LED LUMINAIRE LIFETIME: RECOMMENDATIONS FOR TESTING AND REPORTING

SOLID-STATE LIGHTING
PRODUCT QUALITY INITIATIVE

THIRD EDITION
SEPTEMBER 2014

Next Generation Lighting Industry Alliance
LED Systems Reliability Consortium

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1 INTRODUCTION AND SUMMARY

1.1 BACKGROUND AND OBJECTIVES

As the market for solid-state lighting (SSL) begins to take hold and grow, our understanding of the technology has advanced significantly. Early on, there was a good deal of confusion about expected product life, and many relied on the gradual lumen depreciation of the LED (light-emitting diode) source as the best indicator—resulting, on occasion, in unrealistic claims for product life. To address this issue, the Solid-State Lighting Program of the U. S. Department of Energy (DOE) together with the Next Generation Lighting Industry Alliance (NGLIA) formed SSL Quality Advocates and a Reliability and Lifetime Working Group, which published two editions of the document *LED Luminaire Lifetime: Recommendations for Testing and Reporting.*[1] The intended audience included manufacturers; specifiers, including architects, interior designers, lighting designers, and engineers; utilities and energy efficiency organizations; standards organizations; and regulators and other government agencies.

Since our earlier reports, the number and variety of LED packages and LED arrays has increased. They range from low-power LEDs that operate at less than 0.05 watts per package to COB (chip-on-board) modules that can consume over 50 watts per module. This has allowed a corresponding increase in the number of LED replacement lamps and LED luminaires that are available. Existing data from numerous manufacturers show that today LED sources, when operated conservatively, are highly reliable and long lived. For most LED products, manufacturers strive to take advantage of the long source life to realize a long-lived end product. There is now widespread understanding of the degree to which LED drive current and operating temperature (LED and driver) affect system reliability, with better designs as a result. However, a wide range of design choices to meet specific application and market needs is available for LED luminaires, hence a potentially wide range of product life. The numerous other subsystems and components in a luminaire introduce other potential failure modes which will affect and may actually dominate the determination of system lifetime. **Error! Reference source not found.**, from the first *Recommendations* report, illustrates this concept.[2] This complexity can make the prospect of measuring and characterizing LED system reliability and lifetime very

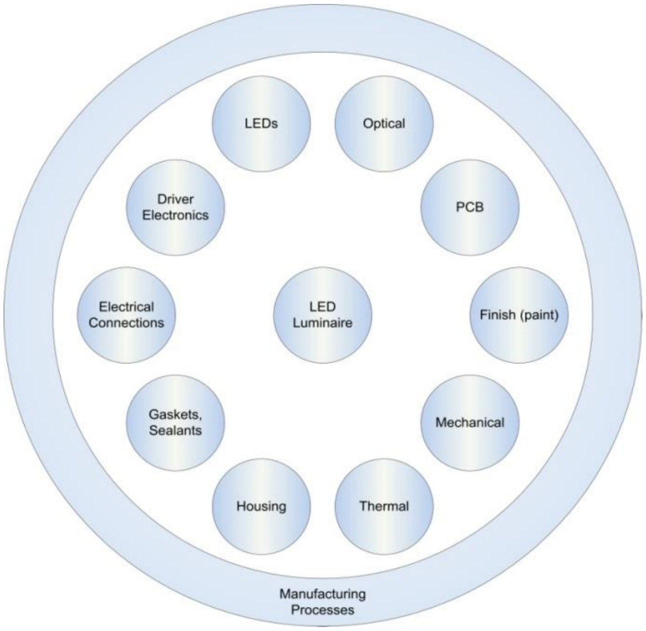

Figure 1. Total system or luminaire reliability is the product of all of the individual reliability considerations: $R_{Luminaire} = R_{LEDs} * R_{Optical} * R_{PCB} * R_{Finish} * R_{Mechanical} * R_{Thermal} * R_{Housing} * R_{Gaskets/Sealants} * R_{Connections} * R_{Driver} * R_{Manufacturing}$

Source: Philips Hadco

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[1] U.S. Department of Energy, *LED Luminaire Lifetime: Recommendations for Testing and Reporting,* http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf.

[2] In this figure "reliability," or $R_{comp,}$ is the probability that the component will be functional at a given time, sometimes referred to as the "availability" of the component, or "probability of success." The probability of failure by that time is (1-R).

daunting, and indeed it is. However, with good design, the overall luminaire reliability will be dominated by a small number of “principal components,” thus reducing the challenge.

Since the first and second editions of the *Recommendations* were published, SSL Quality Advocates was expanded to include more stakeholders and continued its work as the LED Systems Reliability Consortium (LSRC) under NGLIA. The group has contributed to a number of studies, reviewed international efforts for developing tools to project LED-based luminaire lifetime, and researched real-world experience with numerous types of LED-based luminaires. Our objectives have been to better understand what types of failures are most likely to affect system lifetime, to examine possible ways the failures of the principal components might be accelerated to shorten testing times, and to consider the attributes of system models that might assist in the reliable design of LED products. The intent is to provide guidance to both manufacturers and users as to what factors should be considered in developing and testing reliable products, and *not* to provide specific test protocols or data on acceleration factors for specific components nor any type of universal model to predict system reliability. Some manufacturers have devised suitable proprietary methods to estimate the reliability of their specific products, and subsystem manufacturers have improved the information available to designers on the reliability of those products. We encourage those efforts as well as the continued sharing of best practices among producers in the interest of continuous improvement.

Accordingly, it is appropriate to summarize what we have learned, to suggest directions for further work, and to update the LSRC’s recommendations for describing the life and reliability of LED-based luminaires. To that end, here is the third edition of *LED Luminaire Lifetime: Recommendations for Testing and Reporting*.

1.2 WHAT MAKES LED-BASED LUMINAIRES “DIFFERENT”?

LEDs convert electricity to light directly within the device. They do not radiate heat but rather retain it so dissipation must be by convection or conduction. This generally results in higher local temperatures within the luminaire, the extent depending on design, which will accelerate changes within the LED and in nearby electronic components. LEDs do not generate white light directly, necessitating either conversion via phosphor or other means, mixing of multiple monochromatic sources, or both. LED sources emit light potentially for a very long time, and integrated lamps appear to be capable of at least 25,000 hours of operation. Such fundamental differences from traditional lighting technologies have implications for product reliability, a few of which are listed here:

For LED luminaires, the end of life may not be evident. For practically all traditional lighting technologies, the end of life is evident: there is no light. And while it is true that traditional fixtures can corrode or color can shift beyond acceptable limits, requiring replacement, and many technologies show some level of light depreciation, for the most part lights-out failure is what people have come to expect. In contrast, LED sources—the core of an LED lighting system—emit light for a long time. Over that time, depending on design, the light output may continuously fade or the color may slowly shift, possibly to the point where low light output or an unacceptably large color change constitutes practical failure. Indeed, during the early stages of the development of LED technology, lumen depreciation appeared to be the principal mechanism that would define the end of life. However, that means that the “end of life” may no longer be clearly evident, a fundamental departure from our traditional understanding.

The economics of an LED lighting system are different. Today, an LED solution is generally more expensive to implement than a traditional alternative, albeit diminishingly so. That first cost difference may well be offset by energy savings or maintenance savings over the life of the system, but those savings are not always initially apparent to the buyer. These variables can make the buying decision quite complex and very application-dependent.

The order of failure may change. The traditional lamp + fixture paradigm is that the lamp or light source will fail long before the fixture as a whole, so the system is designed to easily replace a relatively inexpensive lamp (or, for some types, ballast) while the fixture lives on. That same model can still be implemented as a "serviceable" LED system. However, because the LED source may well be the part that "lives on," and because the technology is rapidly evolving, which complicates maintaining a replacement inventory, the traditional lamp + fixture paradigm may not always be the most economical solution. A better way may be to think about an LED lighting system as an appliance—more expensive than a traditional lamp but with a much longer life expectancy, and that eventually will need maintenance or replacement.

Useful life is difficult to verify. For LED systems designed to have a very long lifetime, there are new challenges in testing. Straightforward operational aging tests of LED luminaire products can be prohibitively expensive and time-consuming, and manufacturers are increasingly concerned about mandated testing intervals that delay new product introduction and add cost. Many manufacturers have developed proprietary means to estimate product life for their own designs using data on principal components such as the LED package, driver, and optical components, which allows an estimate of the overall luminaire performance. While such practices exist for specific product lines and applications, there is no industry-consensus protocol at this time.

1.3 KEY CONCLUSIONS AND RECOMMENDATIONS

Recommendations from the Second Edition:

The following is a summary of the recommendations from the second edition of *LED Luminaire Lifetime: Recommendations for Testing and Reporting*. Remarks in italics indicate whether these recommendations were unchanged, modified, or dropped in this edition.

- Lumen depreciation is not a proxy for luminaire lifetime.
  Unchanged: This remains an important point. The LED package may not be dominant in determining product lifetime.

- Consider only light output in defining lifetime.
  Modified: This recommendation now includes color shift for those applications where it is relevant.

- Use overstress testing to identify design flaws and manufacturing defects.
  Unchanged: The concept of "robustness" testing, while not a full reliability test, can provide useful screening of products.

- Indicate if a product is serviceable or not.
  Unchanged: Additional discussion of what serviceability means in terms of reliability is in Section 2.2.1.

- LM-80[3] data with TM-21[4] can predict lumen depreciation but not lifetime.
  Unchanged: This relates to the idea that package lumen depreciation is not the only possible failure.

- Develop standard ways to characterize drivers for SSL use.
  Unchanged: While driver characterization is better than it was, there is still a need for testing standards.

- End of life as defined in this document excludes color shift.
  Modified: For products designed for applications requiring color stability, this is not the case.

- To deal with color shift, designate products in one of three categories (lamp replacement, standard grade, specification grade).
  Modified: Designate as color-stable, if relevant, and redefine categories.

- Develop standard qualitative descriptions of the degree of color shift.
  Unchanged: Discussed in this document.

- Define standard luminaire lifetime.
  Dropped: There is no consensus around this approach at this time.

