LED LUMINAIRE LIFETIME: Recommendations for Testing and Reporting

Solid-State Lighting
Product Quality Initiative

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CONTENTS

INTRODUCTION

UNDERSTANDING SSL LUMINAIRE LIFETIME

Surprisingly to many, the true reliability and lifetime of light-emitting diode (LED) lighting systems is generally not known. Even worse, lumen maintenance values of LED devices are widely used as a proxy for the lifetime of an LED lighting system, which is misleading since light degradation or lumen maintenance is but one component of the reliability of a luminaire. In fact, it is quite often that the lifetime of a well-designed and manufactured luminaire is *not* determined by the LED lumen depreciation. For many manufacturers estimating the luminiare lifetime using LED lumen maintenance results can be ascribed to dependence on readily available numbers without developing actual luminaire data. In many cases, neither product providers nor customers are aware of the differences, perhaps in part because the problem has not been sufficiently explored and communicated.

It isn't just about the LED. Good LEDs can be incorporated into poorly engineered products and turn the Methuselah of lighting into the exponent of "live fast, die young." The promise of LED lifetime is often presented in terms of hours and years but with little backgrou nd data. Warranties, as well, may be misstated because of this lack of data, at the manufacturer's peril. The statement of 100,000 hours of LED luminaire lifetime is gradually giving way to the realization that there is little consistency, very little published data, and few hard facts around so-called luminaire lifetime numbers. The situation is better at the LED package level, where reputable manufacturers have thousands of hours of data under varying conditions. But this is not enough.

To manufacturers and specifiers in the solid-state lighting (SSL) community, the dawning realization is that we need to work together towards understanding the issues surrounding true lifetime and reliability. We need to begin by cataloguing failures and developing good models for underlying failure mechanisms. This process of understanding and explanation is very common in technological progress. Steam engines existed long before deep understanding of thermodynamic processes. With LEDs, we have a substantial head-start on the underlying physics and many years of experience in both lighting and semi-conductors as well as reliability of related products.

There is no reason not to begin this journey and every reason to start. We will figure this out, find reliability methods and metrics, and learn the underlying root causes of failure. But without data, experiments and models, it is all conjecture. We need a program to drive to reliability metrics.

WHAT THIS GUIDE IS AND IS NOT

This is the second edition of the guide and, like the first one, is a set of recommendations for reporting and demonstrating luminaire product lifetime. Initially, we sought to provide guidance for the Lighting Facts® program, which gives users, retailers, and manufacturers a common short-form reporting mechanism to improve the quality of solid-state lighting products on the market. The Lighting Facts label provides a summary of key performance criteria but does not include lifetime, for which there have been numerous requests. Ideally, it would be the addition of a single number, e.g., "eight years." We attempted, on the first round, to suggest some descriptions which would better describe lifetime, and it is fair to say that there are fewer of the wildest claims . But there is still not an accepted protocol for measuring and characterizing lifetime. In part, this is due to cost, as a fair number of product samples need to be tested to get good numbers, but it is also due in some measure to the early emphasis by the industry on lumen depreciation; LED productss have been described until recently as "different" from conventional technologies: LEDs will just get dimmer until they just fade away, it has been said. But as we learn more about the behavior of these LED "systems" it is becoming more evident that the life of a fixture may be considerably shorter than what is indicated by nominal light depreciation, albeit still generally longer than many incumbent lighting solutions.

This updated version of the guide addresses a number of these issues and attempts to clarify the general understanding of reliability and how it pertains to lifetime; explore methods of estimating and characterizing lifetiime; distinguish between types of failure and failure modes; look at differences between repairable and non-repairable systems; and to revisit the definition of product life. It reamains important to keep the SSL community focused on this issue. Cooperatively, it should be possible to develop sufficient data and best practices so that lifetime may be more accurately, and more simply described.

These recommendations have been developed by a working group under the U.S. Department of Energy Solid State Lighting program. This group is under the guidance of the SSL Quality Advocates, a joint body of DOE and the Next Generation Lighting Industry Alliance (NGLIA). The reliability and lifetime working group is composed of members of the NGLIA as well as other experts in reliability, lighting, and LED technology. As such, this guide is not an accepted

There are numerous recommendations and observations throughout this document. The main emphasis is on the definition of lifetime, but the following is a shorthand list of where certain others are to be found:

- Lumen depreciation is not a proxy for lifetime (Introduction)
- Only light output is considered in defining lifetime (p.5)
- Use overstress testing to identify design flaws and manufacturing defects (p10)
- Indicate if a product is serviceable or not (p13)
- LM-80 data can predict lumen depreciation but not lifetime (p14)
- Develop standard ways to characterize drivers for SSL use (p16)
- End of life as defined in this document excludes color shift (p17)
- To deal with color shift, designate products in one of 3 categories (p20)
- Develop standard qualitative descriptions of the degree of color shift (p21)
- Standard Luminaire Lifetime defined (p22)
- Reported lifetime should have at least a 50% confidence level (p23)
- Use LM-79 for full luminaire characterization (p24)
- Develop and document a change control process (p25)
- Develop a capability for statistical system design for reliability (p26)
- Add standard LED Luminiare Lifetime to the Lighting Facts label (p26)

international standard. Rather, it is meant to provide standards bodies with recommendations for their work in supporting the needs of the SSL community. These standards organizations will ultimately determine the details of the methods to measure and report the reliability of SSL luminaire products.

This document covers only luminaire lifetime—i.e., changes over time —and does not address initial performance criteria or product consistency. Initial performance criteria for LED luminaires have been separately discussed in the December 2008 publication *Reporting LED Luminaire Product Performance,* found on the DOE SSL Web site at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_productperformanceguide.pdf.

FAILURE, RELIABILITY, AND LIFETIME

Reliability and Lifetime are not synonyms. Rather, these are two separate and equally useful values reported by the component or subsystem manufacturer (see Recommended Additional Reading at the end of this document for sources of detailed information on this subject). Usually a luminaire or lamp design will encompass a number of interdependent components and subsystems, each with different lifetime and reliability values. It is not normally appropriate to use the worst- or best-case of these values, rather the system needs to be evaluated as a whole; this is because there can be inter-device effects (such as thermal impacts) that need to be taken into account.

Lifetime is an estimate of how long any single product can expect to be operating as intended, given a specific set of environmental and mechanical requirements. Intuitively, we understand "lifetime" or "end of life" of a luminaire to be when it no longer emits light. For conventional lighting technologies, the "rated life" of a lamp, for example, is usually considered to be the time when half the lamps have failed (B_{50}). However, we've learned that LEDs fade over time, and so we've modified our definition to mean "when there's no longer enough light", which has sometimes been defined as "useful life". But sometimes *only* lumen depreciation is considered, and then, often, only the lumen depreciation *of the LEDs* is considered in estimating useful life of the luminiare product. Either is a problem, since failure or degradation of drivers, optics degradation, or other components can lead to either total failure, in the traditional sense, or accelerated lumen depreciation of the LEDs. Lifetime does not consider repair or replacement, either of premature failures or in the course of normal maintenance of a servicable system, although the ability to service can be an important attribute of a product.

It is also important to appreciate that insufficient or no light output is not the only reason why a product may no longer be acceptable. Examples include excessive color shift or changes in light distribution due to failure of some but not all of the LEDs. Whether or not to include failures other than in terms of light output in defining lifetime can be a difficult question. In the first edition of this guide, the recommendation was to **consider only light output in defining lifetime**, but to consider all sources of dimunition or failure of light output when arriving at the number. That remains our position but we will address the color shift issue, in particular, in more detail in this document.

Failure of any part may lead to failure of the whole. Some performance degradation of a driver, even short of complete failure, could, for example, result in failure of the LEDs. Because the LEDs themselves are expected to have a long useful life, all of these other components, adhesives, and other materials should also be long-lived, at least to the extent they do not result in an *inappropriately* shortened life. But that last phrase is key: While it may be possible to design the other components to have equally long life, that may not be the most cost-effective solution for the application. The underlying objective of designing for long life is identifying the appropriate balance between statistical certainty and cost. If cost were unconstrained, an extremely long-life, highly reliable system could be created although, even in this case, random failures would be expected. In reality, the luminaire should be designed so that there is an acceptable level of failure over the anticipated lifetime of the system for a reasonable cost. Above all, it is important that the claims match the performance and that customer expectations are met.

Reliability, as defined by IEEE and others is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. It is often reported as Mean Time Between Failures (MTBF) as distinguished from Mean Time To Failure (MTTF). (When the failure times are normally distributed, the mean and median (B_{50}) times to failure are the same, but for other distributions they may be different.) This is an especially useful measure when the system is repairable, as it will determine the maintenance interval. The average time of random failure is calculated by dividing MTBF by a population size. For example, if there are 1,000 devices with a MTBF of 100,000 hours, it is expected that there will be a random failure every 100 hours.

