108	25,528	20,998	23,979
90°C	125	124	124	11,019	12,185	11,657
100°C	131	136	131	7,289	5,308	5,171

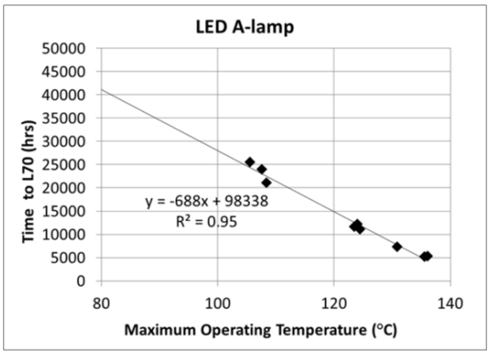


Figure 5.5. Time to failure due to lumen depreciation, L70, as a function of maximum operating temperature.

Conclusions: The results of these studies showed that both catastrophic and parametric failure types exist. The proposed accelerated test procedure can be used to predict LED system life within a 3000-hour testing period by knowing the pin temperature and the on-off switching cycle. The thermal mass of the system and the ambient air surrounding the fixture determines the final LED junction temperature and the time it takes to reach full stabilization. Power cycling reveals catastrophic failure in susceptible products as a result of excessive thermal stress between two adjacent parts caused by different coefficients of thermal expansion (CTE). This makes it clear that LED system life is negatively affected by on-off switching, which was contrary to common belief at the time. Maximum operating temperature influences the lumen depreciation rate. By plotting the catastrophic failure lifetime as a function of time averaged ΔT, and the parametric failure (lumen depreciation) lifetime (L70) as a function of maximum temperature (T_{max}), the system's lifetime can be estimated for a given pin temperature and on-off switching cycle condition.

An *ASSIST recommends* document titled "Recommendations for Testing LED Lighting Systems and Projecting System Lifetime in Different Applications" was developed based on the above validated study [ASSIST, 2020]. This document shows how the results from this type of testing can be used to estimate the expected lifetime of the same product but under two different application conditions (temperature of operation, power cycling pattern). A follow-up study validated the predictions from this method independently and demonstrated that a low-cost setup, short duration test was possible [Narendran et al., 2017].

5.2.3.2 CPUC large-scale laboratory LED lamp test

In 2017, the results of a large-scale, multi-year laboratory test of LED lamps, conducted for the California Public Utilities Commission (CPUC), were published [Itron and Erik Page & Associates, 2017]. The objectives of this study were to: 1) assess the effect of two common temperature-related stress conditions on LED performance and longevity; 2) understand the "real world" conditions that impact LED reliability and performance; and 3) provide the data necessary to develop adjustments to the effective useful life (EUL) assumptions for LED lamps included in California's investor-owned utilities' energy efficiency portfolios. A research plan was designed to assess the impacts of the stress conditions most prevalent in residential homes: high operating temperature and on-off switching patterns that cause lamps to repeatedly fully heat up and then fully cool down (i.e., thermal cycling). Researchers from the LRC were interviewed by one of the authors of this report when developing the test procedure for the CPUC product testing [Itron and Erik Page & Associates, 2017].

The study's authors evaluated the impacts of the stress test conditions on efficacy, color quality, useful life, and differences in performance between LED lamps compliant with the "California Quality Spec" and those that were non-compliant. Test lamps (92 lamp models: A-lamp, globe, torpedo, reflector; 13 recessed downlight retrofit trim kits) were operated in three common residential luminaire types: recessed downlights, ceiling fixtures, and bare sockets. The initial photometric results showed that measured values of performance were largely consistent with rated values and that deviations were mostly in the preferable direction. The measured efficacy of California Quality Spec-compliant lamps was 20% lower compared to that of non-compliant lamps. The maintenance test results showed that 24% of the units tested (160 out of 666) either failed catastrophically or exhibited "pre-failure" behavior within a maximum of 4,500 hours of total on-time, and failure rates were highest among A-lamps. None of the trim kits tested failed catastrophically or exhibited "pre-failure" behavior. The final photometric testing showed that of the test lamps that survived maintenance testing, only 8 test lamps (1.5%) experienced decreases in light output of 30% or more, and only 12 test lamps (2.2%) experienced noticeable/objectionable changes in color temperature. The post-mortem forensic analysis showed that the most common failures were contact failures from poor or degraded solder connections, which is consistent with high heat operation and operating temperature changes due to switching. The authors concluded that the results provide strong evidence that the two test conditions (elevated operating temperature and on-off switching) are significant stress conditions that can lead to early catastrophic failure of LED lamps. The authors state, "Taken together, these findings suggest that the current industry testing standards for LED lamps either do not adequately address two common field conditions (i.e., operating temperature and switching patterns) and/or that certain models have latent manufacturing defects that are exposed as a result of our experimental design. The corollary to this is that we believe the results from this study indicate a distinct opportunity to augment or supplement current standardized performance tests with short-run reliability tests focused on temperature-related early failure modes that could help detect the type of poor-performing models identified in this study." The authors recommended exploring how much total on-time and/or switching is required to be able to reasonably project the failure rates, and developing formal adjustments to the EULs for LED lamps in the various investor-owned utility programs.

The CPUC study is an important step in the development and validation of LED product test methods and conditions. It should be noted, though, that because the cycles used in the CPUC study did not reach full thermal stabilization and did not have dwell time (Figure 5.6), the LED products would not have experienced full thermal stress, and therefore the test results are most likely an overestimate of the time to catastrophic failures. The solder joint between the LED terminal and the PCB cracked and failed due to fatigue damage caused by the stresses introduced by the thermal expansion coefficient mismatch between the PCB and solder. Having a dwell time ensures 100% stabilization, and the stress will be larger than that at 95% stabilization because the temperature change will be higher. As a result, the effective fatigue at 95% stabilization will be less and the time to solder failure will be longer, thus the catastrophic failure lifetime will be longer.

FIGURE 3-6: EXAMPLE OF THERMAL SWITCHING CYCLE FOR AN LED LAMP

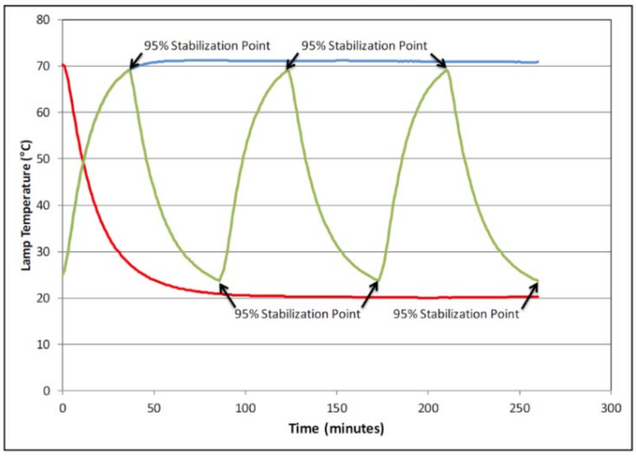


***Figure 5.6. Thermal switching cycle used in the CPUC large-scale laboratory study [Itron and Erik Page* & Associates, 2017].**

5.2.3.3 *European Commission 3600-hour lifetime test validation studies*

In an effort to validate a proposed life test method based on lumen maintenance and endurance for the European Union, the Swedish Energy Agency, the Australian government's Department of Environment and Energy, and CLASP Europe conducted product testing of several LED product types. [Swedish Energy Agency, 2018]. Based on the findings from the three laboratories, it was concluded that the method is effective for life and endurance testing. The laboratories found more failures with the new method than with the current IEC method [IEC 62722, 2014] that uses a rapid switching cycle (30-seconds on/30-seconds-off). The report concluded that most failures occurred after 1000 hours, meaning that shorter test times of 500 or 1000 hours proposed by some groups are not suitable.

As it stands, the European Union Commission's life test method is primarily an endurance test intended to show early failure modes in LED products under the conditions tested. In order for this method to be expanded to predict LED product lifetime under different conditions, the method needs to include more on-off power cycling patterns and include different temperatures. For example, it could be expanded to include three test temperatures and three dwell times. Then, this method could consider both types of failures, parametric (lumen maintenance) and catastrophic, and use the shorter of the two values to report product lifetime. In some cases, the catastrophic lifetime is much shorter than lumen maintenance (L70) lifetime, and reporting lifetime based on lumen maintenance only could set the wrong expectations for consumers. Finally, expanding to other types of LED products beyond the systems tested (e.g., A-lamp, PAR lamp, linear florescent replacement, integrated downlight, streetlight, in-ground outdoor fixtures) would require understanding how the test conditions would affect systems that have more or less thermal mass, for example.