- Reported lifetime should have at least a 50% confidence level.
  Unchanged: This recommendation has not been widely observed but should be.

- Use LM-79[5] for full luminaire characterization.
  Unchanged.

- Develop and document a change control process.
  Unchanged: This is good business practice for manufacturers, but not intended to suggest any industry standard.

- Develop a capability for statistical system design for reliability.
  Dropped: Because of the variety of designs and applications, this is not realistic as a general industry objective, although proprietary methods for specific product groups can be helpful to manufacturers.

- Add standard LED luminaire lifetime to the LED Lighting Facts® label.[6]
  Dropped: While this may have been useful when there were a relatively few types of products available, with the proliferation of products and applications, there is now too much variation in the lifetime for a general recommendation.

Recommendations for Manufacturers:

- Provide clear product warranties, report compliance with industry standard measurements, and communicate your use of and commitment to best practices for designing and developing long-life, reliable products.

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[3] IES LM-80-08, *Approved Method: Measuring Lumen Depreciation of LED Light Sources*, http://www.ies.org/store/product/approved-method-measuring-lumen-maintenance-of-led-light-sources-1096.cfm.

[4] IES TM-21-11, *Projecting Long Term Lumen Maintenance of LED Light Sources*, http://www.ies.org/store/product/projecting-long-term-lumen-maintenance-of-led-light-sources-1253.cfm.

[5] IES LM-79-08, *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*, http://www.ies.org/store/product/approved-method-electrical-and-photometric-measurements-of-solidstate-lighting-products-1095.cfm.

[6] LED Lighting Facts, http://www.lightingfacts.com/.

- Develop, implement, and adhere to design and engineering recommended best practices and document them in a form suitable for general lighting users.

- Achieve industry consensus on screening tests which can identify product designs that are unlikely to meet vendor claims of reliability and lifetime (may be for specific product groups and may involve specific performance ranges).

- Continue to improve and develop industry-consensus methods for measuring and reporting key LED product attributes, such as lumen and color maintenance, particularly efforts to accelerate such testing.

Recommendations for Buyers:

- Focus on qualifying suppliers. Understand what methods the vendor is using to support reliability or lifetime claims, and require data. As they become available, require compliance with industry-consensus robustness tests.

- Understand the warranty. What is covered and what is not? Is the warranty period a reasonable fraction of the claimed lifetime? Will the manufacturer have compatible replacement parts as applicable, when needed?

- Avoid using products for which reliability claims are based on unreliable proxies for luminaire lifetime, such as the lumen maintenance of the LED package. Require and examine additional luminaire product or subsystem data from your qualified manufacturer to support any such claim.

2 DEFINING LIFETIME

2.1 COMBINING ABRUPT AND GRADUAL FAILURES

In earlier editions of this guide, “standard” or “default” lifetime of an LED luminaire (or lamp) was defined only in terms of lumen output and specified as the time when light output of half the product population has fallen below 70% of average initial light output *for any reason* (B_{50}/L_{70}). This definition thus encompasses gradual lumen depreciation of the LED sources, depreciation due to interaction with other components or materials in the luminaire, and catastrophic failure of any component or subsystem, ranging from total failure with no light output to the failure of a subset of the LEDs leading to luminous flux below a specified threshold. We continue to recommend this definition.

For a limited number of applications, excessive color shift may also be considered a failure. It is then natural to extend the definition of lifetime: when light output of half the product population has fallen below 70% of average initial light output or has shifted color beyond a specified limit ($B_{50}/L_{70}/C_{zz}$). C_{zz} depends on specific application needs; there is not a generally accepted level that can be applied to all products. There is also no accepted industry standard for projecting color shift past the test period. For most products, a color shift requirement is probably neither necessary nor appropriate.

For certain LED products in which the LED sources are individually visible (“direct view”), failure of a certain percentage of the LEDs, while not necessarily leading to total depreciation of 30%, may constitute an “aesthetic” failure, similar to color shift. This requirement is very design-specific, and again is not appropriate for the majority of products and should be left as a job specification where needed.

Finally, in some situations the specific limits proposed above may not suffice. These recommendations are not intended to exclude different job-specific requirements, but the same basic definition still applies. For example, the specification may be described as Bxx/L_{XX}, Byy/C_{YY}, Bzz/F for a specific case, where Bxx/L_{XX} means xx% of the product is below XX% lumen depreciation, yy% of the product is below YY% of color shift, and zz% of the product has catastrophic failure (F). There may also be a specification that $xx + yy + zz$ cannot exceed some limit, e.g., 50%. The following sections expand on the various types of failure.

2.1.1 ABRUPT FAILURE TO LIGHT

A critical part can fail to cause an LED luminaire to stop generating light altogether (catastrophic failure). Examples include a power supply failure, corrosion of an electrical connection that stops the electrical flow to critical components, or breakage of a critical part due to vibrations or stresses beyond what the luminaire can handle. Such failure modes are not limited to LED systems. Much has been learned from reliability studies of other electronic systems that is directly relevant to this sort of failure, so it may be possible to apply this knowledge in developing a model of such failures in LED systems.

Mean time to failure (MTTF) can be determined for key components using established acceleration methods for parts other than the LED. Operating temperature is often a key item in calculating mean time to failure for electrical parts. For certain electronic parts, operational voltage and operational current can also impact MTTF and standard models have been proposed for calculating the impact of temperature, voltage, and current on the lifetime of electronic parts.[7] Since current and voltage will also increase the temperature of an electronic device, temperature is perhaps the most fundamental environmental factor for electronic devices. Therefore, local ambient temperatures, dependent on how the luminaire deals with heat, will strongly affect this prediction.

For LED packages, the level of drive current applied to the LED as well as junction temperature are critical determinants and will affect the expected MTTF for those components. One abrupt failure mechanism at the LED package level is the loss of electrical connections through mechanisms such as a broken wire bond or an open solder joint. Other potential failure modes at the LED level include loss of emitter sites due to defect propagation, die cracking, and contact or silver mirror corrosion. All of these mechanisms are impacted by temperature, humidity and current. Finally, electrostatic discharge (ESD) and electrical overstress (EOS) can also produce abrupt failures at the LED package level through damage to the emitter layer or device interconnections. Manufacturers usually can provide extensive data on the performance and reliability of LED packages. They have made great progress in minimizing abrupt failures in LEDs, and field experience suggests this is not a significant factor in overall product performance provided good manufacturing practices are followed and the product is designed within the limits of the LED package. Examples of good manufacturing practices include proper thermal management of the LEDs to achieve controllable junction temperatures, avoiding the use of adhesives and materials which may outgas volatile organic compounds or corrosive materials (e.g., sulfur) that can damage LEDs, proper mechanical protection of the LEDs, and proper grounding practices during assembly.

The mean times to failure for components that are expected to have a significant contribution (“principal components”) can be combined to estimate the mean time to abrupt failure of the LED-based luminaire. If the product design is such that reliability is determined by a *small number* of principal components, and if established best practices learned from conventional lighting product manufacture are followed, it is possible to estimate overall product reliability with a reasonable confidence level. That is the fundamental basis for manufacturers’ proprietary methods of estimating reliability for specific products.

2.1.2 LUMEN MAINTENANCE AND LIMITATIONS

Absent abrupt failure, or as a contributor to combination failure, the light output of the LED luminaire will fade to the point that the end user concludes the luminaire has “failed” and has reached the end of its useful life. Although a reduction in luminous flux by 30% seems to be an accepted value for many applications and standards, and is therefore the default, it is beyond the scope of this document to prescribe that as a universal standard. Rather, the intent is to assist in the understanding of how lumen depreciation fits into a more general definition of lifetime.

LED lumen depreciation information and data gathered from LM-80 testing by the manufacturer of the devices provide a baseline for luminaire system depreciation, which is typically greater than LED lumen depreciation alone. While there are efforts underway to develop standard measurement methods for entire luminaires, product size, sample size requirements, and the time of measurement will often conspire to make these tests impractical for other than the smallest examples, such as replacement lamps. While it may be possible to usefully accelerate such tests on full luminaires or lamps, such as by a significant increase in temperature, one

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[7] IEC International Standard 61709:2011, *Electric components – Reliability – Reference conditions for failure rates and stress models for conversion*, ed. 2.0, http://webstore.iec.ch/Webstore/webstore.nsf/ArtNum_PK/45258!opendocument&preview=1.

must take care to choose experimental conditions that avoid introducing new failure modes not relevant to normal operation. One alternative is to develop accelerated tests for subsystems and components that can be combined with source depreciation data to provide an estimate of luminaire reliability, thus reducing test time and expense. The work of the LSRC provides some guidance as to how such tests might be devised and also helps to establish best practices within the industry, but it is beyond the scope of this effort to develop specific test protocols or requirements.

2.1.3 HOW COLOR SHIFT FITS IN

Color change can be dissatisfying and the limiting factor of product lifetime in some cases. As color shift is monitored in LM-80 measurements, some information is available for any LED that has been tested according to this standard. LEDs are only one of the possible sources of color shift; plastic optical components or reflectors may be another. However, no prediction method for the evolution of chromaticity with time (analogous to TM-21 for lumen maintenance) is currently available.

- Acceptable limits for color shift depend on the application. Users of a space lit by a single light source will be less sensitive to color shift than users of a space lit by two or more light sources that shift differently over time. Even LED products that have identical color shift behavior can lead to color shift complaints. Consider a space lit by lamps on two independent circuits: one circuit is operated for eight hours per day, and the other is on an emergency circuit that operates the lamps for 24 hours per day. Over time, the color difference between the lamps on the two circuits will grow, and may lead to user dissatisfaction at some point.

- There is no intrinsic reason that color cannot be quite stable, as demonstrated by the L Prize®-winning replacement lamp from Philips.[8] But there are many factors that can contribute to color change including LED package design, LED operating temperature, methods and materials used to assemble an LED into a lamp or luminaire, the secondary lens material and its temperature, and the operating environment.