For electronics, the performance of a system composed of a number of components is typically characterized by an initial high failure rate (infant mortality period), followed by a long period with a low rate of random failures, concluding with a high failure rate at the wear-out period or end of life.

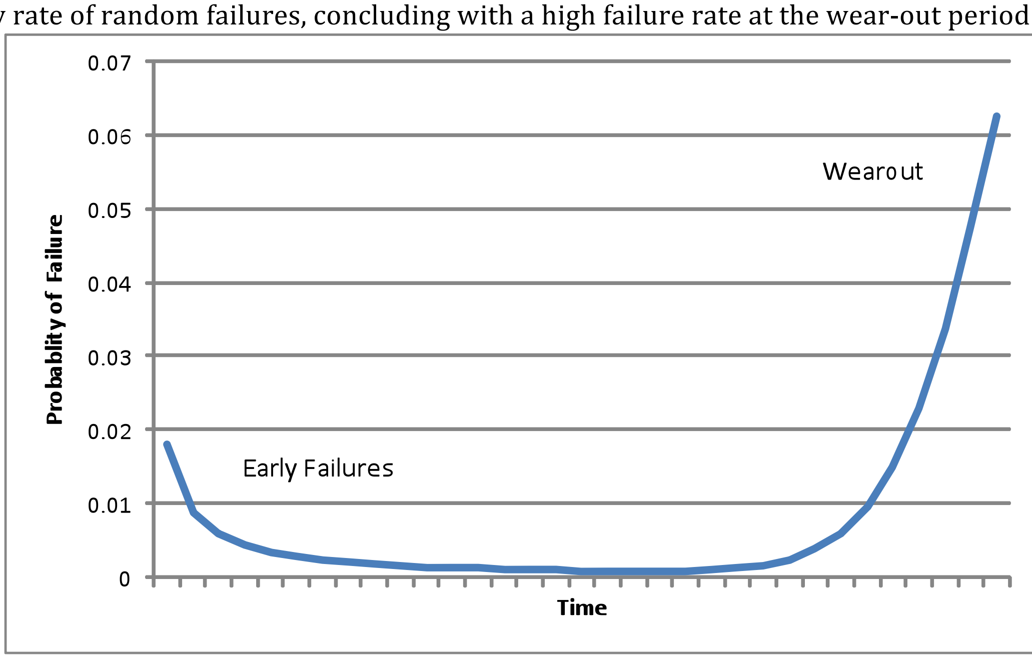

Figure 1 shows what is commonly known as a "bathtub" curve depicting that behavior.

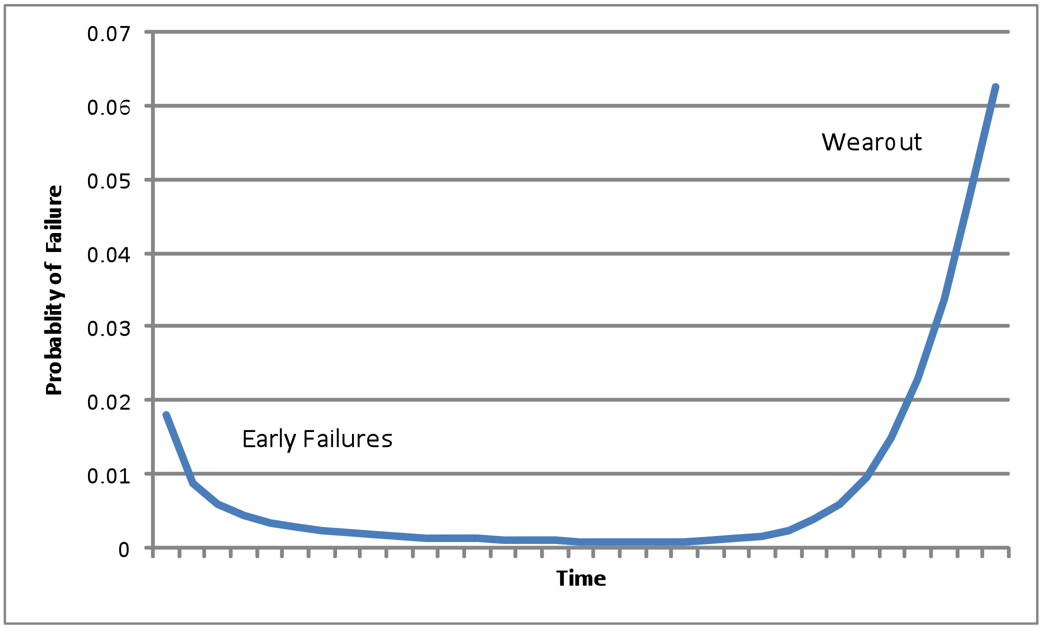

FIGURE 1 THE "BATHTUB" CURVE ILLUSTRATING TYPICAL FAILURE BEHAVIOR OVER TIME OF AN ELECTRONIC SYSTEM

A similar behavior might be expected for a luminaire system, but because the LED technology is still rather new, we should also be conscious of another contributor to failure: design flaws. This is not really a part of estimating product lifetime, but is a fact of current state of the art that needs to be addressed. So, we have divided reliability issues for discussion in this document into three main categories (the period between initial failures and end of life is essentially determined by tails of those distributions):

1. *Design flaws.* As the first LED lighting products appeared on the market, many design flaws were evident. The most common, initially, was poor design (or no design) of heat removal from the chips. This problem often resulted in overheated chips for which the lumious output depreciated quickly leading to quite short lived products. It was further exacerbated by claims that were essentially based on the LED lumen depreciation data. Design flaws, while less common and more subtle than they were only a short time ago, perhaps, still exist: poor thermal management; using incompatible chemicals which degrade the optics or the chips; poorly matching the driver to the LED requirements; overdriving the chips; poor seals allowing moisture penetration, and so forth. Problems of this sort should largely diminish as designers become more familiar with the technology so that claims more closely match performance. Choices of drive current and operating temperature, especially, will affect the *design life* of a product an important concept. That is appropriate engineering for cost control, and we distinguish it from slipshod design which leads to an unpredictable design life. A product with a predictable design life, advertised accurately, and appropriately priced will satisfy a customer need far better than one with excessive and almost surely unmet claims of "lasting forever".

2. *Manufacturing defects.* These will always be with us. Even with a well-designed product, excursions from process control occur from time to time resulting in faulty product. Usually, these result in early failures. They may be partially covered by warranties, but that

may still not be very satisfactory if the incidence of failure of this type is too high. At present this does not seem to be an overly serious issue, at least with the major manufacturers, but it is important as the volumes rise and as less experienced manufacturers enter the market, that close attention be paid to quality controls. Factory testing and "burn-in" can also help. These can lead to additional costs, but can also minimize the customer seeing the early failures.

3. *End of life.* A well-designed system, operated under normal conditions within specifications will, nonetheless, eventually fail. There may be two or three critical modes of failure that eventually make the system unuseable. With well made components, the time of this failure should be fairly predictable, at least to within some range, and this is what lighting users have come to expect is the "lifetime" of the luminiare. Understanding how to evaluate a system and predict end of life accurately is very important for market acceptance of solid state lighting. It is the focus of the discussions in this guide.

There is no standardized method of determining lifetime, but for many electronic systems it can be and is typically estimated using the predicted lifetime of individual components at the anticipated operating conditions, which can then be statistically combined. We do not have sufficient information today on all of the components and interactions for a luminaire to be able to make these predictions. However, that should ultimately be our goal because for now, absent that data, the only remaining option to estimate system MTTF or B_{50} is to do a full LM-79 luminiare test on a population of product. This poses a conundrum. For many manufacturers a full LM-79 test may be too expensive and time-consuming. We recommend the full LM-79 test to establish lifetime taking into account all failure mechanisms but to address this difficulty also suggest a number of alternative approaches to provide some indications of reliable design if not of true lifetime. (See "Labeling Recommendations" on page 27.)

The remainder of this chapter describes additional aspects of some of the above contributors to product reliability.

RELIABLE DESIGN AND MANUFACTURE

Failures within an SSL luminaire often stem from one or more of four functional aspects of luminaire design and manufacture: Power Management, Thermal Management, Optical Management, and Luminaire Assembly Integrity. Figure 2 provides an overview of a contemporary SSL luminaire, and the relationships between the various components and materials and design elements.