5.2.3.4 CLTC long term laboratory test

In a recent publication, the results of a 12,000+ hour laboratory LED lamp test were made available [Hathaway 2020]. In the study, a total of 138 LED replacement lamps were tested. Six samples of each of 23 product types were included. The distribution of products included nine models of medium screwbase lamps (A, BR, PAR), 13 models of linear lamps, and one decorative model of a candelabra base lamp. The lamps were tested following the testing methodology described in IES LM-84 but inside typical residential luminaires to simulate the most stringent thermal environment that each lamp type would encounter in the field. The luminaires included downlights, vanity globes, and wrap-around linear types. After following the methodology described in IES TM-28, Hathaway and colleagues reported that 14 of the 23 product types exceeded the manufacturers' claims of lifetime as defined by the L70 lumen maintenance criterion. Forty-nine of the 138 lamps were found to have failed catastrophically over the duration of the test, but unfortunately the median life and time to failure were not reported. It should be noted that this study, by virtue of being conducted following the IES LM-84 method, did not include power cycling. This study highlights the need to incorporate power cycling as a stress factor that could be used to accelerate the catastrophic failures observed in the samples tested.

5.2.4 The value of field evaluations to inform predictive models and test methods

During the early days of LED system research, an understanding of failure modes of LED systems and the components that frequently failed was not widely available. It is worth pointing out here that data of failure modes and components of LED lighting systems from real-world applications is very useful to understand common failure modes and weak components that cause the different failures of systems. In 2011, a report released by the United States Department of Energy (USDOE) indicated that over 70% of the failure modes in one model of outdoor LED luminaire over several product generations and across a combined 212 million-field operation hours were due to the driver [United States Department of Energy, 2011, 2014]. Even though every lighting system consists of many components, similar to the outdoor fixtures used in the USDOE report, the failure results cannot be generalized because the quality of the components and the application environment can be very different for other systems. For example, another type of LED outdoor fixture when used in applications may experience system failure due a different component or subsystem failure.

5.2.5 Summary of research to develop predictive lifetime test methods

The studies in the literature on LED system failure modes consistently show both parametric and catastrophic modes. All system components including LED, LED array, PCB, optics, and driver can fail, although each would have its own mechanisms and breakdown thresholds. Failure mechanisms include degraded primary and secondary optics, causing lumen degradation and color shift; weakened solder interconnects, causing increased series resistance, lumen depreciation, and eventually interrupted current flow when the solder fails resulting in catastrophic failure; and failed components such as capacitors, diodes, MOSFETs, and opto-isolators in the driver or power supply, causing lumen degradation and catastrophic failure. The following are the key conclusions that can be drawn from the literature on LED system life:

- In applications, LED systems undergo catastrophic and parametric failure modes; therefore, life testing LED systems must consider both types of failure and consider the lesser of the two to rate LED system life.
    - The subsystems that usually fail in LED products are drivers, LED packages, solder joints between LED and printed circuit board, driver components, and the primary and secondary optics.
- Life testing of LED systems must include power cycling and increased temperature conditions.
    - The rate of lumen depreciation is strongly correlated to LED chip temperature: the rate of lumen depreciation increases as LED junction temperature increases.
    - Lumen depreciation in LED products can be due to degradation of the LED package, secondary optics, or the electrical characteristics of the driver. These factors can happen independently or simultaneously.
    - Power cycling LED systems affects LED system lifetime, resulting in catastrophic failure.
        - Power cycling causes solder joint failure because of the mismatch in coefficient of thermal expansion (CTE) of adjacent layers of materials.
        - Power cycling conditions must include dwell time (full stabilization at the lower and upper end of the temperature) for an accurate failure estimate due to catastrophic failure.
        - Power cycling rates have minimal effect on LED package lumen depreciation rate.

5.3 Standards

Presently, several international standards are being used as the basis for LED product life definition and/or testing. The most relevant documents include the ones listed below because, in turn, these documents are the basis for region- or country-specific standards. Although some of these documents now recognize the need to distinguish between parametric and catastrophic failure, none of these standards fully addresses the test conditions and failures modes necessary to predict the lifetime of LED systems in different lighting applications. The following summary and the next section aim at providing guidance on the key points that should be included in such a testing method.

5.3.1 ANSI/IES LM-80 + TM-21

ANSI/IES LM-80-20, *Approved Method: Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays and Modules* [IES, 2020a] is the most recent version of the original standard used by the industry to measure and project the life of LED packages using a lumen maintenance criterion. The measured luminous flux data are used as the basis for projections using the method described in standard ANSI/IES TM-21-19, *Technical Memorandum: Projecting Long-Term Lumen, Photon, and Radiant Flux Maintenance of LED Light Sources* [IES, 2019]. While these two documents have been used widely as the basis for projecting LED product life, it must be noted that the method in LM-80 is meant for LED packages, arrays and modules, not for LED systems, and does not consider power cycling. The major problem is the use of these data and extrapolated values, which are specific to LED packages, to characterize the lifetime of LED systems. The inappropriateness of this approach to characterize systems has been documented in several publications and is rooted in the assumption that LEDs are the main failure point in a system and the fact that it does not consider catastrophic failure modes. To help with this gap, the IES published two documents (LM-84, TM-28) to address LED system, as described in the next item.

5.3.2 ANSI/IES LM-84 + TM-28

Originally published in 2014 [IES, 2014a], IES LM-84, *Approved Method: Measuring Optical Radiation Maintenance of LED Lamps, Light Engines, and Luminaires* [IES, 2020b] builds on the LM-80 document for measuring luminous flux maintenance of LED systems. The measured luminous flux data are used to project lumen maintenance values using the method described in IES TM-28, *Projecting Long-Term Luminous Flux Maintenance of LED Lamps and Luminaries* [IES, 2014b, 2020c]. Together, these two documents provide similar test methods and projection results as those for LED packages in LM-80 plus TM-21 (as well as allowing the use of LM-80 test results to reduce the test duration). Although this is an improvement over the LM-80/TM-21 approach because it considers systems, IES LM-84 does not include catastrophic failures or power cycling. In spite of LM-84 having been available for over six years, present practice continues to be estimating LED product lifetimes using projections from LM-80 data for LED packages.

5.3.3 IEC 62612

IEC 62612:2013+AMD1:2015+AMD2:2018, *Self-ballasted LED lamps for general lighting services with supply voltages > 50 V – Performance requirements* [IEC, 2018], describes the performance requirements together with testing methods of LED lamps. Specifically, for product lifetime, the standard acknowledges that validation testing is not practical or possible given the long-life expectations of LED products and does not provide a test method for determination of its value. Rather, the document establishes lumen maintenance codes (9 for ≥ 90%, 8 for ≥ 80%, 7 for ≥ 70%) at a predetermined test time of 25 percent of rated life (limited to a maximum of 6,000 hours). The standard makes important distinctions, including 1) that the pass/fail criterion as described in the document is different from the general understanding of product lifetime, and thus these lumen maintenance categories are not predictions of attainable product lifetime, and 2) performance claims can deviate when LED lamps are used in luminaires. However, the document establishes that if an LED lamp is claimed to be suitable for operation under different temperature or humidity conditions as those described in the test method, the product should be tested under these alternative conditions.

5.3.4 IEC 62717

IEC 62717:2014/AMD2:2019, *Amendment 2 – LED modules for general lighting – Performance requirements* [IEC, 2019] specifies the conditions, test method, and minimum required test time for categorizing the lumen maintenance of an LED module. The document defines median life of LED products when 50 percent of the samples reach the stated lumen maintenance category (i.e., L70, L80, L90), but provides no test method for determination of its value. One important aspect of this standard is the distinction between two failure mechanisms (abrupt vs. lumen maintenance) and establishes the corresponding conditions for the endurance test.

5.3.5 IEC 62722

IEC 62722-2-1:2014, *Luminaire Performance – Part 2-1: Particular Requirements for LED Luminaires,* [IEC 2014] describes the conditions, test method, and minimum required test time for testing LED product life. This first edition of the standard includes significant technical revisions to the publicly available specification. Importantly, life definitions and testing time associated with system life are now aligned with IEC 62717.