- In addition to color shift over time, which is a reliability concern, there is reversible color shift with temperature and LED current (during dimming, for instance). These color shifts may be intrinsic, based on semiconductors physics. NEMA's LSD 60-2012 standard, *The Effects of Dimming on Color and Efficacy of LED Lamps*,[9] gives an overview of these color shifts.

Because of these complexities, we recommend that including color shift in an estimate of lifetime or specific limits on color shift *not* be applied for standard LED luminaire products for consumer or for general commercial use. Limits may be appropriate for products for specific applications that require color stability or for designer-specified products.

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[8] U.S. Department of Energy, www.lightingprize.org.

[9] NEMA LSD-60-2012, *The Effects of Dimming on Color and Efficacy of LED Lamps*, http://www.nema.org/Standards/Pages/The-Effects-of-Dimming-on-Color-and-Efficacy-of-LED-Lamps.aspx#download.

2.2 PRODUCT RELIABILITY CLASSES

To a much greater extent than other lighting technologies, it is possible to classify products according to their reliability requirements. The design space is sufficiently broad that products with nominally the same appearance, such as replacement A-lamps, may have dramatically different lifetimes and reliability. The differences may be a result of operating temperature, LED drive current, materials and assembly, electronic component choices, or another aspect of the design. For example, a product can be designed to minimize cost, maximize efficacy, maximize light output, minimize color shift, operate in a harsh environment, or address any other performance aspect for a particular application and customer set. For this reason, the usual market segmentations of lighting products[10] may have products within them that have different classes of reliability and lifetime performance requirements.

While it is beyond the scope of this document to define reliability requirements, it may be useful for the industry to move in the direction of defining reliability classes that may be addressed with similar protocols for testing and specifying reliability and lifetime, rather than requiring all products to undergo an extensive “one size fits all” testing regimen. For example, a reflector lamp product might be made offered in a residential model (“standard”), a commercial version (“long life”), and a retail display (“color stable”) model. Each would have a different testing protocol and different reliability specifications. A protocol for testing the “long life” product might then apply to other "long life" classified products.

Some examples of design objectives are:

Products Driven by Initial Cost (“Standard”)
The primary objective is to provide reasonable performance at the lowest possible initial cost. There is less emphasis on lifetime and reliability, although products must meet customer expectations. Products would likely be found in residential or consumer market segments and may include replacement lamps for consumer use; however, there may be examples in other segments as well. This class would have relatively short operating hours as compared with commercial or industrial applications. The environmental stress is generally low (clean power, controlled environment, etc.). As a consequence of the shorter lifetime objective, reliability testing may require shorter times and smaller sample populations in order to establish a reasonable performance.

High Efficiency, Long Lumen Life, and Low Maintenance (“Long Life”) Products
Energy efficiency is a significant factor because of longer operating hours. Outdoor and industrial products may have this objective. Environmental requirements are more severe, especially including humidity or extreme temperature. The products are expected to be in a place for a long time with minimum attention, especially for industrial applications in hard to reach places, roadway lighting, and so forth. Higher costs of reliability testing could be justified in part by lower maintenance costs, for example, but there may be more tolerance for greater color shift and the definition of what constitutes lumen output failure. Longer test times with larger samples would be required. In some cases additional stressors may be appropriate.

“Color Stable” Products
Modest shifts in color may qualify as a failure for these products; beam quality and stability is an issue. Such “designer” products are found in retail, hospitality, or other public spaces, where good lumen maintenance and

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[10] Strategies in Light used the following market segmentation for luminaires in a presentation at the 2013 DOE SSL Manufacturing R&D Workshop: Architectural, Entertainment, Retail Display, Residential, Commercial, Industrial, Consumer Portable, Emergency, Outdoor, Off Grid.

color stability is expected. Reliability testing would be extensive and include color shift. Stability during the specified life may be more important than long life, an interesting challenge for product engineers and for testing protocols.

As noted, these reliability categories may cross market segment lines which are highly varied. However, it may be reasonable to establish a more limited set of standard pass/fail reliability protocols or robustness tests along these lines.

2.2.1 SERVICEABILITY

Another issue that must be addressed with respect to LED-based luminaire lifetime is that some LED luminaires have been designed to be serviceable and some have not.

- *Non-serviceable* LED-based luminaires fail similarly to traditional incandescent light bulbs. If one part fails (for example, the filament or the outer glass bulb breaks), the entire unit no longer works. This is the case with non-serviceable LED-based luminaires. If a critical part fails or the light output falls below the needed light output, the entire luminaire has reached its end of life.

- *Serviceable* LED-based luminaires are more similar to fluorescent luminaires used today. If a fluorescent lamp fails, it is replaced and the luminaire becomes operable again. Similarly, if an LED power supply or LED array fails and it can be replaced, the luminaire becomes operable again. Therefore, the lifetime of a serviceable LED-based luminaire is when a major mechanical or optical part fails that is not serviceable, or the time when replacement parts are no longer available, or the time when luminaires that are more energy efficient or have additional features and benefits can be economically justified to replace the current one.

Serviceability does not preclude the use of reliability classes. The replaceable components of a serviceable product can still be classified according to some scheme such as that above for purposes of defining required testing and the results combined with other components to provide an overall performance estimate of the luminaire product.

A warranty may be written for the life of a serviceable product that assumes some servicing paid by the user, or possibly for the life until service. It is prudent for the buyer to understand what the warranty will cover as the costs could be quite variable.

3 STUDIES OF FAILURE MODES

In order to accurately characterize the reliability performance of any product, it is important to identify and understand those failure modes that materially affect it. In the case of LED lighting products, we are generally familiar with the lumen depreciation of LED packages which will eventually result in the light no longer being useful. We are also aware through experience with traditional lighting as well as LED lighting that another gradual change, color shift, may provide a limit to lifetime as well.

The LSRC has reviewed studies intended to identify potential failure modes and provide additional understanding of product life. We reviewed the results of some highly accelerated multi-variant tests and other available data to learn which failures may be significant and how those failures might be accelerated. Some of the information on failure modes comes from a series of highly accelerated tests executed by RTI International with the help of DOE funding on a limited number of product examples.[11] Other information can be derived from the DOE testing associated with the Philips L Prize-winning LED A-lamp.[12] Systematic field data is of very limited availability (and tilted towards reported failures) but does provide some additional insight into those areas that should receive some attention. Still further non-public information comes from the experience of members of the LSRC and informs the discussions about important failure mechanisms. Members were asked which failure modes they most frequently observed; the results are summarized in Figure 2.

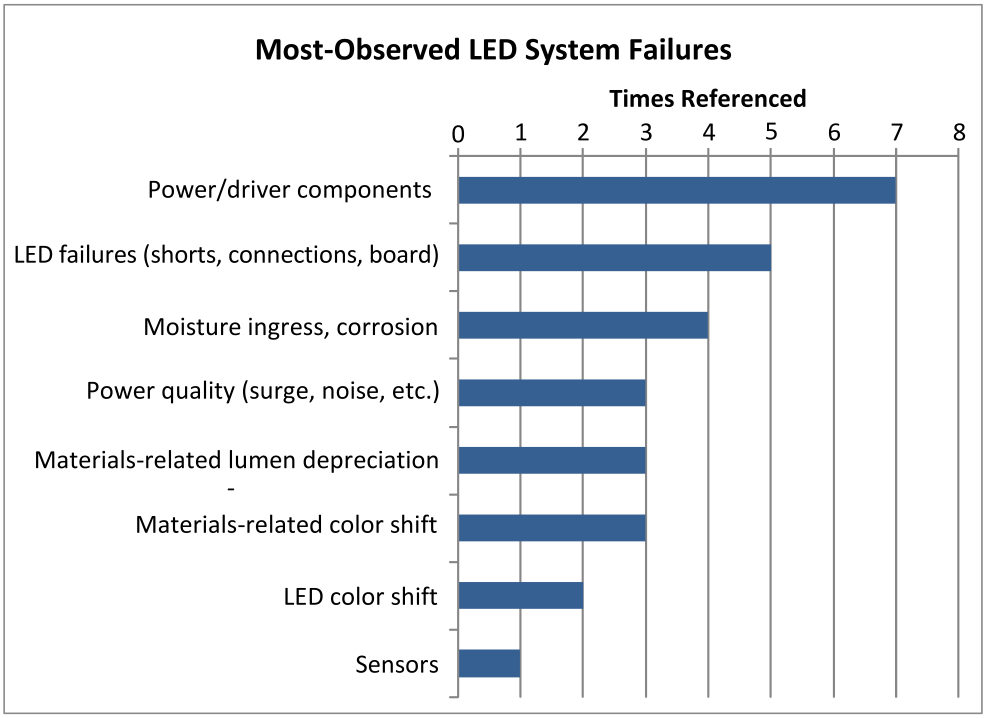

Figure 2. The most commonly observed failures from LSRC member survey. “Times Referenced” means the number of respondents who cited this failure mode.

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[11] RTI International, *Hammer Testing Findings for Solid-State Lighting Luminaires*, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/hammer-testing_Dec2013.pdf.

[12] U.S. Department of Energy, *Lumen Maintenance Testing of the Philips 60-Watt Replacement Lamp L Prize Entry*, http://www.lightingprize.org/pdfs/lprize_60w-lumen-maint-testing.pdf.

3.1 ACCELERATED LIFE TESTS

Accelerated testing is an engineering tool that uses carefully selected environmental conditions to speed up the aging and/or degradation processes associated with components in an SSL device. Among the conditions (i.e., stress levels or stressors) that may be varied in a properly designed accelerated test are temperature (including both high and low temperature extremes), humidity, vibration, electromagnetic irradiation, outdoor UV exposure, chemical exposure, electrical power, and ripple.

Most SSL products are designed to operate under specified ranges for temperature, humidity, electrical power, and other parameters. These products will still function outside these design ranges, but their lifetimes will typically be shorter than under normal operating conditions. For example, LM-80 test data for LEDs has demonstrated that operation at high temperatures (e.g., 125°C), for a given current level will result in faster lumen depreciation than operation at a lower temperature (e.g., 55°C). This is a natural consequence of the chemical kinetics of the degradation of LED components, and since higher temperatures will increase the rate of the processes responsible for degradation, the performance of a device decreases faster under these conditions.