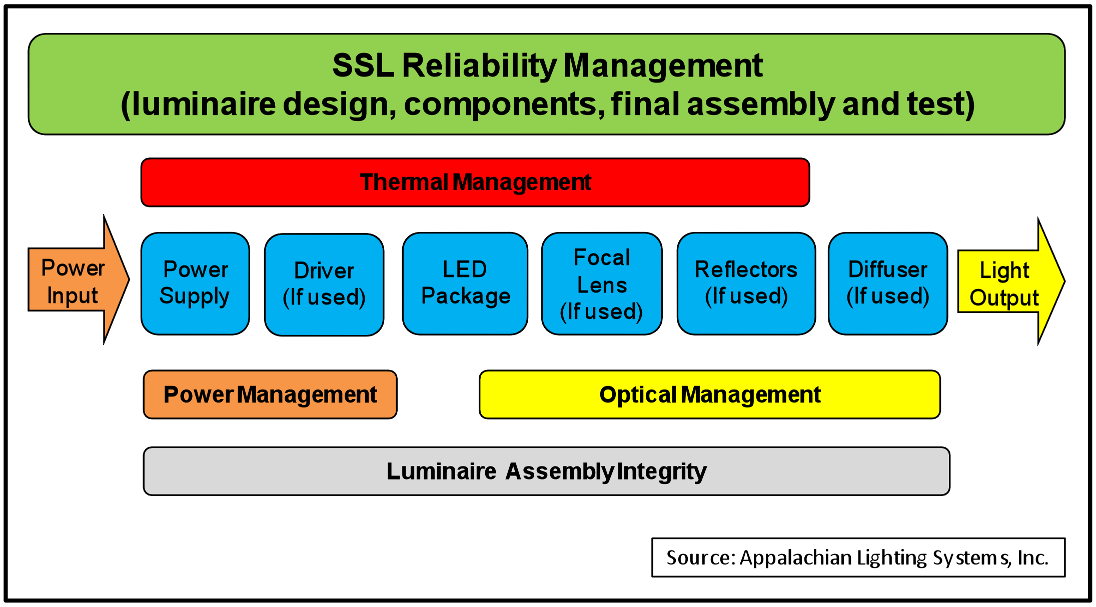

FIGURE 2 SSL LUMINAIRE COMPONENTS AND RELIABILITY CONSIDERATIONS

Design goals and reliability impacts for each of these four functional aspects are described below.

- **Power Management** – ensuring the power delivered to the LED package(s) is appropriately sized and filtered.
  - *Design Goals:* For proper operation, the power supply and related electronics must provide a well-controlled and protected (from electrical transients) drive current and possibly other control and monitoring features, and must be designed to properly function for the anticipated life of the product.
  - *Reliability Impact:* Component failures due to improperly designed and executed power management may often result in a catastrophic failure of the luminaire, but they can also cause less obvious effects such as reduced light output or flicker, for example. Proper power management includes protection against failure caused by electrical transients. This protection might be built into the driver, or might be a separate subsystem of the luminaire.
- **Thermal Management** – ensuring that heat generated by the LED package(s) and the power system components is removed to minimize LED temperatures so as to maximize LED performance and lifetime.
  - *Design Goals:* A reliable heat-conducting design, be it passive or active, is required to remove heat from the LED package and luminaire, and phosphor, if applicable. The design should assure that the LED package operates below a manufacturer-reported LM-80 measurement temperature to achieve the desired lumen maintenance of the fixture (an ENERGY STAR requirement). Also, the design must assure that temperatures for other devices (Power Supply, Control Circuitry, optical components, etc.) do not exceed manufacturer's specified limits.
  - *Reliability Impact:* Improperly designed and executed thermal management will usually result in an accelerated lumen depreciation and potentially degraded color quality or color shift of the LED package(s).
- **Optical Management** – ensuring that light output from the LED package(s) is correctly and efficiently shaped and directed toward the desired surface.

- *Design Goals:* Component choices and manufacturing methods should be chosen so that the optical materials retain their integrity throughout the *life of the produc*t; it is desirable that such components not be life-determining.
- *Reliability Impact:* Optical component failures may degrade lumen output of the luminaire's LED package(s), or, because of discoloring may also result in a color shift, but rarely result in catastrophic failure.

- **Assembly Integrity** –ensuring that the overall housing design and assembly process(es) provide for sufficient long-term protection from dust, moisture, vibration and other adverse environment effects.
  - *Design Goals:* Luminaire housing design and materials must be designed to offer sufficient protection for the LEDs depending on the anticipated environment. Repairable designs should allow simple field-replacement of any failed components without degrading the integrity of the housing or other components.
  - *Reliability Impact:* For outdoor or harsh environment applications, housing failure can lead to catastrophic failure of critical light-producing components. In other cases, mechanical failure may result from insufficient protection for internal components. Any assembly process bears the risk of occasional random manufacturing defect failures that will occur throughout the life of the procuct, but should not seriously affect end of life wearout.

SSL luminaire failure modes are often related; e.g., improper thermal management can lead to premature LED lumen depreciation and/or optical degradation and/or power component failure. The overall luminaire quality—and therefore the probability of satisfactory long term luminaire performance—is directly related to careful, thoughtful, integrated luminaire design, component selection, final assembly, testing and packaging. Further, well-documented installation instructions—and actual installation coordination for complex or large-scale projects—can also have a major impact on initial and long-term luminaire performance.

Even if the SSL luminaire is well-designed to address all of the various failure modes, attention to proper manufacturing steps and quality process controls must be clearly documented and carefully executed. Any of the failure mechanisms inherent in electronic assemblies and other luminaire components, may apply to an SSL luminaire. Figure 3 provides an example of the frequency of these various field failure modes that have been documented for a family of outdoor SSL luminaires from a manufacturer's installed base. For this example of a well-designed set of products, the overall failure rate is very low, and, interestingly, it depends only to a small extent on the LED packages. (Note, however, that this product line example has not yet reached the end of life wearout stage, so it cannot be said that LED failure will not eventually have a larger role.)

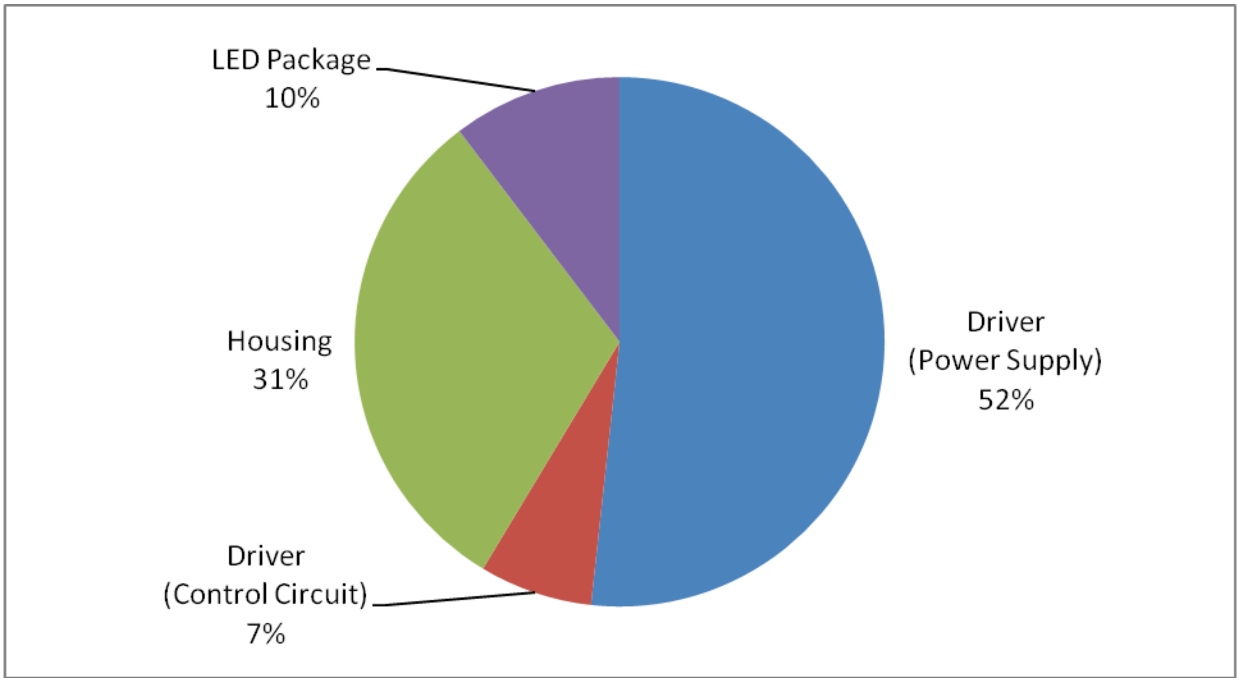

FIGURE 3. DISTRIBUTION OF FAILURES IN 34M OPERATING HOURS FOR A FAMILY OF OUTDOOR LUMINAIRES. TOTAL NUMBER OF FAILURES WAS 29, OR 0.56% OF INSTALLED BASE OF APPROXIMATELY 5,400 FIXTURES.

Over-stress testing is recommended as a useful approach for identifying design flaws or manufacturing defects. Such tests can help to uncover root causes of the premature demise of a product. Selection of such tests is beyond the scope of this guide, but it may be worthy of further study by the industry and a sharing of best practices to promote the overall market. This information would be especially helpful for smaller manufacturers lacking the means to do extensive reliability qualification.