5.3.6 Commission Delegated Regulation (EU) 2019/2015 of 11 March 2019 supplementing Regulation (EU) 2017/1369 of the European Parliament

In December 2019, Annex V of the EU Commission's Lighting Regulation formalized a test method for assessing the lifetime and endurance of lighting products [European Union, 2019]. In this method, longer switching cycles that are more representative of real-life conditions in homes and offices were introduced. This method simultaneously combines a thermal stress "endurance" test with a

3000-hour lumen maintenance test on the same sample, for a total test time of 3,600 hours. The test procedure reduces the time requirements of the previous regulation of separate switching cycle and 6,000-hour lumen maintenance tests.

6 Conclusions and Recommendations

6.1 Assessment of Test Methods

Table 6.1 summarizes the test features included in relevant test methods in the literature that have been proposed for estimating LED system life or reliability. These methods were evaluated against the criteria listed below to help in the process of down selecting the most promising at achieving the IEA 4E SSL Annex's objectives. Ideally, a test method to estimate LED product lifetime should:

a. Test products as a system, without disturbing the integrity of samples under test, and under conditions that include the stress factors present in the intended application
    - ▪ Environmental
        - Temperature
        - Relative humidity
    - ▪ Use pattern
        - Power cycling profiles (on-off)

b. Consider two failure modes
    - o Parametric, based on
        - ▪ Lumen maintenance (e.g., L70, L80, L90)
        - ▪ Chromaticity shift (e.g., 2-step u'v' circle)
    - o Catastrophic, based on
        - ▪ Total failure (e.g., samples fail to produce any light output or produce a drastically low output)
        - ▪ End-of-life behavior (e.g., intermittent operation, cycling on-off, flicker)

c. Be predictive
    - o Given the expected operating conditions of the LED product in the application, the lifetime of that product can be estimated.
        - ▪ Tests should include at least three conditions that cover the range of possible application environments to allow for interpolation, or a single test[2] for the worst case scenario.
    - o The life estimate should be based on the shorter of the predictions made for parametric and catastrophic failure modes.

d. Be as short as possible (i.e., accelerated) without introducing additional failure mechanisms
    - o Anecdotal feedback from the industry indicates that tests longer than 6,000 hours are not practical due to rapid market development cycles for new and existing products.

It should be noted that although many parametric failure modes could be considered for the purposes of defining system life, the two most common and predominant items to investigate are lumen maintenance and chromaticity shift. It is usually more difficult to measure and predict changes in temporal (e.g., flicker), electrical (e.g., dimming range, input power), and spatial (e.g., intensity or chromaticity distribution) characteristics and thus these factors are less commonly considered. However, the change of these characteristics could be included as part of the definition of system life if they are important to the application at hand.

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[2] Testing for the worst case scenario does not allow for lifetime predictions, but a method with such a single test condition would establish a lower limit to the expected life of the representative LED products.

Table 6.1. Relevant test methods to estimate LED system lifetime or reliability that have been described or proposed in the literature.

	Test method or approach (see reference at foot of table)						
Test feature/variable	**ALT/ADT[1]**	**SSADT[2]**	**HALT, HADT HAST[3]**	**Hammer[4]**	**ANSI/IES LM-84 & TM-28[5]**	**EU Regulation[6]**	**LRC ASSIST *recommends*[7]**
System level test	✓	✓	✓	✓	✓	✓	✓
Stress factor: Temperature	✓	✓	✓	✓	✓	✓	✓
Stress factor: Humidity	✓	✓	✓	✓			
Stress factor: Power cycling				✓		✓	✓
Test duration <6000 hours	✓	✓	✓	✓	✓	✓	✓
Parametric failure mode	✓	✓	✓	✓	✓	✓	✓
Catastrophic failure mode			✓	✓		✓	✓
Pass/Fail	✓	✓	✓	✓	✓	✓	✓
Can predict system lifetime for parametric and catastrophic failure modes							✓

References:

1. [Cai 2012; Shepherd 2014; Hao 2016b, 2019; Padmasali et al. 2019]
2. [Hao 2016a, 2017]
3. [Cai 2012; Hao 2019]
4. [RTI 2013]
5. [ANSI/IES 2014a, 2014b]
6. European Commission's Ecodesign Lighting Regulation [European Union 2019]
7. [Narendran et al., 2016, 2017; ASSIST 2020]

As can be seen in Table 6.1, the ALT, ADT, SSADT, and ANSI/IES LM-84+TM-28 methods do not include the stress factor of power cycling and do not meet the criterion of capturing catastrophic failure modes. Additionally, as explained in section 6.2, highly accelerated life (HALT), degradation (HADT), and stress (HAST) testing methods are conducted for the sole purpose of qualitatively identifying or discovering potential weak components or sub-systems in a system during their design or development stages, or to compare two or more alternate systems. The literature does not recommend the use of these methods to estimate useful product or system lifetime (full citing literature in sections 6.2.1.2 and 6.2.1.3). Therefore, these methods are not recommended to estimate LED system lifetime and are thus not relevant for further investigation by the IEA 4E SSL Annex.

The Hammer test was developed as a HALT method for rapid screening and is a pass/fail type testing procedure designed solely to provide qualitative insights into potential failure modes of luminaires during a test period of less than 2,000 hours. Although output parameters such as luminous flux, chromaticity, CCT, flicker, and others are monitored during the test, this test method was not designed to estimate or predict system lifetime based on either parametric or catastrophic failure modes. Importantly, the test conditions are not representative of those found by LED systems in real life applications.

The test method proposed in the European Union is one of the two most promising methods that can be adopted for estimating LED system lifetime [European Union, 2019]. However, this test method is not predictive because the test only includes one environmental condition (temperature and not relative humidity) and one use pattern (power cycling), and it is thus not possible to estimate lifetime under other application conditions. To achieve this goal, it would be necessary to conduct the test under different environmental conditions and use patterns (e.g., three temperatures and three dwell times). Adding relative humidity as an additional independent variable would be important for testing its effect on life of certain products, for example outdoor luminaires. It is also recommended to further analyze and validate the 30-minute off time during each cycle. Both the dwell and off times of each cycle should be timed such that the system under test undergoes a full thermal excursion similar to what the system would experience in a real life application. This is particularly important for systems with larger thermal masses (e.g., outdoor luminaires). In these cases, experimental results have shown that several hours are needed for such luminaires to reach full thermal excursion.

Finally, the other most promising test method for estimating LED system life is the one proposed by the Lighting Research Center (2016) and formalized by ASSIST (2020). This method has the capability to predict LED system lifetime once the environmental conditions and use pattern are specified. The underlying premises of this method have been validated by several studies, including the one conducted for the California Public Utilities Commission [Itron and Erik Page & Associates, 2017], and the studies conducted for the IEA 4E SSL Annex in 2018 by the Swedish Energy Agency and the Department of Environment and Energy in Australia [Swedish Energy Agency, 2018]. As with the EU method, it would be important to expand this test method to include relative humidity as an additional independent variable. Including relative humidity as a variable may result in three more test conditions. Finally, for this method it is also worth exploring further the proposed 1500-hour test duration.

6.2 Identified Areas for Further Research (including investigative product testing)

Besides the above-mentioned recommendations for development of the two relevant test methods, and based upon the findings from the literature review and the analysis of existing and promising test methods in Table 6.1, we suggest the following additional research initiatives:

1) Collect data from large field installations of replacement lamps (A, linear, etc.) and luminaires (especially outdoors and those in harsh environments)
    - Collecting data from real life, field installations provides valuable information regarding the actual lifetime, failure modes for lamps and fixtures, and provides samples that can be analyzed to further identify failure mechanisms in specific components and subsystems. Field installations often include variables that are not considered in laboratory studies, or are controlled, which makes it more difficult to discover failure modes.
2) Conduct a laboratory study at different off times of the endurance test cycles
    - The off time in each cycle during the endurance test is an important parameter as it determines the difference (delta) in maximum temperature experienced by the product between the on and off (ambient, baseline) times. Depending on the thermal mass of each LED product, the duration of the off time may result in a different value of delta temperature as that in real life, and thus over (or under) estimate lifetime predictions. As is, the test method in the European Commission’s regulations includes an off time of 30 minutes. Longer off times (e.g., 45, 60, and 90 minutes) are recommended for investigation and comparison of catastrophic failures.
3) Conduct a laboratory study at different humidity levels
    - Humidity has been shown to have a negative effect on light output depreciation at the LED package level and for electronic components, however, it is not clear how LED systems would be affected by humidity. This test can inform the predictions of

catastrophic failures of lamps used in damp and wet conditions such as lamps in residential bathrooms and outdoor (street, parking) lot fixtures. This recommendation applies to both methods proposed by the European Commission and the Lighting Research Center.