The primary advantage of performing accelerated testing at high stressor levels is that the aging process occurs at a faster rate, so test time is reduced. Properly designed accelerated test methods seek to build a correlation between lifetime under elevated stress levels and normal operational levels. As a result, accelerated testing will typically be performed until failure of the device(s) under test ("DUT"). When failure occurs, an examination of the failed part is performed and the determination of the failure mechanism is critical to understanding the test results and to building scientifically sound correlations to normal operating conditions. Accelerated test methods should also recreate failure mechanisms that are observed under normal operation and not create new failure modes for the test to have the greatest meaning.

There are many different types of accelerated test methods that can be applied, and these methods can be roughly grouped by the number and level of stresses applied to the DUT. In some cases it may be appropriate to apply several of these stresses in succession. Examples of typical accelerated test methods include:

- **Constant environmental accelerated tests.** In this test procedure, a constant environmental stress is applied to the DUT. An example of this type of test is a temperature bake at a value higher than the normal operational value.

- **Cycling environmental accelerated tests.** In this test procedure, the environmental stress is cycled between two or more levels (usually a high state and a low state). Two common examples are *temperature shock*, which involves rapid exposure of the DUT to two temperature extremes (e.g., -50°C and 125°C) with sufficient time for equilibration at each endpoint, and *temperature cycling*, which involves a more gradual cycling of the DUT between the temperature extremes.

- **Multiple environment stress tests.** In this test procedure, two or more environmental stress levels are controlled and the DUTs are subjected to their combined influences. A common example is temperature and humidity testing often performed at 85°C and 85% relative humidity (85/85).

- **Step-stress tests.** In this test procedure, one or more environmental stress levels are held constant for a period time and then increased by a set amount. The process is repeated until failure of the DUT occurs.

One example of a step-stress test would be first subjecting LED lamps to 125°C for 500 hours, then increasing the temperature to 150°C for the next 500 hours, and so forth.

- **Highly accelerated life tests (HALT).** In this test procedure, environmental stress levels well beyond those expected during normal operation are applied to the DUT to promote failure in a short period of time. In many instances HALT methods will use multiple environmental stressors to further reduce test time. The use of step-stress and HALT methods in testing SSL devices is explored further in a 2013 book edited by LSRC members Dr. Willem van Driel and Dr. Xuejun Fan.[13]

For tests used to verify product performance, an important consideration in designing accelerated tests is that the failure modes produced under accelerating conditions should mimic those occurring in normal operation. This consideration often places a limit on environmental stress levels that can be used in accelerated testing.

Extreme environmental conditions, such as highly elevated temperatures or vibration levels that may occur in step-stress or HALT methods, can introduce new failure modes. These tests, sometimes tests to failure, can be useful for identifying potential failure modes in operation, but proper evaluation of these new modes is critical to understanding how or if the test results apply to the product.

3.1.1 EXPERIMENTS ON ACCELERATING FAILURES

In the context of the U.S. Department of Energy's L Prize competition to design a 60W A-lamp equivalent, Pacific Northwest National Laboratory (PNNL) extensively tested the Philips submission entry, including long-term operational performance. As of July 2013, 200 sample lamps had been continuously tested at a 45°C ambient temperature for over 25,000 hours. This is perhaps the largest publicly available data set on LED product reliability, and it is significant that there have been no failures, lumen depreciation is negligible, and average chromaticity shift is less than .002. These tests continue. Figure 3, from PNNL's lumen maintenance testing report,[14] summarizes the results. While this product is a good example of the ability of LED lighting to perform consistently over a long period of time, the data also show that the moderately elevated temperature provides little if any acceleration of lumen depreciation, illustrating the challenge of reducing the test times for such products. Other means will need to be explored to achieve that goal.

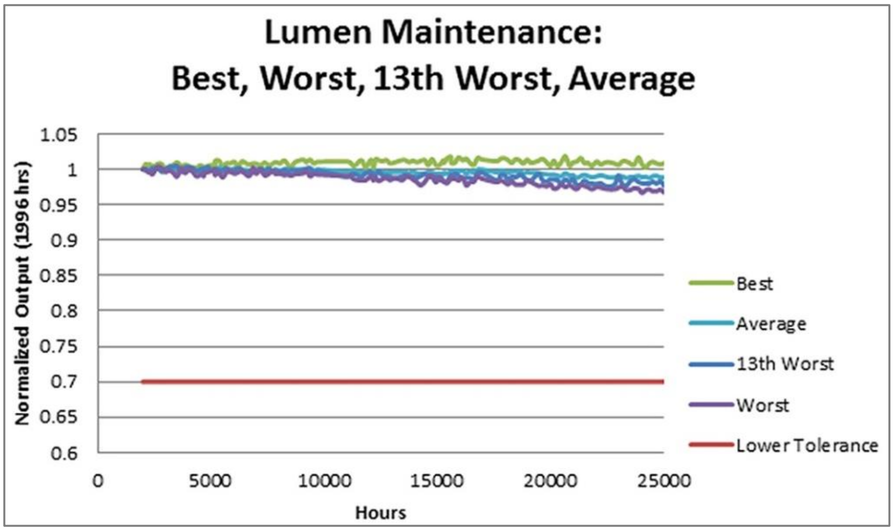

Figure 3. Comparison of best, worst, 13th-worst, and average L Prize lumen maintenance after 25,000 hours. *Source: PNNL*

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[13] W.D. van Driel and X.J. Fan, eds., *Solid State Lighting Reliability: Components to Systems*. Springer, 2013.

[14] U.S. Department of Energy, *Lumen Maintenance Testing of the Philips 60-Watt Replacement Lamp L Prize Entry.*

RTI International, in association with the LSRC, tested commercially available, mass-produced indoor luminaires using a HALT also known as the "Hammer Test."[15] The intent of the Hammer Test was not to develop a new robustness test, but rather to accelerate luminaire failure to less than 1,000 hours by subjecting them to environments outside their design range. Once failure is induced, subsequent tests will be needed to further investigate failure modes and determine acceleration factors.

In the Hammer Test, 6" LED downlights were subjected to a series of sequential environmental stresses including temperature cycling (-50°C to 125°C), wet high temperature operational life test (WHTOL) at 85°C and 85% relative humidity (RH), and high temperature operational life test (HTOL) at 120°C. In addition to these multiple environmental stressors, electrical power to the luminaires was cycled on and off at one-hour intervals to provide electrical stress as well. The study found that such SSL luminaires can exhibit exceptional durability even under the extreme stresses of the Hammer Test. All luminaires examined in the study survived more than 100 cycles of temperature shock (-50°C to 125°C) and nearly half survived more than 300 cycles. The failures that were observed typically occurred in the driver circuit, with board-level failures being most common. The 611 LEDs contained in these luminaires endured nearly one million hours of cumulative exposure to the Hammer Test, and only four failures (<1%) were observed during the testing. These findings reinforce the high reliability of LEDs in lighting systems, even under extreme conditions, and suggest that other elements of the luminaire are more likely to fail first. The level of performance demonstrated by the luminaires examined in this Hammer Test protocol suggests that SSL luminaires will have a low probability of random failure in the field during normal use.

Tests such as the Hammer Test and the step-stress testing on L Prize lamps have demonstrated that well-designed SSL devices are exceptionally robust and can operate for substantial periods of time well outside their specified operational environments. Key findings include:

- Catastrophic failure of LED package failures continues to be rare in testing.
- Lumen depreciation of LED sources operated under proper thermal control and moderate current drive is low, and the device can operate for extended periods without failure or significant lumen depreciation.
- Yellowing of some polymeric optical components may occur and contribute to lumen depreciation and color shift.
- Driver failure is likely to be an eventual cause of catastrophic or abrupt failure in SSL devices, but long-lived drivers are available.
- Failure of electrolytic or film capacitors is a leading cause of driver failure, but de-rating of electrolytic capacitors will extend product life.
- Impedance increases in electrical components (especially capacitors) with aging and can also cause an increase in power dissipation in the driver and a reduction in power factor.

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[15] RTI International, *Hammer Testing Findings for Solid-State Lighting Luminaires*.

3.2 POWER SUPPLY CONSIDERATIONS

Driver electronics can be an important reliability concern for LED luminaire systems, sometimes more important than the LED sources. Historically, in legacy lighting systems that were designed to only function two to three years at most before maintenance was required, power supplies and their components were specified to match this maintenance cycle. With today's SSL light sources, with lumen maintenance periods that can effectively extend into many decades, a three-year power supply spec may not make sense. Highly reliable power supplies can be designed to match the system needs while simultaneously meeting cost objectives. Power supplies can also be separately tested,[16] and much information is available from manufacturers, although generally not in a standard format.

Power management within a properly designed SSL luminaire ensures that the power delivered to the LED package(s) is appropriately sized, filtered, and controlled. A contemporary "driver" (power supply) contains multiple electrical circuits (input power conditioning, AC/DC converter, power factor correction, switching mode control, current regulation, output filtering, etc.) working together to provide regulated output power to LEDs. A failure in any of these circuits can have a cascade effect on driver performance and may ultimately result in a catastrophic failure. LED drivers consist of typical power supply electrical components including capacitors, inductors, power transistors, diodes, bridge rectifiers, resistors, and transformers, and any of these components may fail during operation. Since failure rates of electronic components can be related to their operational temperature, proper thermal management techniques are important to ensure driver longevity. In addition, driver designs that de-rate critical components such as capacitors have an added operational margin.

Hallmarks of a well-designed power supply system include:

- **Thermal management.** A general characteristic of contemporary power supplies is that, to one extent or another, they generate heat. The well-known "10-degree rule" for electronic components states that for every 10 degrees (Celsius) of operating temperature reduction, you can effectively double the life of an electronic component. While this rule of thumb greatly over-simplifies a very complex interaction between operating temperatures of electronics and their expected MTTF, it is nevertheless a generally useful and applicable rule. To carry this philosophy further, a proper SSL luminaire design will also ensure that the *overall* thermal management design of the luminaire accounts for the power supply thermal load, and not just the LED-generated thermal load. Additionally, the luminaire manufacturer should always ensure that the temperature-range rating of the power supply is compliant with the expected operating environment of the luminaire.