Based on experience in the CALiPER program, this guide recommends a minimum 1,000-hour burn-in (continuous use) test of a small number of products to verify that there are no serious, immediately apparent design flaws in a new platform. While this recommendation may be seen as a bit vague and in no way guarantees a good design, any failures that occur in this short period of time are a cause of concern that may warrant another look at the design before product release.

END OF LIFE

Defining and estimating end of life for LED luminaires is complicated by the phenomenon of long-term lumen depreciation. For conventional technologies, the "rated average lamp life" is the point at which half the lamps cease to emit light. All sources lose light output (depreciate) during the rated lamp life as defined by complete, "lights-out" failure of 50% of the population. A well-designed LED package or array, however, would typically not entirely fail for a very long time. Consequently, the rated life of an LED-based lamp or integrated luminiare can, in principal, be much longer than incumbent technologies. Whether or not this is true will depend on the behavior of other components of the luminiare. It could be that another subsytem, e.g the driver, has a shorter life than the LED source and therefore controls the system lifetime. Figure 4 shows a simple example with two principal failure mechanisms having comparable average times to failure to illustrate how this works: Suppose the MTTF of an LED driver is normally distributed with a mean of 55K hours and a 10% standard deviation(SD) is coupled with an LED source (may be multiple LEDs) having a MTTF of 60K hours and a SD of 20%. "Failure" of the LEDs could be predominantly lumen depreciation of more than 30%, say, but there could also be other catastrophic failures of the source that contribute to this estimated MTTF. The resulting MTTF (50% cumulative probablity of failure due to either mechanism) of the lamp would then be about 52K hours, dominated by the driver, but somewhat affected by the LED lumen depreciation.

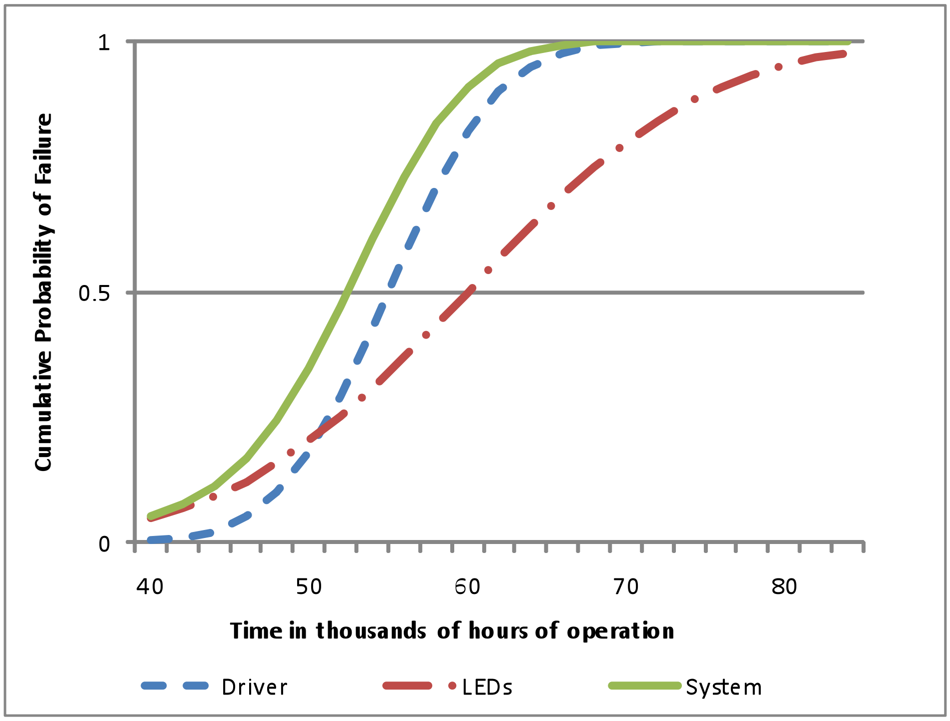

FIGURE 4 ESTIMATED LIFETIME OF A SIMPLE EXAMPLE LED SYSTEM WITH TWO MODES OF FAILURE

The average light output of a population of such lamps would be a gradual dimunition to perhaps 80% of the original light output due to LEDs followed by a rapidly decreasing average light as the drivers begin to fail, extinguishing some lamps altogether. Because of the broader distribution for lumen depreciation, failures before 40K hours (which are few in number) will be mostly due to low light output, but by 60K hours when only half the LED sources have depreciated below 70% of initial light (assuming that is the dominant mechanism), over 90% of the lamps (system) have failed due to the driver. This would be considered a well-designed system, well-behaved in terms of failures. This behavior is not significantly different from the situation with most conventional technologies, although the times are generally longer.

In a realistic system, multiple additional failure mechanisms may need to be considered, the actual numbers may be very different than those in this example, and the distributions may be other than normal. Yet another wrinkle in trying to describe lifetime is that some LED products are being designed to maintain lumen output over time by gradually increasing the driver current to compensate for lumen depreciation. Eventual failure in that case would most likely be characterized by rapid lumen depreciation to below 70% once the driver is no longer capable increasing the drive current.

Because the light source may have appreciable lumen depreciation over it's lifethe effect of lumen depreciation may be more significant in a system where the driver can be replaced. LED lumen depreciation will continue, even as the driver is changed out so in this case it is quite possible that mechanism will dictate when the entire system will need replacement (again, an L_{70} failure). This brings up the issue of serviceability of a fixture, discussed next.

SERVICEABILITY AND LIFETIME

LED-based luminaires can, in principle, be grouped into two classes: Those that are non-serviceable and those that can be serviced or repaired in the field. Lifetime, per se, is independent of serviceability, but the economics and untimate replacement time for the entire fixture will be different for the two classes. This topic has not received a great deal of discussion in the industry, so there is no commonly accepted definition of "servicability", which is itself application-dependent. Nonetheless, the concept is useful, and so for purposes of this document, the working definition of the term derives from what we perceive to be customer expectations: Simply put, a product is field-servicable if the job can be performed by whatever level of personnel currently services the incumbent-technology lighiting fixtures in the field for a given application.

LIFETIME FOR *NON*-SERVICEABLE LED-BASED LUMINAIRES:

An LED-based luminaire manufactured in a manner that it cannot be repaired in the field will "fail" upon failure of any part, and will require complete replacement. In general, this is contrary to current expectations about lighting, and should be addressed on several levels.

- The idea that a customer may be buying one that is “non-serviceable” may not have occurred to them.
- Replacement costs could be well above expectations, leading to a negative reaction to LED technology.
- The LED industry has touted long lifetimes based on slow lumen depreciation, but a different component failure can result in shorter average lifetime.
- High replacement costs could result in delayed replacement which may be unsafe in some circumstances.

A luminaire that has replaceable parts but requires either very specialized skills for field servicing or must be returned to the manufacturer for service should be considered "non-serviceable" for purposes of this discussion.

LIFETIME FOR SERVICEABLE LED-BASED LUMINAIRES:

When the product is designed in a way which allows field repair, a number of new questions arise with regard to lifetime. The purchaser is strongly urged to ask them:

- Which parts are replaceable? (Driver, LED engine, optics, wiring cables)

- What are the expected lifetimes for the various replaceable parts and what is the replacement cost?
- How complex is the replacement? For example, is it necessary to disconnect the luminaire from the building structure or to disconnect power? Does it require a qualified electrician?
- Will the manufacturer have the replacement part when it is needed?
- Issues with respect to determining when the LED light loss has reached the point that repair is needed still apply to servicable fixtures.
- Under what conditions (and when) will the entire fixture require replacement?

Another facet of serviceability is the concept of backward compatibility. Having the option of replacing a light source, for example, with a technologically upgraded version is quite attractive for the rapidly evolving LED luminaire market.

Regardless of whether or not the product design intent is to be field-servicable, it seems clear from the above lists of issues that an important first step would be for vendors to clearly **indicate if the LED-based luminaire is intended to be "field-serviceable" or "non-serviceable"**. Currently, a number of LED module products or light engines are appearing on the market and work is proceding to standardize the interfaces within a luminaire, but these are all works in progress, and there are no standards for replaceable parts today. This limits the usefulness of field serviceability for reasons clear from the above list of issues. This situation is likely to change over time, as standard drivers, light engines, interface standards and other components evolve, leading to multiple sources of supply.

Further discussion of this topic is encouraged to better define norms for various applications and ways to address the many questions that arise when this topic is considered. Accordingly, the committee at this time does not have a specific recommendation as to whether or not to include this in the LightingFacts information, but it will remain under consideration.

KEY ISSUES FOR RELIABILITY AND LIFETIME

While there may be many failure mechanisms in a complex LED luminaire system, a few key issues are worth futher discussion: The character and measurement of lumen depreciation, the behavior and specification of electronic drivers, and considerations regarding color changes as they apply to useful life of a fixture. These are each separately considered below.