4) Verify the accuracy in the predictions of LED driver life based on the models in the Telcordia SR332 standard and the Military Handbook 217F.
   - These two publications address the prediction of electronic components under different stress conditions (electrical, thermal) and although they have been used by the lighting industry to predict lifetime of LED subsystems (e.g., drivers), their accuracy has not be validated.

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Appendix A

Laboratory Validation of LED System Life Prediction Testing Method (details of section 5.2.3.1)

The LRC began investigating LED life testing in 2007, funded by the ASSIST program. Initial studies investigated the failure of LED arrays and light engines. In 2008, LRC graduate student Yinan Wu, in his master's degree thesis started investigating failure mechanisms and the factors that cause failure in LEDs and LED arrays and found that failure could be parametric or catastrophic [Wu 2010], as mentioned in Lee et al.'s 2005 article [Lee et al., 2005]. Wu's thesis showed that life testing an LED array by power cycling, specifically slow cycles, caused the solder (between the LED and the printed circuit board) to fail and result in catastrophic failure. Additional studies in the same year by LRC researchers found that cycles to failure decreased when the delta temperature (defined as maximum minus minimum temperature, expressed as ΔT) experienced by the LEDs in the array increased [Lighting Research Center, 2008]. Additionally, the studies showed a weak relationship between ramp rate (defined as LED temperature increase per unit time) and cycles to failure. With these findings, in 2008 LRC researchers pointed out that the industry practice of basing LED lighting system life on a single component, the LED package, and using lumen maintenance testing per IES LM-80 and projecting lifetime per IES TM-21 standards, would not yield an accurate lifetime of an LED system [Lighting Research Center, 2008]. This is primarily because an LED system has many components, including the LED, printed circuit board, driver, and mechanical and thermal management components, working together. Therefore, one has to consider all possible failure modes for each component instead of a single component single failure mode.

Because there were no defined use-rate cycling standards for LED system testing during that period, LRC researchers explored cycling frequency and amplitude to determine failure. To the best of our knowledge, the LRC studies were the earliest to investigate how switching LED systems on and off affected LED system lifetime. These studies showed that very rapid power or thermal cycling does not cause sufficient damage to the LED systems to cause failure. LRC researchers referred to JEDEC22 - A105C & IEC 60068-2-14 standards to define power and temperature cycling for LED systems. Figure A.1 shows the ramp rate of the temperature increase when an electronic component is powered on. The ramp rate, $[(0.9\,\Delta T - 0.1\,\Delta T) / (t_{90\%} - t_{10\%})]$ and dwell time are defined in this figure per the JEDEC22 standard.

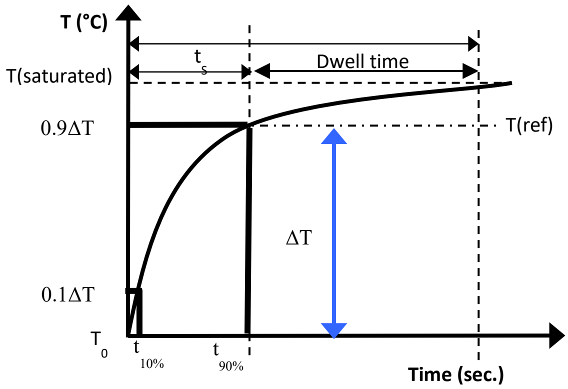


Figure A.1. Temperature profile of an electronic system when powering on, per JEDEC22 - A105C & IEC 60068-2-14.

In the past, many test methods that power or temperature cycle electronics systems allowed products to cycle between 10% and 90% stabilization, rather than full stabilization, to increase the number of cycles during the test period. However, in the case of LED systems, an LRC study in 2012 showed that a longer dwell time—allowing the system to reach full stabilization and remain for an additional time at this stabilized temperature—resulted in fewer cycles to failure, and thus shortened the total time to failure [Lighting Research Center, 2012. Figure A.2 shows examples of temperature profiles of products power cycled without dwell time (between 0.1 ΔT and 0.9 ΔT, partial stabilization, left) and cycles with dwell time (full stabilization at maximum and minimum temperatures, right).

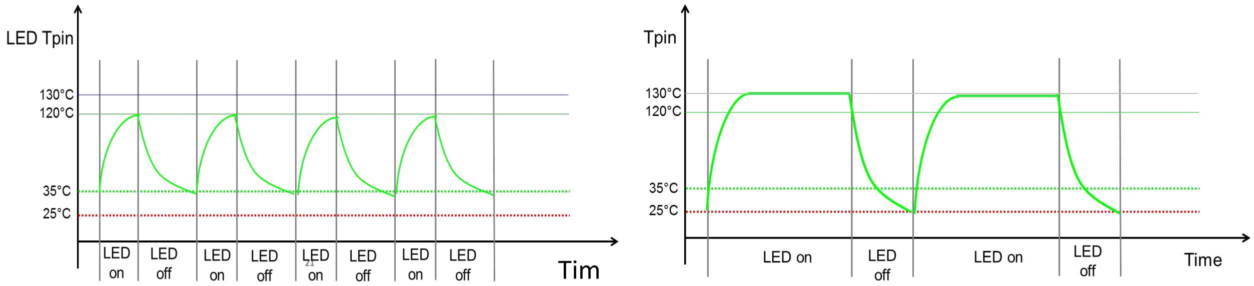


Figure A.2. LED power cycling without (left) and with (right) dwell time.

Results from a 2012 LRC study testing LED replacement lamps found that cycling without dwell time did not show much degradation or failure [Lighting Research Center, 2012]. For the same lamps, cycling with dwell time showed catastrophic failure when the ΔT was large enough and also showed a gradual light output decrease until the lamp failed catastrophically due to multiple failure modes, such as electrical parameter changes of the driver output, optical changes, degraded solder joints, or age-related color changes within the LED lamp package. One lesson learned in this study is when LED systems are tested for lumen depreciation—the parametric failure mechanism—failure can be due to multiple degradation processes. Thus, data extrapolation of lumen maintenance to determine failure time based on a criterion such as L70 could lead to erroneous results.

The following information provides experiment and results details of the LRC study described in section 5.2.3.1.

Experiment conditions

Table A.1 and Table A.2 list the measured average on time, dwell time, and off time durations at each delta temperature for the LED A-lamps and LED MR-16 lamps tested.

Note: In this section, ΔT, Delta T, D, and DT all refer to the same parameter: the temperature difference between the stabilized maximum operating temperature during on-time and the stabilized minimum temperature during off-time, experienced by the LED.

Table A1. LED A-lamp – Measured average on time, dwell time, and off time duration at each delta temperature (ΔT).

Nominal Condition	ΔT (°C)	On Time (hours)	Dwell Time (hours)	Off Time (hours)
2 hours	80	1.7	1.1	0.6
	90	1.6	1.1	0.6
	100	1.6	1.2	0.7
4 hours	80	3.4	2.8	0.7
	90	3.6	2.8	0.7
	100	3.7	3.1	0.8

Table A2. LED MR-16 lamp – Measured average on time, dwell time, and off time duration at each delta temperature (ΔT).

Nominal Condition	ΔT (°C)	On Time (hours)	Dwell Time (hours)	Off Time (hours)
2 hours	80	1.5	1.3	0.6
	90	1.4	1.2	0.6
	100	Not applicable	Not applicable	Not applicable
4 hours	80	3.6	3.0	0.8
	90	3.6	2.6	0.7
	100	3.4	2.9	0.8

For the LED downlight products, Downlight 1 samples were tested at ΔTs of 90°C, 100°C, and 110°C, and Downlight 2 samples were tested at ΔT of 60°C. The dwell times were the same as those for the other LED product types, except Downlight 1 at ΔT of 110°C was tested at only two dwell times (2 hours and 4 hours). Figures A.3, A.4, and A.5 show the temperature profiles experienced by the LED junction during power on and off for the different tested products.