- **Sub-component selection.** Just as appropriate management of a power supply's thermal load will improve its MTTF, of equal if not more importance is the careful specification and selection of individual components within that power supply. Power supply components, such as capacitors, diodes, rectifiers, and transistors, all have a critical functional role within a well-designed and well-manufactured power supply. As previously stated, each component's operating parameters and rated MTTF should be carefully matched to the overall desired MTTF/MTBF (mean time between failures) of the luminaire to optimize the overall ROI of the luminaire. In general, carefully matched components will yield improved efficiency and reliability.

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[16] S. Tarashioon, W.D. van Driel, and G.Q. Zhang. "Multi-physics reliability simulation for solid state lighting drivers," *Microelectronics Reliability* 54 (2014): 1212–1222, doi: 10.1016/j.microrel.2014.02.019.

- **Version control.** Changes in one circuit within a power supply can have a cascade effect that ultimately produces failure in the power supply. Power supply performance is only as good as its weakest link in the environment that it is used. Great care should be exercised by luminaire manufacturers as regards the version control process employed by their power supply manufacturer; any and all engineering changes that are proposed by the power supply manufacturer should be tracked and made available for review, to ensure that any proposed change has been carefully examined, documented, and—ideally—tested. Improperly managed engineering changes, particularly when not thoroughly tested, can lead to a much higher than normal failure rate; when such failure rates happen in certain customer environments—e.g., on streets, bridges and tunnels—repair and/or replacement can be very costly, both in terms of actual repair costs, and in terms of diminished brand reputation.
- **Transient immunity/surge protection.** Solid-state lighting products are subject to the same environmental conditions as their legacy-lighting counterparts: they must contend with power sources that in exterior and/or industrial-commercial installations can subject them to line voltages that may frequently vary widely against a utility's "normal specification." Sometimes these variations can be extreme, and while the duration of these voltage spikes can be very brief—often measured in milliseconds—they can nevertheless have detrimental consequences on the long-term reliability and expected life of the power supply. While many older generations of legacy lighting used "iron-core" ballasts that were more forgiving of such surges and spikes, today's electronic power supplies can be much less forgiving. To address this issue, some luminaire manufacturers will employ surge devices of some type, varying from simple off-the-shelf sacrificial capacitors, one-to-one pass-through transformers, or bespoke designs with remotely accessible health status. Regardless of the design, care should be exercised when designing the luminaire's power system to insure that it is capable of delivering its stated reliability within its intended installation environment.
- **Power factor.** Power factor is generally defined as the ratio of the real power flowing to the load, to the apparent (metered) power in the circuit. A power supply that has an efficient power factor rating is widely recognized as a de facto requirement by most utilities and end users. Luminaire manufacturers must therefore ensure that this performance parameter be properly specified and met by the power supply vendor.

In summary, for proper, long-term reliable luminaire operation, the power supply and related electronics must provide a well-controlled and protected drive current and possibly other control and monitoring features, and must be designed to properly function for the anticipated life of the product. Component failures due to improperly designed and executed SSL power management will usually result in a catastrophic failure of the luminaire, and subsequent costly replacement for the end user or for the manufacturer, if the failure occurs within the warranty period.

While many luminaire manufacturers have achieved good results with power supply performance and have developed good relationships with their suppliers to procure the driver performance they need, for others the performance of the electronic subsystems remains a limitation to overall luminaire reliability. One consistent request from a number of luminaire makers has been to arrive at a more standardized reporting of driver performance, including reliability, in order to better address these issues. To appropriately minimize the probability of such failures, SSL luminaire manufacturers can and should work closely with their power supply manufacturer(s) to define and agree on key reliability factors. Such factors would include clearly specifying:

- Designed MTTF
- Availability of reliability test data
- Operating temperature and voltage range (so-called V,I mapping)
- Surge rating
- Formal revision-control process(es) and communication and approval flows
- HALT testing (completed or planned)
- Regular in-process quality testing

In-process quality testing should also be further defined and agreed, relative to:

- Quality assurance (QA) team qualifications
- QA system(s) and methodology in use
- Frequency of ongoing production testing
- Pass/fail criteria and “non-conforming” response policy
- Availability of historical QA test data
- How and when will QA data be communicated

Some progress has been made in developing new driver measurement standards. The ANSI American National Standard Lighting Group (ANSLG) assembled an ad hoc committee in 2013 to draft a measurement standard for LED drivers.[17] At this point, this standard does not address long-term changes in drivers, although that effort has been contemplated. Such specifications and QA policies or processes outlined above may increase the unit cost of a given power supply to some degree, but such additional costs should be far less than the aggregate costs of unit failures in the field.

3.3 LED PACKAGE FAILURES

The LED package today is a very reliable component and is less likely to be the dominant cause of system failure in current products than when it was first introduced. The two main concerns related to LED packages are the gradual failures due to lumen depreciation and, where applicable, color shift.

3.3.1 LUMEN DEPRECIATION

The gradual diminution of light output from the source components will eventually limit useful life, however defined, absent other, earlier failures. For an LED luminaire, the time to reach output that is too low, typically 70% of the original luminous flux, will define the longest useful life of a luminaire under the same test conditions as those for the packaged LEDs. This has been called the “entitlement” for lifetime. All other failures will reduce this time to a greater or lesser extent depending on design, operating conditions, environment, and so on.

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[17] Jianzhong Jiao, “ANSI Recognizes Need for LED Driver Testing Standards,” *LEDs Magazine*, June 2014, http://www.ledsmagazine.com/articles/print/volume-11/issue-5/features/standards/ansi-recognizes-need-for-led-driver-testing-standards.html.

Quite a bit of work has been done to define test methods for package lumen depreciation (LM-80), including the projection of a limited test time to longer periods (TM-21). Forthcoming standards will provide methods of measurement and projection for lamps or light engine components (LM-84[18] and TM-28[19]), although for practical reasons (product size, sample size, test time, cost) these may be more useful for limited verification of predictions made through other means rather than for routine product life tests. We refer to the standards themselves for more details on the measurement and characterization of lumen depreciation. We also note that LED package lumen depreciation is not a proxy for luminaire life because of the presence of other failure modes.

3.3.2 LED COLOR SHIFT

Defining color shift is itself a complicated issue, and color shift remains a difficult parameter to include in a lifetime definition. The Standard Deviation of Color Matching (SDCM), also called the MacAdam Ellipse, *roughly* approximates the ability of the eye to distinguish color differences. In the CIE 1976 u'v' color space, one SDCM is represented by an approximate circle with a radius of about 0.001 Δu'v'. Such a definition, however, says nothing about the direction of color shift. Relative shifts of LEDs in the same direction are less obvious to the observer than are shifts in opposite directions, for example. And shifts in different directions may be more or less evident or distasteful to the observer as well. Measurement over time is difficult, and there is as yet no agreed method to extrapolate results to longer times.

As noted earlier, color shift is not applicable for all applications or for all products in a particular market segment. Therefore it should be considered as an "add-on" specification only for products sold as "color stable." Additionally, for a *general* statement of color stability, a failure should be described as a shift outside some limit, regardless of the direction of shift. However, for a "specified product" a buyer may add additional requirements.

To expand further: The color point of a light source is generally measured using chromaticity coordinates that are defined by the Commission Internationale de l'Eclairage (CIE). While the CIE has developed several different formats for chromaticity coordinates and the corresponding color spaces, the one most commonly used by LED manufacturers is the CIELUV color space adopted in 1976,[20] because it provides for a nearly uniform chromaticity scale. In the CIELUV color space, the chromaticity coordinates are designated as u' and v'. Hence, the change in color of a light source as it ages can be calculated from its current chromaticity coordinates (i.e., u',v') and its initial chromaticity coordinates (i.e., u_0', v_0') using this formula:

$$\Delta \mathrm{u'v'} = \sqrt{}[(u' - uo')^2 + (v' - vo')^2]$$

As the primary light source, the characteristics of the LED are important in understanding the potential for color shift of the lighting system. LM-80 data published by LED manufacturers provides insights into the color shift characteristics of a specific product under the test conditions used in LM-80 (i.e., constant current, controlled temperature and low humidity). These color shift values are usually given in terms of Δu'v', although sometimes the individual chromaticity coordinates (u',v') are given as well. Note that values of Δu'v' convey the magnitude of the color shift, but do not give the direction of the shift.

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[18] IES LM-84-14, *Approved Method for Measuring Luminous Flux and Color Maintenance of LED Lamps, Light Engines, and Luminaires*, http://www.ies.org/store/product/ies-approved-method-for-measuring-luminous-flux-and-color-maintenance-of-led-lamps-light-engines-and-luminaires-1339.cfm.

[19] IES TM-28-14, *Projecting Long-Term Luminous Flux Maintenance of LED Lamps and Luminaires,* http://www.ies.org/store/product/projecting-longterm-luminous-flux-maintenance-of-led-lamps-and-luminaires-1348.cfm.

[20] N. Ohta and A.R. Robertson. *Colorimetry: Fundamentals and Applications*. New York: Wiley, 2005.

At the LED level, color shift can arise from changes in the emitter, phosphors used to convert emitted blue light into white light, clear encapsulant, and the package containing the LED chip, encapsulant, and the phosphor.[21, 22] Common degradation pathways occurring in LED emitters that will affect color point stability include changes in the emission flux and wavelength. Likewise, aging-related changes in the emission flux and emission spectra of common phosphors used in LEDs can also cause a color shift in light produced by the LED. The magnitude and direction of these shifts is strongly dependent on the phosphor mix, the operating temperature of the phosphor, and ambient contaminants.