LED LUMEN DEPRECIATION

For an individual *LED package*, lifetime has typically been considered to be the hours of operation at which the light output has fallen to 70 percent of its original value ("L_{70}"). LED useful life is usually then reported as the median time to failure of a population of diodes under normal operating conditions, called "B_{50}." In other words, after this period of time, half of the units will fail due to low light output. While B_{50} represents a *time interval*, L_{70} is the lumen *performance level* defining a low-light failure. For some applications the median time, B_{50}, may be unacceptable. Designers in these cases might prefer to know when 10 percent of the product has fallen below the defined level. Depending on the target market, therefore, manufacturers may choose to report B_{50}, B_{10}, or some other time for a particular. L_{70} is widely accepted in LED lighting but for non-demanding cases L_{50} may be acceptable, while in other cases a 30% depreciation would be considered too much.

In order to design and specify LED fixture performance effectively, LED fixture manufacturers need performance data from the LED and driver manufacturers. One important data set LED manufacturers will provide is data collected per *IESNA LM-80-08 Approved Method: Measuring Lumen Maintenance of LED Light Sources*. LM-80 prescribes uniform test methods under controlled conditions for measuring LED lumen maintenance and color shift while controlling the LED's case temperature (T_S) using continuous mode operation for a specified minimum duration. LED fixture manufacturers can then use the LM-80 data to correlate to the LED T_S measured *in situ* during their LED fixture thermal testing to predict LED lumen maintenance when installed in the fixture and to assess the degree of potential color shift for their specific LED operating parameters. Note that these results only provide estimates of lumen depreciation for the LEDs under specified conditions; they are alone *not sufficient* to estimate the fixture lifetime for the reasons outlined above. Apart from entirely independent failure mechanisms other than lumen depreciation, LM-80 data do not take into account any interactions between LEDs in the fixture and other materials or components. For example, if the optics should yellow or otherwise degrade over time from environmental effects, say, the apparent lumen depreciation of the luminaire would be faster than that of the LEDs alone. If the driver current increases over time, by design or otherwise, the LEDs may eventually be driven harder than the specificed LM-80 test current which will change the numbers.

LED DRIVERS AND CONTROLS

The devices and components used to convert line power to direct current suitable to drive and control LEDs affect lifetime and reliability just as do other parts of the lighting system. Capacitors, inductors, transformers, opto-isolators, and other electrical components all have different design lifetimes, are affected by operating and ambient temperature, and are vulnerable to electrical operating parameter variations from surges, spikes, and so forth. An effective LED system reliability evaluation must take all of these aspects into consideration.

TYPES OF POWER CONVERSION

In most lighting systems today there is a need to convert AC power into DC, incorporate control instructions, and regulate the output power. Based on the grouping of these function, the devices can be separated into a few broad categories[1]: LED Drivers, Systems of Power Supplies and LED control circuitry, and AC LEDs .

LED Drivers convert a range of High-Voltage AC inputs, and produces either Constant-Voltage or Constant-Current for an LED or an array of LEDs in a single device. LED Drivers are relatively straightforward to evaluate because the performance, reliability, and conditions-of-use are consolidated. However, options may be limited, rated power may be constrained, and the physical size of the device may affect LED luminaire design.

[1] Refer to IES RP16-10, http://www.ies.org/store/product/nomenclature-and-definitions-for-illuminating-engineeringbr-rp1605-1013.cfm, or UL8750, http://www.ul.com/global/eng/pages/offerings/industries/lighting/lightingindustryservices/standards/ul8750/, for definitions.

A System of AC-DC Power Supplies and LED Controllers offers more flexibility but requires a more complicated analysis. In this case, a common AC-DC Power Supply provides the power conversion role while the LED control circuitry typically incorporates control instructions and regulates the output power. The AC-DC power supplies are available in a wide variety of sizes, power levels, and reliability/lifetime ratings. The LED control circuitry is available in many configurations and can either be incorporated onto the LED array or exist as an independent device[2].

The term "AC LED" typically refers to a package-level device into which integrates power conversion into the package, thus requiring few additional components. The specific design varies by manufacturer.

LED DRIVER

The LED driver consists of a power source and LED control circuitry designed to operate a LED package (component), or a LED array (module) or a LED lamp. The specific choice of design topology affects the number and type of components, as well as the degree to which they are stressed. Many reliability issues come down to component stresses as determined by the method of converter operation – hard switched mode, quasi-resonant or fully resonant, etc.

In general, the product lifetime decreases as temperature increases. The product temperature is a function of power dissipation, thermal resistance and ambient temperature. The power dissipation is directly related to the efficiency of the driver. Higher efficiency and low product thermal resistance can cut down the product temperature rise and improve the lifetime significantly.

To protect the application from various hazards such as over-current, surges, shorts, high temperatures and others, protection circuits are needed. These additional components add more potential sources of failure. Many components affect driver safety and those must be selected to comply with several standards[3], as discussed in the next section.The electrolytic capacitor is probably the shortest-lived component for most LED drivers. The typical life of electrolytic capacitor is cut to half for every 10°C temperature rise. Depending on the application and working environment, a long-life and high-quality electrolytic capacitor should be selected to meet the reliability, cost and performance requirements. Other components also need proper de-rating with respect to both biasing and temperature to ensure reliable performance of the driver.

To assist in luminaire design, the driver product qualification should demonstrate the product's robustness to temperature, humidity, temperature cycle, shock and vibration stress. A test report should include changes in efficiency and output current over time along with details on test conditions, sample size, and confidence interval.

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[2] In the electronics industry, a microchip that performs the actual power regulation is also called a driver, which may lead to confusion. Definitions here refer to IES RP16-10.

[3] For example, EMI/EMC (FCC Part 15; EN61547 Immunity), Safety (UL8750; IEC61347-1, IEC61347-2-13), RoHS/WEEE, ESD and Surge (IEC61000-4-2; IEC61000-4-5), RF (IEC61000-4-6), Other IEC and UL standards provide for dielectric voltage withstand test "Hi-pot", and degrees of protection provided by enclosures (IEC 60259) as required by the application.

Component and assembly-related defects are hard to avoid on volume production but their impact may be reduced by using a burn-in process to identify and eliminate the early failures. The details and stresses (high temperature, temperature or power cycling, or vibration, e.g.) depend on the design and degradation mechanisms. On-going reliability testing should be done at the pre-determined intervals to detect the process and design margin drift and to uncover the problems with components or workmanship.

With the right topology, thermal design, component selection and derating along with product burn-in, the LED driver can avoid becoming the "weakest link" of the lighting system, although for cost-effectiveness it may either be intentionally designed to define an appropriate overall system life, or it may be designed to be replaceable as discussed above. As one might gather from the comments above, the exact test protocol for a driver is design dependent and can be extensive. The specific choice is beyond the scope of this document, but these comments should guide lighting manufacturers in directions that should be considered to achieve an overall reliable end product.

STANDARDS, REGULATIONS, AND PROTECTION

Depending on the type of power conversion utilized for the LED system, there are several areas of regulatory compliance that may be applicable. Because of the variety of system configurations, often the combination of a variety of component types, it is likely that the overall compliance requirements will need to be separately addressed by the different components. Exactly what is required of each subsystem or component is defined by the luminaire system designer, and it is important that any compliance requirements be accurately communicated to the respective suppliers so that proper regulatory compliance is assured.

A number of standard requirements apply to driver use: First and foremost, the system needs to be evaluated against Risk of Fire and Risk of Shock (i.e. Safety Compliance). In the US, UL8750, the ANSI *Standard for Light Emitting Diode (LED) Equipment for Use in Lighting Products* was created in 2009. For Europe and Asia, the applicable standards for LED power conversion devices are found in various sections of IEC 61347.

Systems typically require evaluation to ensure compliance with Electromagnetic Compatibility (EMC) industry standards. Depending on the anticipated useful life, criticality of use, and replacement cost of the system, additional protection of sensitive components may be warranted and must be evaluated. For the most part, these requirements are not unique to LED systems, although they may be meaningful differentiators when comparing LED system components. Examples might be protection for network communications built into the lighting systems, reduced power for operation during periods of high temperatures, and so forth.

Apart from these safety and protection issues, however, luminaire manufacturers strongly recommend that the industry **develop standardized ways to characterize drivers for use in SSL**. The concern is that because of different means of reporting, it is difficult for the lighting manufacturers to compare products and choose the appropriate one for their design. If possible, a standardized test and data set should be devised for the driver component degradation and failure rates.[4] Such data might then, together with LED data, allow an estimate of overall system reliability at least for failures or degradation of these two critical components.