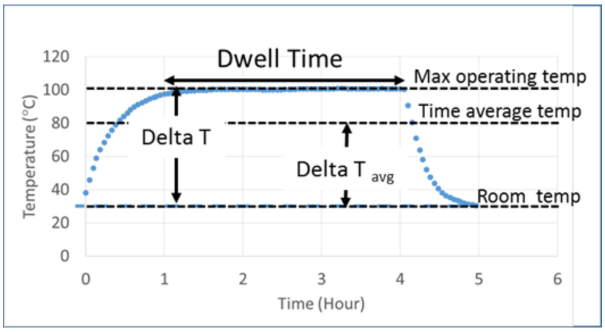


Figure A.3. Temperature cycle profile (temperature measured on the housing of the LED A-lamp).

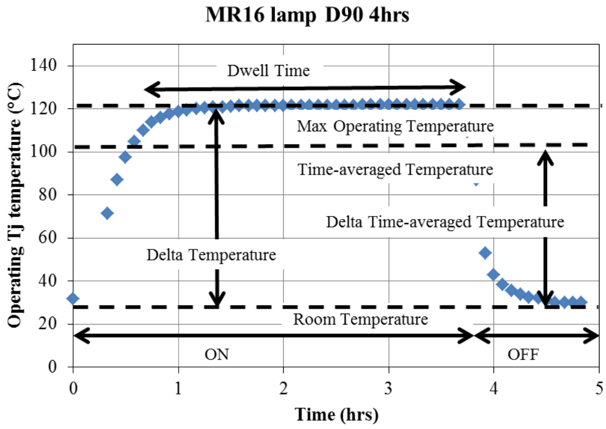


Figure A.4. Measured temperature profile during one operating cycle of an LED MR-16 lamp (ΔT=90°C; dwell time=4 hours).

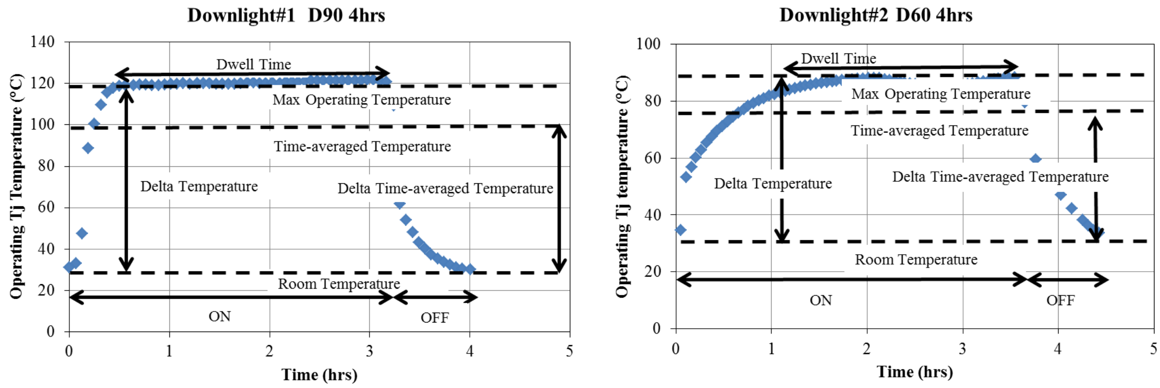


Figure A.5. Measured temperature profile during one operating cycle: (left) LED downlight luminaire 1 (ΔT=90°C; dwell time=4 hours); (right) LED downlight luminaire 2 (ΔT=60°C; dwell time=4 hours).

Experiment setup

The experiment setup for the replacement lamps (A-lamp and MR-16) used a downlight can and a heater pad wrapped around the can to control the T_j of the test lamps. Each lamp sample placed inside the downlight fixture is shown in Figures A.6, A.7, and A.8. Groups of five test fixtures with lamps were placed inside a wooden box. A light sensor box was attached to the opening of the test fixture to monitor the light output and detect catastrophic failure and lumen depreciation for each lamp. At regular intervals, the light sensor box detector was replaced by a spectrometer to gather spectral power distribution data. A thermocouple was attached to the housing to estimate the LED T_j. Control circuits switched the lamps and the heater pad on and off at the designated dwell time and ΔT. All wooden boxes containing the groups of five test fixtures were placed on a rack, and each lamp test assembly was connected to a data acquisition system for continuous monitoring and recording of the dependent variables: light output, spectral power distribution, input power, input current, and lamp housing temperature.

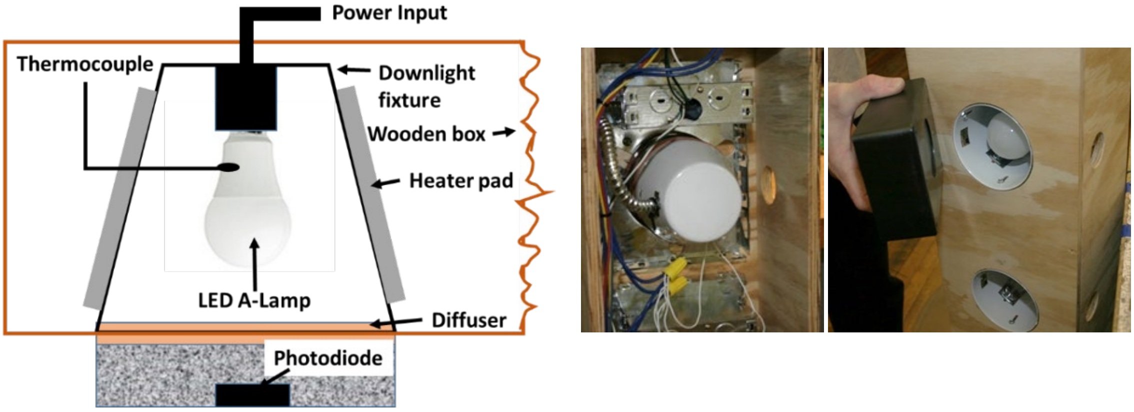
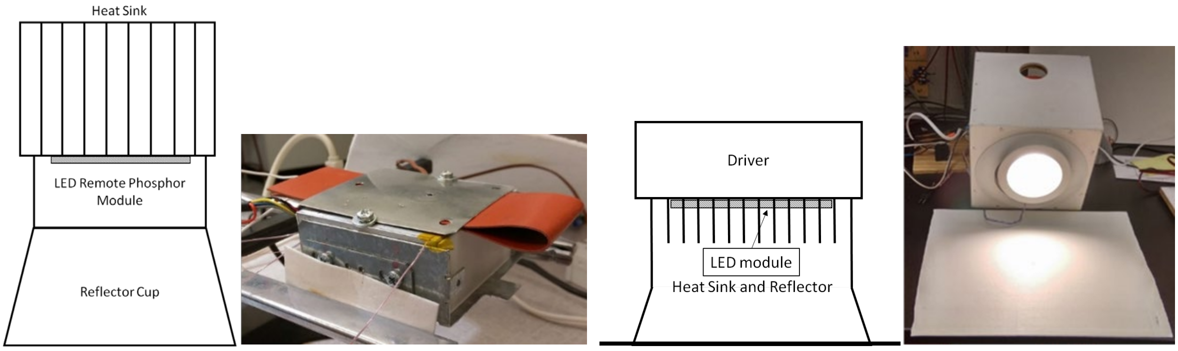


Figure A.6. Experiment setup for life test of LED A-lamps.

Figure A.7. Experiment setup for life test of LED MR-16 lamps.



Downlight 1 *Downlight 2*

Figure A.8. Experiment setup for the life test of LED integrated downlights: (left) downlight 1; (right) downlight 2.

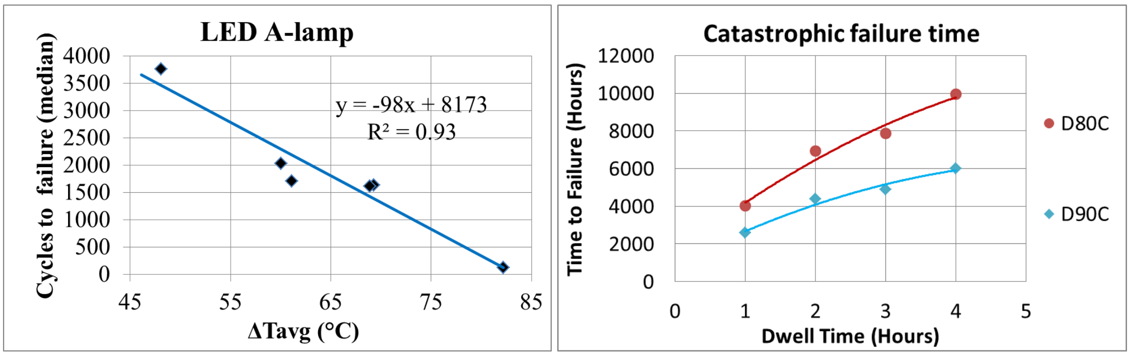
Results

LED A-lamp catastrophic failure results: Table A.3 shows the results summary for catastrophic failure of the LED A-lamps for the different test conditions. The average time between the 5th and the 6th lamp failures was used to denote the median life. As seen in the table, higher ΔT conditions result in shorter time to failure for both dwell time conditions. Also, shorter dwell times result in shorter time to failure for 80°C and 90°C. An exception was for the median time to failure for ΔT at 100°C, where the 4-hour dwell time was shorter than the 2-hour dwell time. This is because the failure takes place due to cumulative damages caused at each transition that are also dependent on the temperature change during the transition. Further analysis of the failed lamps showed that 84% of the failures were due to failure of the solder between the LED and the PCB, and 16% were due to driver failure.