Packaging materials used to protect LEDs can also cause a color shift especially through the oxidation of the plastics used as encapsulants and lenses attached to LEDs. The same effect can also occur at the luminaire level where oxidation of plastics used for optical components such as lenses, diffusers, and reflectors can cause a shift in color. Polymer oxidation tends to produce disproportionately greater light absorption at shorter wavelengths (e.g., blue and green) than at longer wavelengths (e.g., yellow and red), which will shift the color point. The relative influence of these degradation pathways will vary depending on light source type (high brightness LED, mid-power LED, chip-on-board arrays, remote phosphor) and the materials and design used by the product's manufacturer. The relative ease of oxidation of the materials commonly used in luminaire manufacturing is generally known,[23, 24, 25] and adequate design choices can be made by consulting the manufacturers of optical materials.

Most, but not all, of the degradation processes associated with color shift in LEDs and light engines are temperature activated, so control of the LED junction temperature is important in maintaining a consistent color point for installations containing SSL luminaires. In reviewing the LM-80 data of LEDs for potential color shifts over the product lifetime, it is important to examine the propensity of the LED to experience color shift under the expected operating conditions (current and temperature) as well as higher stress conditions. The higher stress conditions can provide an indication of the long-term aging characteristics of the LED for longer test times under milder conditions. However, at this time, standard methods to project LED color point do not currently exist but are under development by standards organizations such as IES.

Other environmental stresses such as moisture or chemical exposure can also accelerate color shift in luminaires unless adequate precautions are taken to protect the optical materials from ingress into the optical cavity. Color shifts in some LED packages due to corrosion of silver surfaces that are used as mirrors to enhanced light extraction have been observed in the presence of sulfur or other corrosives materials.[26] Common sources of sulfur that should be avoided in SSL luminaires include industrial chemicals and vulcanized rubber (e.g., used in gaskets). In a similar manner, volatile organic carbon (VOC) ingress can produce significant discoloration of LEDs resulting in color shifts and lumen depreciation.[27] Common sources of VOCs include outgassing from adhesives used in luminaire assembly and environmental contaminants. LED damage due to corrosive chemicals is

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[21] van Driel and Fan, *Solid-State Lighting Reliability*.

[22] G. Meneghesso et.al. "Recent results on the degradation of white LEDs for lighting," *Journal of Physics D: Applied Physics* 43, no. 35 (2010): 354007. doi:10.1088/0022-3727/43/35/354007.

[23] M. Yazdan Mehr et al. "Reliability and optical properties of LED lens plates under high temperature stress," *Optical Materials,* 05/2014.

[24] M. Yazdan Mehr et al. "Photodegradation of bisphenol A polycarbonate under blue light radiation and its effect on optical properties," *Optical Materials* 35, no. 3 (2013): 504-508. doi: 10.1016/j.optmat.2012.10.001.

[25] J.L. Davis et al. "Insights into accelerated aging of SSL luminaires," *Proc. SPIE* 8835, LED-based Illumination Systems, 88350L (September 30, 2013). doi: 10.1117/12.2025295.

[26] Osram Application Note, "Preventing LED Failures Caused by Corrosive Materials," June 2013.

[27] Cree Application Note, "Cree® XLamp® LEDs Chemical Compatibility," Document CLD-AP63 Rev 5, June 2014.

generally irreversible while that due to VOC absorption may be reversible in some cases. In addition, there is a strong blue light stress influence on both failure modes but exact relations are unknown.

The luminaire power supply can also affect color shift, especially in luminaire systems employing red-green-blue (RGB) emitters and those with hybrid LEDs (e.g., cool white LEDs with red emitters). In addition to the differences in aging characteristics of different emitters, the power supplies operating the different LED colors may also age differently over time and produce a color shift in the luminaire output.[28] This effect can be corrected to some extent in luminaires that have either active color control or a feedback loop to control color point.

Figure 4 illustrates the challenge in predicting color shift over time. The chart, extracted from a publicly available LM-80 test report, shows the chromaticity change of a particular LED package model. The data spans 9000 hours and measurements were made every 1000 hours. Each curve is the average of 3 identically-operated LEDs. The u'v' coordinates were shifted to make trends easier to see. The starting point is indicated with a circular marker. In each case, in the early hours of life, the chromaticity shifted towards the lower left. Color change would then slow near the extreme lower left of each curve. For those LEDs that were driven harder (either higher ambient temperature or higher current), the chromaticity began to shift back towards the (upper) right again. It seems unlikely from these data that a model as simple as that used for lumen maintenance will be able to describe color shift. It is also not likely that all LEDs from all manufacturers will follow the same trend.

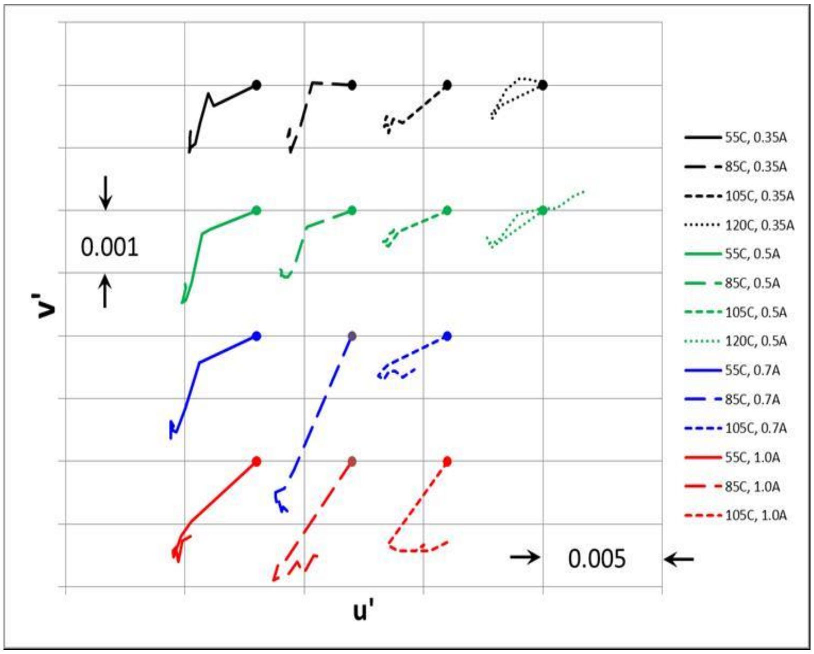

Figure 4. Chromaticity change of a single LED package model. The data spans 9000 hours and measurements were made every 1000 hours. Each curve is the average of three identically operated LEDs. The u'v' coordinates for each individual LED were shifted to make trends easier to see. The u' and v' grid scales indicated on the chart show the magnitude of the changes. The starting point is indicated with a circular marker and shifts then follow the line. The legend shows the temperature and operating current for each group. *Source: Philips Lighting*

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[28] J.L. Davis, et al., "System reliability for LED-based products," 15th International Conference on thermal, mechanical, and multi-physics simulation and experiments in microelectronics and microsystems (EuroSimE 2014). doi: 10.1109/EuroSimE.2014.6813879.

3.4 FIELD DATA

The previous edition of these recommendations contained an example failure-distribution chart that showed the frequency of various field failure modes that had been documented for a family of outdoor SSL luminaires from a manufacturer's installed base. The overall failure rate of this product family was low, representing a >5% cumulative failure rate in the field across 7+ years of production deliveries. The chart showed the relative incidence of failure modes, valuable in trying to understand reliability.

Figure 5 below, an updated version of that chart, cannot be generalized across all types of products. Specifically, in this case, there is a fairly good-sized segment entitled "housing integrity" which generally would not apply to indoor or less-exposed products. Failure of housing integrity can possibly lead to LED package failure or to driver failure, artificially inflating those factors. A different type of product would show different relative failure mode incidences. Regardless of those caveats, field data is a valuable tool for the manufacturer to understand and monitor a given product's performance in actual use. Such data is not generally published but may be available to the buyer from the manufacturer to support claims of reliability and life.

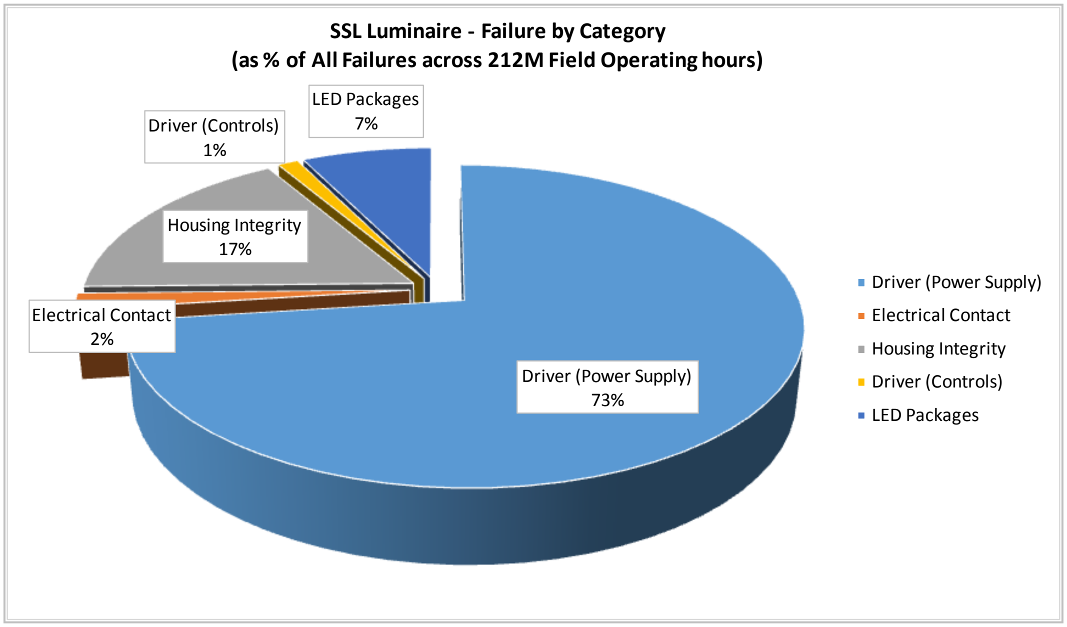

Figure 5. SSL luminaire failure modes, across 212 million field hours. *Source: Appalachian Lighting Systems, Inc.*

The failure categories in this chart are defined as follows:

- **Driver (Power Supply)** includes traditional power supplies and contains all failures related to the power supply or its inability to perform as specified by the luminaire manufacturer.
- **Driver (Control Circuit)** includes control board(s) or other control devices, if they are separate and unique from the power supply. These devices are often used to split and/or electronically condition the output of the power supply, and in some cases may also include wireless, wired or other types of controls that monitor and/or manage the luminaire's operational state.