The best way to find the optimal solution for the LED system being considered is through careful specification of the realistic operating parameters. These specific choices will influence system reliability as well as cost, so there will be design tradeoffs. A representative set of parameters would include:

- Input Power/Voltage Range
- Operating parameters (operating temperature and humidity, dry/damp/wet or IP rating)
- Minimum efficiency
- Minimum power factor correction
- Type of control/dimming
- Usage pattern (on-off cycling)
- Any unique project- or design-specific requirements
- Cost

COLOR SHIFTS

RELATION OF COLOR SHIFT TO LIFETIME

Luminaire system lifetime, as recommended by this document, refers only to lumen output of the fixture, but it includes failures due *not only* to systematic degradation of LED output as measured by LM-80, but also to any other mechanisms of overall lumen degradation, encompassing changes and complete failures in components other than LEDs or through interactions with the LEDs. As defined, therefore, **"end of life" does not take excessive color shift into account**, even though for some applications that might be considered a failure by the user. The decision to emphasize lumen output reflects the fact that lumen maintenance is related to safety issues in various applications while color stability is related to aesthetic concerns. Additionally, system color shift is difficult to define, measure, and project. While great progress has been made by the community in improving color stability, this reality could, nevertheless, result in customer dissatisfaction, so we discuss color shift in this section of the guide.

LM-80 recognizes that color is important[5] and, further, requires that the test report include "chromaticity shift reported over the measurement time."[6] It does not, however, provide any recommendation to project the shift to the end of life, nor does it address color shifts that may be attributable to the luminaire design or manufacturing. Further, there is no consideration of color shift effects in remote phosphor configurations. All of these items would seem appropriate for further study and possible standards in the future.

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[4] For further discussion of this issue, please refer to the latest edition of the *DOE SSL Manufacturing R&D Roadmap*, [link].

[5] LM-80, Section 6.2.

[6] Ibid., Section 8.0, item 13.

Experiments suggest that assuring that the temperature of the LED does not exceed certain limits and that the drive current does not change excessively, it is possible to extrapolate the LED lumen maintenance contribution to lumen depreciation to the luminaire. However, while the IES TM-21 effort to address this issue has suggested means to project limited experimental measurements to the end of life, it does not offer any suggestions as to how to project color shift.

Practically, this approach may not work for color shift. While a single test of color shift is not particularly expensive, assembling sufficient data on a large enough sample of product to characterize color shift accurately can be prohibitive both in terms of the time required as well as the resulting total cost.

THE FOUR CHALLENGES

This section describes a number of challenges of characterizing color, changes in color, and associating it with lifetime in more detail.

IMPACT OF LUMINAIRE DESIGN AND MANUFACTURING PRACTICES

Color stability, like lumen depreciation but to an even greater extent, is not exclusively determined by the performance of the LED. Examples of how luminaire design and manufacturing practices will impact color quality and color shift include:

- Different heat sink designs will mean that LEDs and the associated electronic circuits will likely see different operating conditions despite operating similar times under similar temperature conditions.
- Different materials used in secondary optics may age differently.
- Different environmental conditions (including air quality) may cause materials in different luminaires to behave differently.
- Different luminaire designs may create non-uniform color characteristics such as halos or yellowish, bluish, or greenish hues around the edges of the beam, and these color characteristics may vary over time.
- Some manufacturing processes have tight initial selection criteria, and others loose selection criteria, and that will complicate the determination of color shift over time.
- Finally, some luminaires address color shift with active color management, including sensors and controls. However, sensors and controls may themselves shift over time and affect color.

DESCRIBING COLOR SHIFT[7]

Consumers have no experience with, and cannot be expected to easily relate to, scientific or engineering terms that are used to discuss color, including “chromaticity,” “black body curves,” “LED bins,” or “Macadam ellipse.” There is no standard consumer definition that can be used as an alternative, although the current Lighting Facts label describes color in terms of CCT, or, to be more precise defines an ANSI bin limiting total color variation. For example, CCT of 3000 defines a color

[7] Throughout this section, "color shift" refers to changes occurring under normal operaing conditions and after the luminaire has stabilized after warm-up (not a significant period of time for LEDs, but may be important for fluorescents and other incumbent technologies.

space region defined in C78-377. This, along with qualitative descriptions such as "warm" or "neutral", may be adequate for many applications, as it is similar to descriptions now being used for conventional lighting.

But such expressions are not enough for more demanding applications. Correlated color temperature (CCT) has often been used to describe color and color shift, but that is insufficient for several reasons. For a given CCT value there is a actually a wide range of chromaticity values along the isotherm (both above and below the black body locus) that will all have the same CCT. This means that, for example, a 4000K LED can look greenish-white to purplish-white .

The IEC is considering a different approach to characterizing color and color shift, based on specific color coordinates, with tolerances defined in terms of numbers of "standard deviations of color matching" (MacAdam ellipses). Figure 5 illustrates one example of how such a concept might be applied to color matching, and, by extension, to color lifetime (remaining within some bound defined in terms of n-SDCM steps).

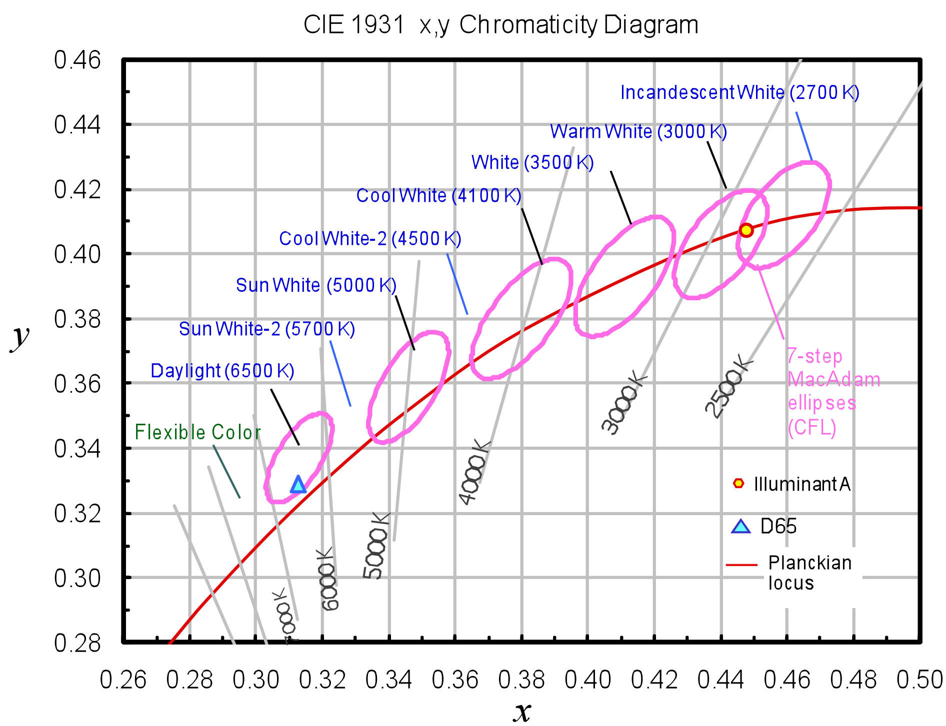

FIGURE 5. COLOR MATCHING TOLERANCES DEFINED IN TERMS OF 7-STEP MACADAM ELLIPSES CENTERED ALONG THE BLACK BODY CURVE. THE ELLIPSES SHOWN ARE DESIGNATED CCTS FOR CFLS. (SOURCE: NIST)

Unless the boundary is fairly tight, however, there can be quite perceptable mis-matches in color over time if different individual products drift in different directions with respect to one another.

PROJECTION OF COLOR SHIFT

Unlike many of the other parameters outlined in this document, color shift is not very well-understood, well-studied, or even commonly used as a metric, even for incumbent technologies. That said, we believe it is worth studying and characterizing as it may well be an important reliability consideration for certain applications because SSL products may remain in place for a long time. Although LM-80 requires LED manufacturers to collect data on color shift over 6,000 hours of operation, there is no accepted standard way to use this data to extrapolate color shift. While the IES TM-21 committee is working to define a method to project long term lumen maintenance of LEDs from LM-80 test data, developing a method to of extrapolating color shift is not within the scope of this committee's task. At present there does not appear to be any standardized color shift projection under consideration. It is also important to note that the actual measurements of color shift for the LM-80 testing are often not done in situ nor at steady state operation, but rather are short-duration, relative photometry measurements at room temperature. Additionally, color changes in luminaires with multiple types of LEDs may not be easy to characterize using single LED LM-80 testing.

Factors that will make color shift so difficult to extrapolate include differences in LED design, materials, manufacturing process, optics applied to the LED, and the temperature and time the LED operates. Many experts indicate that it will be a long while before there is general agreement on how to project color shift for an LED over an extended period of time.

PRACTICAL LIMITATIONS

Finally, there are practical limitations. While color and color shift can be measured relatively easily in an integrating sphere, test and measurement of multiple samples under various operating conditions can become very time-consuming and hence expensive. It may also require specialized equipment, such as a large thermal chamber to test a roadway fixture at different temperatures. While such expenses may be justified in limited professional applications sensitive to color, that is the exception rather than the rule.