Table A3. LED A-lamp catastrophic failure times for each test condition (ΔT and dwell time).

	Delta time-averaged temperature (°C)		**Time to failure (median life) (hours)**	
ΔT/Dwell Condition	**2 hours**	**4 hours**	**2 hours**	**4 hours**
80°C	48	60	7,516	8,801
90°C	61	69	3,411	7,091
100°C	69	82	3,225	521

Figures A.9(a) and (b) clearly show that the life of an LED system is affected by switching it on and off. The left figure, A.9(a), shows that the number of cycles to failure (median life) and delta time-averaged temperature have an inverse linear relationship with goodness-of-fit, $R^2 > 0.9$. From this, the cycles to failure were inferred for 1-hour and 3-hour dwell times. Knowing the total cycle time for each dwell time, the cycles to failure were converted to time to failure, as shown in the right figure, A.9(b). Figure A.9(b), clearly shows that with shorter dwell time, more frequent on-off switching will cause LED systems to fail faster. For the continuous-on condition, the lamps were not switched on and off, and therefore the cycles for all cases were only one. The times to catastrophic failure were zero for 80°C, 7,000 hours for 90°C, and 1,100 hours for 100°C. The number of cycles to failure is not a relevant parameter in this case.



(a) (b)

Figure A.9. (a) Cycles to failure as a function delta time-averaged temperature (ΔTavg); (b) Time to failure as a function of dwell time for the different ΔT values.

LED A-lamp lumen depreciation results: Most of the lamp samples failed catastrophically before the light output reached L70, meaning that catastrophic failure times were shorter than parametric failure times. To understand parametric life, L70 values for each condition were determined by extrapolating the lumen depreciation data that was available before the lamps failed catastrophically. The median lamp life, L70 in hours, is shown in Table A.4. Figure A.10 shows that failure (median life) as a function of maximum operating temperature has an inverse linear relationship with goodness-of-fit, $R^2 > 0.9$. The estimated L70 values decreased when the maximum operating temperature increased. The projected L70 values for the different test conditions are similar, indicating that temperature cycling for this relatively short test duration has minimum effect on lumen depreciation.

Table A4. Maximum operating temperature (ΔT_{avg}) values and time to failure values for the different ΔT and dwell time conditions.

	Maximum operating temperature (°C)			**Time to L70 (hours)**		
ΔT/Dwell Condition	**2 hours**	**4 hours**	**Continuous-on**	**2 hours**	**4 hours**	**Continuous-on**
80°C	106	108	108	25,528	20,998	23,979
90°C	125	124	124	11,019	12,185	11,657
100°C	131	136	131	7,289	5,308	5,171

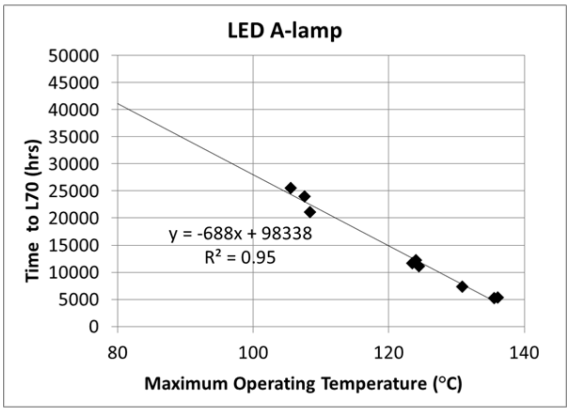


Figure A.10. Time to failure due to lumen depreciation, L70, as a function of maximum operating temperature.

LED MR-16 lamp catastrophic failure results: Table A.5 lists the delta time-averaged temperature (ΔT_{avg}) values and time to failure values for the different ΔT and dwell time conditions of the LED MR-16 lamps. The median lamp life due to catastrophic failure depends on ΔT and the dwell time, with a higher ΔT resulting in a shorter time to failure and a shorter dwell time resulting in a shorter time to failure for 80°C and 90°C ΔT. In the case of ΔT 100°C with 2-hour dwell time condition, the samples came from a different batch due to the limited number of lamps from the original order from the same source. In addition, the heater pads used in these test boxes were unable to achieve ΔT 100°C for these lamps; instead they achieved only ΔT 92°C. As a result, the delta time-averaged temperature was limited to 70°C instead of 75°C. A post-mortem analysis showed almost 98% of the failures were due to driver failure—a different failure mode compared to the LED A-lamp. Figure A.11 shows the cycles to failure (median life) as a function of delta time-averaged temperature and an inverse linear relationship with high goodness-of-fit, ($R^2 > 0.91$). Once again, the results from the LED MR-16 life test study also clearly show that the life of an LED system is affected by switching it on and off.

Table A5. LED MR-16 lamp catastrophic failure times for each test condition (ΔT and dwell time).

	Delta time-averaged temperature (°C)		**Time to failure (median life) (hours)**	
ΔT / Dwell Condition	2 hours	4 hours	2 hours	4 hours
80°C	61	69	4874	6953
90°C	68	76	3373	4702
100°C	70	80	2582	4028

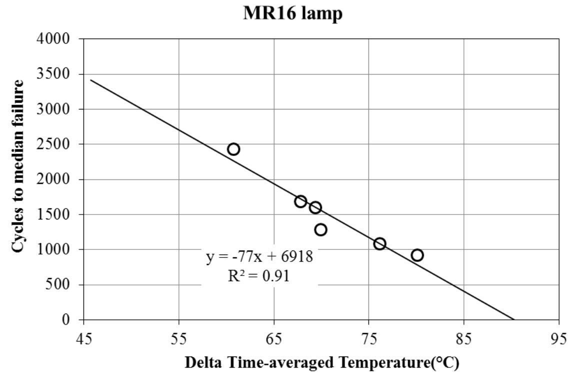


Figure A.11. Cycles to failure as a function delta time-averaged temperature (ΔTavg, in °C).

LED MR-16 lamp lumen depreciation results: Similar to the LED A-lamp test results, most LED MR-16 lamps experienced catastrophic failure before reaching L70. Since the measured lumen values did not change much during the period the lamps were on, it was difficult to project L70 values for all conditions; therefore, only the continuous-on lumen depreciation data were used to project L70 values. These projections were only possible for ΔT 80°C (D80 in graph) and ΔT 90°C (D90 in graph) because at ΔT 100°C (D100 in graph) the lamps failed too quickly. The median lamp life, L70 in hours, is shown in Table A.6. Figure A.12 shows lumen depreciation values just prior to catastrophic failure. Because the catastrophic failures were due to driver failures, and the lumen depreciation was due to optical and electrical parameter changes, it was not easy to project L70 values for the different conditions. Switching on and off for this relatively short test duration seems to have had a minimum effect on parametric failure.

Table A6. Maximum operating temperature and time to L70 failure for the different ΔT and dwell conditions. (* L70 value is 25,000 hours when projected values exceed 25,000 hours.)