- **Housing Integrity** includes failures from loss of housing integrity, resulting in moisture ingress, debris accumulation, structural failures, etc.
- **LED Packages** includes traditional end-of-life lumen degradation, chip package failures, significant color shifts, etc.
- **Electrical Contact** includes wiring and connector failures and any general connectivity issues resulting in failure of the luminaire to light and/or to otherwise operate in a manner that is deemed non-functional.

4 WARRANTIES AND SHARED RISK

As indicated in the first edition of these recommendations, the role of warranty is important and should be considered every bit as carefully as the performance criteria. Absent standard accelerated life testing, which is likely to be the case for most products, the user depends on a reputable, qualified manufacturer to provide a useful and effective warranty. Especially for smaller installations, this may be the only protection a buyer has. During the warranty period, the manufacturer takes on the risk of the cost to replace a failed LED-based luminaire. After the warranty period is over, that risk is passed to the consumer. So, the provider and the buyer truly share in the risk of failure.

Since most failure modes directly relate to the numerous design decisions known only by the manufacturer, the manufacturer may be in the best position to estimate the time to catastrophic failure and the time for the light output to degrade to a set level. The time covered by the warranty, therefore, will relate to how conservative or aggressive the design is and issues such as serviceability and replacement cost. Since our first edition, most reputable manufacturers have had the time to gather the information needed to assess expected performance over time and offer an appropriate warranty. Warranties of up to 10 years are now available. Accordingly, when comparing two different LED-based luminaires, the warranty period should be an important part of the selection process.

At the same time, since design choices made by each manufacturer do strongly impact expected luminaire and replacement lamp life, it is incumbent on the buyer to carefully review and understand the warranty. Usually the warranty will provide a replacement unit but will not pay for the labor cost of uninstalling the defective unit and replacing it. On a more basic level, one must understand what the manufacturer considers to be a failure and how the user can determine if the unit has failed other than catastrophically. Lumen depreciation and other gradual failures mostly depend on operating hours, not time from purchase. In the case of a warranty that is stated as a fixed time, one should know how many operating hours per day the manufacturer has assumed and if that assumption is consistent with the contemplated usage. It is possible that a certain number of operating hours, not “10 years,” is a better description of what is warranted. If the unit is serviceable, the service and parts costs and expected frequency of service will also enter into the overall economics of the system.

5 RELIABILITY TESTING AND STANDARDS

Finding accelerated-testing methods that accurately forecast LED lumen depreciation and color shift has proven to be difficult. The previous section reviews efforts along those lines since publication of the last report. As far as the LED light source (package, array, or module) is concerned, we continue to recommend LM-80 data and the IES-approved TM-21 method to project lumen depreciation. In situ temperature measurement tests, available as a part of the LM-79 testing protocol, may be useful to buyers to assure that operating temperature is well-controlled and to compare products, although it does not directly predict lifetime. IES LM-84-14 is the approved method for measuring luminous flux and color maintenance of LED lamps, light engines, and luminaires, but color maintenance should be considered an "add-on" requirement, not necessary for many, if not most, applications.[29]

Accelerated methods do show promise for reducing test times of principal components, and many manufacturers have developed proprietary protocols for internal reliability verification. Temperature has been the most common accelerator, but there are limits, especially when considering that integrated products as failures not relevant for normal operation may be introduced. Individual manufacturers may use other stressors in their protocols, but in each case the acceleration factors must be determined and verified. Some existing standard methods may be available for characterizing driver electronics but may need modification to deal with the longer lifetimes expected for LED luminaires. The LSRC recommends users qualify their suppliers and ask directly for evidence of reliability for the products they purchase, but there is no new recommendation as to accelerated testing.

5.1 ACCELERATED TESTING

To describe system reliability one would need to test the reliability performance of both the components and the total system. If the total system is intended for long lifetimes, which is usually the case for LED products, a common way of tackling this requirement is to expose the device to sufficient overstress to bring the time to failure to an acceptable, practical level and then to "extrapolate" the information obtained under overstress to normal use conditions. Accelerated life testing (ALT) conditions (stressors) may involve a higher level of temperature, pressure, voltage, load, vibration, and so on, than the corresponding levels occurring in normal use conditions. One must use care in choosing the stressors and interpreting the results: meaningful failure distribution should not include root causes of failures beyond the limiting factors of the materials or design of the component or system itself. For example, if accelerated tests are performed at temperatures beyond the limit of the LED components, this should not be considered in the failure rate model.

There are basically two different reliability test approaches:

- **Test-to-pass** demonstration testing, or zero failure acceptance testing, is an approach in which the component or product must undergo a certain number of test cycles without the occurrence of failures. Test-to-pass only provides pass/fail results, which do not provide any information with respect to reliability as a function of time (or cycles). These limitations are addressed by test to failure.

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[29] For more information on LED product and test standards development, see http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/richman_standards_lightfair2014.pdf.

- **Test-to-fail** is an approach in which tests are continued until at least 65% of the population fails. This approach will provide full information on failure modes, but one limitation could be the long duration of the test.

For the principal components in a LED product, it is feasible to design a test-to-fail approach, possibly using meaningful accelerated tests. For LED products as a system, however, a test-to-pass approach may be the most practical method, as it is very difficult to accelerate failures in a fully assembled complex system without introducing new failure modes or other complexities. Some generic rules for these tests are:

- Each principal component in a system exhibits its own failure behavior that needs to be captured by:
    - Experiments by using at least 3 accelerated testing conditions
    - Numerical/analytical models that describe the reliability physics or physics of failure

- Interactions between the components are captured by:
    - Testing the total system
    - Slightly accelerating environmental user conditions in a physically correct manner

In most industries, standard tests are used in order to quantify the reliability performance of the components and systems. Examples are the MIL standards for military and the JEDEC standards for electronics. Those methods would also apply to the electronic components of an LED system.

Accelerated life tests will tend to emphasize failure modes that are activated by the environmental stress values chosen for the test and may engage other failure modes that are unaffected by the test parameters. For example, temperature shock tests will tend to emphasize failure modes associated with mechanical processes of expansion and contraction of materials in the DUT. In contrast, a high temperature bake of the same DUT will emphasize the chemical reactivity and thermal stability of the materials but will not provide any information on compliance to temperature excursions. In this example, both tests can provide meaningful information if the proper interpretation is applied to the data.

Accelerated life tests will typically be performed on the DUTs until all of the devices fail. Because of the desire to achieve failure of the DUTs without creating new failure modes, accelerated life tests can be long and expensive to perform and interpret. In some cases, the accelerated life test may be terminated before all DUTs have failed in order to save time and money. However, sufficient failure rates must occur in the accelerated test to obtain a meaningful failure distribution that can be extrapolated to normal operational conditions. In accelerated testing, it is important to ensure that failure modes are determined for each DUT in order to build correlations to expected operational lifetime.

Screening tests (also known as “robustness” tests, which could be passed without failure) can also performed on devices in order to ensure that they meet some minimal performance threshold that may have an empirical correlation to expected lifetime. Screening tests are often less expensive and simpler to perform than full accelerated life tests because there is no requirement for any failures to occur. A typical screening test would involve exposing the DUT to one or more environmental stresses for a pre-determined period of time and simply counting the number of operational and failed parts at the end of the test. A common example of a screening test in the LED industry is the use of temperature shock tests to study solder joint integrity, and a typical screening test may last for up to 1,000 cycles between high and low temperatures without any failures.

5.1.1 ACCELERATION FACTORS

When accelerated tests are designed properly, the ratio of the expected DUT lifetime under normal conditions and what is observed under accelerated testing provide the acceleration factor for the test. Accurate determination of acceleration factors requires extensive experimentation. However, the investment in time and money to determine proper acceleration factors is often cost effective in the long run since it can reduce test time.

The calculation of acceleration factors will depend upon the type of accelerated test being performed. An overview of common acceleration factor calculations for SSL devices can be found elsewhere[30] and more detailed discussions can be found in several textbooks, such as Wayne B. Nelson's *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis*.[31]

Assuming consistent test method standards have been established for the critical parameters, a valid objective is then to reduce the test burden for an SSL device with integrated electronic components by accelerating the test. For example, the Arrhenius model, which is suitable to characterize many failures that depend on chemical reactions or diffusion, assumes that the time to failure is exponentially dependent on the ratio of the activation energy and the product of Boltzmann's constant and *absolute* temperature, allowing a simple estimate of an acceleration factor. However, materials selected for the LED system may not able to withstand extremely high temperatures, forcing the use of lower temperatures (assuming the component cannot be removed) that would limit the amount of acceleration possible.

There are models for other accelerants such as humidity, voltage, vibration, and so forth. Each has limits depending on the materials in the system. The common relationship for any acceleration model, empirical or not, is related to the system design and materials used. Understanding the chemical and physical properties of the materials used in an LED system can provide the necessary guide to which tests can be performed to best accelerate aging and which models are best to interpret the results. This approach can lead to the determination of acceleration models/factors which do not exceed the limits of the established standard test method for the critical test parameters. Different parts of the luminaire may respond disproportionately to environmental stresses necessitating the need to test some system components separately. For example, LEDs and some other electrical components can be tested at a higher temperature than many plastics. In such instances it may be beneficial to test the system parts individually rather than test the assembled luminaire.

Color shift behavior is quite dependent on drive current and temperature, as noted earlier, and different LEDs behave in different ways. After 9,000 hours of testing, some LEDs are still shifting in different directions from others. In order to create a model for this behavior, data extending over a longer time span is needed.

We have already noted that the complexity of color shift data available suggests that predicting the changes will be difficult. While it may be possible to find suitable accelerants, there are a number of issues that need to be better understood before this work will be able to advance much more:

- Possible variations in the direction of shift over the product life.
- Possible different shift mechanisms depending on operating conditions.