SEGMENTATION OF THE LUMINAIRE MARKET

It is clear that considerable work remains before we will be in a position to accurately specify end-of-life color shift limits for a specific luminaire design. Given this situation, and pending further work by standards organizations, we **recommend that manufacturers designate products in one of three categories**: "lamp replacement," "luminaire (standard grade)," or "luminaire (specification grade)," and then treat color shift differently for each segment.

1. Lamp replacements are more amenable to LM-80 color shift measurements and projections since the design is consistently repeated, and sales volumes are high. Color can be specified on the Lighting Facts label in general terms for what is assumed to be a non-critical market.
2. Standard-grade luminaires would specify a maximum warranted color shift by specifying an n-step ellipse within which the product will remain within its lifetime. It would be up to the manufacturer to determine what limits should be specified and for how long a period the warranty applies, which may or may not coincide with the lumen lifetime.
3. Specification-grade luminaires are intended for more discerning customers. More sophisticated color metrics may be included in the specifications, and the maximum color

shift over the stated lumen lifetime would be provided. For these types of applications, the defined limit of color shift may need to be very specific, perhaps in terms of Δu'v', the shift of the actual color point. Some professional-use lamp replacements might be included in this category as well.

All three categories require some means for the manufacturer to predict color shift over a period of time, but with greater or lesser precision depending on the classification. Additional work is needed outside the scope of this document to improve these methods.

STANDARDS AND MEASUREMENT WORK

A number of follow-up activities are suggested in order to firm up specifications to promote market adoption:

- For consumer-directed products, there should be a short-term effort to **develop standard, broad qualitative descriptions of the degree of color shift over life.**
- A working group on bulb-replacement specifications should review these recommendations and determine if other specifications are needed.
- Segment-focused specification-grade luminaire teams should determine the appropriate standard specification for individual applications.

In summary, color and color shift are among the more complex issues that need to be addressed with the introduction of LED-based replacement bulbs and luminaires. Segmenting the market into the three broad areas listed above, and then identifying work-around solutions for short-term problems appears to be the best approach. In parallel, individual working groups should begin to address each segment's requirements in more detail to develop documented standards of color shift requirements and measurements.

SPECIFYING AND DEMONSTRATING LIFETIME

As the above discussions should make clear, specifying product lifetime for an LED luminaire can be complex. At the same time, customers require some understanding of lifetime in order to make intelligent decisions regarding the purchase of and LED product, which is often considerably more expensive than the incumbent alternative. Consumers, in particular, want a simple, easy to understand, estimate of product life, and recent rulings by the Federal Trade Commission[8] requires it for certain replacement lamp products. Commercial customers understand the trade-offs among energy efficiency, maintenance costs, and first cost of an LED product, but a clear expectation for each of these factors is essential for a realistic calculation. Many buyers and specifiers have signed on to the DOE LightingFacts program, and are asking that lifetime be included among the information provided through that avenue.

[8] http://www.ftc.gov/opa/2010/06/lightbulbs.shtm

LIFETIME SPECIFICATION

Given the need, and recognizing the limitations, the DOE and NGLIA recommend:
The "standard" or default lifetime of an LED luminaire (or lamp) be defined only in terms of lumen output, and be specified as the time when half the product population has fallen below 70% of average initial light output *for any reason*.

Just to be clear, while emphasizing lumen output, the definition goes beyond lumen depreciation to include *any* mechanisms that lower the light output. The above definition 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.

Whatever the stated lifetime of an LED lighting product, it is a statistical measure of the performance of a given design, in this case the mean time to failure because of low (or no) light output. In the above specification, the *standard reference level* of 70% of LED initial output is referred to as "L_{70}"; the *time* at which half the LEDs have fallen below this level is "B_{50}", and is the same as conventional rated lamp life. The minimum threshold (70%) chosen as the "default" failure level by which we define a "standard" lifetime may not exactly suit every application. For example in certain safety situations depreciation of this magnitude may be unacceptable, or in some cost-sensitive non-critical situations a higher level of depreciation may be acceptable. Nonetheless, the above definition is recommended as a standard life designation by which different products may be compared to one another. Additional specifications, as discussed in the next section, may be added to cover particular applications. These additional specs may cover other aspects of light quality that affect the product usefulness over time, or they may provide what amounts to a different estimate of useful life such as B_{50}/L_{50}, for example. Generally this additional information would be most useful for professionally designed lighting solutions.

ADDITIONAL OPTIONAL SPECIFICATIONS

COLOR SHIFT

For most purposes, specifying life in terms of ability to deliver adequate light is sufficient, although as noted above, some high-end applications may require additional information as regards color shift or different depreciation thresholds. Given the absence of a good way to project color shift for a product population, such information needs to be carefully handled. Until color shift extrapolation methods are developed and proven, the best approach now may be to state average color shift for the product only out to a time that has been measured, e.g. 6000 hours. Two coordinates are necessary to accurately specify color, so both must be considered in defining shift. So, for example, the changes in CCT and Duv (distance from the blackbody curve) could be used, or the actual average color coordinates in a CIE color space could be reported initially and after a specified time interval of operation.

ADDITIONAL FLUX SPECIFICATION

For some applications, the standard lumen lifetime as defined may not suffice. Reporting failure in terms of low light output regardless of cause may not give the designer enough information. If the lifetime is stated to be 40,000 hours, does that mean half the lights are at 70 percent of their initial output, or does it mean half the lights are nearly at full output and the others are completely out, or something in between?

To address this ambiguity, two numbers are needed: the lumen maintenance lifetime, e.g., B_{50} or B_{10}, *and* the conventional electric failure lifetime, e.g., F_{10} when 10 percent of the luminaires fail in a conventional sense. Both times—B and F—must be measured on the complete luminaire because of the interactions among the components.

Together, these B and F numbers can describe three types of luminaire failure:

1. All LEDs light up, but at a reduced light level (defined by time to B_{XX}).
2. There is a single (or a few) catastrophic LED failure(s), but other LEDs are still functional, perhaps running at a reduced light level (defined by time to B_{xx}).
3. No LEDs light up, due to system failure other than the LED (defined by time to F_{yy}).

The choice of *xx* and *yy* is up to the manufacturer and may vary by intended customer base or manufacturer; however, it should be explicitly stated. The examples of B_{50}/F_{10} above might not suit high-performance applications, for example, but may be satisfactory for general use. Such a designation is probably neither necessary nor useful for consumer markets.

DETERMINING AND MAINTAINING SPECIFIED LIFETIME

The means of determining lifetime are not fully standardized at this time. Additional observations concerning the determination of lifetime and methods of projecting lifetime from shorter-term measurements are discussed below.

Ideally, the number or numbers reported should reflect a sufficient set of measurements that can be reported with a reasonable degree of confidence. The **reported lifetime should have at least sufficient measurement accuracy and sample size to provide a 50 percent confidence level**. While this may be a practical limit in the near term, 90 percent or higher is more desirable. The working group recognizes that these measurements are expensive and time-consuming, and not all manufacturers may have the ability to comply when the product is first introduced. If the recommended minimum confidence levels are not achieved, manufacturers may prefer to *warrant* performance for a specific period of time instead of making a specific lifetime claim. If this is done, the working group recommends that the number be stated as a "warranted lifetime" as distinguished from a substantiated lifetime estimate.

When specifying a product's L_{70} lumen maintenance claim of B_{50} lifetime, or any other values, the manufacturer should validate the product life not only upon first release, but also in the event of any changes to the product during its lifetime. Such changes may consist of a design change (which includes product variants), change of component or subsystem material or supplier, a different manufacturing process, in short, anything that may affect product life. The rest of this section addresses some of the necessary steps to demonstrate the product's lumen maintenance life claim, separately considering a new platform, and then how to deal with variations in that platform. While some examples are shown, they are not intended to specify a standard procedure. Responsibility for specific standards lies with standards organizations and is beyond the scope of this guide.

NEW PLATFORM LUMEN MAINTENANCE

The preferred tool for measuring performance of LED systems is *IESNA LM-79-08 Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*. LM-79 prescribes uniform test methods under controlled conditions for photometric and colorimetric performance as well as electrical power measurements for LED fixtures as they would be manufactured for production. A key systemic element of LM-79 is that the LED fixture must be tested using absolute photometry which measures LED performance *in situ*.

For a new platform it is the manufacturer's responsibility to **demonstrate life performance compliance by testing luminous flux, in accordance with LM-79**, in a sufficient sample of product for a sufficient amount of time to have confidence in the lifetime figures.