	Maximum operating temperature	**Time to L70**
ΔT / Dwell Conditions	**Continuous-on**	**Continuous-on**
80°C	111°C	25,000 hours*
90°C	118°C	17,903 hours
100°C	131°C	Failed too fast to predict

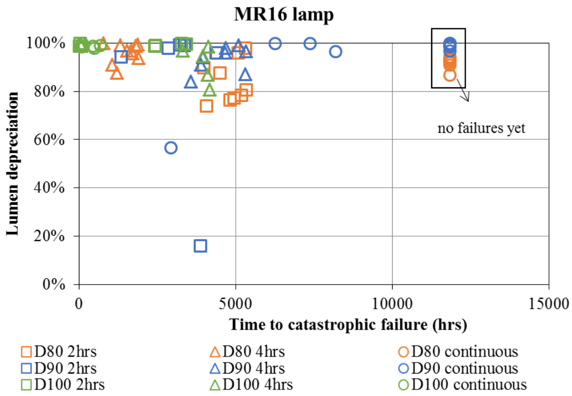


Figure A.12. Lumen depreciation values just prior to catastrophic failure for the LED MR-16 lamps.

LED downlight catastrophic failure results: There were no catastrophic failures observed in downlight 1 and downlight 2.

It is worth noting here that unlike the LED A-lamp or MR-16 lamps, both downlights 1 and 2 seem to have feedback control using thermal information. This is a probable reason for not seeing catastrophic failures in the two downlight groups. However, both systems showed lumen depreciation failure. Because downlights have more space within their fixture design and a higher price tolerance, unlike smaller form factor lamps, it is possible to include more sophisticated electronics to include feedback control. Feedback control is used to prevent a fixture from overheating and failing or to prevent lumen depreciation. Typically, current to the LED is decreased to prevent overheating, or increased to control the lumens at a steady value (i.e., to show no lumen depreciation). Both these cases have implications. Reducing the current to avoid heating results in lower luminous flux output. Increasing the current to compensate for lumen depreciation can result in heating the system. Manufacturers use strategies that are appropriate for their systems based on other components used in the systems.

Lumen depreciation results – Downlight 1: Figure A.13 shows a sample lumen depreciation curve for downlight 1. During the 7000-hour test period, the luminaire showed up to 8% lumen depreciation at the ΔT 100°C condition. Downlight 1 appears to have had feedback control built in to avoid high lumen depreciation, which makes it difficult to accurately project L70. Analysis of input power changes as a function of time for downlight 1 at ΔT 100°C continuous condition showed that until about 3500 hours, the input power remained constant but the lumen output depreciated about 5%. Then beyond that the power started increasing and slowed the lumen depreciation, and even increased it slightly. Using this data to project L70 would yield erroneous results. One way to overcome this difficulty is to use only lumen depreciation data during the constant input power period and project to estimate time to L70. This method was used to project time to L70 for the different test conditions and the resulting plot is shown in Fig. A.14.

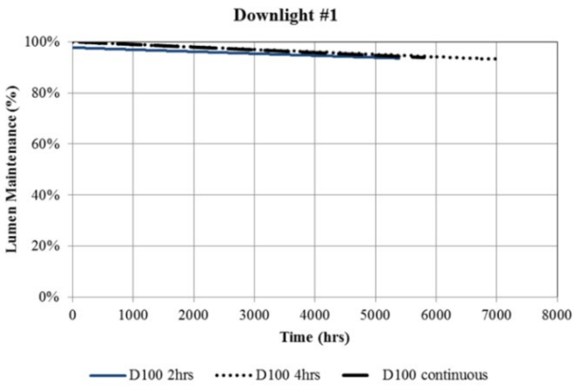


Figure A.13. Lumen depreciation of downlight 1 as a function of time.

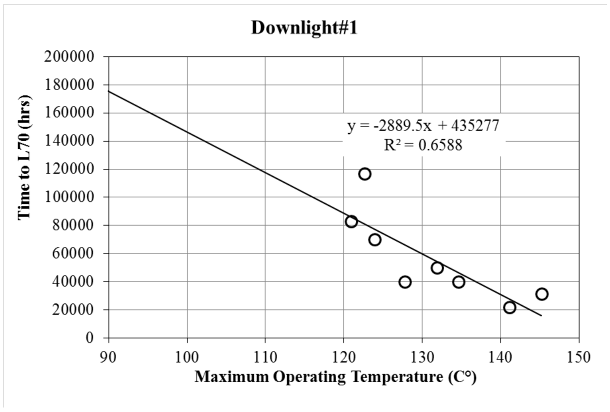


Figure A.14. Time to failure due to lumen depreciation, L70, as a function of maximum operating temperature for downlight 1.

Lumen depreciation results – Downlight 2: Figure A.15 shows the lumen depreciation for downlight 2. During the 5000-hour test period, the lumen maintenance reached 78%. Table A.7 shows estimated L70 values.

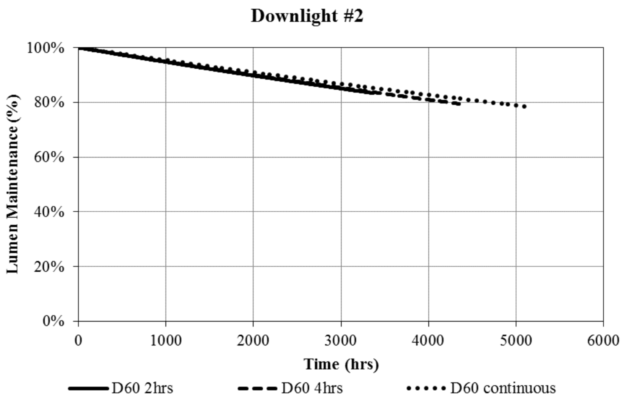


Figure A.15. Lumen depreciation data for downlight 2 as a function of time.

Table A.7. LED downlight 2 – Measured maximum operating temperature in °C and the estimated L70 values in hours

ΔT/Dwell Conditions	**2 hours**	**4 hours**	**Continuous on**
60°C	90.1°C	90.3°C	91.4°C
ΔT/Dwell Conditions	**2 hours**	**4 hours**	**Continuous on**
L70	10,492 hours	9,012 hours	9,627 hours

Predicting lifetime in applications

To show the usefulness of the test method and further illustrate how lifetime is dependent upon application environment and use pattern, two sample applications where the same lamp (the tested LED A-lamp, in this case) can be used were selected to estimate lamp life.

The first application considered was a table lamp that is switched on for 3 hours per day and off during the rest of the day. The maximum operating junction temperature experienced by the LED within the A-lamp, T_j, is 95°C, and the room temperature, T_{room}, is 30°C. The estimated time-averaged temperature, T_{avg}, is 80°C, and therefore $\Delta T_{avg} = (T_{avg} - T_{room})$ is 50°C. The cycles to failure at 50°C is estimated as 3250 cycles, corresponding to 3250 days or 8.9 years (Fig. A.16, left). At 95°C maximum operating temperature, the time to L70 can be estimated as 32,000 hours by extrapolating the linear fit to 95°C (Fig. A.16, right). This corresponds to 29 years. Therefore, in the table lamp application the estimated lifetime of the lamp is 8.9 years, which is the shorter of the two lifetimes, catastrophic and parametric.

The second application considered was a recessed downlight in a non-insulated ceiling switched on for 2 hours per day. The maximum T_j is 129°C at room temperature, T_{room}, which is 30°C, and the corresponding ΔT_{avg} is 77°C. The estimated lamp life values for catastrophic failure and lumen depreciation failure are 1.9 years (700 cycles to failure) and 12.3 years (9000 hours to L70), respectively. Therefore, in this application the same LED A-lamp life is only 1.9 years.

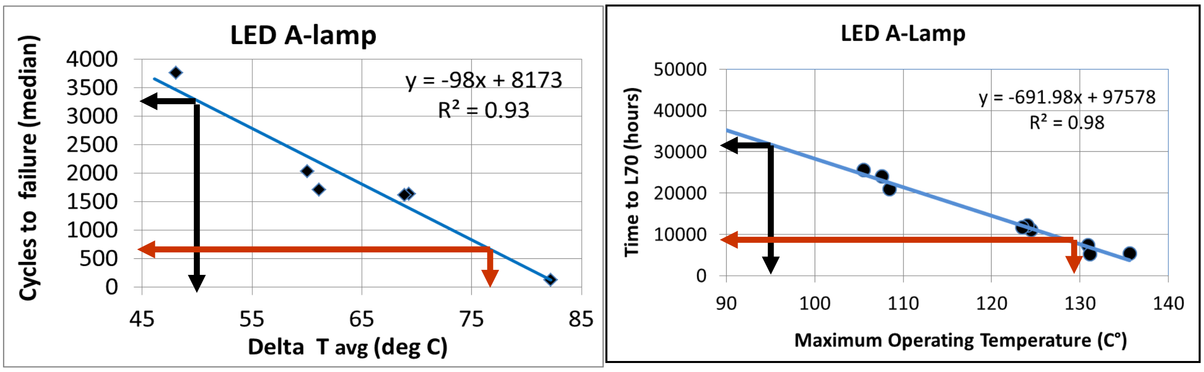


Figure A.16. (left) Cycles to failure and (right) time to L70 for the same LED A-lamp in two different applications.