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[30] van Driel and Fan, *Solid-State Lighting Reliability*.

[31] Nelson, Wayne B. *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis*. New York: Wiley-Interscience, 2004.

- The effects of current and temperature are not uniform.
- There is a variation in shift from LED model to LED model

Accelerated tests would be of great assistance to chromaticity studies, but they may need to be quite product specific. The placement and processing of the phosphor can vary widely among suppliers, which alone will likely affect the behavior. In fact, because of the proliferation of designs and materials in LED luminaires, any highly accelerated test is likely to be quite specific to a product or group of products and is best applied to materials and subsystems rather than entire products, so a general standard protocol may be impractical.

5.1.2 TESTING INTEGRATED LUMINAIRES

For integrated luminaires, disassembly of the LEDs and drivers may be difficult. However, often the LEDs and drivers can be tested as a unit while still attached to the housing. While this does place a limit on the types of tests that can be performed, it can also be a convenient approach to investigate both an LED and a driver design. In these cases it may be beneficial to remove any plastic parts (e.g., lenses) especially if temperatures above the limits of the component specification(s) will be used in the testing.

Historically electronic components have been stress tested for qualification in varied applications such as automotive, consumer electronics, and commercial usage. Military standard testing methods have been established for electronic components used in space and military applications. For general lighting in the U.S., the American National Standards Institute (ANSI) and the National Electronic Manufacturers Association (NEMA) have established certain standards for performance metrics of incumbent lighting technology such as metal halide lamps and new compatibility requirements for solid-state lighting.

- **ANSI C78.43-2013,** American National Standard for Electric Lamps: Single-Ended Metal Halide Lamps.[32] Sets forth the physical and electrical requirements for single-ended metal halide lamps operated on 60 Hz ballasts to ensure interchangeability and safety.

- **NEMA SSL 7A-2013,** Phase Cut Dimming for Solid State Lighting—Basic Compatibility.[33] Provides compatibility requirements when a forward phase cut dimmer is combined with one or more dimmable LED light engines (LLEs).

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[32] ANSI C78.43-2013, *American National Standard for Electric Lamps: Single-Ended Metal Halide Lamps*, http://webstore.ansi.org/RecordDetail.aspx?sku=ANSI+ANSLG+C78.43-2013.

[33] NEMA SSL 7A-2013, *Phase Cut Dimming for Solid State Lighting—Basic Compatibility*, http://www.nema.org/Standards/Pages/Phase-Cut-Dimming-for-Solid-State-Lighting-Basic-Compatibility.aspx.

5.1.3 TEST STANDARDS

The SSL industry could, in principle, create new stress test standards for integrated electronics, but it may also be possible to leverage the existing electronic stress test standards for incumbent lighting electronics. There are clear advantages to the latter, but appropriate data are not always available. The type of reporting that would be helpful has been described above, but the reasoning is as follows:

Electronic component manufacturers typically determine lifetime expectancy differently compared to, for example, the SSL industry TM-21 standard reference. Most electronic component manufactures quote MTTF/MTBF statistics for their customers. Alternatively, electronic component manufacturers may quote failure rates in billions of component hours of operation (i.e., FITs).[34] The details of these statistics are very important. Just like TM-21, statistical calculations require a sample size and test time for each different test condition, so electronic component manufacturers should provide the same testing information which established the MTBF or MTTF data. As an extreme example, if an electronic component manufacturer decides to test one million components for one hour and all the units survive, the MTBF is one million hours. This does not *necessarily* mean the same component will survive 50,000 hours in an integrated SSL luminaire. To gain more confidence in the MTBF value, a longer test time of the component should be provided. The TM-21 document is clear: 6,000 hours is a minimum test time for a minimum sample size of 20 units to establish a 6X acceleration factor for lifetime at the specific test condition for drive current and case temperature per LM-80. Establishing a similar test condition standard with respect to ambient temperature (or if possible the operating electronic component temperature would be best) and drive current conditions for the integrated electronic components in SSL luminaires would be helpful.

5.1.3.1 HANDLING LUMINAIRES BUILT FROM DISCRETE ASSEMBLIES

Luminaires built from discrete assemblies that can be broken down into individual components provide the greatest flexibility in testing. Each component can be stressed independently allowing the maximum flexibility in available testing parameters.

Plastic parts are commonly used in lenses, reflectors, and other optical components in SSL devices. Knowledge of the polymer chemistry of these plastic parts is important in designing accelerated tests, especially if temperatures exceed the limits of the component specification(s). Some common polymeric materials such as polyolefins will warp and distort at elevated temperatures, which will impact the performance of the luminaire in testing. A handbook of material properties and recommended use temperatures can be consulted before testing to determine if the plastic parts in the SSL device can withstand the planned temperature excursions. If the plastic parts will be adversely affected by the accelerated life test, it is recommended that they be removed and, if possible, be reinserted prior to light measurements on the SSL device. When parts are added back to the luminaire, it is essential that no foreign materials are introduced to the device. The removed parts should be evaluated using other known methods.

Acquiring failure rate information about electronics products, either through field returns or experimental testing, is invaluable in determining the reliability of SSL devices. In the absence of such information there are a

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[34] There is a reciprocal mathematic relationship between failure rates and MTBF or MTTF. For example, MTBF = 10^9/(FIT) where FIT is the failure rate in billions of component hours.

couple of sources that can be used. First, suppliers of many electronic components can provide reliability information that is often acquired using standard accelerated test methods. This information can provide an indication of the reliability of components and can be used to calculate system reliability. In addition, tables of historical failure rates for electronic components are available from RiAC and similar organizations.[35] While these tables do provide an indication of historical failure rates, often the information is outdated, and in many instances the conditions under which the failure rate data was acquired are unclear. This places a limitation on the accuracy of such information.

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[35] Reliability Information Analysis Center (RiAC), http://www.theriac.org/.

6 RELIABILITY MODELING

As mentioned in the previous section regarding accelerated testing, the proliferation of LED luminaire products precludes the possibility of a universal model to predict reliability of any design. Nevertheless, it is feasible to develop limited models that adequately describe a particular product or group of products, and many manufacturers have done so to aid in their design-for-reliability process and to give them confidence in their warranty claims. This section is meant to be a brief overview of the considerations that go into a reliability model. Specific manufacturers may be willing to provide additional information on the analysis they use to give their buyers some assurance that their representations of reliability are well-supported.

Many textbooks are available that describe reliability, ranging from its history, (accelerated) testing, system reliability, reliability predictions, and reliability standards. Refer to the References section for a brief list. In this section, only the basic principles and those reliability theories that are important for LED products are discussed.

A system is a collection of components, subsystems, and assemblies arranged in a specific design in order to achieve desired functions with acceptable performance and reliability. The types of components, their quantities and qualities, and the manner in which they are arranged within the system have a direct effect on the system's reliability. Often, the relationship between a system and its components is misunderstood or oversimplified.

From a system reliability point of view, the challenge is to master the reliability of its components. Clearly, each system, however complex, can only last as long as its shortest-lived component. Once a product's failure criteria are established, the reliability may be measured and described in different ways depending on the particular situation. Examples are:

- Mean time to failure (MTTF)
- Number of failures per time unit (failure rate or field call rate)
- The probability that the item does not fail in a time interval [0, t] (survival probability)
- The probability that the item is able to function at time t (availability at time t)

If the item is not repaired after failure, the third and fourth bullets above coincide. (For precise mathematical definitions, refer to the textbooks in the References section.)

Given the application requirements, one can calculate the reliability performance of the system. It is necessary to investigate the physics of failure in order to understand the failure modes or mechanisms, and obtain test information on the specific components for the design. Verification testing is also needed on a product level to ensure the model is correct, further reinforcing that it is generally only feasible to model a specific product or groups of products of similar design.

In system reliability analysis one will always be working with system models. In practical situations the analyst will have to derive these models, or at least choose from several possible models before an analysis can be performed. To be realistic the models should describe the essential features of the system, but do not necessarily have to be exact in all details. One approach is working with an idealized, simplified model of the system. Traditional handbook-based reliability prediction methods for electronic products include MIL-HDBK-

217,[36] Telcordia SR-332[37] (formerly Bellcore), PRISM, FIDES, CNET/RDF (European), and the Chinese GJB-299. These methods rely on analysis of failure data collected from the field and assume that the components of a system have inherent constant failure rates that are derived from the collected data.

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[36] U.S. Department of Defense. (1965) *MIL-HDBK 217: Military Handbook for Reliability Prediction of Electronic Equipment*, Version A. 918.

[37] Telcordia Technologies. (2001) *Special Report SR-332: Reliability Prediction Procedure for Electronic Equipment*, Telcordia Customer Service, Piscataway, NJ.

7 ADDITIONAL REFERENCES

The following informative publications provide information or guidance on reliability studies.

Dodson, Bryan, and Dennis Nolan. *Reliability Engineering Handbook*. QA Publishing, 1999. ISBN: 0-8247-0364-2.

IEC International Standard 60300-3-1:2003, *Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology*, ed. 2.0, http://webstore.iec.ch/Webstore/webstore.nsf/ArtNum_PK/47606!openDocument.

Jensen, Finn V. *An Introduction to Bayesian Networks*, *Volume 1*. Springer, 1996. ISBN: 0-387-91502-8.

Nelson, Wayne B. *Accelerated Testing: Statistical Models, Test Plans, and Data Analyses*. John Wiley & Sons, 1990. ISBN: 0-471-52277-5.

Pecht, Michael. *Product Reliability, Maintainability, and Supportability Handbook, Second Edition*. Taylor & Francis, 2009. ISBN: 978-0-8493-9879-7.

Rausand, Marvin, and and Arnljot Høyland. *System Reliability Theory: Models, Statistical Methods, and Applications*. Wiley, 2004. ISBN: 0-471-47133-X.

Tobias, Paul A, and David C. Trindade. *Applied Reliability*. Chapman & Hall, 1994. ISBN: 0-442-00469-9.