To show compliance, a test report might include the following:

- Graphical presentation (with error bars) of lumen output versus time, color shift versus time, and input power versus time
- Summary table showing in lumen maintenance (percent) change in input power (percent), and change in color after 6,000 hours of testing
- LM-79 reports at T = 0 and T = 6,000 hours
- Description and details of the product under test and test setup
- Sample size and/or confidence interval

Although extrapolated LM-80 data for packaged LEDs has been used as a proxy for luminaire lifetime (and is an ENERGY STAR requirement), it only deals with lumen depreciation of a luminaire indirectly, and then only depreciation due to the LEDs themselves. There is also an issue regarding how to *accurately* extrapolate data of limited duration. The TM-21 committee of the Illuminating Engineering Society of North America (IES) has been exploring ways to deal with this latter problem. As of this writing, the results of this work have not been published, but when available, they may be used to extrapolate to the L_{70} value of the LED packages, but not for the luminaire. The working group therefore recommends LM-79 testing of the complete luminaire to determine lumen output over time.

PRODUCT VARIATION OF NEW PLATFORM

Recognizing possible platform variations to extend the product line for other applications (product groups) or material or design changes, additional measurements may be needed to ensure the platform is still qualified. Consideration may be given to minimize the number of test hours to demonstrate the long-term life performance as described above. In this regard, it is reasonable to consider the different types of change (or model variations) and their likely impacts on lifetime. Ultimately, this is the customer's choice, but it is recommended that manufacturers develop and document specific rules for change control to maintain the integrity of their products.

For example, changes in the following areas may be deemed to require significant retesting:

- Housing/chassis
- Thermal management/heat sink

- Change of assembly method or materials
- Light source (includes operating current, V_f, and LED supplier)
- Power supply

Other changes, such as in finish or out of the optical path, may require less requalification. Analytical data may often be used in part to demonstrate that the change has not influenced the lumen maintenance performance of the luminaire. But typically a small number of luminaires may need to be retested for some, perhaps shorter, period of time. If the manufacturer cannot demonstrate via analytical data or limited testing that life performance is not diminished, then the luminaire should be treated as a new platform and subject to full qualification requirements.

The relevant recommendations from this guide are that **manufacturers develop and document their own change control process**, and that they are responsible for providing sufficient justification to their customers so that any change will be accepted as having no material, deleterious effect on product lifetime.

ADDITIONAL CONSIDERATIONS

The above discussions provide an outline of current understanding of the issues surrounding LED luminaire reliability and lifetime. A basic recommendation for a standard, default designation of product life is provided, along with some suggestions for additional characterization in certain applications or markets. During the course of discussions to create this report, the working group considered a number of additional aspects of product lifetime. Several of these issues are discussed in this section:

- Design for system reliability
- Product labeling
- Warranties

DESIGN FOR SYSTEM RELIABILITY

A thread running through many working group conversations was that the methods available to us today to demonstrate full luminaire performance over time (using LM-79) may be too costly or time-consuming to be practical in many circumstances, especially given the rapid evolution of SSL products. The result is often a fall-back to the use of LED package lumen depreciation as a proxy for product lifetime, and the fear is that this will lead to customer dissatisfaction with this new and promising technology.

LED operation is interdependent upon drive electronics, the thermal management system, and the optical system, as well as upon proper and controlled materials and manufacturing processes. Because of the resulting complexity, it may be more efficient and effective to take a system reliability approach in the design of the LED lighting fixture. By understanding how each of the system's components contributes to failure, one can estimate overall reliability and optimize the design for best performance. Figure 4 is a simple illustration of how information on various individual parts of the system can be combined to arrive at an overall estimate of lifetime. If statistical information on failures were available even for the major subsystems of a luminaire, it would be a big step towards more realistic estimates of product lifetime. While this would not obviate the need to verify lifetime anytime soon, it could eventually reduce the overall testing requirements.

As noted earlier, however, some failure modes may be as a result of interaction between parts of the system, which requires still more sophistication in the analysis. For example, LED manufacturers typically use pulse mode operation with a very short pulse—typically 10 or 20 milliseconds—which will not heat up the LED. On the other hand, *in situ* there may be numerous LEDs, often in close proximity to one another, operated continuously. These conditions elevate T_J above 25°C, thereby affecting photometric and colorimetric performance of the LEDs. This effect is offset by various thermal management approaches incorporated into the luminaire design which the system reliability design will need to take into account.

The DOE SSL *Manufacturing Roadmap* recommends that LED *driver* manufacturers provide uniform data for LED fixture manufacturers to include a number of specific performance results to assist in luminaire design. A similar approach might also be applied to other components and materials. Once such information begins to become available, software to analyze and combine the data into an overall system reliability estimate will be needed. The working group believes that the industry working together to **arrive at standard methods to report and process statistical reliability information** could be highly beneficial in terms of the effort and cost needed to achieve reliable product design, as well as the accuracy of the resulting lifetime predictions.

LABELING RECOMMENDATIONS

The DOE Lighting Facts® label should be augmented to **include the standard LED product lifetime**, L_{70}/B_{50}, as defined in this document. Recognizing that some manufacturers may not have the ability or time to demonstrate lifetime in accordance with these recommendations, the label should not *require* that lifetime be stated, but if it is stated, then it should be reliably established with standard tests. Otherwise, a specific lifetime should not be claimed at all. If lifetime is not stated, then it is recommended that at least one of the other options described below, lumen depreciation or a warranty, or an estimate based on accelerated testing of components, be provided on the label.

The label should also be augmented to indicate whether the product is "serviceable" or "not serviceable" as defined in this document.

OTHER OPTIONS

The DOE Lighting Facts label should also be modified to include, *optionally*, a **warranty period** to cover either lumen lifetime, color shift, or both. The warranty period may or may not coincide with lifetime (if claimed) at the manufacturer's discretion. This warranty may be particularly useful to manufacturers who, while not able to demonstrate a lifetime in accordance with the recommendations, are nonetheless prepared to guarantee performance over some period of time. This may be especially useful for new products also.

Absent lifetime data as prescribed, the manufacturer may alternatively or in addition to a warranty state the LED lumen depreciation time to L_{70} based on LM-80 data and a projection (eventually per TM-21) . Because present practice is often to use this figure as a proxy for lifetime, however, the label should be explicit:

> **The time shown should be described as "LED lumen depreciation to L_{70}", and *not* as "Lifetime" and avoid any implication that it represents tested product lifetime.** Further, this depreciation time value should *only* be shown if the manufacturer can assure that the LEDs are operating at or below the temperature of the LED LM-80 testing that was used to project the designated value, and that the drive current in the luminaire does not exceed that used for LM-80 testing during the stated time period. Additional information that should be readily available to the purchaser, although not on the label itself, should include maximum ambient temperature of operation to achieve this depreciation performance, the number of hours actually tested on which the projection is based, the type of projection if not in accordance with TM-21.

If a manufacturer has developed proprietary techniques for accelerated testing of components and system modeling as suggested in the previous section, then he may choose to designate an **Estimated System Life** on the label using that figure. In no case should this exceed the lumen depreciation period estimate, however.

DOE Lighting Facts may require substantiation of any lifetime claim put forth for use on the label. Also, the burden of proof to show that any platform changes have not materially affected lifetime lies with the manufacturer.

The label should further be modified to show, *optionally*, certain **color shift** information depending on the market segment:

- A general qualitative description of color shift, or
- A maximum color shift warranted for some period of time, or
- The maximum color shift over the stated lifetime

For the short term, color shift, if quantitatively specified, could be described in terms of change in CCT. For some applications, and for professional use, actual limits on the change in color coordinates should be specified, but it is not recommended that they be included on the DOE Lighting Facts label.

Since the original publication of this guide, the FTC has developed requirements for a similar label for certain replacement lighting products. While this label has the same name but is formulated somewhat differently, which may lead to some confusion, the working group hopes if possible that the FTC adopt the same definition of lifetime as recommended in this guide so that there is at least that degree of uniformity among products and labels.

THE ROLE OF WARRANTIES

Given the early stage of LED lighting technology, it is difficult to accurately predict product lifetime. Warranties provide a means for the potential buyer to reduce risk. While this document provides some guidance on what might be included in a warranty, it is ultimately the manufacturer's decision on how best to provide this protection and how much risk to take in doing so. The warranty may logically be shorter than the claimed lifetime as defined below. As there will be a distribution of times of failures for any product, the degree of risk on the part of the manufacturer depends on the level of confidence in the projected lifetime and the amount of variation in that distribution.

RECOMMENDED FURTHER READING

1. IPC-9592A, "Requirements for Power Conversion Devices for the Computer and Telecommunications Industries"
2. Mao, George and Miles, Marshall, "*LED driver lifetime and reliability hold the key to success in LED lighting products"*, LEDs Magazine September/October 2010, pages 33-37.
3. Weiss, Bill, "*Lighting for Life*", Digi-Key TechZone TSL101.US, pages 8-14.
4. Benatti, John, "*MTBF and power supply reliability"*, Electronic Products, August 2009.

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