Lower cost life test setup for testing LED A-lamps

At the conclusion of the long-term life test study, another study was conducted to develop and verify a lower cost, shorter time, life test setup for testing LED A-lamps and to determine the minimum time required to complete the test for a given product [Narendran et al., 2017]. The experiment setup using residential surface-mount light fixtures is shown in Figure A.17.

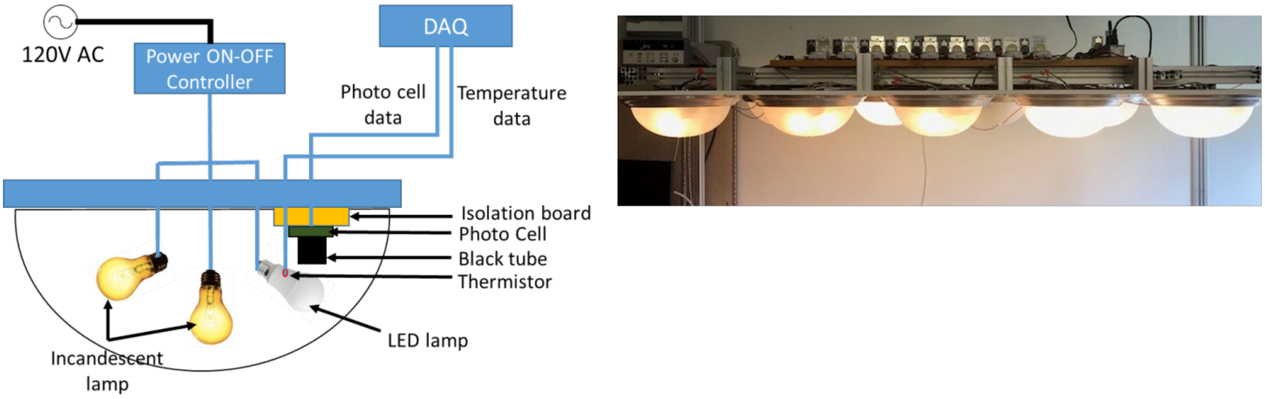
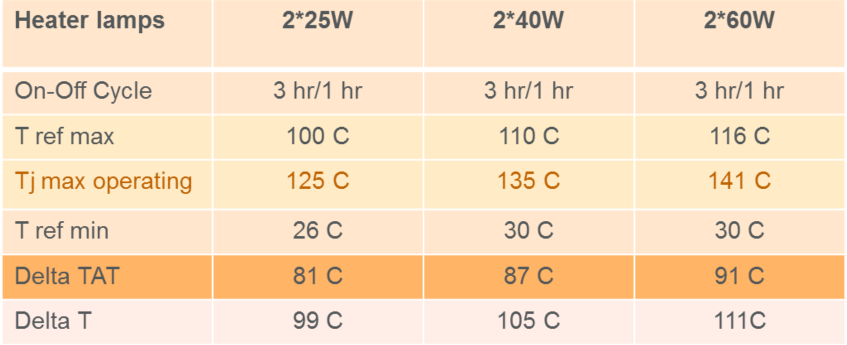

Surface mount light fixture **Test rack**

Figure A.17. Lower cost experiment setup for life testing LED A-lamps.

The setup used three-lamp surface mount light fixtures that can house one LED A-lamp (60W incandescent equivalent) and two incandescent A-lamps of different wattages (25W/40W/60W) to create the necessary delta temperatures, when switched on and off, to stress the LED lamp. A power on-off controller was used to achieve the necessary dwell time, which in this case was set to 3 hours on and 1 hour off. The LED junction temperature, T_j, was estimated by measuring the LED A-lamp housing temperature using a thermistor attached to the lamp body. A photo cell with a black tube aimed at the LED A-lamp was placed inside the surface mount fixture to measure the light output of the lamp. The black tube ensured the measured light was from the LED lamp only. Table A.8 lists the estimated LED T_j maximum operating temperature and the delta time-averaged temperature for each experiment condition.

Table A8. Estimated LED T_j values and the corresponding ΔT values for the different experiment conditions; two 25 W, two 40 W, and two 60 W incandescent lamps are shown. The maximum T_j and the delta time-averaged temperatures for each condition are also shown.



Heater lamps	2*25W	2*40W	2*60W
On-Off Cycle	3 hr/1 hr	3 hr/1 hr	3 hr/1 hr
T ref max	100 C	110 C	116 C
Tj max operating	125 C	135 C	141 C
T ref min	26 C	30 C	30 C
Delta TAT	81 C	87 C	91 C
Delta T	99 C	105 C	111C

The measured light output data as a function of time are shown in Figure A.18. The time to L70 and catastrophic failures are also shown in Figure A.18.

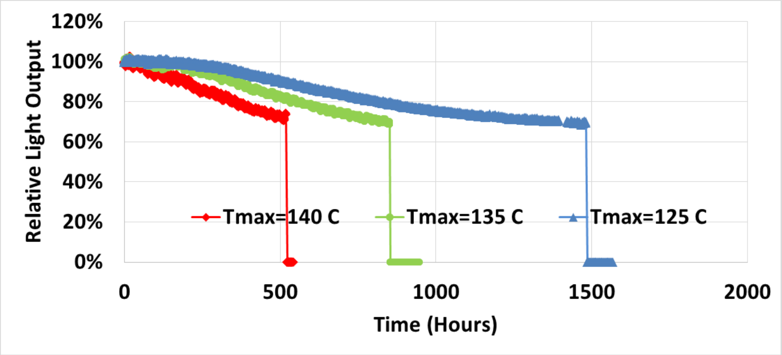


Figure A.18. Relative light output as a function of time for the three test conditions (Tj max= 125°C, 135°C, 140°C) for the tested LED A-lamps.

Times to catastrophic and parametric (L70) failures are shown in Figure A.19.

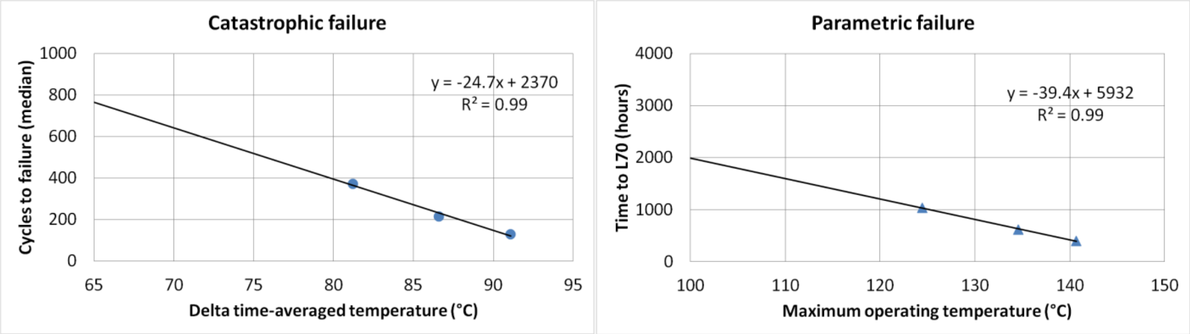


Figure A.19. Left: Cycles to failure as a function of delta time-averaged temperature; Right: Time to L70 as a function of maximum operating (Tj) temperature.

Discussion: The objective of this study was to develop a simpler test setup that manufacturers could employ in-house. Results from the study were similar to the previous study. The cycles to failure (median life) and delta time-averaged temperature had an inverse linear relationship with goodness-of-fit, R^2 = 0.99. The time to parametric failure (L70, median life) as a function of maximum operating temperature also showed an inverse linear relationship with goodness-of-fit, R^2 =0.99. With 3 hours on and 1 hour off per cycle, the total test time for these lamps tested required was less than 1,500 hours. It is worth noting here that if a better designed and built LED A-lamp is used, then there is a possibility the test time can be longer. Similar studies with more LED A-lamp samples would answer the question if the time to test will always be less than 1,500 hours. The shorter time was possible by increasing the stress level. Note: Further studies are needed to validate such a setup. In such studies, it is necessary to validate that the higher stress levels did not introduce additional failure mechanisms.